TECHNISCHE UNIVERSITÄT MÜNCHEN
Lehrstuhl für Produktentwicklung

Systematic identification of Flexible Design Opportunities in offshore drilling systems

David Allaverdi

Vollständiger Abdruck der von der Fakultät für Maschinenwesen der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktor-Ingenieurs

genehmigten Dissertation.

Vorsitzender:	Prof. Dr.-Ing. Hans-Jakob Kaltenbach
Prüfer der Dissertation:	1. Prof. Dr.-Ing. Udo Lindemann
	2. Prof. Tyson R. Browning, Ph.D.
	3. Prof. Dr. rer. nat. Dr. h.c. Ulrich Walter

Die Dissertation wurde am 18.04.2017 bei der Technischen Universität München
eingereicht und durch die Fakultät für Maschinenwesen
am 03.10.2017 angenommen.

FOREWORD OF THE EDITOR

Problem

Technical systems of several industries face strong uncertainties regarding their utilization especially when being exposed to long lifecycles. As a result, the initially designed system oftentimes does not fit to the future changing environment. Especially large-scale systems that entail very large investments are exposed to those long lifecycles and uncertainties; however, both business models and stakeholders dealing with such systems regularly use point forecasts in design without proactively accounting for the eventuality that the actual situations in the future may be very different from the ones the technical system is designed for. As a result, there is a large potential of better strategic planning of those systems and, consequently, enabling a better response to dealing with alternative futures once uncertainties unfold.

The offshore drilling industry is one very relevant representative to strongly benefit from the early consideration of such uncertainties. By embedding or planning for flexible systems in early design phases, the drilling systems can better deal with unfolding uncertainties, as physical changes on the rig then can be performed more efficiently and effectively. Indirectly, flexible design also lowers the threshold of performing those changes in the first place and, thereby, widens the application field on systems that run below their potential.

Objectives

Although research has provided various contributions to deal with future uncertainty, up until now it has still missed a coherent framework to systematically guide the user from an initial design basis to the actual flexible design solutions. In related methodologies the constituents leading to the generation of flexible design solutions are to a large extent identified “ad hoc” and lack comprehensiveness. Mostly the focus is set on the valuation of the suggested design alternatives. In particular, the alternative change strategies and the large number of enablers to facilitate those changes are usually not the focus which certainly limits the confidence in the derived flexible design solutions.

Consequently, based on a very careful and accurately derived industrial need and a profound literature review in the partially still separated academic fields of engineering design, engineering systems, manufacturing and factory planning, this thesis addresses those deficits by introducing a methodology of its own. The suggested methodology pursues the goal of facilitating large drilling system suppliers, the architects of the drilling system, to successfully embed flexibility into technical systems; this, in turn, should allow system users to better deal with unfolding uncertainties when the system is in operation, thereby, lowering the threshold to perform upgrades in the first place and reduce upgrade efforts. The positive effects, however, should not be limited to the system users but positively influence the value chain as a whole.

Results

This thesis provides two main research contributions: First, it suggests a comprehensive methodology accounting for the uncertainties outside of the technical system and guiding the process of identifying affected physical constituents within the technical system. Once the latter are identified, it supports enabling those physical constituents with suitable flexibility and, finally, evaluating those to derive high-performing flexible design solutions. The methodology emphasizes that technical consistencies, e.g. between change strategies and enablers, exist across domains in the identification process which must be accounted for. By providing a multi-domain, matrix-based and customer-project independent sorting framework and database storing all potential elements and relations, the identification is performed in a separate matrix-based execution model that uses that database and the tacit knowledge of experts to assess the relevancy of constituents and relations for the specific customer project of concern. The methodology is enhanced by facilitators such as consistency matrices or portfolios to better meet the requirements of the methodology. The second research contribution is represented by the systematization of change strategies, in particular a limited set of operators, and specific enablers being design guidelines for facilitating that change.

The methodology is validated with a major and relevant use case in the offshore drilling industry. To ensure the validity of the findings, an expert evaluation was performed which confirmed both the relevancy of the methodology and its fulfillment by strongly meeting the underlying requirements that guided the development of the methodology.

Conclusions for industrial applications and scientific research

As David Allaverdi was given comprehensive access to resources in the industry, in particular a large drilling system supplier, and with his background knowledge on the boundary conditions of the offshore drilling industry, the thesis was developed in strong alignment with the industrial needs. Consequently, the final results, as being confirmed by the expert evaluation, are both strongly relevant and also suitably implemented for being practically applicable in the addressed industrial context. Despite the focus on the offshore drilling industry, however, the field of application is seen to be much wider and, consequently, should be as well considered by practitioners of related industries (e.g. factory planning).

Both the industrial need and the research gap were carefully confronted to derive an industrially as well as scientifically very relevant research. This thesis represents a work with a thoroughly identified research gap and strong rigor that significantly extends the status-quo of research in engineering design.

Garching, January 2018

Prof. Dr.-Ing. Udo Lindemann

TUM Emeritus of Excellence
Chair of Product Development
Technical University of Munich

ACKNOWLEDGEMENTS

I want to take the opportunity to pause for a moment and recall the people that have contributed to my research. First and foremost, I would like to thank my doctoral advisor Prof. Udo Lindemann for giving me the opportunity to become part of the team at the Chair of Product Development and the continuous support across the way. Prof. Lindemann's industrial and academic experience were essential to confirm and guide the industrially motivated research and, thereby, balance its relevancy and rigor. Special thanks also go to Prof. Tyson R. Browning of the Neeley School of Business in Fort Worth (Texas) who gave me very useful feedback and challenged me by asking the right questions to further increase the quality of my thesis. As matrix-based methods play an essential role in this thesis, it was a privilege to have been guided by Prof. Browning who has substantially coined this field. Next, I highly appreciate Prof. Ulrich Walter also being my co-examiner. Not only did it remind me of my childhood dream of becoming an astronaut, but the field of "space systems" and "space systems engineering" was especially relevant as it represents another related field of application of my research. At last, I am grateful to Prof. Hans-Jakob Kaltenbach having agreed to act as a chairperson of the examination board and by managing the dissertation process so smoothly.

As this research was industrially motivated and funded, I would like to express my special thanks to MHWirth AS (formerly Aker Solutions Drilling Technologies) and the colleagues of the department "Technology & Innovation": They supported my interest in research and provided me the opportunity to spend time on this topic in the first place. I was also provided freedom and trust to identify and clarify the industrial and company need for this research. MHWirth AS has generously helped me to bridge the geographically separated locations of company office and chair between southern Norway and southern Germany. Being embedded at the industrial site, I was provided access to precious expertise that allowed me to gain the depth that was required to understand the needs and develop my research contents. I do appreciate MHWirth AS supporting me as planned despite facing difficult times when the crisis hit the oil & gas sector. Many colleagues supported me that I cannot mention individually. Nevertheless, the following people cannot be left unmentioned as they played a major role across the entire process:

Kristin Wallevik and Sjur Henning Hollekim who guided and supported me along this process by especially helping me to find the right balance between the industrial and academic perspective. I will always remember our valuable status and one-to-one meetings. Geir Ingebretsen with his unprecedented practical experience on offshore drilling who strongly contributed to deepening and validating my understanding on the offshore drilling market, drilling systems and processes. He always walked the extra mile with a smile on his face. Trond Ove Nygård who not only significantly contributed with his experience on upgrade projects and enthusiasm for innovations, but also by believing and even continuously quantifying the value of my research. Finally, my special thanks go to Hallgeir Angel for appreciating the relevancy of my research, the various coffee cup discussions and by having made efforts of promoting my research in the organization.

With this research having been co-funded by the Research Council of Norway, I also express my gratitude to them for having accepted and supported me across the way.

At this stage I also want to thank my former colleagues at the Chair of Product Development who not only gave me essential insights on my research but let me enjoy that time and the breaks in between. My special thanks go to Matthias Kreimeyer for his continuous believe in me and his precious mentoring along the way after having left the chair. Sincere thanks also to Arne Herberg who has always been an important "sparring partner" across different phases of my research. I'm also indebted to the students that I supervised and who have contributed to the maturation of my thesis, especially Florian Schlather and Dimitrios Carathanassis.

My thanks also go to Michel-Alexandre Cardin (Assistant Professor at the Department of Industrial Systems Engineering and Management, NUS, Singapore) who actively supported me with his deep background on "Design for flexibility". In particular, I thank him for the various talks at conferences and skype calls allowing me to find the focus in my research.

This research could not have been performed without the support of my family. They have not only believed in me but provided me with the freedom and the environment to pursue my research without disturbance. I dedicate this work to my deceased grandparents, especially Babička, my loving grandma, who passed away during the time of my research and right after my wedding. Special thanks go also to my parents: Helmut who has supported me in so many life situations, reviewing my homework before I stopped growing and giving me guidance since I am an adult. My mom Iva, whom I could dedicate an own section, who has always given me the best support, no matter what it was.

I want to close by thanking especially my wife Lisa who has persevered through the turbulent times at different phases of my research. The love she has given me made me continue and pursue my goal. Thanks go also to her parents, my parents-in-law, for their continued encouragement.

All of you. Thank you so much. I will always remember your contribution.

Munich, February 2018 David Allaverdi

THE FOLLOWING PUBLICATIONS ARE PART OF THE WORK PRESENTED IN THIS THESIS:

ALLAVERDI 2012
Allaverdi, D.: Systematization of context and external influences for more efficient drilling processes of floaters. In: Proceedings of Systems Engineering in Ship & Offshore Design Conference. Systems Engineering in Ship & Offshore Design. London [UK], 28.03.-29.03.2012. The Royal Institution of Naval Architects (RINA) 2012.

ALLAVERDI ET AL. 2013
Allaverdi, D.; Herberg, A.; Lindemann, U.: Lifecycle perspective on uncertainty and value robustness in the offshore drilling industry. In: Proceedings of 7th Annual IEEE Systems Conference (SysCon 2013). Orlando [FL, USA], 15.04.-18.04.2013. Piscataway [NJ, USA]: IEEE 2013, pp. 886–893. ISBN 9781467331074.

ALLAVERDI ET AL. 2014
Allaverdi, D.; Herberg, A.; Lindemann, U.: Identification of Flexible Design Opportunities (FDO) in offshore drilling systems by market segmentation. In: D. Marjanović, M. Štorga, N. Pavković and N. Bojčetić (Eds.): Proceedings of the 13th International Design Conference (DESIGN 2014). Dubrovnik [Croatia], 19.05.-22.05.2014. Glasgow [UK]: The Design Society 2014, pp. 1451–1462.

ALLAVERDI ET AL. 2015
Allaverdi, D.; Herberg, A.; Lindemann, U.: Identifying Flexible Design Opportunities: Getting from a Procedural to an Execution Model. In: C. Weber, S. Husung, M. Cantamessa, G. Cascini, D. Marjanović and S. Venkataraman (Eds.): Proceedings of the 20th International Conference on Engineering Design (ICED '15). Milan [IT], 27.07.-30.07.2015. Glasgow [UK]: The Design Society 2015. ISBN 978-1-904670-73-5.

CONTENTS

LIST OF ABBREVIATIONS

AAV	Architecture Adaptability Value
BC	Boundary Condition
BFE	Builder Furnished Equipment
BOP	Blowout Preventer
BR	Basic Requirement
Cap	Capability
CAPEX	Capital Expenditures
CCTV	Closed-Circuit Television
CE	Conformité Européenne
CIRT	Change Initiators and Relationship Types
CMEA	Change Modes and Effects Analysis
COM	Compatibility
CON	Connectivity
Cond	Condition
Const	Constraint
CPI	Change Propagation Index
CPM	Change Prediction Method
DCC	Drillers Control Cabin
DCF	Discounted Cash Flow
D-CPTs	Detected Changeability Potential Type
DFS	Desired Flexibility Score
DML	Dedicated Manufacturing Lines
DMM	Domain Mapping Matrix
DNF	Disjunctive Normal Form
DNV	Det Norske Veritas
DRM	Design Research Methodology
DS	Descriptive Study
DSM	Design Structure Matrix

E&P	Exploration & Production
ED	Enabler-Driven (approach)
ESM	Engineering Systems Matrix (also ES-MDM)
ES-MDM	Engineering Systems MDM
FDO	Flexible Design Opportunity
FDO EM	FDO Execution Model
FDO PM	FDO Procedural Model
FFMS	Focused Flexibility Manufacturing System
FMS	Flexible Manufacturing System
FPDP	Flexible Platform Design Process
FPSO	Floating, Production, Storage and Offloading
GBM	Geometric Brownian Motion
HoQ	House of Quality
HRR	High Revisit Rate
HSE	Health Safety Environment
HVAC	Heating, Ventilation and Air Conditioning
ICI	Incoming Change Impact
ICL	Incoming Change Likelihood
IDR	Invariant Design Rules
IRF	Integrated Real Options Framework
ITT	Invitation to Tender
KPI	Key Performance Indicator
LCE	Lifecycle Engineering
LR	Long-Range
LRR	Low Revisit Rate
MAV	Micro Air Vehicle
MDM	Multiple-Domain Matrix
MGS	Mud Gas Separator
MOB	Mobility
MOD	Modularity
MODU	Mobile Offshore Drilling Unit
MPD	Managed Pressure Drilling

NCS	Norwegian Continental Shelf
NPT	Non-Productive Time
NPV	Net Present Value
OCR	Outgoing Change Risk
OEE	Overall Equipment Effectiveness
OFE	Owner Furnished Equipment
PCA	Principal Components Analysis
P-CPT	Preliminary Changeability Potential Type
PS	Prescriptive Study
PSS	Product-Service-System
QFD	Quality Function Deployment
QKC	Qualitative Knowledge Construction
RAS	Reconfigurable Assembly System
RC	Research Clarifications
RDD	Riser Drilling Device
RFI	Request For Information
RFP	Request For Proposal
RFQ	Request For Quote
RGHD	Riser Gas Handling Device
RMS	Reconfigurable Manufacturing System
ROA	Real Options Analysis
RSI	Risk Susceptibility Index
SC	Switching Cost
SCA	Scalability
sDSM	Sensivitity Design Structure Matrix
SIC	Seal Integrity Circuit
SMaRT	System Modeling and Representation Tool
SoS	Systems-of-Systems
SPE	Society of Petroleum Engineers
SR	Short-Range
TC	Transition Cost
TD	Transition-Driven (approach)

TRF	Transformable Factory
TRIZ	Theory of Inventive Problem Solving
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
UMGS	Ultra High Rate Mud Gas Separator
UNI	Universality
VOF	Value of Flexibility
WTE	Waste-To-Energy

1. Introduction: Focus of research in thesis

*The offshore drilling business environment is complex and uncertain leading to limited strategic planning of drilling systems and reactive behavior [*WHITESIDE *2001]. Oftentimes, rigid, i.e. non-flexible design prevails without accounting for future uncertainties when the system concept is defined. This leads to major value losses across the lifecycle for the users of the system and leaves a lot of potentials across the value chain unused.*

This work suggests to support System Suppliers in the identification of a suitable flexibility for customers and system users by following a methodology that is developed and evaluated as part of this research. Being industrially motivated, this work addresses the carefully identified research gap regarding the identification of high-performing flexible design solutions in real-world conditions.

In the following section 1.1 the background and situation in the offshore drilling industry is introduced as it is essential for understanding the need and the constituents of this research. Subsequently, an industrial based problem description highlights the deficits and potentials of better dealing with the addressed uncertainty (section 1.2). Section 1.3 bases upon the problem description and defines the research scope and objectives of the methodology. Based on that the research approach and methods are introduced (section 1.4) which is followed by a presentation of the thesis structure (section 1.5).

1.1 Basics and situation in offshore drilling industry

An important contribution in the oil & gas industry is the upstream oil & gas sector also known as the exploration & production sector (E&P). “Offshore drilling”, in particular, refers to drilling wellbores below seabed, either for exploration or extraction of petroleum and gas from those oil fields. In section 1.1.1 a basic understanding of the offshore drilling environment is provided by introducing rig types, the process of making a well and the main topside drilling systems that enable the drilling process. Section 1.1.2 focuses on the main stakeholders, stakeholder constellations and business models of this industry which have implications on the research focus and results. Section 1.1.3 focuses solely on the status-quo of the upgrade market and the potentials of handling uncertainty better. Finally, in section 1.1.4 an industrially relevant case is shown that illustrates the need for preparing drilling systems for future changes.

1.1.1 Basics in offshore drilling and engineering

Rig types

An offshore drilling rig is a large structure placed offshore to house workers and machinery in order to drill and, often, also produce oil and natural gas through wells. The rig may either float or be (semi-)permanently attached to the seabed (Figure 1-1). Depending on the different technical, economic, governmental, and safety requirements to accomplish a specific drilling program, offshore drilling rig vary in type, size and capability [Infield Systems Ltd 2016].

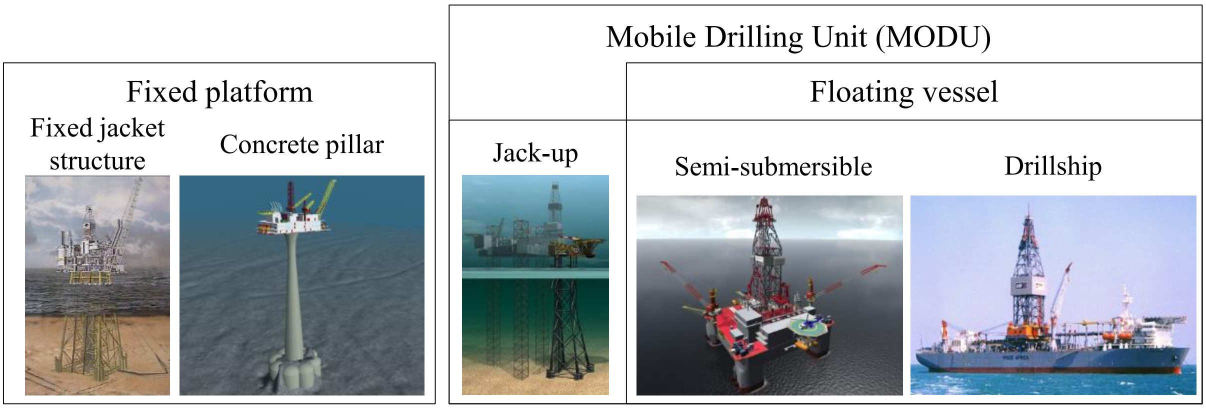


Figure 1-1 Main rig types in offshore drilling industry (Images: MHWirth AS)

Fixed platforms are rigs that are permanently fixed to the seabed mainly by steel jacket structures or concrete pillar and meant for long-term drilling and production. They have high construction costs, are immobile and limited to shallow water depths only (approx. 500 m). They are economically feasible for very large oil reservoirs and able to withstand extreme weather phenomena as they are not floating. In contrast, Mobile Offshore Drilling Units (MODUs) are mobile drilling rigs which can be moved without substantial effort and are not permanently fixed to the seabed. They include floating vessels but also jack-up rigs that are temporarily placed on the seabed.

Jack-ups are hybrid rigs that are neither fixed permanently to the seabed nor floating during operations. The buoyant hull is fitted with a number of movable legs capable of raising its hull over the surface of the sea. Operations, both exploration and production drilling, can only be performed in very shallow water depths of up to 120 m [Mather 2000, p. 14] as the jackets are placed on seabed. Jack-ups are either towed to the drilling position by tug boats or carried on the back of a submersible heavy lift ship. Jack-ups combine the advantages of floating vessels by being mobile while withstanding harsh environments similarly to fixed platforms.

Semi-submersibles are floating vessels which have a number of pontoons that are submerged beneath the water line to float and remain stable in one location. The deck is positioned above the water line and sits on top of columns which connect the hull to the submerged pontoons. Semi-submersibles must be towed between drilling locations as a main propulsion plant is missing. Oftentimes, however, they are self-propelled by azimuthing thruster units to maintain position in areas above 650 m where anchoring is impractical [Mather 2000, p. 7]. Semi-submersibles offer a high level of stability and accurate station-keeping even in harsh environments.

Drillships, the other large group of floating vessels, are self-propelled units with a large payload capacity, hence, making them more independent from supply vessels. They are suited for mid-water until ultra-deep water depths and, due to their operational flexibility, are very suitable for exploration drilling, i.e. searching for information on formations in yet unexplored areas by having a main propulsion plant.

Although other less prevalent types of rigs exist, they are not relevant to be introduced in this research context. All types of rigs follow generally a similar process of drilling and performing well completion before production begins. However, being exposed to strong uncertainties[1] and therefore considered to be most relevant for this research, the process of making a well is described for floating vessels only.

Making a well

A very abstract typical process is presented as further details of the process that could differ (e.g. due to specific rig functions, objectives, environmental circumstances) are irrelevant to differentiate in this research (Figure 1-2). It represents the main drilling process with the main phases from start until completion of a well.

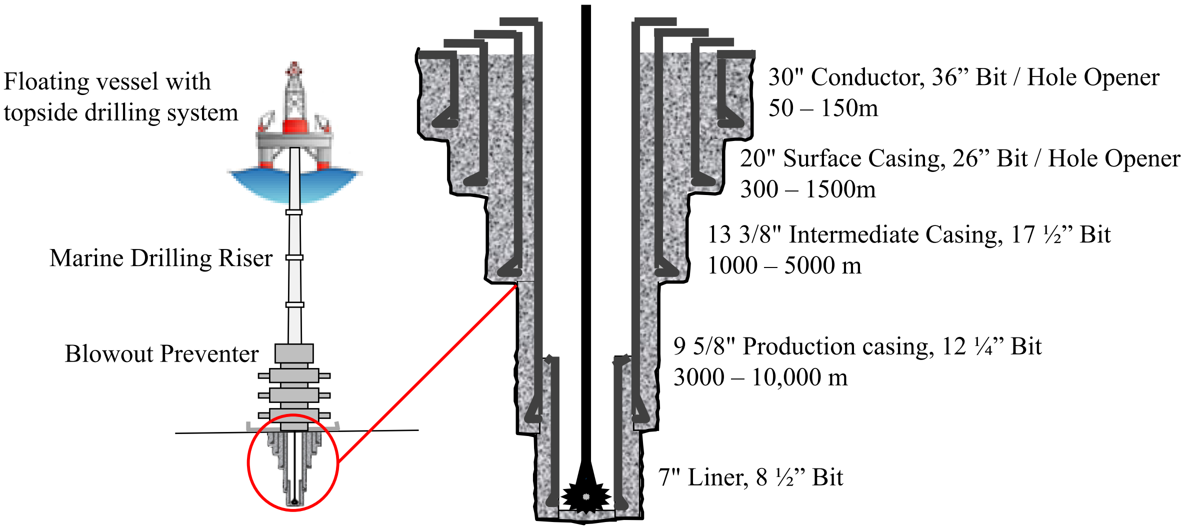


Figure 1-2 Typical well performed offshore by floating vessel (Images: MHWirth AS)

A large diameter drill bit (36"), also referred to as "hole opener", is usually attached to the drillstring, a high-strength steel pipe, which is lowered to the seabed. Drilling of the upper section (50 m – 150 m) is performed by rotating the drillstring and keeping pressure bottom-hole. The formation is broken apart mechanically by the bit containing cutting elements. The circulation of high-density mud[2] powers the drill bit that produces cuttings which are usually removed from the wellbore and returned to the surface by circulating mud through the drillstring and up the annulus. After tripping out of the hole, a casing string of less diameter, a 30" Conductor, is run into the hole. The mud in the annulus is displaced and the conductor cemented in place. As all upcoming casings, the casing is hung-off in the wellhead that is placed on the seabed.

A subsea Blowout Preventer (BOP), which represents a large valve to prevent uncontrolled release of oil and natural gas from the well is then set on the wellhead. Marine Drilling Risers, which are large diameter pipes that represent a temporary extension of the wellbore, connect

---

[1] Floating vessels can operate in diverse environments and world locations being exposed to even stronger uncertainties in comparison to other rig types.

[2] In upper sections the mud is usually water-based and not oil-based as in the other well sections.

the subsea BOP to the floating vessel guiding the mud returns to the surface [Schlumberger 2015].

The process of drilling and casing setting is repeated with a smaller diameter drillstring assembly (26” drill bit) that is lowered through the Riser and BOP up to a drilling depth of 1500 m. The previous process of casing cementing is repeated by setting a 20” surface casing.

Depending on the wellbore stability and length various other intermediate casings may be set before the production casing is installed as shown in Figure 1-2. In contrast to the other casings, the production liner that is set into the productive formation is hung-off at the end of the production casing. A production tubing and packers are set to guide the flow through the production tubing once the liner in the productive formation is perforated to produce the well (not visualized in Figure 1-2). During completion, a Christmas Tree, an assembly of valves, spools, pressure gauges and chokes are set on the wellhead to control the flow of formation fluids from the well [Schlumberger 2016]. Once production is successful the BOP is removed and only the Christmas Tree remains on sea bottom. This finalizes the making of the well and sets the starting point for pipeline production.

The topside drilling system enables the making of a well. Hence, the topside systems that define the scope of the System Supplier are briefly introduced below.

Topside drilling systems

The main drilling process is enabled by supportive processes that occur on the rig [ALLAVERDI 2012]. As they can mainly be attributed to activities above sea level, they are referred to as “topside processes”. Depending on the main drilling process, different types, scope and interactions of topside drilling systems are required on the rig. Figure 1-3 illustrates a typical conventional topside drilling system.

The conventional hoisting system consists of machinery that helps to lift and lower the drillstring by Drawworks, Crown Block, Travelling Block, Deadline Anchor that are aligned on the drill line and a Derrick structure for supporting the drillstring and the machinery. The Topdrive is freely suspended enabling the turning of the drillstring and by moving up and down the Derrick, lifting and lowering the drillstring which facilitates the drilling operation. A back-up system for turning the drillstring is the Rotatory Table that is located in well center.

Floating vessels require compensation systems for the drillstring to compensate for the rig motion between the oscillating rig and the static seabed or bottom-hole. Drillstring Compensation Systems are mounted on the top of the Derrick; they compensate the relative movement of the drillstring passively and, oftentimes, also actively by Active Heave Compensation. The Riser Tensioning System, in contrast, is located in the lower rig “moonpool area” preventing buckling by a nearly constant pull on the riser string.

Figure 1-3 A typical conventional topside drilling system[3] *(Image: MHWirth AS)*

Single tubular such as drill pipes, risers and casings are usually stored in a horizontal position on pipe deck or on riser deck respectively. Horizontal-to-vertical tubular handling refers to the process of transporting and changing the orientation of those tubular from a horizontal to a vertical position on drill floor[4]. This requires several Cranes, Chutes and Feeding Machines for handling. In the vertical position casings and drill pipes are usually racked to stands and stored in Finger Boards of the Derrick structure to increase drillstring running efficiency. Risers, in contrast, are always run as single tubular and stored in separate Finger Boards. The vertical handling of tubular between storage areas and well center is referred to as "vertical tubular handling" performed by miscellaneous Cranes and Arms. Making up and breaking of tubular, can either directly contribute to the drilling process at well center or "offline" away from the well center to fill storage areas first. Either is mostly done by a dedicated machine, the Roughneck.

The heavy equipment handling system located in the moon pool area mainly deals with transporting, lifting and guiding heavy equipment, especially BOP and Christmas Trees by various Cranes, Skidding and Structural Support Systems. It facilitates both the main drilling process but also auxiliary processes such as inspection and testing.

A mud circulating system is used to break up formation and carry cuttings to the surface. Drilling mud is the main medium that, on the one hand, removes and carries cuttings to the surface, on the other hand, cools, lubricates the drill bit and drillstring. The circulating system mainly contains Bulk Storage Tanks for mud and cement, Mixing Equipment, High and Low Pressure Pumps, Mud Treatment Equipment and Cuttings Storage Facilities. Conventional

---

[3] Figure 1-3 only highlights main drilling systems. The circulating system is not visualized.

[4] The relatively small work area around well center in which the rig crew conducts operations, usually adding or removing tubulars to or from the drillstring.

drilling is performed under atmospheric pressure opposed to Managed Pressured Drilling (section 1.1.4).

Power Generating Units, usually centrally allocated on a rig, provide power to the machinery on the drilling rig by either diesel or gas fueled engines or gas turbines to be independent from rig external power sources [MATHER 2000, p. 23]. The electric power, in turn, either powers electrically-driven machines directly or, indirectly, by converting the electric power to hydraulic power in Hydraulic Power Units. Usually the generated hydraulic power is then distributed through a ringline system on the rig to the hydraulically powered equipment.

The Drilling Control & Monitoring System constitutes both physical and software-related solutions for controlling and monitoring all main- and topside process-related operations such as Drillers Control Cabins, Drilling Control Systems, Anti-Collision Systems, CCTV, etc.

In the following the main characteristics of the offshore drilling business environment are introduced.

1.1.2 Offshore drilling business environment – Stakeholders, constellations and business models

The offshore drilling industry[5] constitutes various stakeholders that actively contribute in the value chain. E&P companies[6] or also referred to as "Operators" that control the rights of oil reserves represent the end customers in the addressed upstream oil & gas sector. Various product and service suppliers contribute to the production of oil.

The Operator is responsible for project planning, budgeting and the control of drilling operations in the utilization phase of the drilling system. The Operator authorizes a Drilling Contractor to perform drilling operations which he is responsible for. Services that involve specialized equipment and competency (e.g. well logging, wireline operations, and subsea completion) are mostly outsourced to so-called Service Companies. They are subcontracted either directly by the Operator or by the Drilling Contractor. Operators usually pay fixed day-rates to Drilling Contractors where the Operator takes most of the responsibility and economic risks; in contrast, the Drilling Contractor that provides the drilling rig and systems together with the personnel is accountable for the technical execution [MÜNCH 2013, p. 39]. The day-rates are paid independently of the performance of the Drilling Contractor; however, lower day-rates or even stops of payment might occur in case of downtime (e.g. wait-on-weather, repair) or constrained operations.

Turnkey contracts, in contrast, shift the responsibility to Drilling Contractors by determining a fixed price upfront for making a well according to a drilling plan pre-defined by the Operator [CHAFCOULOFF ET AL. 1995]. In incentive-based contracts the responsibilities between Operator and Drilling Contractor are similarly split as in day-rate contracts; however, payments to Dril-

---

[5] Again, the focus lies on floating vessels such as semisubmersibles and drillships. Note that in contrast to fixed platforms, floating vessels are usually owned by the Operators.

[6] E&P companies are also often referred to as "Oil companies".

ling Contractors vary depending on the performance, measured by "key-performance-indicators" or "KPIs". Naturally, hybrid contract types exist that combine those three main representatives. Day-rate contracts, however, represent the large majority of contracts in the offshore drilling industry.

In the system development phase the System Supplier develops, manufactures and delivers drilling systems which may vary in scope from project to project. Its main activities usually include the development of the drilling system (e.g. cranes, pumps, topdrives, skids), layout planning, engineering (structure, piping, cabling, etc.), manufacturing and the integration and commissioning on shipyard site. The tasks include the development of new rig concepts which strongly vary in novelty depending on the type of tender project. System Suppliers also offer lifecycle services by supporting maintenance, repair, overhauls, modifications and upgrades of drilling systems.

The Shipyard manufactures the hull and integrates, commissions drilling systems together with the System Supplier. The hull is usually designed by a separate Hull Designer where the design can be considered as a blueprint that is repetitively manufactured by the Shipyard based on an obtained license.

Based on MÜNCH [2013, pp. 30–38] the following three main constellations of system development and tenders can be differentiated:

- Operator-dominated system development: In this constellation, the Operator initiates and coordinates the long-term development of a new rig concept and is responsible for the gradual elimination of candidates including Hull Designers, Shipyards and System Suppliers in different phases of the tender process. For instance, so-called "Cat"[7] projects are typical representatives where the Operator (here Statoil) builds different categories of rigs to make them fit better to their tasks and operating environment as discussed in EIKILL & ATTRAMADAL [2013]. Hence, this type of system development allows better meeting the Operator's expectations and ensures long-term contracts with Drilling Contractors at reasonable daily rates. In this constellation, the customer of the System Supplier is the Operator.

HOPE ET AL. [2012] differentiate two typical constellations:

- Owner Furnished Equipment (OFE): In this constellation, the Contractor dominates by being the main project leader of development, purchaser and future owner / user of the drilling rig. In this way, the Contractor can directly contribute to the development of the drilling rig and system with its own operational experience. However, deficits can be seen in inefficient project management and a missing cost focus and standardization of the drilling rig. In this constellation, the customer of the System Supplier is the Contractor.

---

[7] "Cat" stands for different "rig categories" on the Norwegian Continental Shelf (NCS) pursuing the strategy of each rig being a fit-for-purpose Mobile Offshore Drilling Unit (MODU) that better meets the operating requirements and, hence, also achieves higher operation efficiency [EIKILL & ATTRAMADAL 2013].

- Builder Furnished Equipment (BFE): In this constellation, the Shipyard represents the responsible for delivering a completely integrated drilling rig to the Contractor[8]. The Contractor profits from the strong competencies of purchasing and a stronger purchasing power of the Shipyard. In this constellation, the customer of the System Supplier is the Shipyard. The direct communication between those two leads to a stronger cost focus while often neglecting operational demands compared to the OFE constellation.

The majority of constellations are now BFE models that have shifted from OFE constellations in the last new-build cycles [HOPE ET AL. 2012]. Rigs are often built on a speculative basis [ODELL 2014] especially in those two constellations where the end customer (Operator) is often unclear leading to significant uncertainty in system development phases.

Each of the three system development constellations undergo competitive tenders which are initiated by an Invitation to Tender or ITT varying in time frame and level of specification[9]. According to BEIL [2010] they can be divided into two main types of customer requests[10] although various hybrid forms also exist:

- Request for proposal (RFP) issued when buyer has a sense of the marketplace and has a statement of work containing a set of performance requirements that the buyer wants to be fulfilled. As the level of specification is usually still low, an iterative process between buyer and supplier is required.
- Request for quote (RFQ) issued when the buyer can develop a statement of work that states the exact specifications of the goods or services needed. RFQs are appropriate for procurement of items that are standard and well known in the marketplace.

In response to ITTs, System Suppliers submit their bids simultaneously which, in the offshore drilling environment are “sealed”, i.e. the bid is only known to the buyer and supplier who submitted it and “discriminatory” implying that there is only one winner of the auction. Depending on the stakeholder constellations, specific stakeholders and type of requests, the negotiation process of competitive tendering might be a “Take-it-or-leave-it” offer, whereby the buyer, which represents the customer, refuses further consideration if the desired price is not met; however, it can also be the starting point for general and unstructured bargaining between System Supplier and customer to finalize contract terms that both parties agree on [BEIL 2010].

---

[8] In some cases, an investor might initiate such a project instead of a Contractor by referring to already existing rigs or blueprints.

[9] Operator-dominated constellations can be considered as time extended tenders where the selection process by Operators is not performed based on a single ITT but on the results of the extensive collaborative phases of development.

[10] Request for information (RFI) represents another type of request that is a starting point for negotiation. Here, the buyer seeks to gain market intelligence regarding what alternatives and possibilities are available to meet the buyer’s needs [BEIL 2010]. System Suppliers, however, usually respond to those requests only if they expect the buyer to issue an RFP (request for proposal) or RFQ (request for quote).

Between ITT and contract award, the System Supplier generates an initial rig concept to ensure a technically feasible and economically realistic offer. It is also a required part of the bid that is expected by the customer. The detailing of the rig concept and detailed design is continued after and if the contract award[11] is given.

1.1.3 The offshore drilling upgrade market

According to KAISER & SNYDER [2013] the offshore drilling industry consists of five markets: MODUs are owned and operated in the contract drilling services market (system utilization phase) and constructed in the new-build market (system development phase); they are exchanged in the second-hand market, maintained and enhanced in the upgrade market and complete their lifecycle in the scrap market.

In addition to periodic maintenance, at least once over the course of their lifetime rigs are upgraded to embed new technology and in order to remain competitive which increases the value of the rig and its replacement cost [KAISER & SNYDER 2013]. This involves major capital expenditures by performing structural changes on the rig, installation or exchange of drilling equipment, piping and electrical system replacement.

Upgrades are sometimes performed before the commencement of a contract between Operator and Drilling Contractor, without changing major rig specifications, which are usually charged to the Operator of the rig. In contrast, upgrades that significantly alter rig specifications or extend the lifecycle are usually attributed to the Drilling Contractor's capital costs [KAISER & SNYDER 2013]. Nevertheless, the borders of cost attribution highly depend on the market situation: High oil prices usually lead to a strong demand for offshore drilling rigs (seller's market). As in those times the market is often "empty" for rigs, Operators pay high day rates, perform rig changes at their own cost or accept inadequate offshore drilling rigs with low performance and high environmental impact. In this situation, it lies especially in the Operator's interest to prepare the rig for future changes in early phases of design. In contrast, low oil prices usually lead to a weak demand for offshore drilling rigs (buyer's market). As in those times the market has an overcapacity of rigs, many of them must be warm- or even cold-stacked[12]. Hence, in a weak market the Operators' requirements for contract commencement are stricter than when rigs are short in supply [HARRIS 1989]. In this situation, Drilling Contractors receive much lower day rates and should be able to offer rigs that are "fit-for-purpose" regarding the Operator's demands. Here it is especially in the Drilling Contractor's interest to prepare the rig for future changes.

Upgrades are usually performed at the Shipyard with upgrade costs varying extremely depending on the type of rig and scope of the upgrade [KAISER & SNYDER 2013]. Whereas jack-up upgrades usually range between $10 and $30 million, upgrade costs for floating vessels can

---

[11] As section 1.2.5 shows, however, the degrees of freedom in design are highly reduced after the contract award.

[12] In contrast to active rigs which are working under contract, warm-stacked rigs are temporarily idle, i.e. without a contract and ready to use with minor preparation. Cold-stacked rigs are inactive for several months and years requiring significant capital and time to be re-activated [KAISER & SNYDER 2013].

go up to \$350 million if complete rebuilds on existing hulls are performed; the frequent mid-range upgrades of floating vessels, however, vary usually between \$75 and \$150 million [KAISER & SNYDER 2013]. Between 2000 and 2010 a total of 287 MODUs were upgraded which represents half of the active fleet with an estimated average annual value between \$1 and \$3.4 billion[13] [KAISER & SNYDER 2013]. Although no specific numbers exist of how much of those upgrades are related to unfolding uncertainty during utilization phases, it can only be presumed from informal interviews (section 1.4) that it represents a large portion that could have been reduced by preparing the drilling rig in early design phases.

1.1.4 A practical application: Managed Pressure Drilling (MPD)

Managed Pressure Drilling (MPD) is an alternative drilling method to the prevalent conventional drilling. In contrast to conventional drilling MPD is not performed under atmospheric pressure but is pressurized. Hereby, the annular pressure profile can be controlled better while enabling instant reactions in case of downhole pressure changes. Especially in complex formations with narrow pressure margins[14] they can significantly reduce non-productive time (NPT) by better controlling the bottom-hole pressure (P_{BH}). Despite a modification of existing drilling systems when shifting from conventional drilling to MPD, it requires especially the installation of dedicated drilling systems enabling the new capability such as well control and mud circulation systems. A more detailed description on the MPD drilling process and systems is provided in section 8.1.1.

Despite the value of MPD, the uptake of MPD technology is still slow [JACOBS & DONNELLY 2011]. Based on a 2011 questionnaire of 600 SPE[15] members of various oil companies, so far MPD had relatively limited acceptance amongst them despite having the potential of being a widely-used technology in the future. The embedment of this “new” drilling technology still represents a high risk to many oil companies, especially as investment costs are high [JACOBS & DONNELLY 2011]. Additionally, as rigs are often built on speculation without contracts and by non-drillers, the investment into MPD technology for newbuild rigs is hard to justify [PAVEL & HUMPHREYS 2012]. Making MPD technology fit to existing rigs usually requires time consuming and costly rig surveys and modifications, oftentimes requiring long lead times and preventing such changes to be performed in the first place [PAVEL & HUMPHREYS 2012].

---

[13] As described by KAISER & SNYDER [2013] the reasons for providing ranges of upgrade costs lie in the following: “Estimating market revenue is complicated by the wide range of costs associated with upgrades and the definition of what constitutes an upgrade. Shipyards generally do not breakout rig upgrade cost in their financial reports, and for private shipyards, no financial data is reported at all, therefore, a range of market values is provided by assuming a minimum and maximum expected upgrade cost per rig.”

[14] The delta between formation pore pressure and fracture pressure exists especially in mature fields with already highly depleted wells or areas with a strong overburden of seawater, i.e. especially in deeper waters.

[15] Society of Petroleum Engineers (SPE) is a non-profit professional organization to collect, disseminate and exchange technical knowledge concerning the exploration, development and production of oil and gas resources and related technologies for the public benefit.

The industry acknowledges the benefit of preparing the drilling rig for integrating MPD technology by making it “ready” for dealing with uncertainties (e.g. general MPD technology uptake, oil price) and the subsequent shifts of needs. This so-called “MPD readiness” refers to the rig being ready to accept “MPD components”[16] [PAVEL & HUMPHREYS 2012]. However, so far, there is no suitable systematic approach for the identification and enablement of those components; neither, is there a suitable approach for facilitating the execution of such physical changes.

Hence, as the value of MPD is usually uncertain in early tendering and design phases, it represents a relevant example for the flexible, late integration of MPD across the lifecycle once favorable circumstances occur. The option and ease of embedding MPD at this later lifecycle phase, however, must be accounted for in early phases of design. Section 8.1 uses MPD as a relevant use case for embedding flexible design by applying the developed methodology of this research. Besides this example, there are numerous other relevant cases that have large potential both within and beyond the offshore drilling industry.

In the following a problem description is provided emphasizing both the limited uncertainty handling in the offshore industry and its negative implications. It suggests responses to better deal with those uncertainties.

1.2 Problem description

In the following sections the status-quo (section 1.2.1) and negative effects of limited uncertainty handling in the offshore drilling industry (section 1.2.2) are highlighted. Section 1.2.3 provides an overview of alternatives to avoid or facilitate changes across the lifecycle and suggests flexible design as the most relevant means that is addressed in this work. Section 1.2.4 illustrates how flexible design contributes to reducing value losses across the lifecycle. The problem description closes by emphasizing the important role of the System Supplier in the stakeholder network to successfully address flexible design in the offshore drilling industry (section 1.2.5).

1.2.1 Limited uncertainty handling

Offshore drilling rigs face an uncertain future especially being sensitive towards political, market, legal and environmental conditions that strongly fluctuate across the long lifetime (25+ years) of a rig [ALLAVERDI ET AL. 2013]. This especially applies to floating vessels that must operate in changing legal contexts and under different environmental conditions over its lifecycle. In the prevalent BFE or OFE constellations (section 1.1.2), the Operator and, hence, the operating conditions and requirements are usually unknown. At the same time the contracts between Drilling Contractors and Operators are usually of short nature leading to continuously changing and uncertain requirements for Drilling Contractors as Operators change multiple times across their lifecycle. Hence, Drilling Contractors deal with the risk of not being rewarded higher day-rates by Operators as compensation for embedding effective measures of uncertainty

---

[16] The suggested methodology of this research refers to those “components” as “Objects”.

handling. Additionally, as upgrades are often performed at Operators' costs, Drilling Contractors often lack incentives to prepare offshore drilling rigs for uncertainties in the future.

However, the reasons for limited uncertainty handling can also be found in the system development phase. Competencies on operations and design have been strongly split in the past between the builders of the rig (Shipyards) and drilling system (System Suppliers) and the users of the system (Drilling Contractors, Operators). In addition, as several System Suppliers usually contribute to the system, piece-wise requirements specification occurs which leads to individual subsystems[17] that are specified by "sub-system" experts without consideration of the overall capability [BURROWES & SQUAIR 1999].

When several stakeholders contribute to the design this usually creates agency problems as stakeholder interests are not aligned [CARDIN 2014; BROWNING & HONOUR 2008; ROSS & RHODES 2007]. Especially with the most governing BFE constellations, operational requirements and lifecycle considerations usually have lower priority than the initial capital expenditures (initial CAPEX) that fulfill the desired specifications[18]. Those agency problems and the negative side effects also apply within organizations: For instance, purchasing departments of Drilling Contractors usually deal with own budgets constraining spending in the purchasing phase. After awarding the contract to a System Supplier those projects are then handed over to their operating divisions which usually prefer a lifecycle perspective on drilling systems. According to MURMAN [2002, pp. 217–246] this task division in organizations hinders multi-stakeholder thinking about dealing with lifecycle value which strongly applies to the observations made in the offshore drilling industry.

As a result of those ineffective business models performance and innovation is inhibited [WARDT 2014]. This is also reflected in the slow technology acceptance in the petroleum sector compared to other industries [JACOBS & DONNELLY 2011]. According to WHITESIDE [2001], the entire oil industry has "dealt with uncertainty and options by ignoring them in the planning process and dealing with them as they arise".

As observed in the offshore drilling industry, sales engineers of System Suppliers usually bundle resources to meet the articulated needs by customers without challenging them exhaustively to maintain efficiency in tender phases and avoid the risk of diverging from actual customer needs. As system designers usually neither explore how changes in specifications and market factors might change the design itself [NEUFVILLE & SCHOLTES 2011, p. 6], anticipated uncertainties that unfold during utilization phases are often being ignored in early design phases.

---

[17] For instance, interfaces to drilling systems run by service companies, i.e. sub-contractors that are usually temporarily on the rig, often remain unconsidered in this phase. This, in turn, usually leads to complications in utilization phases when those services are needed.

[18] Despite the fact that in particular flexible design often entails a reduction of initial CAPEX since it leads to smaller and inherently less expensive initial systems as not everything must be of full scope from the beginning [NEUFVILLE & SCHOLTES 2011, p. 39]. However, in those cases the reduction of scope is perceived as an unfavorable way of reducing initial CAPEX.

This limited strategic planning and the prevalence of rigid designs[19], as also discussed in ALLAVERDI ET AL. [2013], however, have negative side effects that are presented in the following.

1.2.2 Effects of limited uncertainty handling and trend

The circumstances in the offshore drilling industry discussed in the previous section often lead to postponing the consideration of uncertainties to rig utilization phases, and oftentimes they are dealt with "as they arise" [WHITESIDE 2001]. However, this postponement significantly increases costs as displayed by the "Rule of Ten" which states that with each subsequent program phase the implementation of a change becomes ten times costlier (e.g. REINHART ET AL. [1996, p. 49]). Once those rigid systems enter the utilization phase this leads to excessive costs for physical changes.

In Figure 1-4 the behavior of lifecycle value[20] is shown over time for a rigid system where value "is a perceived quality stemming from subjective preferences" [BROWNING & HONOUR 2008]. Preferences (e.g. preference on "high safety") should be met by fulfilling relevant requirements. The value desired by customers, here also referred to as "customer expectations", increases over time. With the start of the utilization phase losses occur due to a deterioration of the system (e.g. wear and tear) or discrete changes[21] (e.g. change of use context). Upgrades partially offset those value declines. The "major upgrades" in the offshore drilling industry require several months to perform and bound large costs as discussed in section 1.1.3. Hence, upgrades of rigid systems are performed very seldom with significant value losses as they are deferred. Once a newbuild rig is more advantageous than performing an upgrade on an existing rig, the rig is replaced by a new one (new system).

---

[19] A rigid design (concept) represents the counterpart of a flexible design as it "cannot adapt flexibly to changing conditions" [CARDIN 2014].

[20] Value is considered to be the worth in monetary terms of the technical, economic, service and social benefits a customer company receives in exchange for the price it pays for a market offering [ANDERSON & NARUS 1998]. The customer company often concides with the system user depending on the system development stakeholder constellation (section 1.1.2).

[21] Discrete changes of value are not illustrated in Figure 1-4.

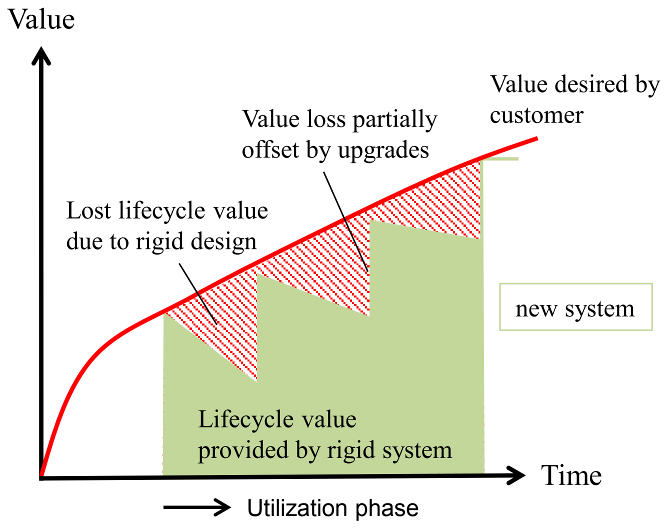


Figure 1-4 Lifecycle value of rigid system (adapted from BROWNING *&* HONOUR *[2008])*

As highlighted by ALLAVERDI ET AL. [2013], the following downsides of rigid designs could be observed in the offshore drilling industry:

- Operational inefficiencies due to undershooting or overshooting ideal system behavior as system configurations are locked under changing requirements. Undershooting may lead to deficits in performance or affecting the quality of operations[22]. Overshooting, in contrast, usually triggers higher operating expenses which includes operational and maintenance costs.
- Upgrades in utilization phases becoming very expensive as a result of longer upgrade periods, more physical effort and allocated resources.
- Missed opportunities due to long periods of upgrading and rigs being unavailable for operations in that time period (availability losses). Being a strong deterrent, upgrades are usually only performed if the entire operation is at stake[23] such as by excessive wear and tear. Upgrades may also be performed for rigs which fail to satisfy certification requirements [KVALØY & SØRENES 2009]. Hence, based on that observation, the value of the upgrade market shown in section 1.1.3 is underestimated if potential unperformed upgrades were also considered.
- Missed opportunities due to the drilling rig not meeting the Operator's demands and a subsequent rejection of orders if upgrades cannot be performed or only at very high costs.

At the same time the need for accounting for operational uncertainty is continuously increasing. Racing for the remaining oil and gas reservoirs, drilling in more challenging areas such as in ultra-deep water, complex formations or unknown and harsh environments (e.g. Arctic drilling)

---

[22] Based on the theory of Overall Equipment Effectiveness (OEE) that regards availability, performance and quality losses as main indicators (section 6.4.2). The definition of quality losses is extended to also include "safety" relevant aspects.

[23] As highlighted in section 1.2.4 this represents systems in the "must upgrade" zone.

lead to new risks and opportunities. Catastrophic events like the “Deepwater Horizon” accident in 2010 also demonstrate the strong sensitivity of the upstream drilling sector to single events. Suddenly new rules and regulations may require technological changes for newbuilds but also existing rigs.

With Operators’ margins under pressure, increasing competition and strong fluctuations of crude prices, the market conditions are favorable to account for more lifecycle value during design. The tendency of more Operator-dominated system developments, such as the “Cat” projects introduced in section 1.1.2, illustrates that Operators would like to have more influence on the lifecycle performance of their systems. Trends in the last years can be seen in the entire industry where current business models are challenged as more collaborative system development environments are embedded [EIKILL & ATTRAMADAL 2013; FULKS & COOK 2002], new technologies such as “Managed Pressure Drilling" are adopted [JACOBS & DONNELLY 2011] or drilling operations are automated [RASSENFOSS 2015]. Additionally, there exist already niche markets in the offshore drilling industry that offer more operational flexibility and cost efficiency by building modular drilling rigs such as by Archer [2013]. The increasingly stronger emphasis on total lifecycle value rather than on performance alone is an indication of a natural shift of an industry to a mature phase [MURMAN 2002, p. 195].

As a result, the highlighted value losses and the trend towards more focus on lifecycle value in the industry depicts that a better handling of uncertainty has a chance to be taken seriously. Section 1.2.3 discusses the alternatives to overcoming value losses that stem from uncertainties in utilization phases.

1.2.3 Alternatives to overcoming value losses

There are programmatic or technical things to avoid or manage risks and/or exploit opportunities [MCMANUS & HASTINGS 2004]. With regards to the offshore drilling industry and Figure 1-4, there are various alternatives to close the gap between the value desired by the customer and the lifecycle value provided by the system. Figure 1-5 illustrates important alternatives and highlights the means that are suitable.

General programmatic changes in this context of application are provided by different means: First, proper verification & testing after production can ensure that unnecessary value losses of systems are avoided in the first place. An adequate scheduling of operations**,** instead, helps to close the value gap by aligning upgrade processes with ongoing planned stops like overhauls, transits, wait-on-weather. In contrast to the addressed exogenous uncertainties during utilization (section 1.2.1), verification & testing mainly addresses minimizing the risk of unfolding system internal uncertainties. Improved scheduling allows better aligning upgrade cycles, independently of internal or exogenous uncertainties, but usually lies outside the scope of System Suppliers and, hence, represents an irrelevant means to be addressed from that perspective.

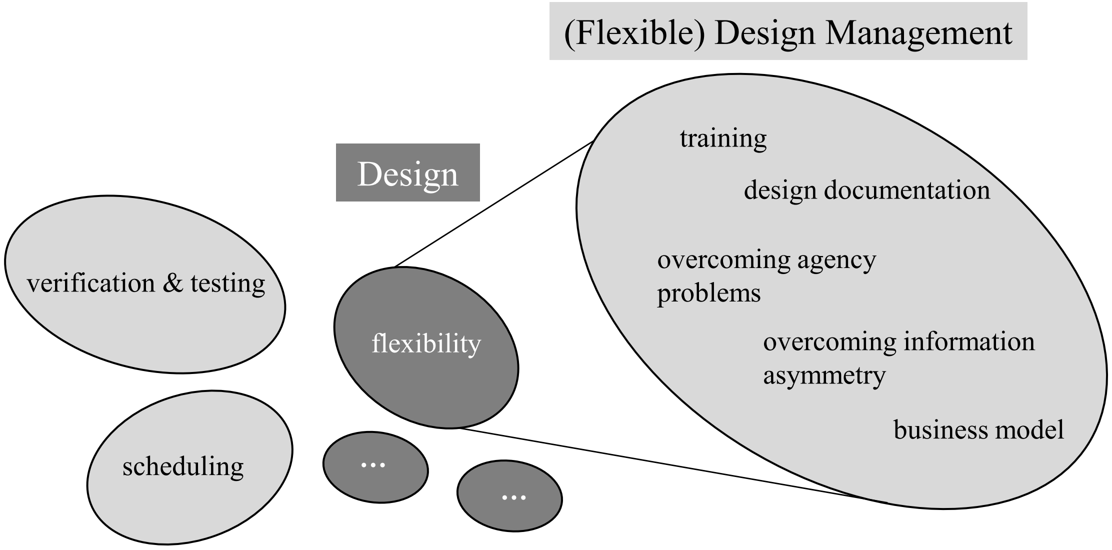


Figure 1-5 Alternative measures to close value gap

Design measures represent an alternative to the suggested programmatic ones. The identification of suitable flexibility can directly be addressed by System Suppliers in order to enable closing the value gap across the lifecycle. Naturally, besides flexibility also other design mitigation strategies exist which are introduced in section 2.4. Beyond the consideration of flexible design, its management represents an important subsequent means to realize closing the value gap.

In this regard, sufficient training on properly embedding flexible design and its proper exercise represents an opportunity to avoid misinvestments and misalignments. Additionally, properly formulated design documentation**,** especially related to the proper exercise of future options, is relevant to close the gap and avoid idle performance. Overcoming agency problems across stakeholders can resolve challenges in introducing and exercising options across the lifecycle. This is also true for overcoming information asymmetries amongst stakeholders.

Additionally, new business models could act as facilitators for embedding and exercising flexibility. The offshore drilling industry with its various stakeholder represents a "Product-Service-System" [MÜNCH 2013, p. 3]. A shift from a strongly product-orientated to a more use-oriented business model by e.g. leasing out products[24], could change the role of System Suppliers. Especially combined with flexible design and the incentives to minimize upgrade efforts, this change of business model could positively affect the system's lifecycle value.

For the addressed measures on flexible design management, the identification of suitable flexibility is a prerequisite. Next to that, certain measures must be addressed from different (e.g. customer) or higher perspectives (e.g. entire E&P sector) to be facilitated. Especially business models are not under control of a single System Supplier and, hence, are another reason for not being addressed in this research.

---

[24] According to TUKKER [2004] "product lease" represents one of the eight archetypal business models which can be attributed to a "user oriented" PSS.

This research focuses on overcoming value losses when facing uncertain and anticipated futures across the lifecycle. In the following, the positive effects of embedding flexible design are highlighted.

1.2.4 Response to value losses by flexible design

The utilization of offshore drilling systems is subject to uncertainty (section 1.2.1) and "anticipation" is required. Anticipation mainly refers to looking forward in order to take a future decision and action [RHODES & ROSS 2009]. Within each engineering organization "anticipatory capacity"[25] must be established to increase lifecycle value under this uncertainty. Flexibility can be embedded in early design phases to respond to the anticipated uncertain futures. Figure 1-6, that bases upon BROWNING & HONOUR [2008], illustrates the lifecycle value of a flexible[26] system. In contrast to rigid design, the flexible system allows:

- Enabling optional upgrades that must not but should be performed as efforts and opportunity costs for upgrades are low
- Enabling smaller and more frequent upgrades as efforts and opportunity costs for upgrades are low
- Extending the lifecycle of the system as upgrades remain valuable before being replaced by a new system (newbuilds)

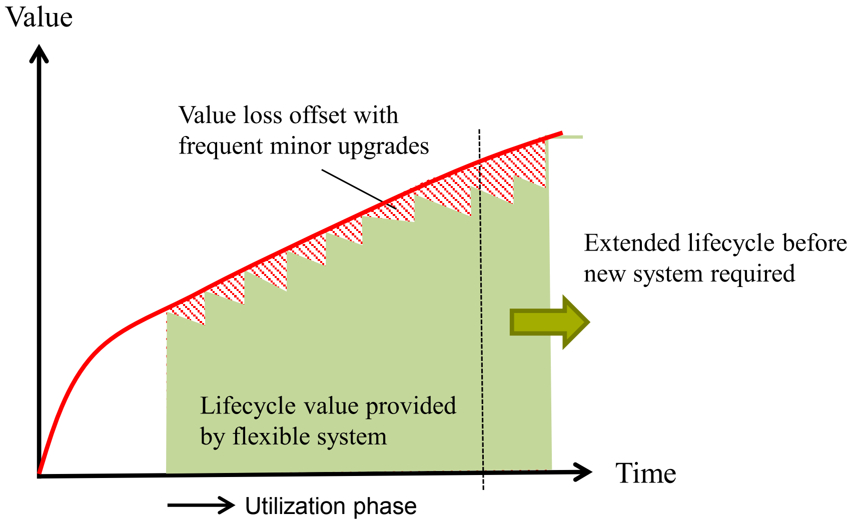


Figure 1-6 Lifecycle value of flexible system (adapted from BROWNING & HONOUR [2008])

The result is an overall higher lifecycle value compared to a rigid system. Although continuous deterioration of the system is often the reason for performing upgrades in the offshore drilling

---

[25] "The capacity to continuously develop and apply knowledge acquired through a structured approach to anticipate changing scenarios as stakeholder needs and system context change over time, to consider their consequences, and to formulate design decisions in response." [RHODES & ROSS 2009]

[26] In original reference referred to as "adaptability". The definition of flexibility is deduced in section 2.4.

industry, limited uncertainty handling can also lead to abrupt value changes over the lifecycle[27] as discussed in section 1.2.2. Based on Ross & Rhodes [2008], discrete changes of value are displayed over time (Figure 1-7) where each epoch has fixed system design characteristics, expectations and context variables. Multiple consecutive epochs can be strung together to create an era, which represents a longer run view of system evolution. Epoch shifts are subject to uncertainty and limited strategic planning.

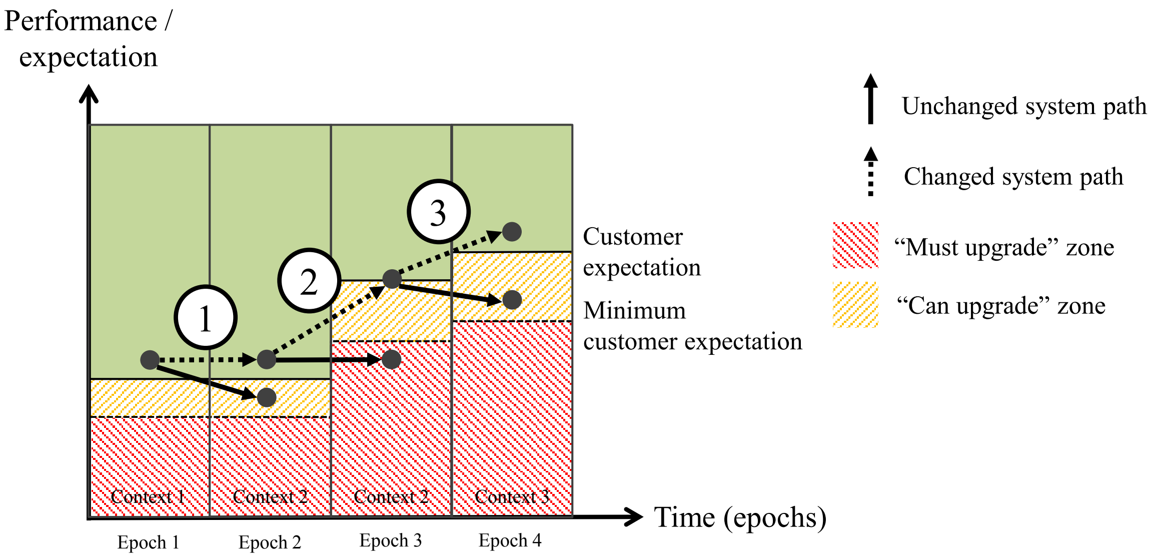


Figure 1-7 Value losses and robustness across epochs (adapted from Ross & Rhodes [2008])

There are two main alternatives for drops of value within this framework. On the one hand, the value of the system can drop due to performance[28] changes in response to context changes, which represent dropping "unchanged system paths" in Figure 1-7. On the other hand, the value may drop as higher expectations may change the desired level of performance. Figure 1-7 differentiates furthermore "minimum customer expectations" below which operations cannot be continued and "customer expectations" below which operations can continue but only in a suboptimal manner. As highlighted in Allaverdi et al. [2013] this results in three alternative cases of value losses and gaps which are illustrated in Figure 1-7:

1. Context changes usually lead to a drop of performance. For instance, this may represent a shift of floating vessels from deep water operating environments to more shallow ones [Kadiyala & Whooley 2011] or vice versa as illustrated by Wilburn et al. [1998]. Such a shift usually results in deficient operations due to less suitable systems that negatively affect performance or even hinder operations to be performed in the first place.
2. Changes, usually increases, of customer expectations as a response to exogenous factors (e.g. technological development) or within organizations (e.g. increased safety standards of

---

[27] Continuous fluctuations within epochs such as changes in wind speeds, formation, etc. also affect the performance of the system but are not related to limited handling of uncertainty, hence, also do not represent epoch shifts.

[28] Here "performance" relates to all possible deteriorations of the system that can occur.

Drilling Contractor). In this case, the performance of the system remains stable across epochs.

3. A combination of case "1" and "2" where, for instance, a change of operating environments (e.g. rig move to Norwegian Continental Shelf) leads to more stringent certification requirements[29] but also leads to drops in system performance (e.g. due to too heavy equipment being suitable for deeper water).

Those value losses ask for value robustness to continue to deliver stakeholder[30] value in the face of changing contexts and needs [ROSS & RHODES 2008]. This can be achieved through either passive or active means[31], with the former akin to traditional robust approaches, and the latter embracing changeability as a dynamic strategy for value sustainment [ROSS ET AL. 2008]. Those means allow following alternative system paths to reestablish[32] value (changed system path), which vary in costs, i.e. both in time and money [ROSS ET AL. 2008]. According to NEUFVILLE & SCHOLTES [2011, p. 39], flexibility in the design of projects can increase performance (e.g. measured in financial terms) by at least 25 percent compared to standard design procedures. By preparing systems for change and easing the future upgrades, even upgrades in the "can upgrade zone" of Figure 1-7 are more likely to be performed as thresholds would also be reduced due to lower efforts and opportunity costs (also Figure 1-6).

Such measures, however, require the System Supplier to take a leading role in the stakeholder network addressed in the next section.

1.2.5 Contribution of Drilling System Supplier and effect in stakeholder network

At the beginning of the lifecycle the designer has great degrees of freedom which become increasingly limited in later phases when changes require great expenses [ULLMAN 2010, p. 20]. Hence, uncertainty in design is handled most effectively in early stages as then decisions have the strongest impact on the final product [LINDEMANN & LORENZ 2008]. Additionally, the environment of competitive tenders amplifies the urgency of dealing early with uncertainties as specifications are difficult to be renegotiated after contract awards. Depending on the boundary conditions in a project system architects and designers of various stakeholders (mainly Hull Designer, Shipyard, System Supplier) must collaborate in early design to better deal with the uncertainties and increase lifecycle value [ALLAVERDI ET AL. 2013].

---

[29] According to the "Det Norske Veritas" (DNV) and the "Petroleum Safety Authority Norway", Norwegian certification requirements are more stringent than in other parts of the world [KVALØY & SØRENES 2009].

[30] In this context of application, "stakeholders" refer to system users, in particular Drilling Contractors and Operators.

[31] DE NEUFVILLE [2004] also introduces "controlling uncertainty" by demand management as a third option.

[32] Robust approaches should not lead to value drops in the first place, hence, a change of system paths should not be required.

The System Supplier contributes to this network by knowledge on drilling systems and the ability to influence the design to most extent[33]. Additionally, with their knowledge on drilling operations, System Suppliers can challenge customer specifications and positively influence the lifecycle value of the drilling system by addressing uncertainty in utilization phases.

If the incentives of the customer and System Supplier are aligned rather than in conflict, as opposed to a zero sum game, they can both benefit from such an endeavor [Beil 2010]. The only negative side effect for the System Supplier of actively accounting for uncertainty in utilization phases is the potentially smaller initial scope of the system due to letting system users stage investments across their lifecycle. Nevertheless, from a System Supplier's perspective the positive aspects should certainly surpass[34] the negative aspects due to:

- Providing the ability of staging investments improving the hit rates in competitive tenders
- Additional revenues for the embedment of design measures to deal with future uncertainty
- More follow-up contracts and revenue in after sales market especially as upgrade frequency is increased and "can upgrades" are performed (section 1.2.4)

Thus, embracing flexible design may provide competitive advantages for both System Suppliers[35] and system users. However, due to the various reasons highlighted in section 1.1.2, it still only represents a potential that must be proven in the industry. Still, this potential is considered to suffice to be addressed by this research. Consequently, in the following the research scope and objectives are introduced.

1.3 Research scope and objectives

Based on the problem description of section 1.2, the research scope and the objectives of this work are defined. In section 1.3.1, the overall goal of this work and the relevancy for other fields of application are emphasized. Section 1.3.2 introduces the unique boundary conditions of the offshore drilling industry that guide the development of the methodology. Based on those, the basic requirements on the methodology and the main research contributions are deduced (section 1.3.3). In section 1.3.4 the main and underlying research questions are formulated by anticipating the research gap.

1.3.1 Goal of methodology

With the profound problem description in section 1.2, the limited handling of uncertainty and the potentials of incorporating flexible design are emphasized. The System Suppliers can contribute significantly in early design phases, however, must meet customer acceptance in the

---

[33] As oftentimes the hull is already well defined and even built when System Suppliers get involved, there are, however, already strong constraints in the degrees of freedom in those early phases.

[34] This consideration is hypothetical and must be proven in practice.

[35] The considerations and benefits are similarly valid for Shipyards.

first place. Based on the needs the goal of the methodology that is to be developed is summarized as follows:

The goal of this work is to support System Suppliers in early design phases to successfully embed flexibility into technical systems by following a [aspect 3] methodology that facilitates the [aspect 2] identification of [aspect 1] Flexible Design Opportunities. This should allow system users to better deal with unfolding uncertainty in utilization phases.

In this regard, Flexible Design Opportunities (FDOs) represent the relevant physical components enabling flexibility in the system [CARDIN & NEUFVILLE 2008] and, additionally, the reasons (e.g. drivers for change) that lead to the need of embedding flexibility in the first place.

Each aspect of the goal description describes the features of the methodology that are based on the boundary conditions (section 1.3.2) and represent the derived basic requirements of section 1.3.3. Those aspects focus on:

- The result by using the methodology (aspect 1)
- The way the methodology is used (aspect 2)
- The way the methodology is built and maintained (aspect 3)

The direct beneficiaries of the methodology are system users of those drilling systems as they are able to significantly reduce risks and take advantage of arising opportunities in utilization phases which reduces value losses and, consequently, increases the lifecycle value of the system (section 1.2.4).

Due to the role in the stakeholder network and the benefits of addressing potential changes in design early (section 1.2.5), the methodology is to be applied by System Suppliers in early phases of design, usually in parallel to competitive tenders, when there are still sufficient degrees of freedom to influence the design. This concerns the phase of “need identification” and “conceptual design” (Figure 1-8) when using the typical design process defined by CLARKSON & ECKERT [2005, p. 5]. The methodology targets mainly concept and sales engineering departments[36] of System Suppliers.

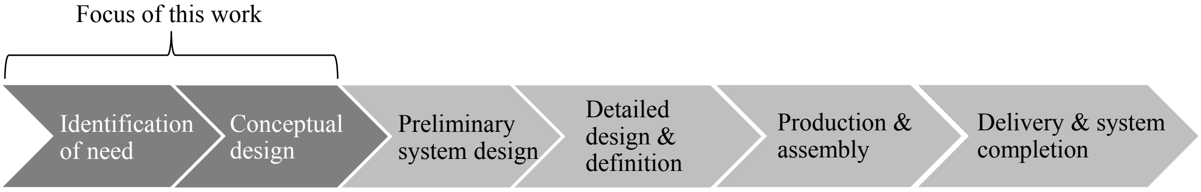


Figure 1-8 Typical design process (adapted from CLARKSON & ECKERT [2005, p. 5]) and focus of this work

Although the motivation for the methodology is industry-specific, the relevancy and application of the methodology may equally[37] apply to industries that have a need in embedding flexibility

---

[36] Both departments also strongly contribute to the evaluation of the methodology (section 8.3.1).

[37] Although the overall methodology is considered to be applicable across industries, the generated results from section 5.3 contain partially industry specific results that are not directly transferable.

as a response to limited uncertainty handling. Thereby, embedding flexibility has most value for industries that have long lifecycles, face large uncertainty in user needs and, additionally, perform large (partially) irreversible investments[38] [DE WECK 2007, 2008].

The addressed systems shall represent "one of a kind" systems that are adapted from baseline systems and are defined during competitive tenders. Typical industries that fulfill those criteria apply to: "plant engineering", "production engineering", "factory planning", "construction", "infrastructure" and "space" industries. Naturally, other sectors in the "oil and gas" industry such as in the mid- and downstream[39] may be equally applicable.

The boundary conditions in the offshore drilling industry presented in the next section represent the foundation based on which the requirements and, consequently, the methodology is built upon.

1.3.2 Industrial boundary conditions for methodology

Attaining the goals of the FDO Methodology requires accounting for certain boundary conditions under which the approach is to be built, applied and maintained. Based on the research methods presented in section 1.4, in particular informal interviews and the participation in a "Operator dominated" system development project, those boundary conditions have been elicited and concretized. They are directly related to the general basic requirements of the FDO Methodology (section 1.3.3) and, subsequently, the FDO Methodology specific requirements that are presented in section 4.3.2.

The boundary conditions can mainly be attributed to two categories: On the one hand, "market conditions" have to be accounted for which base upon the specific circumstances of the market (section 1.1.2), the reasons for limited uncertainty handling in the past (section 1.2.1) and the changing trend in the industry (1.2.2). On the other hand, "corporate conditions" refer to the typical organizational and technical circumstances at System Suppliers in this industry that must be accounted for when addressing the methodology. In the following the individual conditions of those two categories are discussed starting with the main category of market conditions.

Market conditions

The first group of market conditions describes the status-quo of stable conditions in the offshore drilling industry at the time of research. The following ones were relevant to consider:

---

[38] Also referred to as "sunk costs", i.e. costs that have already been incurred and cannot be recovered. According to PINDYCK [2007] irreversible investments are often industry-specific (e.g. equipment) and its resale value is strongly linked to the economic situation of the industry; hence, the economic value of the asset would move up or down with the economic conditions in the industry making the investment irreversible. In all cases, the installation and removal costs that may contribute substantially to the overall investment are irreversible.

[39] Whereas the midstream sector processes, stores, markets and transports commodities such as crude oil, natural gas, natural gas liquids / sulphur, the downstream sector includes oil refineries, petrochemical plants, petroleum products distributors, retail outlets and natural gas distribution companies [PSAC 2016].

- BC1, Fixed deadlines during tenders for making offers: Tenders have fixed deadlines that can hardly be extended, especially not on behalf of the System Supplier.
- BC2, Excessive time constraints and pressure in most competitive tenders: Mostly tenders undergo extreme time pressure as tender deadlines are often announced on short notice. Although there are exceptions, especially as types of tenders vary (BC5), this is the rule rather than the exception.
- BC3, Conservatism and risk aversion in market: Due to its circumstances, the market is very risk averse and historically proven solutions are usually preferred [ALLAVERDI ET AL. 2013].
- BC4, Fragmented and incomplete articulation by customers regarding needs on flexible design: In general, customers articulate only parts of their needs explicitly. As observed by ROSS & RHODES [2007] this is usually due to forgetting, not knowing, difficulty in expression, implying already knowledge by the designer or nondisclosure.

Despite those stable conditions, the market of the offshore drilling industry is also subject to strong variations. Those variations can be related to:

- BC5, Variation of stakeholder constellations and tender conditions during system development: As described 1.1.2, the stakeholder constellations can vary during system development represented by OFE, BFE or Operator-dominated constellations. This strongly affects the tender conditions such as timeframe and the required resources[40].
- BC6, Variation of type and detail level of customer specifications: Customer specifications can vary in what is actually expressed as a need (e.g. operating conditions, system specific requirements, desired solutions), how it is expressed (oral, written) and on which level of detail it is expressed. Depending on the extreme customer requests of RFPs and RFQs, the engineer has more or less degrees of freedom for an offer.
- BC7, Variation of decision-making criteria of customers for awarding contracts: The preferences and, hence, the decision-making criteria vary across customers, their departments or even individuals within departments (section 1.2.1). Customers may have a strong cost focus (mainly initial CAPEX) or prefer to invest in increased lifecycle value.
- BC8, Variation of customer expectations regarding types and scope of flexible design embedment: The preference on embedding flexible systems strongly depend on “BC5” and “BC7”. Customers may expect that System Suppliers offer a range of alternative solutions on flexible design also based on unarticulated needs, only respond to articulated needs on flexible design or meet only articulated needs without any consideration of flexible design.

---

[40] BFE constellations which dominated at the time of this research are usually short tenders responding to requests for quotes (RFQ). Operator-dominated constellations, instead, usually leave more degrees of freedom (request for proposal or RFP) with long feasibility studies upfront which also require more resources.

Despite the variation of conditions in the market, there are also market trends at the time of research that are of relevancy[41]:

- BC9, Abruptly higher customer expectations and stronger penalties on unsatisfactory results: In the past offshore drilling systems have picked up rather slowly on the technological progress compared to other industries [ROGERS 2011]. However, the increasingly competitive market and the shorter innovation cycles and adoption of new technologies have led to an abrupt increase of customer expectations. Although those expectations vary with the market situation (e.g. oil price), this recent increase might be stronger than in other industries that have had a steadier development of customer expectations in the past.

Despite market conditions, corporate conditions also play an essential role and are elaborated on in the following.

Corporate conditions

Corporate conditions address typical circumstances[42] of System Suppliers and distinctive technical features that must be accounted for to successfully deduce requirements on the methodology. The first group addresses boundary conditions under which tenders are performed:

- BC10, Often highly experienced and change resistant engineers performing tenders: Experienced sales engineers are usually required for dealing with heterogeneous customer requests and a wide scope of technical challenges while being exposed to strong time pressure. Oftentimes, however, this required experience comes with a resistance against new promising procedures or working habits.
- BC11, Limited resources for handling of tenders: Limited resources of experienced engineers with sufficient competency to handle tender projects.
- BC12, Limited resources for build-up and maintenance of database: Besides the limited resources for handling tenders, resources for building and maintaining a database are scarce.
- BC13, Heterogeneous experience levels of engineers on flexible design: The knowledge on flexible design strongly depends on the individual engineer as it depends on the past roles, individual preferences and experiences made.
- BC14, High expectations on accurate and up-to-date models for application: The potential users of new methodologies expect applications to be accurate and up-to-date as any deficits (e.g. inconsistencies) are unlikely to be uncovered during tender projects which may have major negative consequences for customers, system users or System Supplier.

---

[41] Note that trends that are not relevant with regards to determining requirements on the suggested methodology are not further considered.

[42] Those corporate conditions might vary across different System Suppliers which could not be validated in this study.

- BC15, Overwhelming amount of flexibility potentials in drilling systems: There is a large scope of design variables that can be addressed within the System Supplier's product portfolio to make drilling systems flexible.

Corporate conditions should also account for "typical" working behavior:

- BC16, Hardly challenge of customer specifications: Oftentimes customer specifications cannot be (fully) challenged especially due to strong time pressure in competitive tenders.
- BC17, Limited experience with decision-support tools: Usually the suggested engineering solutions are based on experience and intuition rather than on decision-support (e.g. by use methods, tools) that fosters the process of identification, assessment and decision-making.
- BC18, Reference design as starting point for new offers: Engineering solutions usually build upon previously delivered and proven solutions that are adapted to fit individual customer specifications rather than generating entirely new solutions. This reduces the risk of delivering immature systems while being able to efficiently handle customer requests in competitive tenders.
- BC19, Local focus on flexible design potentials and solutions: Flexible design is usually applied by either strictly following articulated customer needs or by suggesting isolated flexible solutions to an existing problem. A holistic consideration of uncertainties, affected systems and flexible design alternatives for better handling is usually not the focus.

Those boundary conditions play different roles when defining basic requirements. Whereas some of those conditions represent unchangeable constraints (e.g. "Conservatism and risk aversion in market" (BC3)), other boundary conditions represent unfavorable conditions that must be positively changed by the methodology (e.g. "Local focus on flexible design potentials and solutions" (BC19)). However, they may also represent boundary conditions that positively influence and enrich the methodology such as the "Reference design as starting point for new offers" (BC18) which is in line with flexible design that "must start from an existing design configuration" [CARDIN 2014].

Based on those boundary conditions the basic requirements for the methodology are deduced and introduced in the following section.

1.3.3 Basic requirements and research contributions

In order to account for the market and corporate conditions, seven different basic requirements were defined to meet the goal presented in section 1.3.1. They build upon the boundary conditions defined in section 1.3.2 and can be traced in Table 1-1. The boundary conditions are clustered to groups[43] that can be clearly assigned to basic requirements. The two relation types "market" or "corporate" of Table 1-1 differentiate the origin of attributed boundary conditions further.

---

[43] The only exception is "BR III" that bases on boundary conditions that cannot be assigned to a specific group.

Table 1-1 Basic requirements of FDO Methodology basing upon underlying boundary conditions

		BC3	**BC9**	**BC15**	**BC4**	**BC16**	**BC19**	**BC10**	**BC17**	**BC5**	**BC6**	**BC8**	**BC13**	**BC1**	**BC2**	**BC11**	**BC18**	**BC7**	**BC12**	**BC14**
Identification of effective FDOs	**BR I**	m	m	c																
Comprehensive identification of FDOs	**BR II**				m	c	c													
Customer-oriented identification of FDOs	**BR III**	m				c						m						m		
Efficient identification of FDOs	**BR IV**													m	m	c	c			
Appropriate usability for engineers	**BR V**							c	c											
Flexible application of FDO Methodology	**BR VI**									m	m	m	c							
Efficient build-up and maintenance of database	**BR VII**																		c	c

m Contribution by "market" conditions
c Contribution by "corporate" conditions

The “Identification of effective FDOs” (BR I) aims at the identification of a relevant set of uncertainties and relevant, feasible concepts that result in high-performing solutions.

The “Comprehensive identification of FDOs” (BR II) addresses a holistic identification. By considering both articulated and unarticulated needs [ROSS & RHODES 2007], this requirement supports widening the scope of uncertainties and also supports identifying the range of affected system constituents and flexibility alternatives.

The “Customer-oriented identification of FDOs” (BR III) ensures that only customer relevant solutions are generated that depend on the individual preferences of the customer. As “BR II” it is strongly related to the effective identification of FDOs (BR I).

The “Efficient identification of FDOs” (BR IV) addresses meeting the imposed time and resource constraints in projects which can reduce the threshold of applying the FDO Methodology in the first place.

The “Appropriate usability for engineers” (BR V) emphasizes the need of making the methodology easily understandable and applicable to its users. Thereby the threshold for applying the methodology shall be reduced. Additionally, the methodology shall allow a correct and envisioned application of the methodology.

The “Flexible application of FDO Methodology” (BR VI) targets a situation dependent application of the methodology without having to follow strict and rigid procedures. This serves to better deal with the strong variations in projects by reducing the threshold of application and enabling a situation-dependent identification of FDOs.

The “Efficient build-up and maintenance of database” (BR VII) is to reduce the threshold and the overall effort of incorporating the FDO Methodology when building and maintaining the database of the methodology.

Although all basic requirements are considered for the development and the evaluation of the methodology, “BR I” and “BR IV” are identified as the top-level requirements that mainly contribute to the research goal (section 1.3.1). They represent showstoppers as their non-fulfillment makes other basic requirements dispensable (e.g. customer-orientation). However, due to the strong interdependency of basic requirements (e.g. “comprehensiveness” strongly supports “effectiveness” of FDOs), all basic requirements were accounted for during the development of the methodology either directly or indirectly. Strongly interdependent requirements are clustered to “aspects” as shown in Table 1-2. Each aspect contributes to meeting the goal defined in section 1.3.1.

Table 1-2 Core and contributive aspects derived from basic requirements for goal specification

		Aspect 1	**Aspect 2**	**Aspect 3**
Identification of effective FDOs	**BR I**	effective		
Comprehensive identification of FDOs	**BR II**	comprehensive		
Customer-oriented identification of FDOs	**BR III**	customer-oriented		
Efficient identification of FDOs	**BR IV**		efficient	
Appropriate usability for engineers	**BR V**		user-oriented	
Flexible application of FDO Methodology	**BR VI**		flexible	
Efficient build-up and maintenance of database	**BR VII**			efficiently built and maintainable

Core
Contributive

In parallel to the development of the FDO Methodology, those general basic requirements could be broken down further to more detailed FDO requirements as described in section 4.3. Finally, the fulfillment of those FDO requirements and, hence indirectly, also of the basic requirements is rated by running an expert evaluation on the suggested FDO Methodology (section 8.3.3).

By anticipating the core findings of this research, the following two main research contributions can be formulated:

- As observed by Cardin [2014], procedures and research efforts on flexible design are not well organized into a consolidated framework. This work addresses this need by providing an “end-to-end”[44] methodology: Hereby important constituents within and outside of the technical system should be identified such as uncertainties and affected system constituents for which suitable flexible design concepts and final flexible design solutions are identified. The methodology should embed systematized empirical data and heuristics to guide the user interactively[45], hence, accounting for the user’s expertise when being run. The focus lies especially on the phase of concept generation where “more research is needed to develop new procedures or adapt existing ones” [Cardin 2013].

---

[44] The term goes back to Bartolomei [2007] (emphasized in section 3.2.1) that refers to the “Engineering Systems Matrix” (ESM or ES-MDM) as an “end-to-end” representation of an engineering system by including endogenous interactions across system views but also interactions within a system’s environment. This “extended” perspective of the technical system is now transferred to the need of a methodology that accounts for the underlying reasons for change that are external to the system (input of methodology) leading to the generation of flexible design solutions within that system (output of methodology).

[45] The interaction is opposed to an automated support where interactions are mostly received from the support with some replies at the beginning and end of the interaction [Blessing & Chakrabarti 2009, p. 163].

- Specific heuristics for the phase of concept generation which address both the Transition, i.e. the type of change that is to occur (section 5.3.5) and the Change Enablers that facilitate that change of Objects (section 5.3.4).

As literature reviews indicate (section 3), current approaches are insufficient to attain the addressed goal of section 1.3.1 by meeting the underlying basic requirements. Hence, in line with BLESSING & CHAKRABARTI [2009, p. 46], the research on the methodology and the pursued contributions are considered to be both academically and practically worthwhile while being realistic in scope, especially as priorities are set to focus the research[46].

1.3.4 Research questions

Based on the defined research goal (section 1.3.1), the main research question is defined as follows:

Which methods and tools enable designers in early stages of system design to successfully identify and offer flexible design solutions to their customers to allow system users better deal with uncertainty in utilization phases?

This research question can be further divided into two categories that contain sub-questions. The first group handles the procedural aspects of that research question:

- How can all relevant Objects that are subject to utilization uncertainty be identified in technical systems?
- How can those Change Objects be enabled to reduce upgrade efforts in utilization phases under consideration of different upgrade strategies?
- How and when shall the concepts of enabled Change Objects be assessed and solutions be derived?
- How can the identification of FDOs be enhanced by complementary supportive methods?
- How can the procedure be supported by a tool?

Furthermore, the systematization of data is addressed that is relevant for performing the procedure:

- Which domains are relevant for determining flexible solutions? How are they defined?
- Which are relevant dependencies of those domains?
- How must elements of the domains be defined and systematized to be applicable in the procedure?
- How and to which extent can application context-dependent knowledge be reused and integrated into the procedure?
- How can the data model build-up and maintenance be supported?

---

[46] Especially by prioritizing basic requirements or only partial elicitation of relevant data to develop and evaluate the methodology.

Those questions are confronted with the research goal and the underlying basic requirements that are to be fulfilled by the methodology which strongly influences the characteristics of the solution.

In the following the research approach and the research methods are introduced that support answering those questions.

1.4 Research approach and methods

In this work, the researcher has direct and extensive access to resources of a large Drilling System Supplier where he is partly embedded. Hence, the research approach and methods, especially the extensive empirical studies, are explicitly chosen so that this research is both industrially and academically relevant while being rigorous in nature.

According to BLESSING & CHAKRABARTI [2009, pp. 6–12] the Design Research Methodology (DRM) is applied as a basis framework in order to prevent shortcomings in design research. It comprises a four-stage process which is represented as a matrix in Figure 1-9.

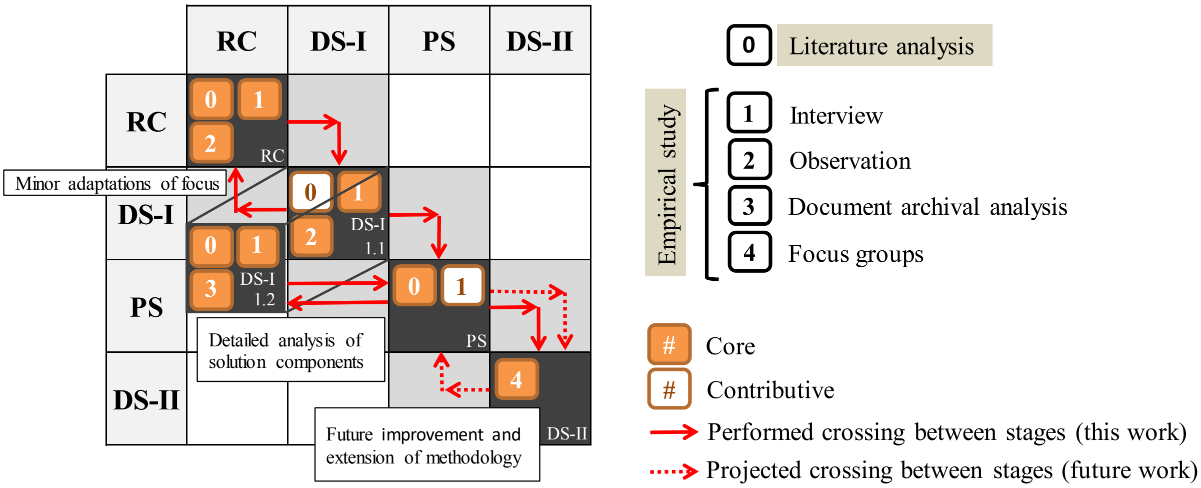


Figure 1-9 DRM research approach with main research methods

Each of the four stages has its own objectives and deliverables which can be attained by the use of different research methods. Iterations have been performed within and across those stages by making adaptations and improvements of tentative results or taking a more detailed perspective on the previously defined ones. Depending on the research goal, research question and the boundary conditions under which the research is performed, the suitable research methods can vary. In the following each stage is discussed with a primary focus on the selected research methods that have been applied to meet the research goal.

The first stage “Research Clarifications” (RC) aims at identifying and refining a research problem that is both academically and practically worthwhile and realistic and, thereby, defining the research goal [BLESSING & CHAKRABARTI 2009, p. 43]. Especially informal interviews and observations made in trainings on drilling systems and operations that highlighted various relevant project cases allowed recognizing or deducing the challenges of planning future drilling operations and systems. A literature study was performed to address the problem both from an industrial and academic perspective. Both literature and the interviews, observations resulted in a problem description (section 1.2) and contributed to the specification of the research goal (section 1.3.1) and research questions (section 1.3.4).

The "Descriptive Study I" (DS-I) aims at gaining sufficient understanding on the topic of interest and the factors that undermine its success [BLESSING & CHAKRABARTI 2009, p. 75]. Through informal interviews and participatory observation[47] (DS-I, 1.1) of an Operator-dominated system development project[48], relevant industry-specific boundary conditions were defined (section 1.3.2). This led to iterations to the RC stage and minor adaptations of the research focus. Based on that the basic requirements of the methodology were defined (section 1.3.3) in order to meet the research goal (section 1.3.1).

As part of the prescriptive study (PS) an extensive literature analysis was performed to gain insights on prevalent methodologies for identifying FDOs which are summarized in section 3.1 and 3.2. Based on this literature analysis and complementary informal interviews in this phase, an initial design support was developed to close the research gap and, at the same time, contribute to the industrial problem.

With a first procedural model at hand, further research on the solution components, i.e. relevant domains and domain elements, was performed (DS-I, 1.2) that is required for the identification of FDOs. This entailed another extensive literature analysis, especially on the concept generation constituents of FDOs represented in section 3.3, a large series of semi-structured case-based interviews which is described in detail in section 5.2.1 and a complementary company internal document archival analysis which targeted both project documentation on tenders and product documentation (such as drawings, technical descriptions, etc.). The detailed FDO requirements were iteratively defined as described in section 4.3.1.

The subsequent activities related to processing, data extension and verification are documented in section 5.2.2 and were performed by SCHLATHER [2015] and CARATHANASSIS [2015] based on the results from the RS and DC-I stages. This allowed populating the data model of the methodology and, hence, represented new input for the PS stage (section 5.3). Regular reporting on the current status of the methodology with subsequent informal interviews represented support evaluations ensuring that errors and deviations could be accounted for early while synthetizing additional FDO requirements that were still to be embedded as illustrated in section 4.3.1.

Finally, in "Descriptive Study II" (DS-II) the application and impact of the design support is evaluated as recommended by BLESSING & CHAKRABARTI [2009, p. 181]. Based on the application of the methodology on a relevant use case (section 8.1) and the theoretical contributions

---

[47] Represents a long-term case study in a natural setting. Researcher with knowledge on offshore drilling systems was moderately observing, i.e. with limited participation by the researcher.

[48] The project addressed the development of a new rig concept for an Arctic drillship which faces significant utilization uncertainty and was intended to stretch over years. Participation meant, on the one hand, the attendance at regular internal meetings of the concept design team (System Supplier) and, on the other hand, at important multi-stakeholder meetings during the tender process.

to the fulfillment of FDO requirements (section 8.2), an expert evaluation with selected focus groups was run (section 8.3) to show the usefulness of the methodology (success evaluation). The feedback from the evaluation was not implemented in this work (PS stage) but should be considered in the future for improving and extending the methodology further. Naturally, this should also be followed by an expert evaluation (DS-II).

The following section provides an overview on the structure of the thesis.

1.5 Structure of thesis

This thesis can be divided into six main themes that are visualized in Figure 1-10:

- An introduction to this research (chapter 1)
- An extensive theoretical background to generate transparency on focus, a common understanding and terminology for this thesis (chapter 2)
- "State-of-the-art" to provide an overview of related research and highlight the research gap, research contribution of the FDO Methodology (chapter 3)
- The suggested FDO Methodology with its various constituents (chapter 4-7)
- The application and evaluation of the suggested FDO Methodology (chapter 8)
- A final conclusion and outlook of the FDO Methodology (chapter 9)

The already introduced chapter 1 provides background information of the industry and the situation that motivates this research topic and allows deducing a problem description. Subsequently, the objectives of this research are derived and a research methodology is defined addressing both the guiding research approach and questions.

Chapter 2 provides a common understanding and terminology based on various relevant literature for this work. Concretely, it interprets offshore drilling for the larger field of plant engineering, systematizes the field of uncertainty and uncertainty modeling and narrows down the lifecycle phases and types of changes that are targeted by the methodology. This is followed by elaborating and consolidating the ambiguous field of flexible design before providing an understanding on systems and their requirements.

Chapter 3 introduces a reference taxonomy for the identification of FDOs and general relevant end-to-end procedural models from different relevant academic disciplines which are then compared and evaluated. As a matrix-based approach is regarded most suitable to meet the requirements of the targeted FDO Methodology, alternative relevant matrix-based methodologies are highlighted in detail and benchmarked. This allows deducing the research gap. Finally, as "concept generation" represents a research contribution on its own, a literature review on relevant constituents of the methodology is performed.

Chapter 4 introduces the overall framework of the suggested FDO Methodology. It suggests three models that are necessary to support the identification of FDOs. The main model, the FDO Procedural Model, is described in detail. Then the process of identifying FDO requirements for the FDO Methodology is provided and the results are presented.

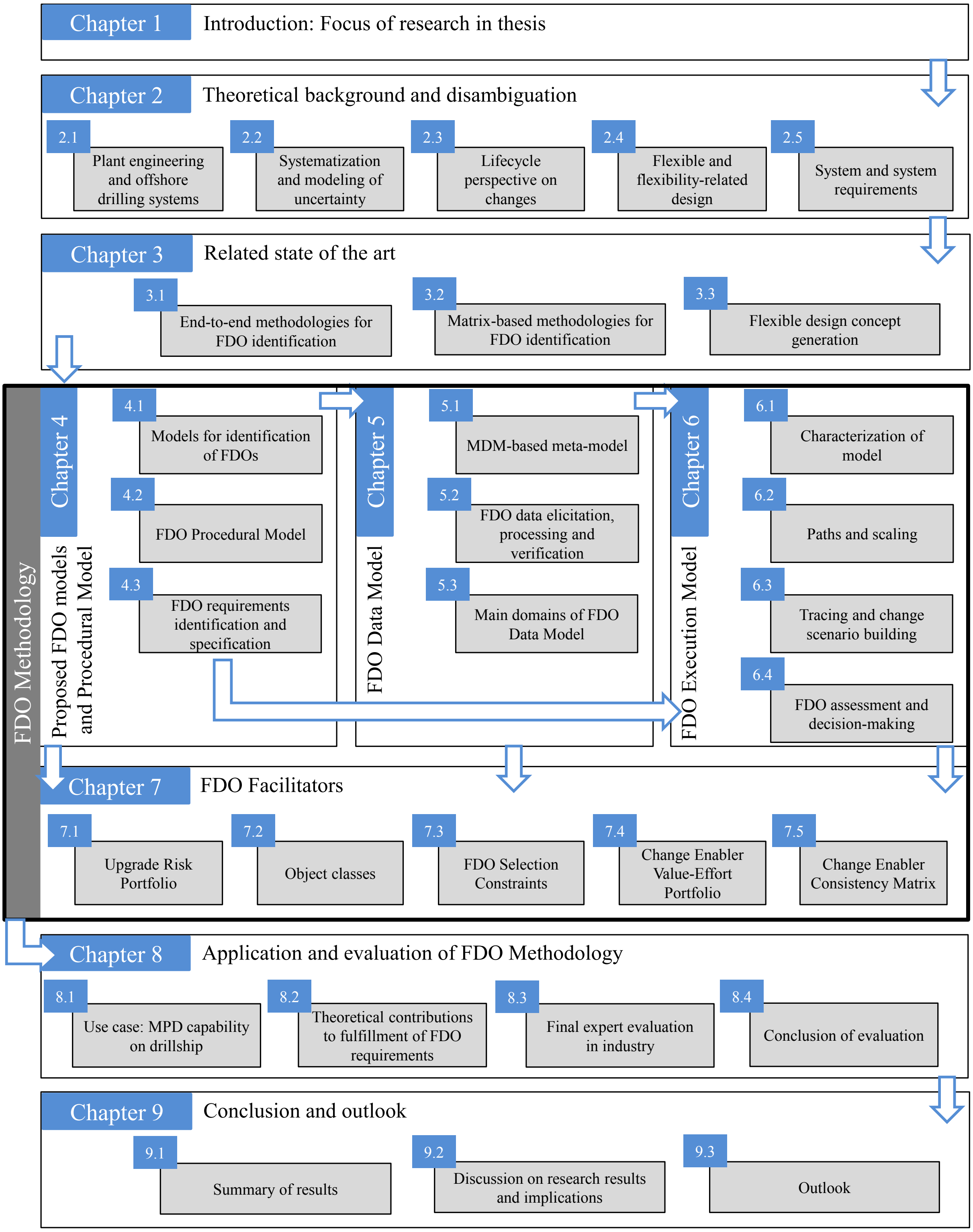


Figure 1-10 Structure of this thesis

Chapter 5 presents the FDO Data Model which builds upon the FDO Procedural Model and acts as an organizing framework of relevant domains and their constituents. The process from eliciting empirical data to the embedment into the FDO Data Model is described followed by a detailed presentation of the constituents and categories of each of the domains.

Chapter 6 presents the application model (FDO Execution Model) which is based both on the FDO Procedural Model and FDO Data Model. First the build-up of the model and the available selections are highlighted. This is followed by demonstrating the alternative and scalable paths the user can follow. Then the technique of tracing is introduced which represents an important aspect of building change scenarios which are illustrated subsequently. Finally, insights into the assessment and decision-making of FDOs are addressed both when running through the FDO Execution Model and when “Flexible Design Concepts” are already generated from which suitable solutions are deduced.

Chapter 7 focuses on the complementary support to meet the defined FDO requirements when applying the FDO Methodology. Those FDO Facilitators target different phases of the methodology including the build-up and maintenance phase of the FDO Data Model.

Chapter 8 applies the FDO Methodology based on an industrially relevant use case. Then the theoretical contributions of the FDO Methodology are introduced that depict how the FDO requirements were intended to be met. Finally, the process, the results and a reflection of the expert evaluation are provided that are based both on the introduced use case and the theoretical contribution of the same chapter.

Chapter 9 first summarizes the results of the FDO Methodology. Then the research results and the implications of this research are discussed. This is done, on the one hand, by addressing the strengths and weaknesses of the developed methodology that refer to the initially defined research sub-questions. On the other hand, the contribution to research and industry is highlighted separately. Finally, an outlook depicts further potentials that were not addressed in this research, yet may provide interesting contributions in the future.

To complete this work, the appendix provides more relevant aspects and details that were only briefly addressed in the main body of this thesis.

2. Theoretical background and disambiguation

The following sections base upon relevant fields of literature to further highlight the research focus and generate a common understanding and terminology for the subsequent chapters of this thesis. Hereby, first the broader industrial field of plant engineering is addressed that offshore drilling systems represent (section 2.1). Furthermore, the relevant field of uncertainty is systematized both by addressing it from a perspective of accessible knowledge and from a perspective of its sources within and outside of the technical system (section 2.2). Additionally, since a large amount of alternative uncertainty modeling techniques exists, they are elaborated on by differentiating between formal and practical approaches focusing explicitly on the most relevant one for this research context. As changes can occur at different times across the system's lifecycle and also be of different nature, the addressed phases and targeted types of changes are isolated (section 2.3). In section 2.4 the large and ambiguous field of flexible design is introduced as a means of dealing with uncertainty; it is regarded in a larger context and under consideration of various academic disciplines before being consolidated for this research. Finally, this chapter closes by providing an understanding of the system, its system architecture and the underlying system requirements (section 2.5).

2.1 Plant engineering and offshore drilling systems

This section is to introduce plant engineering as the broader industrial field representing offshore drilling systems. This categorization supports, on the one hand, accessing information and building upon a broader reference basis that shares the same or alike characteristics, hence, supporting the development of the methodology. On the other hand, it also provides a broader context of application of the methodology beyond the narrow application field of offshore drilling systems. The characterization of plant engineering and the delimitation to offshore drilling systems bases strongly upon insights provided by HERBERG [2016, pp. 15–26].

According to VDMA [1976] plants are defined as a "combination of single, in their function not independent units like machines, devices, electric power units, controls and the connecting elements like electrical connection lines […], which altogether cause a certain production- and working process […]". Furthermore, those plants represent "independent and stationary or stationary used functional units which are not deployed solely temporarily or at constantly changing locations" [BStMUGV 2009, p. 5].

According to FÖRSTER [2003, p. 10] and based on GAUSEMEIER ET AL. [2000], machinery and plant engineering[49] can be separated from five other company groups: Producers of units, electrical devices, production machinery, motor vehicles and supplier of components and individual parts. FÖRSTER [2003, p. 12] provides examples in the field of relevance such as textile, packaging, food processing machines or rail vehicles, large diesel engines and printing machines. Plant engineering can be confined further into large scale plants which consist of e.g.

---

[49] In Germany always referring to both machinery and plant engineering (ger.: Maschinen- und Anlagenbau).

raw material production-[50] and processing facilities, power or chemical plants and wood-processing plants [VDMA 2011, p. 4].

The field of plant engineering possesses typical characteristics which separates it strongly from other fields, especially those of consumer goods and serial production as illustrated in the following:

In contrast to consumer goods, plants represent capital goods [Förster 2003, p. 15], which serve as means for the production or processing of other goods. They are exposed to long lifecycles to amortize those investments and generate profit [Förster 2003, p. 16] leading to a large share of lifecycle costs and revenues to be realized after initial sales [Mateika 2005, p. 2]. Thereby, a significant share in revenues comes from after sales services [Mateika 2005, p. 22].

In contrast to consumer-oriented mass markets, there is not a customer anonymity but known customers ask for individual products [Mateika 2005, p. 14]. Requirements elicitation is performed by complete surveys, mainly qualitative, not basing itself on quantifiable averages of specific market segments [Berekoven et al. 2009, pp. 303–307]. The individual processing of orders highlights a need-driven and not a prognosis-driven product development [Baumberger 2007, p. 151]. As requirements come directly from customers, this leads to a high amount of in-house development [Mateika 2005, p. 16]. It also increases market transparency especially as a result of negotiations on various topics such as quality, price, delivery time, etc. [Berekoven et al. 2009, pp. 303–307]. A negative side effect of this individualization, in comparison to a series production, is the increased complexity [Förster 2003, pp. 10–11]. This complexity is amplified by the importance of the after sales market and the long-term spare part availability [Förster 2003, p. 16]. The individualization of products and systems requires a make-to-order production with workshop character and small batch sizes [Mateika 2005, p. 16] which leads to almost no economies of scale and stresses the need to reduce fixed costs to remain competitive [Mateika 2005, p. 17].

In plant engineering sales precede the actual creation of the good [Mateika 2005, p. 15]. According to Förster [2003, p. 4] during “projection planning” the requirements analysis and concept generation of the plant is performed. As defined by Tropschuh [1988], this phase marks “the activities between customer inquiry and the submission of an offer by the customer” which coincides with the tendering activities described by Beil [2010] shown in section 1.1.2. In this phase the information level on requirements is still low while time pressure is high leading typically to the use of baseline systems and subsystems as a starting point [Förster 2003, p. 87]. In those early phases negotiations usually have a strong emphasis on commercial aspects [Herberg 2016, p. 18]. At the same time as a result of the limited development capacity compared to serial production, the main objectives concern fulfilling the desired functions by the customized system and an on-time delivery [Förster 2003, p. 15]. However, as decision-making is usually performed intuitively without considering implications over the lifecycle [Mateika 2005, p. 4], this leads to uncalculated technical, temporal and economic risks [Herberg 2016, p. 18]. Especially as plants, in contrast to a serial production, can mainly only

---

[50] Offshore drilling systems can be attributed to this category [Herberg 2016, p. 16].

be tested and examined after system integration of the physical system [HERBERG 2016, p. 19], this risk is even amplified.

The characteristics that apply for plant engineering, in general, are equally applicable for the specific application field of offshore drilling systems. Aspects that may further specify the field of offshore drilling, especially regarding the business environment and market, were introduced in section 1.1.2 and 1.1.3. Further differentiating features of the technical and operating environment are:

- Discontinuously working systems: As shown in section 1.1.1, an offshore drilling rig represents a discontinuously working facility, in contrast to continuously working facilities such as power plants, process plants or production lines [HERBERG 2016, p. 22].
- Mobility: Although offshore drilling systems constitute mainly stationary equipment (section 1.1.1), the entire Mobile Offshore Drilling Unit (MODU) may change operating locations.
- Operating context-dependency and influences: The performance and system output of offshore drilling rigs, especially MODUs, depend extremely on exogenous factors from metocean[51], geology, human and regulatory which are highly uncertain [ALLAVERDI 2012; ALLAVERDI ET AL. 2013]. Hence, those factors strongly govern design specifications.
- Constraints: Offshore drilling units, especially MODUs, face extraordinary spatial constraints, which are strongly determined by the hull design and mass constraints on the rig and in certain rig areas [HERBERG 2016, p. 25]. Additionally, as introduced in section 1.1.1 for the realization of downhole drilling processes when making a well, the tight area around the well center represents a chokepoint [HERBERG 2016, p. 25] which governs the speed of interrelated topside activities and possibly leading to downtime of the entire rig in case of disturbances.

Although offshore drilling systems represent a unique field of plant engineering, due to the multifaceted characteristics of offshore drilling systems, various other fields must also be considered. For instance, the mission character of offshore drilling rigs and systems during operations make space systems (e.g. LAFLEUR & SALEH [2010]) an important field of consideration. Additionally, when considering the common characteristics where flexible design is most relevant[52] (section 1.2.4) there are also other fields of interest that go beyond plant engineering such as construction as illustrated in section 1.3.1. Hence, although offshore drilling systems can be allocated to the field of plant engineering, both the reference basis as well as the field of application of the methodology depends especially on the individual characteristics of those domains rather than a top-down classification.

---

[51] Metocean parameters include factors attributed to: winds, waves, water depths and sea level variations, currents, air and sea temperatures, snow and ice, marine growths and their combinations [HSE 2001; ALLAVERDI 2012].

[52] Systems with large and mostly irreversible investments, exposed to long lifecycles and large usage / requirements uncertainty [DE WECK 2007, 2008].

2.2 Systematization and modeling of uncertainty

Uncertainty is prevalent in different fields including philosophy, statistics, economics, finance, insurance, psychology, engineering and science [DE WECK ET AL. 2007]. In this context of application, the uncertainty in early design phases is addressed that comes from yet unknown utilization in the future of technical systems.

Uncertainty is present in all areas of design and designing related to products, processes, users and organizations [EARL ET AL. 2005]. According to EARL ET AL. [2005] "new designs have parameters and behaviors which are not known completely beforehand, processes have uncertain durations and uncertain effects, users and conditions of use can change, organizations change and, more widely, contexts, environments and long-term conditions of use are unpredictable". This complicates the design process by the increasing numbers and combinations of possible outcomes.

CHUCHOLOWSKI ET AL. [2013] differentiate engineering changes in general by considering their causality: "Reasons" (also: "objective", "motivation") are arguments that motivate the change or objectives pursued by the change. "Initiators" (also: "sources") are domains that indicate or require the change. "Causes" are considered to be the circumstances / factors that lead to the "target deviation" (also: "trigger") as part of a cause-effect network (section 4.2.1). Root causes are the specific underlying causes that can be reasonably identified and controlled by management. According to CHUCHOLOWSKI ET AL. [2013] "root causes" can be used synonymously to "drivers".

In general, as uncertainties represent the reasons for change, they are often all referred to as "change drivers" such as by HERNÁNDEZ [2003], WESTKÄMPER & ZAHN [2009], RÖSIÖ [2012], KLEMKE [2014]. Other terms used are simply "uncertainties" [DE WECK ET AL. 2007], "system drivers" [BARTOLOMEI 2007, p. 74], "drivers" [NEUFVILLE & SCHOLTES 2011, p. 70], "causes of perturbation" [MEKDECI ET AL. 2012] or "uncertainty drivers" [CARDIN 2014]. They represent "disturbance variables" [KLEMKE 2014, p. 44], "influences that claim a change" [RÖSIÖ 2012, p. 20] or "initiators of change" [HERNÁNDEZ 2003, p. 32] that must be responded to.

Uncertainties can be systematized differently. Section 2.2.1 provides two relevant alternatives of systematization: On the one hand, uncertainties can be characterized by the knowledge on uncertainty. On the other hand, uncertainty sources can be used for systematization. Next to systematizing uncertainties, the alternatives to modeling uncertainties are discussed in section 2.2.2.

2.2.1 Uncertainty knowledge and sources

Knowledge on uncertainty

MCMANUS & HASTINGS [2004] differentiate uncertainties from the view of a system architect or designer. According to MCMANUS & HASTINGS [2004] uncertainties can be categorized by the accessibility of knowledge; although being a continuum they are represented as three discrete categories: First, they can represent statistically characterized (random) variables / phenomena, i.e. "things that cannot always be known precisely, but which can be statistically characterized, or at least bounded". This includes e.g. environmental variables such as the weather in a specific region. Secondly, they may be "known unknowns" (things we know we don't know) which are at best bounded and may have entirely unknown values. Thirdly, the most uncertain category is represented by "unknown unknowns"[53], also referred to as "unk-unks", that are things we don't know we don't know. EARL ET AL. [2005] and BROWNING & RAMASESH [2015], amongst others, do not differentiate between the first and second category both referring to them as "known unknowns". Whereas known unknowns can be handled by conventional risk management [MCMANUS & HASTINGS 2004; BROWNING & RAMASESH 2015], unk-unks require conservative mitigation strategies [MCMANUS & HASTINGS 2004].

On the one hand, uncertainties can be considered from the knowledge base of a person or organization and are not static but evolve over time as more information is collected [MCMANUS & HASTINGS 2004]. On the other hand, as "many planners resist wasting resources on planning projects that may never happen", this can lead to a large gap of what is knowable and what is actually known [BROWNING & RAMASESH 2015]. Hence, as suggested by BROWNING & RAMASESH [2015] some unk-unks can be converted[54] to known unknowns where the techniques of conventional risk management apply again (Figure 2-1).

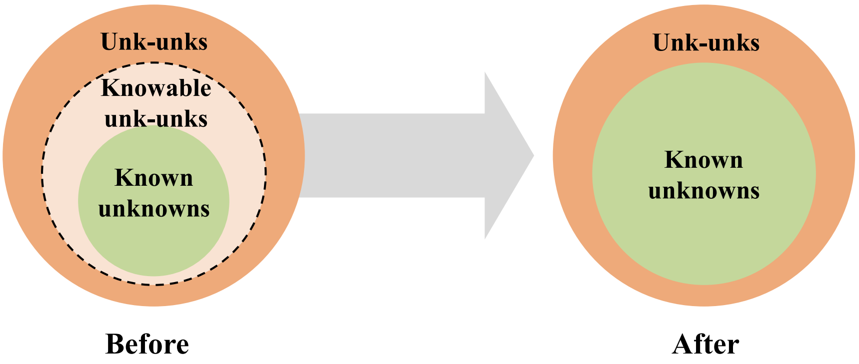


Figure 2-1 Converting knowable unk-unks to known unknowns (adapted from BROWNING & RAMASESH [2015])

Especially by considering the unarticulated needs which are explicitly addressed by BR II (Comprehensive identification of FDOs), the methodology is to support the conversion of knowable unk-unks to known-unknowns which, in turn, allows them to be targeted specifically. Unk-unks that are not knowable, hence, cannot be identified through additional efforts require general and conservative mitigation strategies and are not targeted by the methodology.

Sources of uncertainty

In system design uncertainties can be differentiated between endogenous and exogenous ones[55] depending on whether the sources of those uncertainties lie within or outside the system

---

[53] Wholly unknown uncertainties or "insurance against all future eventualities" as defined by SUH ET AL. [2007].

[54] BROWNING & RAMASESH [2015] suggest "directed recognition" as a combination of targets, methods and tools.

[55] In line with DE WECK ET AL. [2007], this differentiation also applies to this work.

boundary or sphere of influence [DE WECK ET AL. 2007]. Thereby, two types of uncertainties within the system are differentiated:

- Product context: Uncertainty relates to the technical risk of the product due to its novelty. Uncertainty also arises by integrating proven components into other proven products causing unknown interactions or exceeding tolerance margins. Additionally, unmodeled interactions between parts of the system may lead to uncertain change propagations once changes occur. The reliability of a component and the durability, i.e. wear and tear of a component, may also be uncertain leading to unscheduled deterioration or failures.
- Corporate context: Here uncertainties are addressed that relate to the business context in which the product is designed. This may include uncertainties due to internal ill-planning (product strategies) or unexpected product changes due to contractual agreements.

Exogenous uncertainties are beyond the company's control and as section 1.2.1 highlighted the main uncertainties of concern in this work:

- Use context: Uncertainty related to the way a product is used and the conditions under which it has to operate, e.g. different weather conditions, skills of system operators, etc.
- Market context: Uncertainty related to changes in demand profiles which also highly depend on the behavior of competitors in the market. This category also includes changes in the economy such as changes of exchange rates affecting the cost of manufacturing, etc.
- Political and cultural context: Uncertainty related to changing legislation and regulations which affect both the design of products and the operability of existing products. Uncertainty is also driven by political decisions and new trends, policies and fashions across different cultures and globally.

Various authors in the field of product and system design and factory planning highlight similar change driver categories and individual drivers as suggested by DE WECK ET AL. [2007]:

For instance, resulting from two workshops with 12 participants of various industries, ECKERT ET AL. [2009] differentiate similar causes for changes which partially include the highlighted sources of uncertainty including: "requirements", "regulations", "competition / market opportunities", "technology", "quality, cost, capability", "sustainability", "errors / problems / system integration", "project management", "change to use the product" and "design for service / upgrades / technology obsolescence". GREDEN [2005, p. 61] which addresses the building industry, differentiates similarly amongst market, climate, regulatory, technological and future use uncertainties. SHARIFI & ZHANG [1999] provide a more comprehensive view on changes in a manufacturing firm as a whole, introducing the five change driver categories "changes in market", "changes in competition", "changes in customer requirements", "changes in technology" and "changes in social factors".

Literature dedicated solely to factory planning also differentiates between internal and external change drivers (e.g. HERNÁNDEZ [2003, pp. 109–112], KLEMKE [2014, p. 15], WESTKÄMPER & ZAHN [2009, pp. 9–12]). In particular, HERNÁNDEZ [2003, pp. 157–163] defines 13 manageable internal divisions related to the factory surround (e.g. corporate management, sales planning, research / development). Additionally, he distinguishes between non-manageable external fields, which consist, on the one hand, of 11 divisions related to the corporate surround (e.g.

competitors, market, customers) and, on the other hand, of 6 divisions in the global surround (e.g. politics, economy, society / public). KLEMKE [2014, pp. 167–169] defines a total 39 change drivers[56] differentiating amongst the categories: "quantity and variant driver" (factors influencing quantity and variants), "target drivers" (factors influencing cost, quality and time targets) and "process- and element driver" (factors influencing objects in the factory).

A smaller subset of considered change drivers can be found in the field of production engineering. Here the focus lies on change drivers related to the "product", "volume", "technology" and "strategy" as summarized from various relevant literature by RÖSIÖ [2012, p. 21].

Those uncertainties affect each other [DE WECK ET AL. 2007; CHUCHOLOWSKI ET AL. 2013], however, do not all overlap and many endogenous uncertainties are even independent of exogenous uncertainties [DE WECK ET AL. 2007]. KREBS [2011, pp. 16–17] differentiates further amongst qualitative and quantitative relationships. HERNÁNDEZ [2003, pp. 112–115] uses those interdependencies in order to generate scenarios.

Although various literature and application fields share common change drivers, especially on a higher level of aggregation, at a more detailed level they are usually system or domain specific (e.g. SCHUH ET AL. [2009], SHARIFI & ZHANG [1999]). SHARIFI & ZHANG [1999] address even the contradictive meaning of change drivers where "a change that may be a harmful incident for a company may not be bad for another company or even the same company in a different situation. It could even be an opportunity in a different time or place". In line with this observation, NEUFVILLE & SCHOLTES [2011, p. 70] highlight that "there is no convenient checklist of drivers" and that "we need to think deeply about our system and identify the factors that will influence its performance". Hence, this process usually requires the collaboration of a range of experts [NEUFVILLE & SCHOLTES 2011, p. 70; KLEMKE [2014, p. 63].

Consequently, whereas the identified sources of uncertainties can be generally applicable on higher levels of aggregation and support the identification of specific change drivers in the application fields of interest, its constituents can hardly be generalized across those fields and must be elicited separately.

2.2.2 Uncertainty modeling

In line with DE WECK ET AL. [2007], one can differentiate between formal and practical approaches to uncertainty modeling. Formal approaches are extensively elaborated on in HALPERN [2003] and mainly include numeric expressions of the likelihood of future events. Practical approaches instead are more prevalent in the engineering context. The alternative approaches to uncertainty modeling are based on DE WECK ET AL. [2007] which are introduced the following and visualized in Figure 2-2.

---

[56] Explicitly neglecting "extreme" change drivers such as financial crisis or natural catastrophes as they can hardly be predicted.

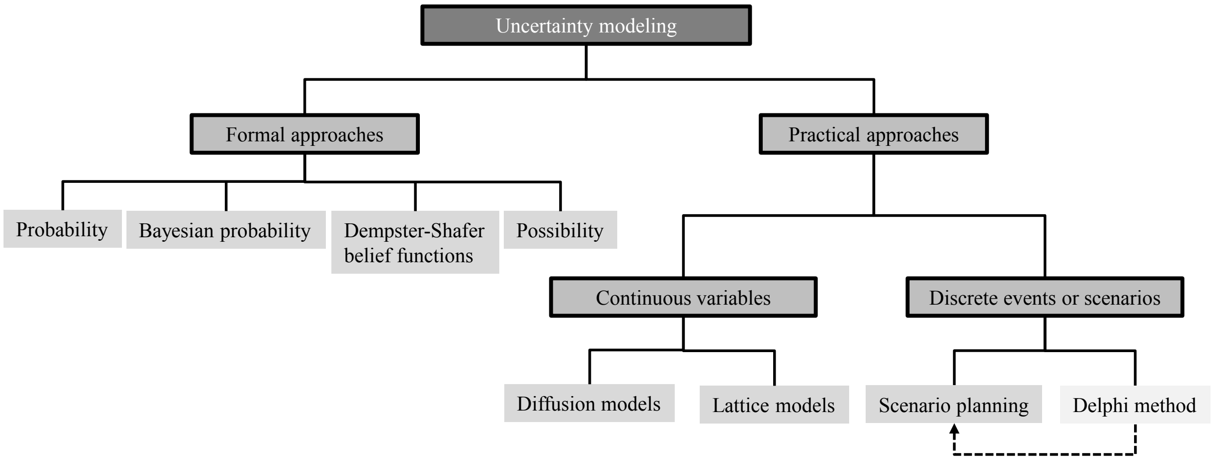


Figure 2-2 Alternative approaches to uncertainty modeling (based on DE WECK ET AL. *[2007])*

Formal approaches to uncertainty modeling

"Probability theory" considers the extent to which something is likely to happen or be the case. It is used extensively in areas such as statistics, mathematics, science, philosophy to draw conclusions about the likelihood of potential events and the underlying mechanics of complex systems. "Bayesian probability theory" defines probability as the degree to which a person believes a proposition. Bayesian theory also suggests that Bayes' theorem can be used as a rule to deduce or update the degree of belief with the occurrence of new information. The "Dempster-Shafer theory" [DEMPSTER 1967; SHAFER 1976] is based on the mathematical theory of evidence based on belief functions and plausible reasoning being used to combine evidence from different sources and determine the probability of an event. "Possibility theory" is mathematical theory, an alternative to probability theory, dealing with certain types of uncertainty. ZADEH [1978] bases upon and extends the theory of fuzzy sets and fuzzy logic, where information is considered as incomplete or imprecise and memberships of elements can be gradually assessed.

As highlighted in CARDIN [2014], probability, bayesian and possibility theory are useful when knowledge is available on the underlying phenomena; in contrast, for applying the Dempster-Shafer theory expert knowledge is required to elicit distributions. As emphasized by DE WECK ET AL. [2007], due to various reasons (e.g. time and financial constraints, engineering educational background) those methods are often inaccessible to designers and engineers seeking to incorporate future uncertainty into their thinking and design work. Hence, this provides the basis for less formal and more practical approaches in systems design.

Practical approaches to uncertainty modeling

According to DE WECK ET AL. [2007], practical approaches can be divided into two main categories, namely models representing continuous uncertainty variables and those representing discrete ones:

Continuous variables represent uncertainty as a random variable over time (e.g. prices of commodities, raw materials). Here "diffusion models" (e.g. De Weck, Olivier L et al. [2004]) are addressed where the initial state is known and there is diffusion due to randomness using a mathematical description, usually Geometric Brownian Motion (GBM). As a large number of scenarios can occur, this is usually handled by Monte Carlo simulation. Alternatively, “lattice models” can be applied [COX ET AL. 1979] where the evolution of the uncertain factor (e.g. price, market value, demand, etc.) is depicted as a binomial model. This means a state with a certain value (V) at time (t) can only progress to either an up state with value uV and with probability p, or to a down state with value dV and probability 1 – p.

Next to modeling continuous variables, more discrete uncertainties are addressed represented by discrete events (e.g. earthquake, hurricane) or scenarios which can be covered by “scenario planning”. The idea is to generate a finite set of future scenarios that collectively capture the possible future outcomes. According to GAUSEMEIER ET AL. [2001, p. 79] “a scenario is a universal description of a possible situation in the future that bases upon a complex network of influencing factors. Furthermore, a scenario can include the representation of a development that evolves from the present to that situation”.

A general procedure of scenario generation is provided in Figure 2-3. According to GAUSEMEIER ET AL. [2001, pp. 84–116], scenario management follows a five-step process: First, with the scenario preparation (phase 1), the project goal and project organization is determined and the design field[57] is analyzed and defined. When performing the scenario field analysis (phase 2), the scenario field is described by the corresponding influencing factors which drive the change of a design field and, hence, correspond to the introduced change drivers of section 2.2.1. Three alternative scenario fields exist which determine those types of influencing factors: The scenario field may lie outside of the design field and cannot be affected (outer field scenario). Alternatively, the scenario may only refer to internal factors which can be affected and, as they are part of the design field, form the so-called “design field scenario”. Oftentimes, however, a mixture of both scenarios exist which result in so-called “system scenarios”. Hence, the considered influencing factors may both come from outside and inside the design field. The generated key factors, which act as representatives of various influencing factors, result from the analysis of the interdependencies amongst influencing factors. The scenario prognosis (phase 3) represents the core of scenario management. Here the alternative developments of the previously specified key factors (also referred to as “projections”) are determined and the most characteristic ones selected. Based on those relevant projections and during scenario generation (phase 4), a handful of coherent and applicable scenarios are defined[58]. In the fifth and last phase (scenario transfer) the impact of those scenarios on the defined “design field” is analyzed. Based on the alternative development possibilities, explanations for strategic decisions and the development of suitable handling strategies are derived. Hereby, GAUSEMEIER ET AL. [2001, p. 105] differentiate between two alternative strategies that depend on the extent of scenarios: A strategy that bases upon one scenario only is considered to be “focused” whereas a strategy that accounts for multiple future scenarios, usually similar ones to limit the effort, is referred to as “future robust”.

---

[57] Those areas that should be designed when addressing scenario project such as product, service or technology.

[58] GAUSEMEIER ET AL. [2001, pp. 96–99] divide this phase into two stages. Based on the projection consistent projection clusters are generated. Those projection clusters, in turn, are again compared amongst each other and merged into internally consistent groups resulting in a handful of very different “raw scenarios”.

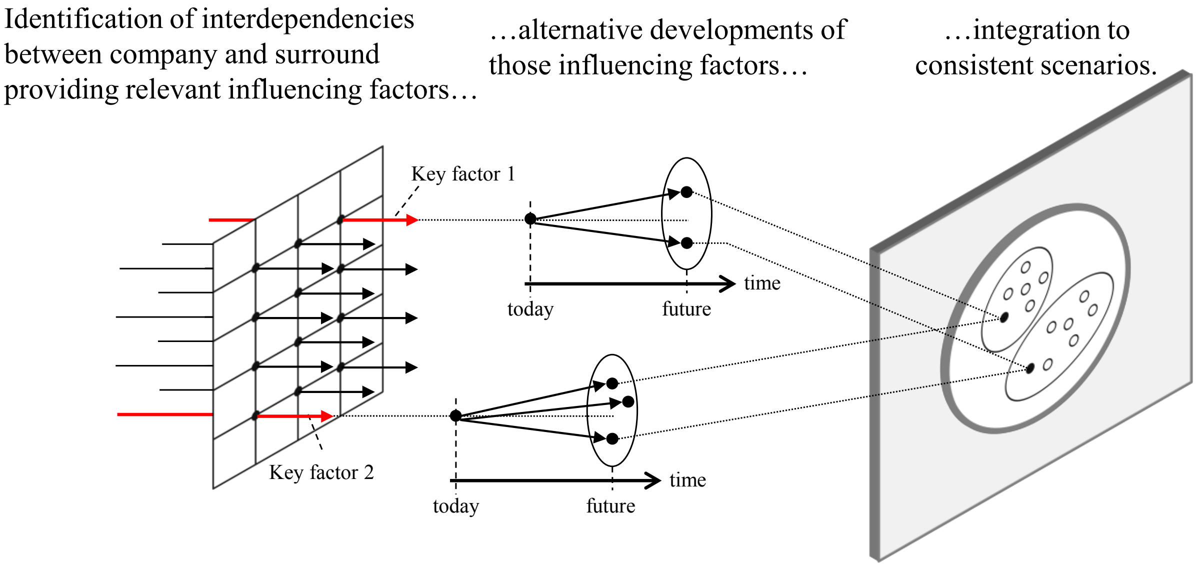


Figure 2-3 General procedure of scenario generation [GAUSEMEIER ET AL. 2001, p. 85]

Strongly associated with scenario planning and described by HELMER-HIRSCHBERG [1967], the Delphi method represents a systematic, multistage interview technique that supports the identification of future trends, events, technical developments, etc. Domain experts are provided with questions or theses of the future and generate their prognosis independently while adjusting their written statements depending on anonymous feedback of other experts. In the end the intention is to arrive at a consensus amongst those experts. As highlighted by DE WECK ET AL. [2007], the Delphi method describes a formal way for generating the future scenarios based on an expert group opinion, hence, it is considered complementary to scenario planning, especially supporting the phase of scenario prognosis.

Due to the important basic requirement "BR V" (Appropriate usability for engineers), practical approaches are favored in this work. Additionally, as the addressed epoch shifts lead to abrupt value losses (section 1.2.4), a modeling of discrete events and scenarios is pursued. Hence, scenario planning is considered to be the most suitable uncertainty modeling method for the methodology.

2.3 Lifecycle perspective on changes

Building on Figure 1-8 and adapted from SALEH ET AL. [2003], Figure 2-4 displays a typical system lifecycle where changes can occur across different phases. According to SALEH ET AL. [2003] and highlighted in Figure 2-4, only those changes are relevant that occur when systems are in operation, i.e. after they have been fielded. As literature provides a very inconsistent and mixed taxonomy on upgrades and related fields [MÖRTL 2002, p. 26], they must be addressed and delimited carefully to focus the targeted types of changes for this work.

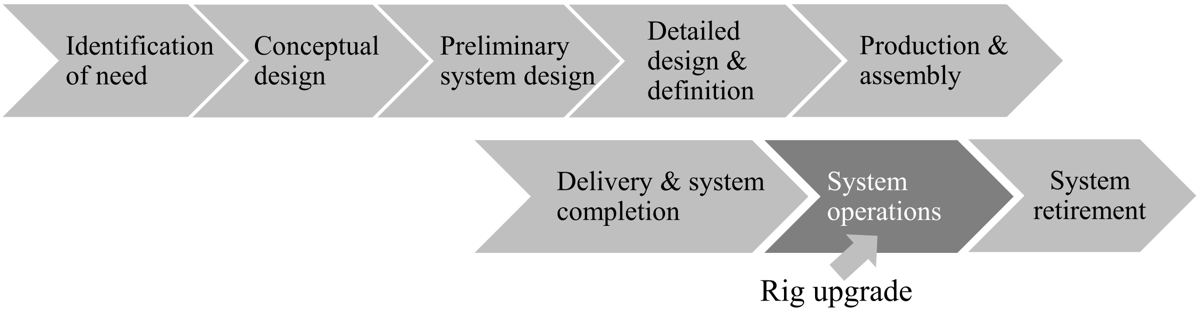


Figure 2-4 Typical system lifecycle and targeted phase (adapted from SALEH ET AL. [2003])

Changes of systems and underlying products[59] differ across their utilization phase. Based on MÖRTL [2002, p. 28], MATEIKA [2005, p. 23] and ULRICH [1995], the following main types[60] are condensed to:

- Maintenance & repair: Checking the deteriorated actual state against the initially defined target state of product or system and, if required, re-establishing target state without changing the technological level[61].
- Overhaul: Dismantling, cleaning, checking, refurbishment or exchange of component parts performed within pre-scheduled intervals to keep desired target state at same technological level.
- Upcycling / Retrofit: Adaptation or replacement of component parts and modules of products and systems to a higher technological level. It also involves exchanging entire products with modern ones at the end of their lifecycle, usually during planned production shutdowns, while reusing the existing engineering infrastructure such as piping, cabling, cabinets, etc. as much as possible.
- Upgrade: Increase of utility by adding or changing functionality of product or system, hence, leading to the integration of additional modules and component parts to attain a higher technological level.
- Adaptation: Changes of products and systems due to application in different use environments, hence, increasing utility without necessarily changing the technological level [ULRICH 1995].

---

[59] As section 2.5.2 and 5.3.3 will show, whereas the "system" comprises all physical constituents that a system is made up of, "products" refer to a very important sub-system where each one fulfills an important function and, thereby, contributes directly to the overall fulfillment of the process. Both the entire system, in general, and the underlying products, in particular, are relevant with regards to the addressed "rig upgrades".

[60] Although those main types were strictly separated here, they are partially interrelated and, hence, in practice used interchangeably to some extent.

[61] MÖRTL [2002, p. 28] refers to "technological level" as the technical standard that is embodied by the product or system. By changes over the lifetime, the technological level of a product or system may be kept the same or, in order to prevent technical obsolescence, be modified to an up-to-date technology superseding the old one.

Figure 2-5 delimits the changes that are considered in this work from the ones that are excluded.

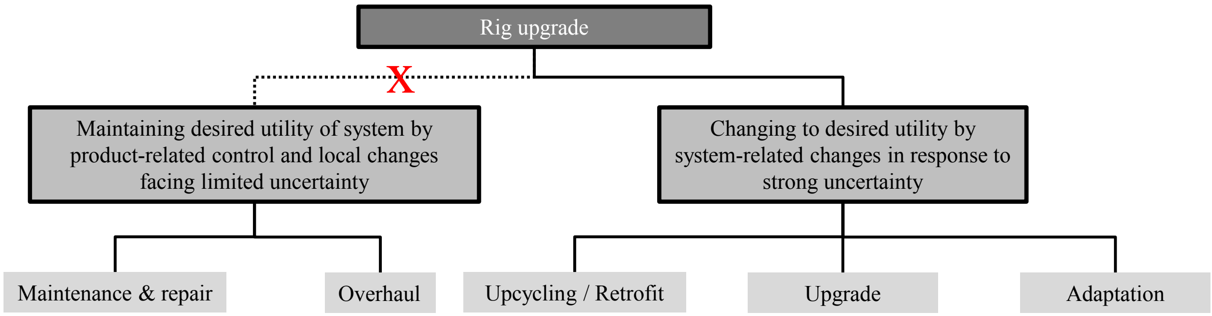


Figure 2-5 Different types of changes and delimitation of rig upgrades

As discussed in section 1.3.1 for flexible design to be of value, the addressed system should have a long lifecycle, face large uncertainty in user needs and perform large (partially) irreversible investments [DE WECK 2007, 2008]. Therefore, the types of changes that are of concern should also be the consequence of strong uncertainty, be of large scale and, hence, face significant efforts to be realized. Consequently, "upcycling / retrofit", "upgrade" and "adaptation" represent most relevant candidate changes as they result from strong utilization uncertainty while requiring a high effort to realize them. They are referred to as the larger scale "rig upgrades" in order to modify rig functions and systems in the face of known and knowable uncertainty (section 2.2.1) to provide additional utility to system users.

Those rig upgrades can be facilitated by changeable and flexible design being addressed in the following section.

2.4 Flexible and flexibility-related design

The definition of "flexibility" is highly ambiguous and confusing as discussed in various literature [SALEH ET AL. 2003; ROSS ET AL. 2008; SALEH ET AL. 2009; KISSEL ET AL. 2012; ROSS & RHODES 2015]. As "flexibility" the strongly related term of "changeability" is also inconsistently defined [HERNÁNDEZ 2003, p. 26]. Hence, for this thesis it is important to introduce the relevant main concepts of flexibility and related terms followed by a synthesis and delimitation of the most applicable definitions for this work.

The following three academic fields of relevance are addressed separately in the following sections:

- Changeability and flexibility in engineering design (section 2.4.1)
- Changeability and flexibility in manufacturing and factory planning (section 2.4.2)
- Real options and managerial flexibility of engineering systems (section 2.4.3)

Based on those three fields, a definition for this research is synthetized in section 2.4.4.

2.4.1 Changeability and flexibility in engineering design

When addressing "flexibility" it is important to define and disambiguate that term from related terms that also address a change of systems but have a different focus. For an initial definition and disambiguation, the consideration of lifecycle properties of engineering systems, or so-called "ilities"[62], is considered to be a suitable framework. It differentiates properties of systems that usually manifest themselves after a system has been put to its initial use and typically concerns wider system impacts with respect to time and stakeholders [DE WECK ET AL. 2011]. Preliminary results on ilities indicate that at least three semantic fields exist including "change-type", "architecture-type" and "new ability-type" ilities [ROSS & RHODES 2015]. Change-type ilities, in particular, are relevant in this regard as they address change or resistance of changing systems which also includes "flexibility".

An explorative study with individuals researching and applying ilities uncovered potential means-end[63] hierarchical relationships amongst a set of change-type ilities [DE WECK ET AL. 2012; ROSS & RHODES 2015]. Table 2-1 shows the definitions of the change-type ilities that were provided to the groups for this exercise[64]. The aggregated view from the different groups under investigation implied that "value robustness" is regarded as a top-level change-type ility under which it includes "changeability", "robustness" and "survivability".

Table 2-1 Change-type ilities for means-end hierarchy exercise [DE WECK ET AL. 2012]

Ility Name	Definition ("ability of system...")
adaptability	to be changed by a system-internal change agent with intent
agility	to change in a timely fashion
changeability	to alter its operations or form, and consequently possibly its function, at an acceptable level of resources
evolvability	design to be inherited and changed across generations (over time)
extensibility	to accommodate new features after design
flexibility	to be changed by a system-external change agent with intent
modifiability	to change the current set of specified system parameters
reconfigurability	to change its component arrangement and links reversibly
robustness	to maintain its level and/or set of specified parameters in the context of changing system external and internal forces
scalability	to change the current level of a specified system parameter
survivability	to minimize the impact of a finite duration disturbance on value delivery
value robustness	to maintain value delivery in spite of changes in needs or context
versatility	to satisfy diverse needs for the system without having to change form

The change-type ilities were extended by MEKDECI [2013, pp. 141–155] who additionally introduced the term "pliability"[65]. It refers to "the ability of a system to change, without breaking its system architecture", i.e. considering pliable sets where all validated designs can be transitioned to within a system architecture. New change-type ilities are likely to be added to the existing set in the future.

---

[62] Usually but not always terms ending with "-ility".

[63] Multiple child-parent links.

[64] The ilities "modularity" and "interoperability" were initially on this list. However, through this exercise they were later identified as "bottom-end" ilities, i.e. appear at lower levels and serve as enablers for higher level ilities. They are considered to belong to the semantic field of "architecture-types" [ROSS & RHODES 2015].

[65] Changeability is considered to be a prerequisite for "pliability". However, in addition to facilitating a transition to a new system (changeability), it requires that the new system is part of the same system architecture which is not a requirement for changeability [MEKDECI 2013, p. 153].

“Flexibility” is considered further within the framework of change-type ilities to resolve the ambiguousness and define it for this work.

Focusing changeability types and flexibility

Apart from the means-end hierarchy study, Ross & Rhodes [2015] define changeability as the higher or overarching ility that encompasses other ilities. They are introduced in Ross et al. [2008] and include: adaptability, flexibility, robustness, scalability and modifiability.

Ross et al. [2008] differentiate in that context between “change mechanisms”, “change effects” and “change agents”. According to Ross et al. [2008] the change mechanism is the path[66] the system must take in order to transition from its prior to its post state as deepened in section 3.3.1. Both change effects and change agents affect the type of “changeability” that is addressed.

Change effects address the parameter sets and values such as for a car with the parameter sets {number of wheels, color of vehicle, quietness of cabin} and the parameter values {4, “red”, “moderately quiet”}[67]. Depending on the change effects, three different changeability types can be differentiated:

- “Modifiability” means that the current set of specified parameters is changed (e.g. by adding the new parameter “fraction cabin open” to the existing parameter set)
- “Scalability” means that the current value of the specified parameter changes (e.g. color of vehicle changes from “red” to “blue”)
- “Robustness” means that both the set and the values of parameters can be maintained despite changes in the operating environment

The other means for differentiating changeability types are through change agents which refer to instigators, i.e. the forces for setting the change in motion (Figure 2-6). Whereas flexible changes are regarded those that are initiated by external agents (e.g. upgrades by humans), adaptable changes are those that are initiated internally (e.g. by software).

Fricke & Schulz [2005], in contrast, refer to only four types of changeability represented by: flexibility, agility, robustness and adaptability. The understanding of the flexibility types by Ross et al. [2008] and Fricke & Schulz [2005] is still in line and corresponds to the definitions in Table 2-1. However, Fricke & Schulz [2005], differentiate “flexibility” further by highlighting the “ease of system change”, where agility focuses on the “rapidness of system change”. Flexibility is regarded as a prerequisite for “agility” implying that latter has a higher “system intelligence” than flexibility [Schulz & Fricke 1999]. Similarly, “adaptability” is regarded as a higher intelligent changeability type than “robustness” where external changes are not required for any of those two. Latter differentiation is also made by Olewnik et al.

---

[66] According to Ross et al. [2008], “changeability” is determined by the number of acceptable change paths that can be taken which depends on the possible number of end states and the number of change mechanisms available.

[67] Whereas parameters strongly correspond to the definition of “attributes”, parameter values strongly coincide with “characteristics” of which both make up “object properties” (section 7.2.1).

[2004] who consider "adaptable design parameters to be capable of accommodating predictable changes in operating environment, while robust design parameters are capable of accommodating unforeseeable changes in the operating environment".

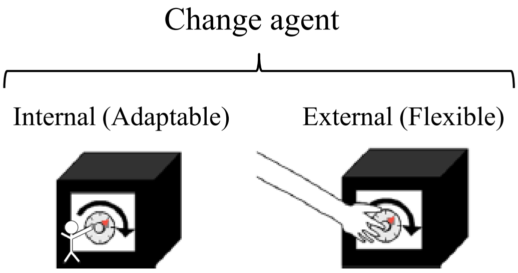


Figure 2-6 Change agent location (internal or external) for distinguishing between "adaptability" and "flexibility" [Ross et al. 2008]

Saleh et al. [2003] also differentiate between flexibility and robustness: "Whereas flexibility implies the ability of a design to satisfy changing requirements after the system has been fielded, robustness involves satisfying a fixed set of requirements despite changes in the system environment (or within the system itself)". Figure 2-7 depicts this by illustrating the relation between system objectives and environment. Fixed or changing system objectives correspond to the introduced variations of either "parameter set" and/or "values" defined by Ross et al. [2008].

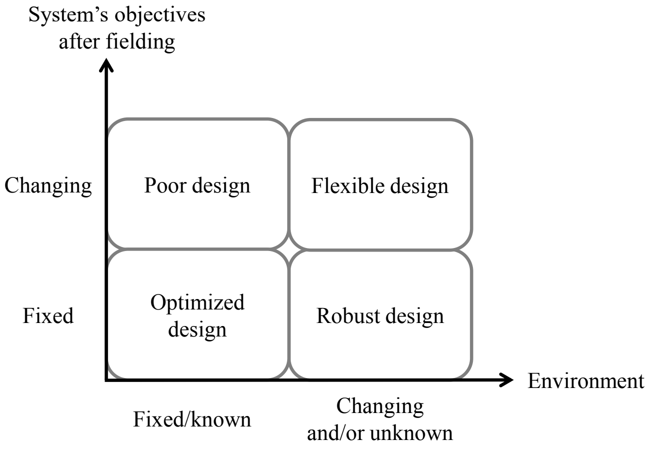


Figure 2-7 Flexibility and robustness as a function of the system's objectives and environment [Saleh et al. 2003]

Furthermore, as highlighted by Kissel et al. [2012] heterogeneous definitions of flexibility and adaptability contribute majorly to the ambiguity in this field as they often have opposite meanings in literature. The reason lies in an opposed change agent perspective when referring to flexibility or adaptability as used in e.g. Gu et al. [2009] or Hashemian [2005]. Despite those different definitions, the underlying concepts are still relevant for either field of literature and are consequently accounted for. In order to avoid confusion, however, in the following section both "adaptability" and "flexibility" refer to external changes of the product or system.

Differentiating flexibility from lifecycle perspective

According to SALEH ET AL. [2003] flexibility in engineering can be separated into two[68] different time intervals across the lifecycle, one addressing changes before and one after fielding the system: On the one hand, it addresses “flexibility in the design process” before the system operations commence (T_{ops}) denoting a willingness and ability to include requirement changes and characterizing the interaction between customers and designers working on separate subsystems of complex engineering design. Here flexibility addresses “process flexibility” by including activities, methods and tools devised to mitigate the risks resulting from requirement changes before fielding a system (e.g. flexible requirements until decision-making, flexibility by offering a range of solutions instead of single point solutions). In this context LINDEMANN & REICHWALD [1998] emphasize the need for “integrated engineering change management” to improve the efficiency and effectiveness of changes in companies. Also targeting change before fielding, BISCHOF [2010, p. 26] differentiates between coping with changes of requirements in the design phase by “flexibility of a product under development”[69] which may be also be supported by specific methodologies concerning flexibility (e.g. flexible product platforms by SUH ET AL. [2007]) or design guidelines focusing on easing changes in design phases (e.g. QURESHI ET AL. [2006], KEESE ET AL. [2007]). On the other hand, flexibility in engineering design can also relate to “flexibility of a design after fielding” which addresses handling requirement changes of physically existing systems that are already in operation.

As section 2.3 highlights, flexibility of a design after the fielding is explicitly addressed in this work and flexibility related to “engineering in the design process” is of no concern. Although the focus is not specifically on “flexibility of a product under development”, literature in this field, especially as it usually lacks a clear delimitation, provides important insights that is applicable, and, hence, is considered further.

“Flexibility of a product under development” coincides with the definition of “design-time adaptability” [CHMARRA ET AL. 2008] which refers to the “reuse of the existing design in order to produce different products”. It also coincides with definition of “design adaptability” by HASHEMIAN [2005, p. 69] which “results in the creation of a variety of designs based on a common adaptable blueprint, and in the upgrading of new models through the modification of old designs”. “Flexibility of a design after fielding” can be further split into “runtime adaptability” and “lifetime adaptability” [CHMARRA ET AL. 2008] where both coincide with the definition of “product adaptability” by HASHEMIAN [2005]. “Runtime adaptability” concerns increasing utility by flexibility when the product performs a task (e.g. ease of switching between two tasks). In contrast, through “lifetime adaptability” the product’s service life is prolonged in its normal operational mode and by adapting it to new operational modes [CHMARRA ET AL.

---

[68] Regarding the timing of change and the related flexibility, MOSES [2010] differentiates even between three different types related to the phase of initial design, redesign of an existing system and the operation of the system.

[69] “Flexibility of a product under development” and “Flexibility of a design after fielding” bases upon the original expressions of “design” and “product” in the two references BISCHOF [2010, p. 26] and SALEH ET AL. [2003] respectively. “Design” and “product” can, however, be used interchangeably.

2008]. Figure 2-8 summarizes the relevant definitions of flexibility from a lifecycle perspective basing on the time frame suggested by Saleh et al. [2003].

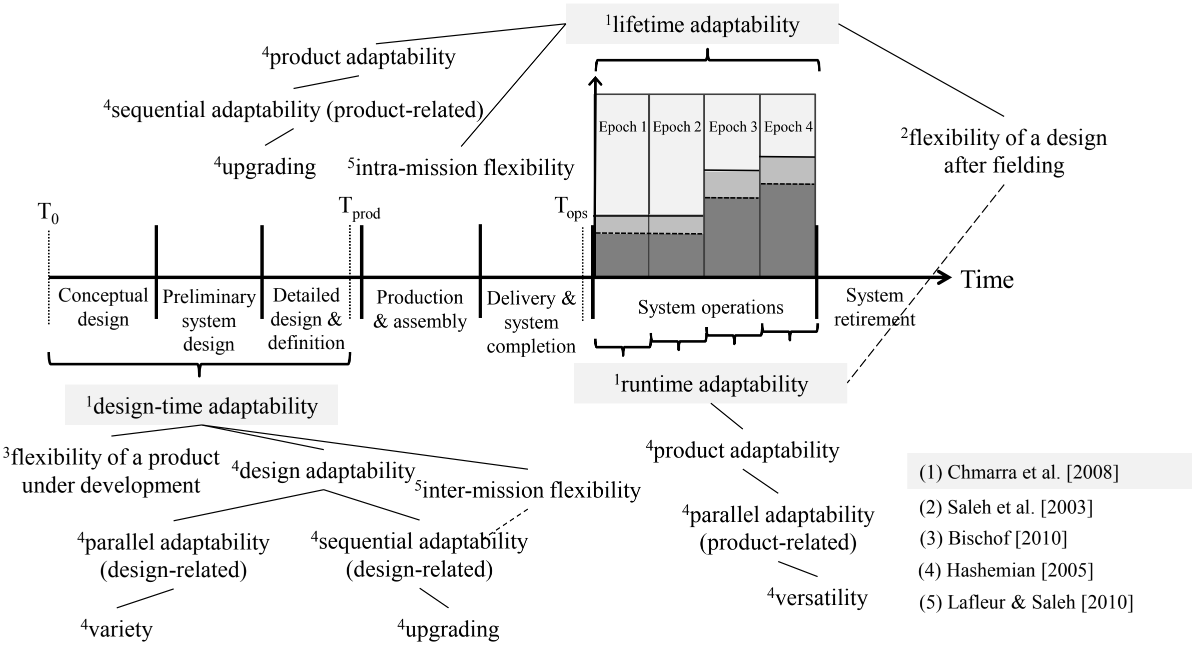


Figure 2-8 Lifecycle perspective on flexibility with relevant references in engineering design

With regards to the "epoch-era" perspective on lifecycle value [Ross & Rhodes 2008] highlighted in section 1.2.4, runtime adaptability can be attributed to planned changes within epochs (e.g. easing rigging activities), whereas lifetime adaptability can be regarded as higher effort adaptations across epoch shifts (e.g. easing system upgrades due to changes in operational and legal environment).

Besides differentiating between design and product adaptability, Hashemian [2005, pp. 71–73] distinguishes also between sequential and parallel adaptability:

Sequential adaptations consider coping with the extension of the service life of a design or product related to emergent technologies, alterations of legal regulations or the time-related changes of requirements. Sequential design adaptations represent the evolutions of designs within a program such as the V2 ballistic missile by Werner von Braun [Hashemian 2005, p. 72]. According to Hashemian [2005, p. 70], product related sequential adaptations could be related to adaptable homes where changes happen continually as the needs or the lifestyle of residents change which strongly corresponds to the introduced "lifetime adaptability". Hashemian [2005, p. 74] refers to both types of sequential adaptations as "upgrades".

Parallel adaptations, in contrast, extend the usage of a product or design into new applications widening the service scope of the system. Parallel adaptations of products or designs are usually reversible. For designs during development this would mean the ease of adapting the design to produce a "variety" of products for different customers or to limit costs of customized products [Hashemian 2005, p. 75]. For products after fielding this would mean the ability of setting-up up the same product in various ways to perform different functions referred to as "versatility"

[HASHEMIAN 2005, p. 74] or “functional versatility” [ROSS & RHODES 2015]. Hence, it can be attributed to “runtime adaptability” that occurs within epochs.

HASHEMIAN [2005, 7-8: 73-74] further differentiates the certainty under which the system is designed for. General adaptability accounts for adapting to unforeseen changes in the absence of forecast information, i.e. unk-unks that are not knowable (section 2.2.1). In this case, no specific adaptations can be targeted during the design process. Instead, specific adaptability is the ability of the system to adapt itself to foreseeable changes (known unknowns) where the provisions in the design are made for specific adaptations which are known in advance. The differentiation between general and specific adaptability cannot be attributed to a specific lifecycle phase and, hence, is not addressed in Figure 2-8.

Another relevant distinction of flexibility addresses the mission character of offshore drilling operations by accounting for inter- and intra-mission flexibility of space systems in response to uncertain operating environments [LAFLEUR & SALEH 2010]. Each mission can be considered as a new epoch. Hereby, inter-mission flexibility refers to multiple (space) vehicles that are fielded in series and whose design is adapted in the course of the program. In contrast, intra-mission flexibility regards a fielded one-of-a kind system which is then modified over time to adapt to changing operating environments. Hence, whereas inter-mission flexibility belongs to design-time adaptability and coincides, in particular, with the definition of sequential design adaptations, intra-mission flexibility can be attributed to lifetime adaptability.

In the following the definitions of changeability and flexibility for manufacturing and factory planning are discussed.

2.4.2 Changeability and flexibility in manufacturing and factory planning

In the field of manufacturing systems TONI & TONCHIA [1998] refer to flexibility as “the ability to change or react with little penalty in time, effort, cost, or performance” in response to “variety of products and processes, and the uncertainty of demand”. Complementary, flexibility can be considered as “a passive attribute for changes in a predefined flexible system scope” [WESTKÄMPER & ZAHN 2009, p. 47] or, as described by REINHART & GRUNWALD [2001], “coping with changes in one or in only a few dimensions in preplanned flexibility corridors”. Based on BROWNE ET AL. [1984] and SETHI & SETHI [1990], ELMARAGHY [2005] classifies 10 basic types of manifesting systems flexibilities. This includes, for instance, “volume flexibility” as the ability to vary production volumes profitably with production capacity. Those manufacturing flexibilities can be attained by different means:

Dedicated Manufacturing Lines (DML) which do not have any embedded flexibility only focus on cost-effectiveness designed for production of a specific part type at high volume [ELMARAGHY 2005]. Instead Flexible Manufacturing Systems (FMS), an integrated system of machine modules and material handling equipment under computer control, allow manufacturing several types of parts at minimum changeover costs on the same system at the required volume and quality [ELMARAGHY 2005]. Changes of processes and production volume can be attained within the pre-defined boundaries without any physical changes of the manufacturing system itself [ELMARAGHY & WIENDAHL 2009, p. 4]. However, due to their high costs, they are only adequate for large part variations that are produced in small quantities [HUTCHINSON

& PFLUGHOEFT 1994]. The high acquisition costs of FMS, in turn, also significantly influence the cost to produce a part [TERKAJ ET AL. 2009]. Reconfigurable Manufacturing Systems (RMS), instead, facilitate cost effective and rapid responses to the market and product changes through customized flexibility that is required at that moment, by performing structural changes [KOREN & SHPITALNI 2011]. They allow changes in functionality and scalable capacity “by physically changing the components of the system through adding, removing or modifying machine modules, machines, cells, material handling units and/or complete lines” [ELMARAGHY & WIENDAHL 2009, p. 4]. Finally, Focused Flexibility Manufacturing Systems (FFMS) consider a mix of built-in flexibility and reconfigurability that is balanced in such a way to ensure lowest costs [TERKAJ ET AL. 2009].

According to GÜNTHNER ET AL. [2006, p. 6] and based on HILDEBRAND ET AL. [2005, pp. 30–31], flexibility can be further differentiated regarding the “timing of activation”: Flexibility that is required during operations and is already considered in the initial investment is referred to as “basic flexibility”. In contrast, flexibility that is required and activated at later stages over the lifecycle, requires a subsequent investment representing “extended flexibility”. In both cases, however, the changes can be sufficiently anticipated and, hence, are planned for with the difference that “extended flexibility” reduces initial investments as the timing of the investment is postponed to operational phases.

However, manufacturing companies face turbulent environments that are especially governed by technology, globalization of markets and permanent changes of demand and supply [WESTKÄMPER & ZAHN 2009, p. 9]. In response, beyond the defensive responses to immediate needs in manufacturing, factories must have a more proactive tactical or even strategic focus on changes that goes beyond the given structures and procedures [ELMARAGHY & WIENDAHL 2009, pp. 9–10]. Consequently, systems are referred to as changeable when its “processes, structures and behavior inherently possess a specific, implementable variability. Changeable systems are capable of not only adapting in reaction but also able to intervene in anticipation” [WESTKÄMPER ET AL. 2000]. REINHART & GRUNWALD [2001] consider changeability as going beyond the predefined flexibility corridor as a combination of “flexibility” and “responsiveness” to deal with any, also unanticipated changes, that represent opportunities. Furthermore, REINHART ET AL. [2008] regard changeability as “the potential which makes it possible to quickly adapt also beyond given corridors in relation to organization and technology without having to extensively invest”. According to GÜNTHNER ET AL. [2006, p. 36], beyond basic and extended flexibility, changeability can be considered as the ability of the system to respond to planned but, additionally, also unplanned events efficiently and effectively.

WIENDAHL ET AL. [2007] define changeability as “characteristics to accomplish early and foresighted adjustments of the factory’s structures and processes on all levels to change impulses economically”. It is considered as an umbrella term concept[70] that encompasses many change enablers at various levels of an industrial company [ELMARAGHY & WIENDAHL 2009, p. 3]. Hence, in contrast to flexibility which applies to especially to the manufacturing and

---

[70] REINHART & GRUNWALD [2001] delimitate “changeability” from “flexibility” by the limited strategic planning of future changes. Instead, WIENDAHL ET AL. [2007] regard “changeability” as an umbrella term for changeover ability, reconfigurability, flexibility, transformability and agility.

assembly levels of a factory, the scope of "changeability" must be extended to the entire factory [ElMaraghy & Wiendahl 2009, p. 11]. According to ElMaraghy & Wiendahl [2009, pp. 11–12] six factory levels can be differentiated that are addressed by the different classes of changeability. The main focus of changeability lies on the intermediate product and production levels[71] addressing flexibility, reconfigurability as a basis and especially the transformability of systems [Wiendahl et al. 2007; ElMaraghy & Wiendahl 2009, p. 13]. Transformability applies to the entire factory and calls for structural intervention in the production and logistics systems, in the structure and facilities of the building, in the organization structure and process and in the area of personnel [ElMaraghy & Wiendahl 2009, p. 13]. Those transformations can involve dismantling options as a basic attribute [Wiendahl et al. 2015, p. 97].

Concerning the type of change in a factory, Hernández [2003, pp. 44–47] provides a system theoretical understanding: Flexibility represents changes in the structure coupling such as redirecting an order to another machine where only relations between the system elements change. In contrast, transformability requires a transformation of the system which beyond the changes of relations also affects the number, order, allocation and functionality of elements.

At last real options and managerial flexibility of engineering systems are addressed in the next section.

2.4.3 Real options and managerial flexibility of engineering systems

Real options derive from finance and economics ("financial options") where flexibility is regarded as an option with the "right but not the obligation to exercise a feature of a contract at a future date" [Higham 2004]. They are especially targeting engineering systems which are "characterized by a high degree of technical complexity, social intricacy, and elaborate processes, aimed at fulfilling important functions in society" [MIT Engineering Systems Division 2008]. They face long lifecycles (+20yr), require large irreversible investments, face large uncertainty over their lifetime and, in addition, have a large number of design variables and parameters [Cardin 2014].

Managerial flexibility refers to the ability of the management to affect the course of a project by acting in response to the resolution of market uncertainty. As new information arrives and uncertainty about market conditions and future cash flows is gradually resolved, management may have valuable flexibility to alter its operating strategy in order to capitalize on future opportunities or mitigate losses [Trigeorgis 1993]. In that context two types of options are differentiated [Trigeorgis 1996, pp. 1–4]:

- Call option: gives the right, with no obligation, to acquire the underlying asset by paying a pre-specified price on or before a given maturity
- Put option: gives the right to sell the underlying asset and receive the exercise price

---

[71] Whereas "changeover ability" addresses machine tools and assembly systems design on the lowest hierarchical level, "agility" lies above the factory level and is treated as a strategic approach for the design of a changeable factory.

Neufville & Scholtes [2011] demonstrate that by the use of real option analysis, alternative designs can be compared analytically by quantifying alternative possibilities as the value of flexibility can be calculated in present terms. As discussed in Saleh et al. [2009] it regards the value of "flexibility" ("How much is flexibility worth?) rather than its measure of flexibility ("How flexible is the system?"). Latter is addressed in e.g. decision theory as discussed in Mandelbaum & Buzacott [1990] where they consider flexibility as the number of options still open in the second period after a decision has been made in the first period.

Real options "on" projects are financial options taken on technical things, treating the particular system as a black box. As Trigeorgis [1996] summarizes common real options "on" projects may be e.g. the "option to defer" (call option) or "option to switch" (mix of put and call option) that are "yes/no" options on entire projects. Those change strategies are also referred to as "types" by Mikaelian et al. [2011]. In contrast, real options "in" projects, are options created by changing the system design [Wang & Neufville 2005]. It is similar to the definition of "mechanism" by Mikaelian et al. [2011] and represents "what is done to the physical infrastructure design and management to provide and use the flexibility in operations" [Cardin 2014]. Both aspects of "concept generation" are thoroughly discussed in section 3.3 with respect to the contribution of this work.

A further extension is the concept of "architecture options" that provides "a quantitative means of exploring the optimal degree of design flexibility in a system to maximize its lifetime value for varied stakeholders [Engel & Browning 2008]. Schrieverhoff et al. [2012] add that "architecture options provide a quantitative means for decision support on the degree of flexibility to design a system for".

Based on those three academic fields of relevance, the definitions are consolidated to deduce a suitable definition for this work.

2.4.4 Consolidation and definition of flexibility

Sections 2.4.1 to 2.4.3 provide an overview over relevant academic fields and definitions of flexibility. Multiple definitions must be considered, however, as they reflect different relevant aspects of flexibility that only together subsume an overall understanding of what is to be addressed by flexible design in this work. This is accounted for by highlighting relevant definitions and disassociating them from related definitions in Table 2-2.

Table 2-2 Contributing and excluded definitions for flexible design used for this work

	Reference	Contributing	Excluded
Section 2.4.1: Changeability and flexibility in engineering design	ROSS ET AL. [2008]	"Flexible" with external change agent	"Adaptable" with internal change agent
	FRICKE AND SCHULZ [2005]	Flexibility, Agility, Robustness*	Adaptability
	SALEH ET AL. [2003] BISCHOF [2010]	Flexibility of a design after fielding	- Process flexibility - Flexibility of a product under development
	CHMARRA ET AL. [2008]	Lifetime adaptability	- Design time adaptability - Run-time adaptability
	HASHEMIAN [2005]	Product adaptability	Design adaptability
		Sequential adaptability (product-related)	Parallel adaptability
		Specific adaptability	General adaptability
	LAFLEUR AND SALEH [2010]	Intra-mission flexibility	Inter-mission flexibility
Section 2.4.2: Changeability and flexibility in manufacturing and factory planning	REINHART & GRUNWALD [2001] REINHART ET AL. [2008]	"Changeability" outside of preplanned flexibility corridors	"Flexibility" within preplanned corridors
	GÜNTHNER ET AL. [2006]	Extended flexibility	Basic flexibility
	HERNÁNDEZ [2003]	Transformation of system	Changes in structure coupling
Section 2.4.3: Real options and managerial flexibility of engineering systems	ENGEL AND BROWNING [2008]	Architecture options	- Real options “on” projects - Real options "in" projects

* "Robustness" only indirectly considered as part of solution

The first academic field addressed is “changeability and flexibility in engineering design” (section 2.4.1). The definition by Ross et al. [2008] considering changes by external agents as “flexible” is considered further in this work. As defined by Fricke & Schulz [2005] with “flexibility” both the correlated aspects of “ease of system change” (flexibility) and “rapidness of system change” (agility) are meant. Robust design represents a passive approach to deal with uncertainties which will perform only “adequately” over a large range of future operating conditions [de Weck 2008]. It also “commits all capital upfront and is, thus, very costly because only one of the futures will occur” [Neufville & Scholtes 2011, p. 97]. Nevertheless, robust design cannot be ignored and “considering only one of the two approaches[72] might not be the best solution […] in changing and uncertain environments” [Bischof 2010, p. 29]. The need for an integrated consideration of flexible and robust design is also emphasized in e.g. Olewnik et al. [2004]. Consequently, despite that fact that the methodology targets primarily flexibility due to the reasons highlighted in section 1.2.4, robust design must also be accounted for: On the one hand, it ensures to achieve better global solutions as robust designs may outperform rigid or even flexible designs. On the other hand, robust designs often facilitate the embedment of flexibility in the first place which makes them indispensable when addressing flexibility.

In line with Saleh et al. [2003] this work targets changes and flexibility of already fielded systems. Both “lifetime adaptability” [Chmarra et al. 2008] and, more specifically, “intra-mission flexibility” [Lafleur & Saleh 2010] are addressed in this work as flexibility strongly deals with handling fielded one-of-a kind systems (drilling rigs) that are exposed to changing operating environments and requirements. Based on the classification of adaptability by Hashemian [2005], the following definitions are also relevant for this work:

- “Product adaptability” as changes apply to fielded and physical systems

---

[72] Flexible or robust design.

- Product-related “sequential adaptability” as this work deals with physical (rig) upgrades and the extension of the service life of fielded systems
- “Specific adaptability” as flexible designs should deal with specific future scenarios on known uncertainty

In the academic field of “Manufacturing and factory planning”, REINHART & GRUNWALD [2001] and REINHART ET AL. [2008] describe “changeability” as significant changes also outside of the flexibility corridors. Although in the context of this work, especially the changes outside those corridors are meant (section 1.2.4), they cannot be equalized to “responsiveness” as this would target unanticipated and “spontaneous” changes that cannot be planned in advance and usually are required by unfolding unk-unks (section 2.2.1). However, the primary focus of this work lies upon preparing the offshore drilling rig for blurry but nevertheless anticipated future changes[73]. As a delimitation of “changeability” and “extended flexibility” is missing [GÜNTHNER ET AL. 2006, p. 35][74], both definitions are considered to be relevant: The consideration of “extended flexibility” is suitable as it considers postponing investments to later lifecycle phases (as considered for use case in section 8.1). With regards to HERNÁNDEZ [2003, pp. 44–47], changes that address permanent “transformations” rather than changes of “structural couplings” are also relevant for this work.

As “architecture options”, the focus of this work lies on providing and facilitating system constituents with a large set of flexibility options in the system architecture with an optimal degree of design flexibility to its stakeholders. Hereby, however, the focus and the optimal degree of design flexibility does not consider “modularity” alone but a whole range of specific enablers that can facilitate the change of fielded systems (section 3.3.2). Although the definition of flexibility is suitable, the concept of architecture options as a means for quantifying the value of flexibility is not further pursued.

The overall definition of flexibility by SALEH ET AL. [2003] applies equally for this work:

“Flexibility of a design [...] as the property of a system that allows it to respond to changes in its initial objectives and requirements [...] occurring after the system has been fielded, i.e. is in operation, in a timely and cost-effective way.”

Furthermore, CARDIN & NEUFVILLE [2008] define Flexible Design Opportunities (FDOs) as physical components enabling flexibility “in” a system where flexibility exploits technical aspects of the design to make the system adaptable to its environment. As already introduced in section 1.3.1 for the context of this work, however, this definition is extended by also

---

[73] As discussed in section 2.2.1, this may require a previous conversion from knowable unk-unks to known unknowns.

[74] The avoidance of the term “changeability” and the description of the adaptation potential by referring to “basic flexibility” and “extended flexibility” in HILDEBRAND ET AL. [2005] is also subject of discussion in GÜNTHNER ET AL. [2006, p. 35].

including the reasons (e.g. drivers for change) that lead to the need of embedding flexibility in the first place[75].

The definition of FDOs for this work is extended to all phases that target the identification of flexible design concepts and solutions which also includes non-physical components such as uncertainties as they represent opportunities leading to flexibility.

2.5 System and system requirements

As introduced in section 1.3.1 and highlighted by CLARKSON & ECKERT [2005, p. 5], the early phases of design can be divided into "need identification" and "conceptual design" (Figure 1-8). The need usually results from "extensive market and commercial analysis, or more rarely from a response to a direct customer request" [CLARKSON & ECKERT 2005, p. 6]. In the application context of this work (section 4.2.1) the need is driven by customer requests during tenders (section 1.1.2) and known or knowable exogenous uncertainties (section 2.2.1) where a future violation of system requirements justifies the embedment of flexible design.

During conceptual design "the designers pull diverse information together, consider multiple trade-offs and synthetize several solutions" [CLARKSON & ECKERT 2005, p. 7]. They generate "principle solutions"[76] by combining working principles which are based on sub-functions and are combined into a working structure which is then evaluated [PAHL ET AL. 2007, pp. 159–225]. According to SUH [1990, pp. 30–35] in general two different approaches exist, namely creating a major new innovation vs. the improvement of an existing design. As "design for flexibility must start from an existing design configuration" [CARDIN 2014], design concepts embedding flexibility have a baseline design to start from.

First, with regards to the phase of need identification, a basis on "system requirements" is provided (section 2.5.1). For both the phases of "need identification" and "concept generation" an abstract view on the system is required leading to a brief introduction on system's theory and system architecture in section 2.5.2. This section closes by presenting an understanding of system and system architecture in this work.

2.5.1 System requirements

According to PONN & LINDEMANN [2011, p. 35] requirements are demanded properties of the product (or system) that is to be developed. They are both the measure guiding the generation of solutions and the basis for assessing design concepts and design embodiments. A missing or wrong definition can have significant negative side-effects such as higher costs and efforts in design phases due to changes, delays of market introduction or even quality deficits which can

---

[75] As section 5.1 will show, FDOs are elements of the domains "Change Driver", "System Requirement", "Object", "Transition" and "Change Enabler".

[76] As section 4.2.1 will show, in this context of application, flexible design solutions (principle solutions) are generated based on deriving suitable flexible design concepts (working structure) which represent a combination of enablers (working principles) that facilitate a change (function) for a system constituent.

jeopardize the success of the product or system [PONN & LINDEMANN 2011, p. 35]. Hence, accounting for requirements appropriately in particular their identification, structuring, analysis, coordination and communication, adaptation and maintenance is important during product or system development. With increasing project maturity those requirements can be concretized by going from higher level requirements to more specific ones which can be used for assessment and decision-making. Next to the contribution to product development, requirements also play an important external role towards other stakeholders such as suppliers or partners by e.g. contributing to contract specifications [PONN & LINDEMANN 2011, p. 35].

As highlighted by CARATHANASSIS [2015, p. 15], various types of requirements are mentioned in literature that have the same meaning despite a different wording and vice versa. A differentiation based on their intended focus of those requirements led to the synthesis of the following main categories [CARATHANASSIS 2015, p. 16]:

- Describing stakeholders' needs and expectations (e.g. business requirements, user requirements, organizational requirements)
- Describing the (development of the) artifact (e.g. technical requirements, (non-)functional requirements, design requirements)
- Describing different maturity levels (e.g. unknown requirements, verified requirements, validated requirements)
- Addressing different levels of abstraction (system requirements, subsystem requirements, component requirements)

Requirements have various definitions in literature. Table 2-3 provides an excerpt of relevant ones which emphasize the constituents of requirements.

Table 2-3 Relevant definitions of requirements

Source	Definition
IEEE 610 [1990, p. 62]	(1) A condition or capability needed by a user to solve a problem or achieve an objective. (2) A condition or capability that must be met or possessed by a system or system component to satisfy a contract, standard, specification, or other formally imposed documents. (3) A documented representation of a condition or capability as in (1) or (2).
IEEE 1233 [1996, p. 11]	A well-formed requirement is a statement of system functionality (a capability) that can be validated, must be met or possessed by a system to solve a customer problem or to achieve a customer objective, and is qualified by measurable conditions and bounded by constraints.
YOUNG [2004, pp. 1-2]	A requirement is a necessary attribute in a system, a statement that identifies a capability, characteristics or quality factor of a system in order for it to have value and utility to a customer or user.
JUNG [2006, p. 175]	A requirement is a demand of certain properties (ger. "Eigenschaften") or functions which have to be fulfilled by a product. The requirement can be claimed consciously or unconsciously by a person who has an interest in the fulfillment of the requirement. A requirement always consists like a property of a describing attribute (ger. "Merkmal") and a defined characteristic (ger. "Ausprägung").
PONN & LINDEMANN [2011, p. 428]	Demanded properties with respect to the product or process under development. Requirements can be formally expressed as attributes (ger. "Merkmal") and characteristics (ger. "Ausprägung").

Hence, as evident from Table 2-3, requirements always consist of two parts, namely the describing purpose or task and a measurable part. In line with IEEE 1233 [1996, p. 11] and based on IEEE 610 [1990, p. 62], former part can be referred to as a "capability" whereas latter part can be referred to as a “condition”. Additionally, IEEE 1233 [1996, p. 11] differentiates another measurable part, namely the “constraint”. As a result, according to IEEE 1233 [1996, pp. 11–12], three different constituents make up a system requirement:

- “Capabilities” are the fundamental requirements of the system and represent the features or functions of the system needed or desired by the customer. A capability should usually be stated in such a way that it describes “what the system should do”, hence, addressing system-related requirements at higher levels of abstraction.
- “Conditions” are measurable qualitative and quantitative attributes[77] and characteristics that are stipulated for a capability. They further qualify a capability that is needed, and provide attributes which permit a capability to be formulated and stated in a manner that can be validated and verified.
- “Constraints” are requirements that are imposed on the solution by circumstance, force, or compulsion. Constraints limit absolutely the options open to a designer of a solution by imposing immovable boundaries and limits. They may apply across all requirements or be specified in a relationship to a specific capability or set of capabilities.

Within this work the meaning and build-up of “System Requirements” strongly leans on the understanding provided by IEEE 1233 [1996, pp. 11–12][78].

2.5.2 System and system architecture

System theory deals with the general properties and principles of “entireness”, independently of its specific nature and the nature of its components [BERTALANFFY 1970, p. 75]. The following summarizes the relevant aspects of system theoretical considerations by GÖPFERT [1998, pp. 10–18]:

A system represents a unity which is delimited from its environment or system context by a system border. The environment only represents the excerpt that is relevant for the system. The system is, hypothetically, either isolated from its environment (closed system) or, realistically, linked to the environment (open system) by either “input” from or “output” to the environment. The system can be decomposed into subsystems where constituents that cannot be further

---

[77] According to HERNÁNDEZ [2003, pp. 85–86], attributes, in general, can be differentiated further into quantitative and qualitative ones: Quantitative ones can be described either by a discrete (integer) or continuous scale of values (real number). In contrast, qualitative ones can be described by an ordinal scale, which bases upon a monotonically increasing scale of classes or grades (e.g. low, medium, high). Alternatively, qualitative attributes may also be represented on a nominal scale using binary attributes (e.g. no, yes). In addition to those qualitative attributes, a categorical variable may apply that varies in type or kind [JOHNSON & CHRISTENSEN 2008, p. 39] and where there is no intrinsic ordering to the categories.

[78] Nevertheless, the definition by YOUNG [2004, pp. 1–2], JUNG [2006, p. 175] and PONN & LINDEMANN [2011, p. 428] are considered as complementary and consistent definitions to the one in IEEE 1233 [1996, pp. 11–12].

divided are referred to as "elements"[79]. This decomposition leads to the establishment of a system hierarchy at different levels of abstraction with a "is part of relationship" implying a nested hierarchy.

Besides the dependencies to its environment, system internal dependencies exist which can be horizontal between subsystems and vertical towards subsystems at different hierarchical levels making up the hierarchical structure. GÖPFERT [1998, p. 20] defines a system architecture as the "hierarchical" and "dependency structure" of the system. According to GÖPFERT [1998, pp. 91–92] product architecture[80] can be defined as follows:

- the functional structure, i.e. the decomposition of desired functions into sub-functions and their dependencies
- the physical structure, i.e. the physical composition of product components and their dependencies
- the transformation between functional and physical structure, i.e. the relationship between the functional and physical description of the product

ULRICH [1995] emphasizes additionally the specification of interfaces between interacting components as another aspect of product architecture. Other authors depict certain aspects of that definition or enhance that definition by referring to product or system architecture as:

- "The fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution" [CLOUTIER 2006, p. 12; IEEE 1471:2000, p. 3]
- "Summation of a system's entities and capabilities at levels of abstraction that support all stages of deployment, operations, and support" [INCOSE 2010, p. 97]
- "System architecture is an abstract description of the entities of a system and the relationships between those entities." [CRAWLEY 2004]

System architectures represent only a snapshot of the current structure as they are dynamically changing [GÖPFERT 1998, p. 21]. They have a strong influence on the system's behavior rooted in changing complexity, functional behavior, emergent behavior[81] and "ilities"[82] (section 2.4.1). As CRAWLEY [2004] suggests system architectures may arise from different mechanisms such as from the process of deliberate de novo design[83] of a system or by e.g. resulting from an

---

[79] This relativistic definition implies that each element can, again, represent a subsystem which is subdivided further [GÖPFERT 1998, p. 16].

[80] A differentiation between product and system architecture is not considered as used inconsistently in literature.

[81] Emergent behavior leads to entirely new properties on higher system levels [GÖPFERT 1998, p. 23].

[82] ULRICH [1995] emphasizes that the (product) architecture determines how the product can be changed.

[83] As CRAWLEY [2004] highlights, however, despite the benefit of defining ideal architectures, de novo architectures are rather used for generating benchmarks for comparison to real architectures. Only few architectures are actually created in the "pure" environment.

evolution of previous designs[84]. They can be modeled by “3D system models”, “hierarchical models”, “graphs” and “matrices” [GÖPFERT 1998, p. 22].

Figure 2-9 displays the understanding of system and system context by anticipating the results of this work. The system that represents the technical system is divided from its environment, referred to as “system context”, by a system boundary. As flexible design is motivated by responding to exogenous uncertainties or “Change Drivers” affecting the technical system as highlighted in section 1.2.1 and 2.2.1, the system context must be accounted for. Consequently, the technical system is considered to be “open”; on the contrary, the effects of flexible design when responding to changes in the technical system are considered to have no effect on the system context, i.e. no outputs to the system context exist.

The technical system that lies within the system boundary makes up the system architecture which takes a perspective beyond the functional structure, physical structure and their relationships as described by e.g. GÖPFERT [1998, pp. 91–92]; it also accounts for flexibility relevant domains and interrelationships within the technical system. Hence, it contains both influenceable domains (within the system boundary of Figure 2-9) and subjacent entities / elements (not visualized in Figure 2-9) that are relevant when identifying FDOs in the technical system. Both the domains and the individual entities are interrelated[85]; entities may be related to entities of the same domain or to those of other domains.

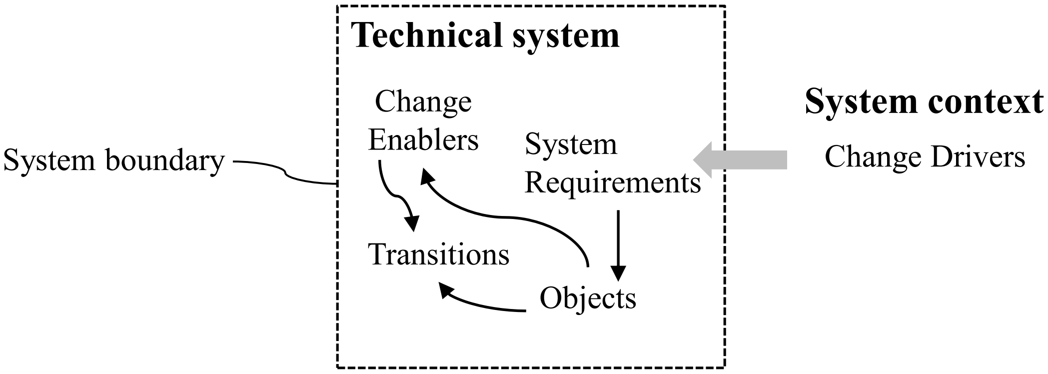


Figure 2-9 Technical system and system context in this work

The technical system consists of the addressed “System Requirements” (section 2.5.1 and 5.3.2) and the physical constituents of the technical system, also referred to as “Objects”, that are hierarchically represented in section 5.3.3 for the context of this work. On the one hand, those Objects may be “products” that fulfill certain functions and thereby contribute directly to the overall fulfillment of (topside) processes (section 1.1.1). On the other hand, the system can be subdivided into other subsystems as Objects that have a passive function (e.g. “bulk items”) such as the physical structure or electrical cabling working as facilitators for those products and, hence, contributing indirectly to the fulfillment of those processes. Those types of Objects that are affected and must be changed in order to re-fulfill their requirements are referred to as “Change Objects” (section 4.2.1).

---

[84] Similar to the addressed differentiation by SUH [1990, pp. 30–35].

[85] Note that the interrelations of domains are not further discussed and will be introduced in section 5.1.

Additionally, in order to allow generating flexible design concepts, the technical system contains change strategies or so-called “Transitions” that determine the type of change the Object undergoes (highlighted in section 3.3.1 and 5.3.5). The other aspect to consider regarding the generation of flexible design concepts is the enablers that ease this change, also referred to as “Change Enablers”, emphasized in section 3.3.2 and 5.3.4.

3. Related state of the art

This section targets the state-of-the-art that is related to the two anticipated main contributions for this work introduced in section 1.3.3:

First, it concerns methodologies aimed at supporting the identification of Flexible Design Opportunities (FDOs). This is done in two stages: First, in section 3.1 the more general methodologies and procedural models that guide the user from change drivers and change initiation towards flexible design concepts and solutions (end-to-end models) are presented to highlight differences amongst them followed by stressing the potentials for a matrix-based approach. Then in section 3.2 relevant matrix-based methodologies are presented in detail to provide the reader with sufficient knowledge on the main alternative concepts that exist which is required for following the subsequent benchmarking that unfolds the research gap.

Second, in section 3.3 literature on the second major contribution addressing the phase of concept generation is systematized focusing on design guidelines, principles and operators for change enablers and strategy generation to uncover further potentials addressed by this research.

3.1 End-to-end methodologies for FDO identification

In section 3.1.1 a taxonomy of procedures for enabling and managing flexibility in engineering systems is suggested as a framework for the organization of existing works and contributions in this thesis. In section 3.1.2 an overview of relevant end-to-end methodologies is provided followed by comparing the individual steps of their procedural models. This is the basis to benchmark those methodologies with respect to the defined basic requirements and allows highlighting the potentials and justifying the focus of matrix-based approaches for this work (section 3.1.3).

3.1.1 Reference taxonomy of procedures by CARDIN [2014]

CARDIN [2014] introduces a five-phase cohesive and systematic design framework for enabling and managing flexibility in engineering systems operating under uncertainty (Figure 3-1). It builds upon existing taxonomies and, hence, suggests a more complete framework to guide practitioners, researchers and educators through the identification and valuation of FDOs which is considered to be very fragmented so far.

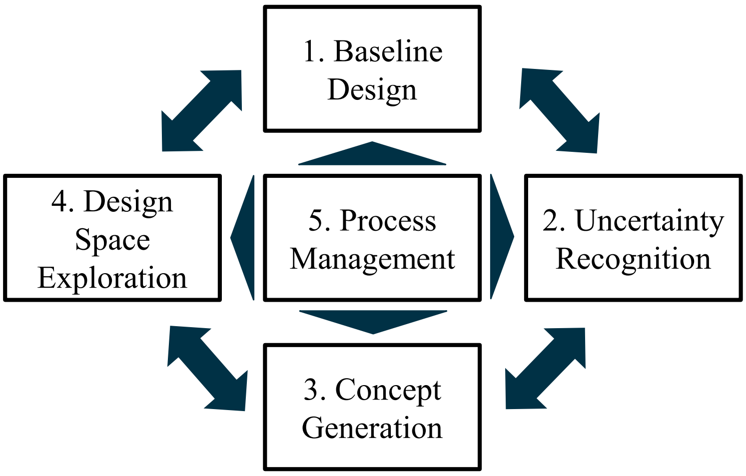


Figure 3-1 Taxonomy of procedures to support the design of engineering systems for flexibility [CARDIN 2014]

The following five organizing principles exist that also represent the different phases of the design framework:

- Phase 1, Baseline Design: Design for flexibility bases upon an existing design configuration (design architecture captured by detailed sketch, computer aided design, etc.), referred to as "baseline design concept" which may have already accounted for uncertainties and represents the starting point for further analysis. This is because "starting a design from scratch for flexibility may render the design space very large, with many possible moving parts, and the task may become easily intractable" [HU & CARDIN 2015].
- Phase 2, Uncertainty Recognition: In this phase, the major sources of uncertainty that can affect lifecycle performance are identified and modeled. This usually results in either formal and/or practical approaches (section 2.2.2) enabling explicit evaluation of the existing baseline design concepts and the generated flexible design concept alternatives.
- Phase 3, Concept Generation: In this phase, flexible systems design concepts are generated that deal proactively with the changing operating conditions identified in phase 2. Each concept contains a strategy (e.g. expand, contract, abandon) that defines how the system will change in the face of uncertainty and enablers (e.g. by modularity, scalability) which specify the embedded flexibility and how it is managed.
- Phase 4, Design Space Exploration: In this phase designers explore the design space for the most valuable systems design concepts and decision rules[86] to operate the system. CARDIN [2014] emphasizes the valuation, i.e. the use of quantitative procedures in this phase, resulting in a set of recommended flexible systems design concepts with more precise design specifications and recommendations on decision-rules. In the application context of this work, however, this step also considers qualitative evaluations (section 3.1.2, 3.2.2).

---

[86] Decision rules are applied to determine the appropriate timing of exercising flexibility in operations, when observing the main sources of uncertainty. They are important to lifecycle value assessment of flexible (systems) design concepts [CARDIN 2014].

- Phase 5, Process Management: This phase proposes setting favorable conditions in the social and collaborative environment under which flexibility is generated, evaluated and deployed more productively. It suggests reducing barriers to implementation, stimulate creativity, deal with study agency problems, i.e. conflicting stakeholder interests, and with information asymmetries of stakeholders when going through phases 1-4. The objective is to enable a successful deployment of flexibility and the proper exercise / management of flexible designs once fielded[87].

As the taxonomy of procedures of Figure 3-1 already suggests, CARDIN [2014] emphasizes the flexible use by designers who may not follow a sequential flow but go back and forth between phases or explore those phases in any suitable order.

In the following this taxonomy of procedures is used as an organizing framework for comparing relevant methodologies that address the identification of FDOs.

3.1.2 Relevant methodologies and procedural models

In this section methodologies and their procedural models are compared against each other that should cover both the steps leading to the identification of Objects that are to be changed (also referred to as “Change Objects”) and the subsequent identification of flexible design concepts to initiate the embodiment phase of the design process. Procedural models that have a dedicated focus on only specific phases such as the evaluation phase (e.g. by BABAJIDE ET AL. [2009], BOURANI ET AL. [2013] or HEGER [2007]), are not the focus of this section. Next to the width, the depth of those models should be abstract enough[88] to be “independent” from very specific theories[89]. Also besides their intended fields of applications, they should be applicable to other or similar fields (e.g. not only bound to manufacturing planning). A sufficient level of abstraction also facilitates the benchmarking that is performed in this section.

Based on those selection criteria and by targeting flexibility for physically fielded systems[90] (section 2.4.4), relevant methodologies are introduced in Table 3-1 that can be assigned to the academic fields of “engineering systems” and “manufacturing and factory planning”.

The methodologies of engineering systems often target specific application contexts (e.g. building), which however, according to the authors, are also applicable across various other fields of engineering systems. They all relate to “lifetime adaptability” but partially also support “runtime adaptability”, targeting especially operational flexibility that eases the configurational

---

[87] NEUFVILLE & SCHOLTES [2011, pp. 165–194] refer to former as “integrated preventive actions” and to latter as “ongoing operational actions”.

[88] Naturally, even procedural models of the relevant references vary in their level of abstraction.

[89] E.g. “time-expanded decision networks” relying on network optimization by SILVER & DE WECK [2007].

[90] In contrast to those that support flexibility of a “design under development” only.

changes of “systems of systems”[91] (e.g. NILCHIANI & HASTINGS [2007], MIKAELIAN ET AL. [2011]).

Literature related to “manufacturing and factory planning” usually addresses the entire factory with its different levels of hierarchy or focuses on specific underlying levels such as manufacturing (e.g. SCHUH ET AL. [2009]) or assembly systems (BAUDZUS ET AL. [2013]). Although, again, “lifetime adaptability” is addressed, some authors also regard their applicability for other types of changeability (e.g. reconfigurability during operations) respectively. In the following, each of those methodologies are introduced briefly.

Table 3-1 Categorization of literature on methodologies addressing the identification of FDOs

		Engineering systems					Manufacturing and factory planning					
		CARDIN [2014]	GREDEN [2005, pp. 55-76]	NILCHIANI & HASTINGS [2007]	NEUFVILLE & SCHOLTES [2011]	MIKAELIAN ET AL. [2011]	HERNÁNDEZ [2003, pp. 92-153]	NYHUIS ET AL. [2005]	SCHUH ET AL. [2009]	BAUDZUS ET AL. [2013]	FRANCALANZA ET AL. [2014]	KLEMKE [2014, pp. 83-107]
Application context	Engineering systems (general)	x	x	x	x	x						
	Building / Construction		x									
	(Aero-)space system			x		x						
	Factory planning (general)						x	x				x
	Manufacturing system								x		x	
	(Manual) assembly system									x		
Lifecycle perspective on flexibility	Flexibility of a design under development			x					x			
	Flexibility of a design after fielding - Runtime adaptability		x	x		x				x	x	
	Flexibility of a design after fielding - Lifetime adaptability	x	x	x	x	x	x	x	x	x	x	x

Overview of FDO methodologies

The methodology by GREDEN [2005] addresses two shortcomings in the design and decision-making practices that are especially prevalent in the building industry: On the one hand, systems are designed as if they remain static entities despite facing significant uncertainties over their lifecycle. On the other hand, typical decision-making methods (e.g. net present value, lifecycle costing) do not recognize uncertainty and the ability to postpone decisions to the future when uncertainties are resolved. GREDEN [2005, pp. 55–76] developed a real options methodology to designing and valuing flexible systems that are exposed to identified future uncertainties. The methodology addresses the identification of uncertainties, defining flexibility, designing and

---

[91] “Systems-of-Systems” (SoS) are systems-of-interest whose system elements are themselves systems; typically, these entail large-scale inter-disciplinary problems involving multiple, heterogeneous, distributed systems. These interoperating collections of component systems usually produce results unachievable by the individual systems alone. [INCOSE 2010, p. 11]

evaluating real options, making decisions and transfer & manage flexibility in operational phases. She applies this methodology for two cases addressing sustainable building design.

NILCHIANI & HASTINGS [2007] target the need for a comprehensive framework enabling decision-makers to measure the value of flexible design. They propose a unified and comprehensive methodology (6E flexibility framework) for measuring the value of flexible design in space systems that base upon six fundamental elements[92] that define the problem and clarify the boundaries. It consists of 12 steps that start with the problem definition and end with a final "Flexibility Tradespace Exploration" of design concept alternatives. Despite being targeted for the application field of space systems as demonstrated in the case study, this methodology is said to be generally applicable for many engineering systems.

NEUFVILLE & SCHOLTES [2011] address the challenge that designers of complex, long-lasting projects usually follow fixed specifications and narrow forecasts to determine their design. Those rigid designs underperform compared to their flexible counterparts as in contrast to former, latter are able to take advantage of opportunities while avoiding harmful losses over the lifecycle. NEUFVILLE & SCHOLTES [2011] suggest a four-phase methodology by estimating the distribution of future possibilities, identifying candidate flexibilities, evaluating (real options) and choosing flexible designs and, finally, implementing flexibility. They apply their methodology for the different phases exemplarily on large scale systems across various industries (e.g. building, oil & gas).

MIKAELIAN ET AL. [2011] target the deficits of real options analysis (ROA) which so far focused mainly on the valuation rather than the identification of real options. They introduce a methodology, the integrated real options framework or IRF, for a holistic consideration of real options in an enterprise context and across different enterprise views (e.g. strategy, organization, process, product). It supports strategy generation based on the characterization of real options in enterprises as a combination of "mechanisms" that enable real options (e.g. modularity) and "types" (e.g. expansion, switching) being emphasized in section 3.3. Based on the recognition of relevant uncertainty drivers, a mapping exercise between mechanism patterns and types stimulates the designers' creativity to identify new real options. Those flexible design concepts can then be evaluated by traditional real option analysis (ROA). They apply that methodology through application to a surveillance mission of unmanned aerial vehicles (UAVs).

HERNÁNDEZ [2003], first mentioned in section 2.4.2, addresses the increasingly turbulent environment of production enterprises that faces significant and radical change efforts across their lifecycle while lacking the ability to adjust to these new requirements. In this regard, he addresses the factory's transformability[93] being decisive for the success of a production enterprise. Basing himself on system's theory, he systematizes transformability by elaborating especially on the necessary constituents and objects for the transformation. HERNÁNDEZ [2003,

---

[92] They make up the coordinates of the flexibility that is to be measured. They consist of: system boundary, system aspect, time window of interest, uncertainty profile within time window, degree of access and value delivery in response to change.

[93] As mentioned in section 2.4.2 and by REINHART & GRUNWALD [2001], this ability to change can also be referred to as "changeability".

pp. 92–153] also introduces a methodology for the systematic identification of transformability. He emphasizes especially the process of scenario planning to detect transformation needs and pursues the systematic identification of robust measures for selected (groups of) objects. The systematization and the methodology are applied for the planning of a new factory.

NYHUIS ET AL. [2005] respond to the need of a methodology for the systematic assessment of factory transformability[94] based on a target-actual comparison. They suggest a six-step-methodology for evaluating the transformability of a factory: First, the actual state and transformability of the factory are analyzed. Based on the development of scenarios, future requirements are deduced and the target transformability is assessed. As a result of the target-actual comparison on transformability, suitable measures for action are derived if required.

SCHUH ET AL. [2009] target the need of increasing individualization and high dynamics of demanded products. This requires production companies to adjust its production system to future needs and conditions at minimum effort. Hence, SCHUH ET AL. [2009] suggest a methodology consisting of four steps that introduces object-oriented design to production systems. Based on an analysis on change drivers, the production system and their interdependencies, it pursues the idea that system elements (subassemblies) that change at the same time for the same reason can be encapsulated in identical objects; in contrast, system elements that do change for different reasons are separated. This ensures that the influence of change drivers is limited to very small areas and not spread across the whole system. The implementation and impact of this methodology is shown by two case studies.

BAUDZUS ET AL. [2013] address the fact that manufacturing companies face high fluctuations in sales volume or increasing product variety. By embedding changeable production systems, the system can be adjusted outside of the flexibility corridors at less effort. BAUDZUS ET AL. [2013] present a methodology to support designers of assembly systems in the process of creating changeable solutions. In order to limit investments in changeability, only presumable trends and, hence, changeable solutions for specific changes are considered. This is done by considering the dimensions of change (e.g. quantity, quality), the affected characteristics of enablers (e.g. degree of automation, transportability). Latter are then confronted with the discrete and predefined change enabling solutions where the most promising ones are selected and translated into specific designs. The methodology is applied on assembly systems which produce high-tech precision mechanical equipment in single- and small series production.

FRANCALANZA ET AL. [2014] address the continuously changing customer demands regarding factories and the subjacent manufacturing systems that were not sufficiently targeted in the past. Based on a comparative analysis of methodologies addressing systematic "product design" and "manufacturing systems design", FRANCALANZA ET AL. [2014] synthetize a systematic methodology to changeable manufacturing design. After an analysis of possibly changing requirements due to future unfolding uncertainties, the synthesis focuses on determining manufacturing system design elements, their level of changeability (e.g. reconfigurability, flexibility) and suitable enablers (e.g. modularity, scalability). This is followed by a simulation of the provisional design solution, a subsequent evaluation where expected properties are

---

[94] "Transformability" referring to the ability of changes on factory / site level.

compared against initial design criteria and a final decision on the provisional design. The methodology is applied briefly in a case study.

KLEMKE [2014] addresses the continuous environmental changes of producing companies and the ability of factories to be changeable. He targets the need for a methodology that allows an examination of changeability under consideration of all technological, logistical, organizational and human factory elements, their relations as well as the production goals of quantity, variants, costs, time and quality. KLEMKE [2014, pp. 83–107] suggests a methodology for the planning and design of systemic factory changeability. The methodology can be divided into two stages: First, during change monitoring the possible change needs of factories are identified by analyzing the company's environment. Secondly, during change evaluation it is determined if the available changeability is sufficient for the needs of change; in case of insufficient changeability of factory elements, potentials are deduced for their increase. The methodology was validated on two sites by a large manufacturer of laboratory and process technology.

Confrontation of procedural models

As the main steps of procedural models usually contain various sub-steps to be accounted for, this required an additional analysis of their descriptions. Based on this analysis and a comparison across the procedural models of the introduced methodologies, their main steps could be broken down into homogenized sub-steps[95]. For each procedural model, the numbering[96] in Table 3-2 indicates the order of sub-steps. Those sub-steps, in turn, are also assigned to the sorting framework by CARDIN [2014] presented in section 3.1.1[97]. The sub-steps and their affiliation are represented separately in appendix 11.1.1. For transparency, appendix 11.1.2 provides an overview of the original steps of the procedural models that are confronted with the homogenized sub-steps.

---

[95] Hence, naturally due to splitting those steps into homogenized units, they do not correspond to the original formulation and number of steps provided by the authors.

[96] Note that sub-steps marked as "# (!)" refer to those that are input to the methodology and are not explicitly elaborated on. In contrast, "(#)" refers to sub-steps that are explicitly marked as optional steps in literature. If one author has identical step numbers in the procedure, it represents a concurrently occurring step.

[97] As already highlighted in section 3.1.1, the meaning of "design space exploration" is extended referring to any intermediate or final evaluations (quantitative, qualitative).

Table 3-2 Confrontation of procedural models by use of homogenized sub-steps

I - Baseline Design
II - Uncertainty Recognition
III - Concept Generation
IV - Design Space Exploration (Evaluation)
V - Process Management

	Engineering systems				Manufacturing and factory planning						
	GREDEN [2005, pp. 55-76]	NILCHIANI & HASTINGS [2007]	NEUFVILLE & SCHOLTES [2011]	MIKAELIAN ET AL. [2011]	HERNÁNDEZ [2003, pp. 92-153]	NYHUIS ET AL. [2005]	SCHUH ET AL. [2009]	BAUDZUS ET AL. [2013]	FRANCALANZA ET AL. [2014]	KLEMKE [2014, pp. 83-107]	
I		2				1				1*	(a) Determining and characterizing system scope
							4				(b) Decomposition of system into multiple subsystems and elements
		7									(c) Identifying suitable rigid baseline of Object from which flexible designs are developed and compared against.
II	1	4	1	1 (!)	1	3	1	1 (!)		2	(a) Defining relevant sources of uncertainties / Change Drivers
	2	5	2		2	4	2	2 (!)		3	(b) Consideration of uncertainty profile over time / scenario building
							3				(c) Classifying uncertainties according to attributes (e.g. entry frequency, cause)
III									4		(a) Determining changeability type depending on factory level (reconfigurability, transformability, etc.)
	3	3									(b) Determining time window of addressed flexibility (frequent runtime changes vs. larger scale lifetime changes)
	4	1			6					10	(c) Identifying suitable change measures / flexible design strategies for Change Objects (e.g. extend, switch, replace machine)
							5				(d) Determining and classifying change profiles of Change Objects (frequency, amplitude)
							6				(e) Characterizing interdependencies between Change Objects (type, number, frequency of interaction)
				2		2		(4)			(f) Identifying already existing flexibility in Objects to deal with uncertainty
										7	(g) Determining action alternatives (e.g. increase automation) and modifications of Change Objects (e.g. equip with sensors)
					4				1		(h) Identifying new Object requirements as a result of unfolding uncertainty
										11	(i) Determining change requirements on allowable time and costs to perform change
					7	5		3	5	14	(j) Identifying required flexibility / suitable Change Enablers for Change Objects (e.g. modular machine, space for extension)
							7				(k) Separation of complex and complicated system elements
	5	8		3	9	7	9	6	6	17	(l) Specifying flexible design concepts for Change Objects
		(10)									(m) Modifying rigid baseline of Object to flexible design concept
	9	14	8	6				7	9		(n) Selecting best performing flexible design concepts and initiate embodiment / integration
					8		8			4	(o) Short listing / delimiting affected or uncertainty sensitive Objects
					8				3	6	(p) Short-listing / delimiting Objects not fulfilling future requirements
										9	(q) Selecting Objects affected by other Objects (change propagation)
										13	(r) Selecting Objects not fulfilling changeability requirements (e.g. time for change)
			4								(s) Short-listing flexible candidate designs of Change Objects
IV					3						(a) Assessing change sensitivity of Objects with regards to unfolding uncertainties
					5				2	5	(b) Assessing Objects' fulfillment of future requirements
										8	(c) Assessing impact on indirectly affected Objects (systemic consideration)
										12	(d) Assessing Objects' fulfillment of change requirements (e.g. time for change)
			3								(e) Screening flexible candidate designs of Change Objects
	6									15/18	(f) Estimating cost-benefit of measures / flexible design concepts
										16	(g) Risk assessment of sufficient extent of Change Enablers in case of simultanously unfolding uncertainties
		6									(h) Determining criteria for measurable value delivery (e.g. operational costs) related to monetary and non-monetary benefits
		11									(i) Selecting suitable evaluation methodology (e.g. Monte Carlo simulation, decision analysis)
	7	12	5	4		8 (!)			7		(j) Valuating flexible design alternatives and baseline design
						6		(5)			(k) Confronting actual and target flexibility of Objects
	8	13	6	5					8		(l) Comparing performance amongst flexibly designed Change Objects
			7								(m) Sensitivity analysis of Change Objects concerning flexible design performance
V			9								(a) General initial preventive actions (e.g. integrating stakeholders during system development)
			10								(b) General ongoing operational actions (e.g. maintaining the legal permission and knowledge to exercise flexiblity)
	10										(c) Specific initial preventive actions: Record proper exercise of flexibility and relevant data
		9									(d) Specific initial preventive actions: Selection of flexibility that is accessible / can be exercised across lifecycle
	11										(e) Specific ongoing operational actions: Transfer knowledge to responsible for proper management of flexibility
	12										(f) Specific ongoing operational actions: Monitoring of uncertain events to occur and feedback

* "System" usually includes potential Change Objects to be enabled (e.g. manufacturing system). However, here the identification of to-be manufactured product families is meant that are subject to variation. Changes of product variants (e.g. in their shape, number) are subject to uncertainty and lead to changes of relevant Objects in the manufacturing system (e.g. workholding device of manufacturing machine).

Based on those results, the following general observations can be made:

- Steps in phases II, III and IV are mainly[98] accounted for across all references.
- All procedural models target the specification of flexible design concepts with most of them also ending up in evaluated solutions that are the starting point for embodiment design.

---

[98] With the exception of FRANCALANZA ET AL. [2014] where “uncertainties” are only accounted for indirectly by their affected requirements and SCHUH ET AL. [2009] that does not address an evaluation explicitly.

- The starting phases vary across references (i.e. phase I, II or III) and neither those phases nor the underlying steps in each phase are performed in a strict consecutive order. This is in line with CARDIN [2014] that highlights that the identification of FDOs does not necessarily follow a sequential flow across phases but usually involves or should somehow involve those phases as discussed in section 3.1.1.
- Although a baseline design[99] (phase I) is always needed for the addressed references, their selection is often performed "ad hoc" without mentioning and, hence, is often missing in Table 3-2. The identification of a suitable baseline design for the identification of flexible design concepts is explicitly addressed only by NILCHIANI & HASTINGS [2007]; however, relevant sub-steps and criteria for such a selection are not provided.
- Process engineering (phase V) is only considered by certain authors in the field of "engineering systems".
- Whereas in the field of "engineering systems" the emphasis often lies on the extensive quantitative assessment of a high number of flexible design concepts based on a limited amount of design variables and for a limited number of Change Objects, the field of "manufacturing and factory planning" stresses the gradual identification and containment of various flexible design concepts based on many alternative design variables for numerous Change Objects.
- Whereas some references such as NILCHIANI & HASTINGS [2007] or FRANCALANZA ET AL. [2014] intentionally embed the selection of flexibility relevant aspects (e.g. selecting changeability type, suitable evaluation methodology) as a separate step being output of the procedural model, others constrain such aspects and pursue a specific goal from the beginning (e.g. SCHUH ET AL. [2009] targeting "modularity" of Change Objects only).

In the following the methodologies and underlying procedural models are considered with regards to the defined basic requirements (section 1.3.3). Matrix-based methods are suggested to better meet those basic requirements.

3.1.3 Benchmarking of methodologies and conclusion

The methodologies and underlying procedural models targeting the identification of FDOs are compared to each other[100] regarding their fulfillment of FDO basic requirements defined in section 1.3.3 to better illustrate research gaps and potentials in this work.

---

[99] This also includes activities related to system definition and structuring.

[100] The mapping of individual steps, however, and hence the comparison faces challenges especially due to: heterogeneous detail of information on the methodologies, oftentimes only implicit information available and, additionally, due to existing interdependencies across those requirements.

Table 3-3 Benchmarking of selected methodologies against pre-set basic requirements

			GREDEN [2005, pp. 55-76]	NILCHIANI & HASTINGS [2007]	NEUFVILLE & SCHOLTES [2011]	MIKAELIAN ET AL. [2011]	HERNÁNDEZ [2003, pp. 92-153]	NYHUIS ET AL. [2005]	SCHUH ET AL. [2009]	BAUDZUS ET AL. [2013]	FRANCALANZA ET AL. [2014]	KLEMKE [2014, pp. 83-107]
			Engineering systems				Manufacturing and factory planning					
Aspect 1	BR I	Identification of effective FDOs	◕	◕	◕	◕	◕	◕	◕	◔	◍	◕
	BR II	Comprehensive identification of FDOs	◔	◔	◕	◕	◕	◍	◔	◔	◔	◕
	BR III	Customer-oriented identification of FDOs	◔	◕	◕	◔	◔	◍	○	●	◔	●
Aspect 2	BR IV	Efficient identification of FDOs	◔	◔	◕	◕	◕	◕	◔	○	○	◔
	BR V	Appropriate usability for engineers	◔	◔	◔	◔	◕	●	◍	◕	◍	●
	BR VI	Flexible application of FDO Methodology	◔	◕	◕	◔	◔	◍	○	◔	◕	○
Aspect 3	BR VII	Efficient build-up and maintenance of database	◍	◍	◔	◔	◕	◍	◍	◍	◔	◍

● fulfilled
◕ partially fulfilled
◔ slightly fulfilled
○ not fulfilled
◍ not applicable / difficult to assess

As indicated in section 1.3.3, BR I represents a very important basic requirement of "aspect 1". Although existing methodologies already partially support the fulfillment of this basic requirement, they mostly lack the comprehensive consideration of the problems leading to flexibility (such as baseline designs, uncertainties) and the generation of flexible design concepts (BR II). For instance, a thorough "design space exploration" may still lead to inferior designs than if all available and suitable baseline designs were accounted for from the beginning. At the same time the selection of effective solutions is subjective, hence, also requires more consideration of the customer perspective for making decisions (BR III).

BR IV, the other main requirement and core of "aspect 2", is insufficiently addressed although certain authors have introduced solutions to make the identification of FDOs more efficient in certain phases (e.g. use of simpler "screening models" for a quicker evaluation of design performance [NEUFVILLE & SCHOLTES 2011, pp. 99–127]). Both BR V and BR VI represent important basic requirements on their own and must have more focus to contribute to a more efficient identification.

BR VII, which represents a basic requirement and a considered "aspect" at the same time, has not received much focus in the reference literature. This is evident by the rather weak documentation and isolated, brief descriptions on database build-up and maintenance. Also, as the presented methodologies mostly acquire data when running the methodology for a specific case, either fully (e.g. NEUFVILLE & SCHOLTES [2011]) or partly (e.g. KLEMKE [2014]), the efficiency of building-up a data model becomes even more important[101].

---

[101] As will be shown in section 7, in this work the build-up and maintenance of the database is performed independently from running the methodology which, however, is often done differently as the addressed references suggest.

Building upon the identified potentials, matrix-based or DSM methods[102] (section 3.2) are relevant to consider, demonstrated also by the growing interest to use matrix-based models for the identification of real options [MIKAELIAN ET AL. 2012]. Matrix-based methods offer the following advantages when modeling system architecture according to EPPINGER & BROWNING [2012, p. 9]:

- Conciseness: compact representation format of a large and complex system
- Visualization: highlighting relationship patterns of particular interest to system designer and by system-level view enabling globally optimal decision-making and focus on particular elements
- Intuitive understanding: once properly displayed, quick understanding by target audience on the basic structure of complex system
- Analysis: enabling powerful analysis and illumination of certain patterns and effects (e.g. change propagation)
- Flexibility: highly flexible modeling tool for modification and extension (such as graphics, colors, additional data) by both researchers and practitioners

Those advantages are considered to contribute to the fulfillment of the basic requirements as illustrated in Table 3-4. Whereas certain advantages address the fulfillment of basic requirements directly, others contribute to core basic requirements through contributive ones (section 1.3.3).

Table 3-4 Advantages of matrix-based approach by contribution to fulfilling FDO requirements

		Identification of effective FDOs	Comprehensive identification of FDOs	Customer-oriented identification of FDOs	Efficient identification of FDOs	Appropriate usability for engineers	Flexible application of FDO Methodology	Efficient build-up and maintenance of database
		BR I	BR II	BR III	BR IV	BR V	BR VI	BR VII
		Basic requirements						
Advantages DSM	Conciseness	(x)	x					x
	Visualization	x	x	x		x		
	Intuitive understanding				(x)	x		
	Analysis	x						
	Flexibility	(x)		x	(x)		x	

x	direct contribution to fulfillment
(x)	indirect contribution to fulfillment

Hence, the use of matrix-based methods is suggested to better meet those basic requirements. In the following relevant matrix-based methodologies are presented that either fully or partially

---

[102] The term “matrix-based” is used interchangeably to “DSM-based” in this work.

address the identification of FDOs and, consequently, represent relevant references for this work.

3.2 Matrix-based methodologies for FDO identification

The focus of this section lies on describing and comparing relevant matrix-based methodologies for the identification of FDOs. In contrast to section 3.1, this section explicitly considers literature on matrix-based methodologies that are also beyond the relevant flexibility for fielded systems. Insights on matrix-based methodologies can be relevant and/or be transferred beyond the specific addressed type of flexibility. This is especially relevant as there is only a very limited reference basis on matrix-based methodologies for flexibility of fielded systems (section 3.2.2).

In section 3.2.1 a brief introduction to matrix-based approaches is provided followed by a description and evaluation of each matrix-based methodology. In section 3.2.2 those approaches are then benchmarked followed by concluding on the research gap which legitimates the direction of this research.

3.2.1 Relevant matrix-based methodologies

The DSM methodology appeared in the early 1980s when scholars showed how graph theory can be used to analyze complex engineering projects [STEWARD 1981]. STEWARD [1981] demonstrated the ability to show sequences of design tasks as a network of interactions where nodes represent individual tasks and links depict information flows. This allowed the analytical identification of inefficiencies and redundancies amongst others.

Design Structure Matrix (DSM) methods is a networking modeling tool to represent the elements comprising a system and their interactions, thereby, highlighting the system architecture [EPPINGER & BROWNING 2012, p. 2]. The following types of DSM models can be differentiated according to EPPINGER & BROWNING [2012, pp. 11–12]:

- Static architecture models which represent systems whose elements exist simultaneously[103]. They either show the interaction of product-related elements (functions, components, subsystems in product architecture DSMs) or the communication between members of organizations (individual, teams and departments in organization architecture DSM).
- Temporal flow models represent systems whose elements may be activated over time and represent different types of processes. Time-based models include both activity-based and parameter-based matrices.

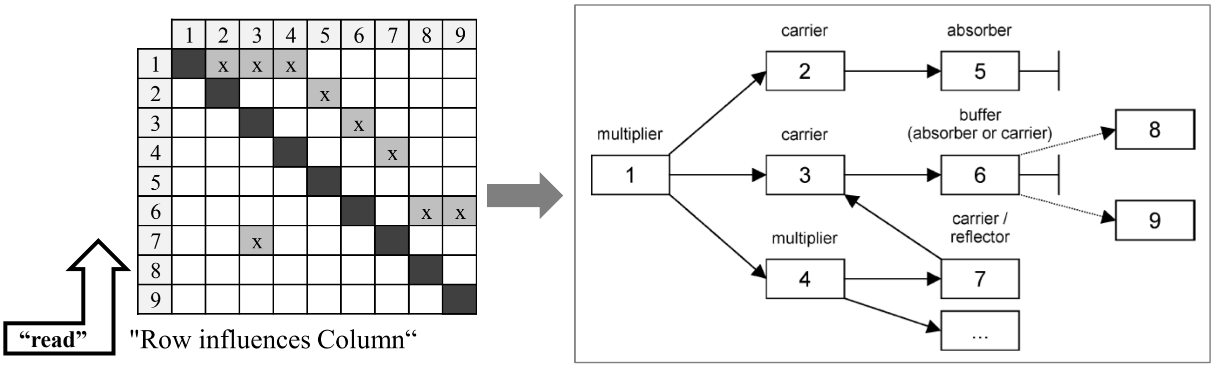
---

[103] Hence, only “snapshots” in time of organizations and products are considered [EPPINGER & BROWNING 2012, p. 12].

- Multiple-Domain Matrix[104] (MDM) bases upon the definition by MAURER [2007, pp. 72–82] and represents different domains (e.g. product, process, organization) in a single matrix. The MDM includes both DSMs (Design Structure Matrix) relating identical domains on the diagonal of the MDM and DMMs (Domain Mapping Matrix) relating different domains with each other.

As observed by MIKAELIAN ET AL. [2012] both DSM and MDM models are "relatively well suited for modeling and analysis of complex engineered systems compared to other representation frameworks". Although interview methods are usually used to elicit relevant information, information can oftentimes also be extracted at less effort from available data sets where the targeted results can be determined directly or indirectly [LINDEMANN ET AL. 2009, pp. 79–117].

Various applications of DSM methods exist to support the management of complex systems also focusing on the identification of FDOs. MDMs, i.e. both within and across DSMs and DMMs, allow the systematic "tracing" of dependency chains in both directions of causality [LINDEMANN ET AL. 2009, p. 89]. In particular, change propagation plays an overarching role for most of the considered methodologies as section 3.2.2 illustrates. ECKERT ET AL. [2004] suggest a differentiation amongst different types of change propagation depending on the number of incoming and outgoing parameters to deal with product changes during design as shown in Figure 3-2.



	1	2	3	4	5	6	7	8	9
1	■	x	x	x					
2		■			x				
3			■			x			
4				■			x		
5					■				
6						■		x	x
7			x				■		
8								■	
9									■

Figure 3-2 Change propagation tree of systems (right) with different change behaviors [ECKERT ET AL. 2004] and corresponding DSM (left)

Whereas multipliers are elements that generate more changes than they absorb, carriers absorb a similar number of changes. Absorbers, in contrast, are elements that can absorb more change than they actually cause. Finally, constants are defined as elements that remain unaffected by change. Most systems are designed to include tolerance margins, so-called buffers, which can absorb some degree of change and prevent change propagation [ECKERT ET AL. 2012]. In some cases, despite the need of changes, elements are sometimes not handled as a response to a management policy which does not allow handling changes with significant effort or conse-

---

[104] MDMs are also referred to as "multidomain matrices" in e.g. EPPINGER & BROWNING [2012, pp. 233–324]. The research and especially application of structural complexity management and MDMs for the field of product design were strongly elaborated by LINDEMANN ET AL. [2009].

quences. They are referred to as “resistors”. As a change often cannot be ignored entirely and other more easily changeable systems must compensate for this lack of change, resistors are also referred to as “reflectors”.

Based on this brief introduction to DSM methodology and change propagation, the most relevant matrix-based methodologies that deal with the identification of FDOs are represented and discussed in the following. This includes reference literature that highlights the systematic identification of FDOs within and across domains through the different phases highlighted by CARDIN [2014], primarily focusing on identifying the width of opportunities from baseline and uncertainty recognition to concept generation. In contrast, matrix-based approaches that take a deep dive on certain domains and aim for an optimization rather than the identification of higher level “opportunities” are not targeted specifically. For instance, ENGEL ET AL. [2016] focus on product architecture and the Change Enabler “modularity” by suggesting an approach and measure (Architecture Adaptability Value or AAV) trading of the interface costs and the architecture options to determine the right level of modularity and the most suitable assignment of components to those modules. Additionally, in the following akin matrix-based identification methodologies are excluded that do not address flexibility specifically but pursue other related goals such as targeting a variant-optimized product program such as discussed by SCHUH ET AL. [2007].

A detailed description on each of them is provided in appendix 11.2 and recommended to readers that are not yet familiar with those. For ensuring the best understanding by the reader, the order of introducing those works accounts for both the logical interdependencies amongst works and the chronology of publication.

Change prediction method by CLARKSON ET AL. [2004]

Products are continuously changed across their lifecycle where the change of one part ends up with the modification of other parts. Hence, CLARKSON ET AL. [2004] provide a method (Change Prediction Method or CPM) to predict changes in redesign and customization of complex products. By knowing change propagation paths with high likelihood and impact, design efforts can be directed towards avoiding changes of expensive sub-systems and allowing change where it is easier to implement[105]. The change propagation method can be divided into the steps “initial analysis”, “case-by-case analysis” and “redesign”. The methodology is based on a case study and initially validated on Westland Helicopters. A more detailed description of the methodology can be found in appendix 11.2.1.

The CPM method is a change prediction method that accounts for indirect change propagation in addition to the direct change propagation between adjacent sub-systems. However, as ECKERT ET AL. [2004] highlight, prediction of change involves two activities, namely the prediction of the cause of change and the prediction of changes that results from those changes. CLARKSON ET AL. [2004] focus strongly on latter where the identification and mapping of requirements on instigating sub-systems is done “ad hoc” without systematic support by the

---

[105] Hence, flexibility as a means to ease those changes is not addressed.

methodology. Additionally, CLARKSON ET AL. [2004] do not account for the risk of the instigating sub-system changes triggered by exogenous factors / requirements.

In the end the risk scatter graph allows viewing the combined risk for the case, where the criticality of sub-systems can be compared and sub-systems can be prioritized. The generation and evaluation of design strategies, in particular flexible design concepts, that are based on those results are not addressed by that methodology.

HoQ-CPM approach to assess the changeability in complex engineering systems by KOH ET AL. [2012]

KOH ET AL. [2012] present a modeling method that seeks to support the prediction and management of undesired engineering change during the design and development of complex products. The methodology builds upon the QFD method, in particular, the House of Quality (HoQ) described by HAUSER & CLAUSING [1988] and the change prediction method (CPM) by CLARKSON ET AL. [2004]. It expands change propagation analysis from one design domain, i.e. product component domain, to a "product requirement" and "change option" domain which enables cross-domain tracing of changes. The objective is to better evaluate the suitability of change options to address the relevant product requirements by accounting for the effects of change propagation. The CPM-HoQ approach is applied in a case study addressing a jet engine fan. A more detailed description of the methodology can be found in appendix 11.2.2.

The focus of KOH ET AL. [2012] lies upon selecting the most performing change options by also accounting for undesired change, i.e. change propagation effects across product components. In contrast to CLARKSON ET AL. [2004] and KOH ET AL. [2013], the approach considers three different design domains dealing with change and enabling tracing amongst them. However, besides the ability of change options being "conform" with system requirements, the lifecycle performance also depends on targeting the relevant product requirements in the first place. With the ability to use the methodology for identifying change options that are searched for due to specific requirement changes, the methodology lacks the consideration for the reasons leading to changes. Hence, the steps leading to changing requirements by accounting for uncertainty factors (e.g. related to technical obsolescence, regulations) and scenarios are not emphasized. As only the aspect of "change options" is accounted by flexibility without considering enablers for facilitating that change, a subsequent evaluation could not be performed.

Step-based CPM by KOH ET AL. [2013]

The step-based CPM bases upon the Change Prediction Method (CPM) by CLARKSON ET AL. [2004]. It introduces a dependency modeling technique to assess the changeability of complex engineering systems. The approach contains three different steps: capturing change data (1), compute change indices (2) and the assessment combined with recommendations (3). The methodology is applied on a case addressing a heavy-duty diesel engine. A more detailed description of the methodology can be found in appendix 11.2.3.

The step-based CPM method is used to provide an estimation of system changeability by the use of indices. The results provide the basis for addressing changeability alternatives to deal with relevant components. Despite its value, there are downsides that must be addressed with respect to this work: the building of matrices concerning planned changes and direct change propagation that mainly bases upon values from expert interviews are extreme and may often be impractical, especially for the targeted complex engineering system. Furthermore, the inclusion of the highly relevant exogenous factors as change initiators are only considered as unspecific "placeholders" for the calculation. A systematic specification of those uncertain exogenous factors or the building of alternative scenarios is missing. Although the step-based CPM supports the identification of Change Objects by visualizing them in the ICI-ICL and OCR charts[106], respectively, a guide for the systematic identification of specific alternative flexible design concepts is also missing. Consequently, also a subsequent evaluation is not part of the methodology.

Sensitivity DSM by KALLIGEROS [2006]

KALLIGEROS [2006] suggests a methodology for two "assets" ("variants") that are built sequentially which can be partially based on the same platform, i.e. share the design of some of the components and systems. It is assumed that the decision to standardize certain components between those two assets is done when the second asset is designed following standardization strategies, i.e. the selection of common components, based on the state at that time. The value of the initially defined system is determined by the flexibility to embed yet uncertain standardization strategies in the second development. The developed methodology is applied on a large offshore floating vessel, an FPSO[107] unit [KALLIGEROS 2006, pp. 105–135].

The contribution by KALLIGEROS [2006] is twofold: On the one hand, KALLIGEROS [2006, pp. 55–77] suggests a methodology and algorithm for the exploration of the best standardization opportunities to choose from by using a DSM-based methodology (Invariant Design Rules or IDR). Hereby invariable platform and customizable components are identified first, followed by the subsequent integration of suitable standardization strategies for customizable components by removing their sensitivity (e.g. over-sizing). On the other hand, KALLIGEROS [2006, pp. 79–103] suggests valuing the initial design[108] by rating its flexibility to deploy suitable standardization strategies in the future. However, being relevant for this work only the IDR was considered. A more detailed description of the IDR methodology and the Sensitivity DSM (sDSM) can be found in appendix 11.2.4.

The main focus of the IDR methodology is the identification of most suitable standardization strategies for customizable components. Although in KALLIGEROS [2006] customized components are considered as potential platform candidates by removing their sensitivity, they can equally be considered as flexibility candidates or "hot spots" for flexibility [BARTOLOMEI 2007, p. 134] and, hence, the methodology becomes relevant for this work. However, in KALLIGEROS [2006] the identification of uncertainties (exogenous factors) is not supported explicitly. Additionally, the sDSM only accounts for changes between directly related variables but not beyond, i.e. without accounting for indirect change propagation. Due to the different objective

---

[106] ICI: incoming change impact; ICL: incoming change likelihood; OCR: outgoing change risk.

[107] FPSO: Floating, Production, Storage and Offloading.

[108] KALLIGEROS [2006] assumes that the system architecture of the initial design can be favorable or disadvantageous regarding future standardization strategies.

of KALLIGEROS [2006] compared to the one in this work (section 1.3), the generation of flexible design concepts for the identified customized components x_c is also not considered.

Flexible platform design process by SUH ET AL. [2007]

SUH ET AL. [2007] emphasize that product platforms and unique components are designed by experience and formal methods in literature without considering exogenous uncertainty. They suggest that if the right subsets of elements are designed with flexibility, the platform will avoid expensive redesigns and manufacturing switching costs. A seven-step flexible platform design process (FPDP) is suggested. The entire methodology is applied on a use case that targets the introduction of a new automotive platform that is to accommodate three vehicle variants. A more detailed description of the FPDP can be found in appendix 11.2.5.

The methodology suggested by SUH ET AL. [2007] offers an end-to-end approach on the identification of flexible components in product platforms. They account for the identification of uncertainty, however, without a comprehensive consideration of alternative futures. The subsequent identification of instigating components (Change Objects), in particular the mapping of uncertainties to customer attributes are not explicitly addressed; at the same time the mapping of uncertainty relevant customer attributes to design variables is suggested to be performed by principal components analysis (PCA) for non-trivial relationships that may depict limits when large amounts of attributes and design variables are addressed. The mapping of design variables to components relies on a decomposition of the physical system by constraining the physical space under consideration which may lead to left out potentials outside of the considered system boundary.

According to SUH ET AL. [2007] the main contribution of the methodology, also the only DSM based part of the methodology, lies in the identification of critical platform elements for embedding flexibility (step IV) as it represents the most critical and difficult step. Recommended decision rules to prioritize product platform components for flexible design are provided. However, indirect change propagation is not considered. Recommendations on generating suitable flexible design concepts (step V) are addressed “ad hoc” (e.g. allow trimming of a component to enable production of other variant) without a systematic consideration of flexible design alternatives. Naturally, as product platforms are addressed, only flexibility of a product under development is targeted, where flexible design alternatives are not directly applicable to the addressed flexibility of fielded systems (section 2.4.4). The evaluation is then performed quantitatively by the use of real options which can also be challenging as section 3.2.2 describes.

Engineering Systems MDM framework by BARTOLOMEI [2007]

BARTOLOMEI [2007] provides a methodology which incorporates the strengths of the sDSM and change propagation analysis by using a holistic framework for representing the social-technical system. The Engineering Systems Matrix (ESM) or ES-MDM[109] organizes the infor-

---

[109] The ESM was in later publications (e.g. BARTOLOMEI ET AL. [2012], EPPINGER & BROWNING [2012, pp. 308–316]) referred to as “ES-MDM”. Consequently, it is also referred to “ES-MDM” in the following.

mation of DSMs and DMMs in the already introduced Multiple Design Matrix (MDM), i.e. a network graph of nodes (components) and edges (relationships). It is built based on a methodology for Qualitative Knowledge Construction (QKC) which offers an iterative, systematic process for constructing knowledge of a complex system and a customized software tool (SMaRT) to streamline the modeling process. Within the ES-MDM framework, BARTOLOMEI [2007, p. 135] suggests a nine-step process which enables the identification of flexibility by detecting "hot spots"[110] in socio-technical systems. A more detailed description of the ES-MDM framework and the hot spot analysis can be found in appendix 11.2.6.

Unfortunately, as also highlighted by WILDS [2008, pp. 35–36], BARTOLOMEI [2007] only provides a conceptual thought experiment on the hot spot identification process by application on a Micro Air Vehicle (MAV) without a formal analysis, demonstration and verification. This makes the approach less tangible as it misses important details which also motivates the approach by WILDS [2008].

As highlighted by BARTOLOMEI [2007, p. 134], the suggested methodology by BARTOLOMEI [2007] extends the approach of KALLIGEROS [2006] and SUH ET AL. [2007] by going beyond technical and functional domains to also address social, process and environmental domains. As all DSMs and DMMs can theoretically serve the identification of FDOs, this provides a large application flexibility; however, at the same time users may be overwhelmed as they lack clear guidance for the identification of FDOs. Additionally, depending on the stakeholder role and degree of influence by the user, certain domains may not be accessible or only represent boundary conditions instead of actual means when addressing FDOs.

In particular, although the FDO identification process describes multiple scenarios, an aggregation technique of those is not suggested. In addition, the hotspot identification process indicates neither if and how the three criteria for FDO identification, namely uncertainty / volatility, benefit and cost, are weighted against each other to identify FDOs nor does it provide a ranking of how the hot spots compare to each other [WILDS 2008, p. 36]. Basing upon the sDSM by KALLIGEROS [2006], only direct change propagations between elements are explicitly considered. Especially the generation of flexible design concepts that follows the identification of Change Objects is done "ad hoc" before they are valued by real option analysis.

In general, a more detailed description and application of hot spot identification would be important to further understand and assess the contribution of that methodology within the ES-MDM framework.

Methodology for identification of FDOs by WILDS [2008]

WILDS [2008] bases strongly on the work of BARTOLOMEI [2007] and suggests that the identification of FDOs[111] is based on two contributions: a combination of sensitivity and change

---

[110] "Hot spots" in design relate to the location of the best opportunities for options in the design [BARTOLOMEI 2007, p. 134]. Hereby, the magnitude of "hotness" represents a ranking amongst flexibility candidates.

[111] WILDS [2008, p. 23] defines FDOs as system components that offer opportunities for embedding flexibility which only partially reflects the definition in this work (section 2.4.4).

propagation (1) and scalability (2). Whereas sensitivity techniques emphasize the magnitude of change in performance due to each component, change propagation techniques assess the change behavior, i.e. if components are multipliers, absorbers, or carriers [WILDS 2008, p. 40]. Both together help identifying where to embed flexibility. Scalability, in contrast, addresses the possibility of analyzing systems of different, in particular, larger sizes and levels of complexity. Hereby, using different levels of abstraction, iterative analysis on gradually lower levels of abstraction and better management of complexity of the required human-input by decomposing the interactions in the ES-MDM are targeted. Based on the available data on the Micro Air Vehicle case study by BARTOLOMEI [2007], the methodology is applied while making assumptions for simplification in each of the steps. A more detailed description of the methodology can be found in appendix 11.2.7.

Unlike BARTOLOMEI [2007], WILDS [2008] offers a metric (Desired Flexibility Score or DFS) to rank and prioritize Change Objects regarding their suitability to embed flexibility by accounting for various domains of the ES-MDM. Additionally, indirect relationships within domains (in particular, the Object's domain) are explicitly accounted for.

Nevertheless, the usability of the approach is limited: The effort of data elicitation and model execution is extreme (e.g. ES-MDM, CIRT[112] Pairings with various types of change initiators and relationships, different change scenarios, complete consideration of change propagation subgraphs) leading to challenges of embedment in practice, especially with the usually large and varying scope of data in engineering systems. WILDS [2008] does also not offer clear guidelines on how uncertainties are identified based on system drivers (corresponding to "Change Drivers") and how change scenarios are built. Additionally, basing upon the identified system drivers and change scenarios clear guidance is missing which alternative paths must be followed and lead to the identification of change initiators, i.e. the instigating Change Objects, in the ES-MDM; as suggested by WILDS [2008, pp. 70–71] this may be done either by a direct identification or require a flow down to components in other domains first (e.g. stakeholder, objective, function domain). Furthermore, the execution of the approach requires switching between graphs and matrices which limits the usability and could be solved within the ES-MDM itself. Last, as the focus of the presented methodology only lies on the identification of Objects that are suitable for embedding flexibility, a consideration of the alternative flexible design concepts is only addressed exemplarily without providing guidance and also lacking a subsequent valuation.

Logical-MDM by MIKAELIAN ET AL. [2012]

MIKAELIAN ET AL. [2012] acknowledge that so far traditional approaches have only used "ad hoc" identification of various flexibilities for uncertainty management without looking on how these flexibilities are obtained. The large amount of alternatives can hardly be handled by a single analyst as "the possibilities may be unknown or too numerous" [MIKAELIAN ET AL. 2012]. They introduce a structured approach to identify where real options are or can be embedded by suggesting a Logical-MDM, a variant of the MDM by also representing "or" relationships for displaying choices and, hence, flexibility, followed by a subsequent valuation of

---

[112] Change initiators and relationship types.

those real options. Hereby a real option tuple <Mechanism, Type> that bases upon the integrated real options framework (IRF) by MIKAELIAN ET AL. [2011] is defined (section 3.1.2). The Logical-MDM methodology is applied on "end user operations" of unmanned air vehicles (UAVs). A more detailed description of the methodology can be found in appendix 11.2.8.

The Logical-MDM by MIKAELIAN ET AL. [2012] facilitates a systematic identification of real options in contrast to their prevalent "ad hoc" identification. However, this time uncertainty sensitive Objects are identified "ad hoc" or are input to the methodology. In this regard, Change Objects (e.g. UAVs) and the enablers of change, the mechanisms (e.g. configuration of UAVs), are not explicitly differentiated. In contrast to handling uncertainties related to design changes, the approach addresses "existing or potential options for managing more general uncertainties that are resolved in the future" [MIKAELIAN ET AL. 2012], which concerns especially facilitating operational flexibility and configurational changes such as in the illustrated case study on "Systems-of-Systems" (SoS) (section 3.1.2.). This also relativizes the need for change propagation that addresses especially design changes. As highlighted by HU & CARDIN [2015] the approach also lacks considering efforts during the tuple selection process, i.e. when generating flexible design concepts, before a valuation takes place.

Hence, the Logical-MDM is a novel framework to represent and choose real options, however, lacks comprehensiveness to guide the entire process of FDO identification that is targeted in this work.

Flexibility in the design of engineering systems by HU & CARDIN [2015]

The suggested methodology builds upon previous works [HU 2012; HU ET AL. 2013] and extends the ES-MDM methodology by BARTOLOMEI [2007]. It integrates a Bayesian network methodology and models complex change propagation within multiple domains of an engineering system. HU & CARDIN [2015] apply the methodology on an exemplary case related to a waste-to-energy (WTE) plant relying on anaerobic digestion. A more detailed description of the methodology can be found in appendix 11.2.9.

The focus of the approach lies upon phases 1-4 of the "reference taxonomy of procedures" by CARDIN [2014] introduced in section 3.1.1. The emphasis in HU & CARDIN [2015] was put on the identification of Change Objects by also considering resulting probabilities from indirect relationships and also the costs of change. However, using the risk susceptibility index (RSI) as the sole decision-making criterion for Change Objects may be critical, as it presumes that changes of a system component cause the same $R^{Generated}$[113] independently if rigid or flexible designs are embedded. However, by embedding flexible design to ease changes (e.g. modular design, standardized interfaces to surrounding of system component), flexibility may significantly reduce the risk of change propagation compared to the rigid peer design.

Next to that the approach misses a systematic selection of flexible design concepts which consist of flexible strategies (e.g. expand, switch in WTE use case) and enablers (e.g. structural

---

[113] Indicates the degree of risk generated by a change in system element s_i under uncertainty U.

reinforcement[114], more land reserved, modular design for WTE use case). Hence, the generated flexible design concepts may still represent suboptimal solutions despite their valuation as potentially better ones may remain unconsidered. Additionally, as all considered flexible design concepts are also valuated without prior filtering, the valuation effort remains high or must be constrained to a limited number of flexible design concepts from the beginning. This effect is even amplified if a large amount of Change Objects is considered of which each requires a flexible design concept on its own.

Other non-matrix FDO identification methodologies for concept generation

Despite DSM-based methodologies and the suggested end-to-end methodologies of section 3.1 for the identification of FDOs, other approaches exist that especially concern the relevant phase of generating flexible design concepts, i.e. phase 3 of the taxonomy of procedures by CARDIN [2014]. The following provides an overview of the alternative fields where aspects of concept generation of flexible designs are aimed for:

Guiding change strategies are defined by various authors. TRIGEORGIS [1996, pp. 2–3] suggested a number of generic real option strategies in order to stimulate the strategy generation. Other authors (e.g. COPELAND & ANTIKAROV [2001], BALDWIN & CLARK [2000]) contribute to the definition of change strategies on different hierarchical levels. In contrast, CARDIN ET AL. [2012] integrate a short lecture on the topic of flexible design and apply a structured prompting mechanism to stimulate the generation of alternative flexibility strategies by designers. Despite step 3 of the reference taxonomy of procedures, in this case also “process management” (phase 5) is addressed as it targets the improvement of collaborative engineering.

Next to the change strategies, the enablers for changes must be addressed for the generation of flexible design concepts. The identification of those Change Enablers can be addressed by industry guidelines. FRICKE & SCHULZ [2005], amongst others, support concept generation by defining high level changeability principles (e.g. simplicity, ideality, modularity). Specific guidelines for the development of flexible products are provided by e.g. BISCHOF [2010, pp. 63–107]. The CMEA method (Change Modes and Effects Analysis), table and procedure by PALANI RAJAN ET AL. [2005] to evaluate product flexibility is performed as an empirical study (vacuum cleaner) where also guidelines for flexible design are derived (modularity, parts reduction, etc.). Instead, GIL [2007] targets specifically complex products and systems by addressing a case study on an airport expansion program concerning 5 projects and 12 options which provides recommendations on alternative safeguarding strategies[115] to deal with future uncertainty.

---

[114] Those examples show that partially robust enablers were accounted for to enable changes in the future. Hence, the distinction between robust and flexible design enablers is often difficult as they are highly interdependent.

[115] Passive safeguarding involves only design work (e.g. account for additional space required in future) and is recommended when uncertainty of exercising is high and modularity low. Active safeguarding, in contrast, is recommended when the exercise uncertainty is rather low as it involves design and physical execution work for the initial product or system.

Especially existing guidance on the identification of Transitions and Change Enablers are not regarded as alternatives but rather complementary to the matrix-based methodologies for this work. Hence, section 3.3 discusses relevant references in more detail. Before, however, the introduced matrix-based methodologies are benchmarked resulting in the identification of the research gap.

3.2.2 Benchmarking of methodologies and research gap

The relevant matrix-based methodologies on the identification of FDOs (section 3.2.1) are benchmarked in Table 3-5 according to the introduced reference taxonomy of procedures by CARDIN [2014] presented in section 3.1.1[116]. This also includes methodologies where only certain aspects of flexibility are targeted (such as “change options” in KOH ET AL. [2012]) or those that serve primarily a different purpose (e.g. “customized components” in KALLIGEROS [2006]). Although each of the provided references embeds DSMs / MDMs, the extent within the methodology varies as highlighted in Table 3-5. The methodologies also vary in the targeted type of flexibility: Especially “flexibility of a product under development” is targeted by most authors. MIKAELIAN ET AL. [2012] focus especially on enabling operational flexibility for System-of-Systems (SoS). HU & CARDIN [2015] represent the only work[117] that explicitly targets flexibility of fielded systems which is also the focus of this work as discussed in section 2.4.4.

All provided methodologies consider an initial design basis for the identification of FDOs. However, whereas most authors only assume a baseline design intuitively without a systematic identification, HU & CARDIN [2015] emphasize the identification of the best performing design basis[118] before flexibility is even considered.

Although most of the reference methodologies account for uncertainties and scenarios, only some embed them as core elements in their methodology as Table 3-5 suggests. Besides MIKAELIAN ET AL. [2012], their primary focus lies on the identification of Change Objects and the subsequent prioritization and selection. Hereby the aim is especially on the identification of change instigating Objects and direct change propagation between Change Objects. Indirect change propagation is only partially emphasized. If accounted for, it mainly concerns the “calculation” of concluding metrics across the change propagation chain of Objects to prioritize critical Change Objects. This prioritization, however, might already be performed outside of the matrix-based methodology (e.g. by use of risk portfolio).

---

[116] Note that “process management” (phase 5) being neither major focus of the benchmarked approaches nor emphasized in the developed FDO Methodology is not addressed in Table 3-5.

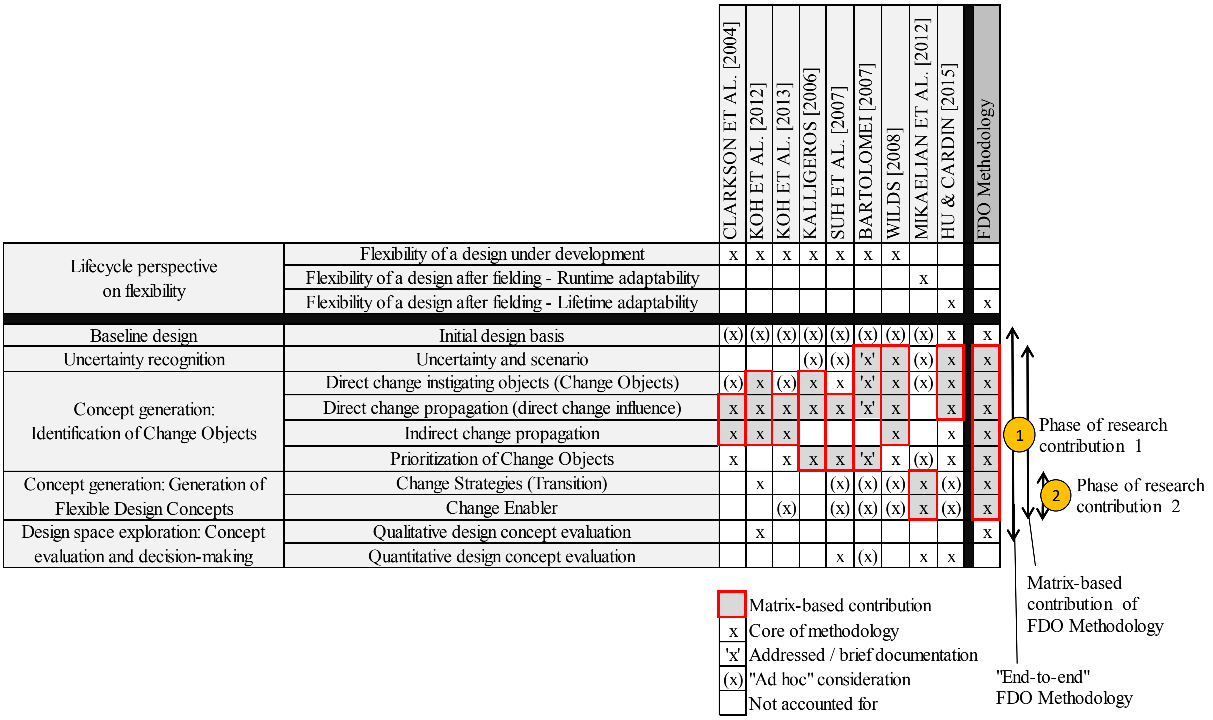
[117] Note that many authors do not explicitly mention the phase that is aimed for by flexibility; although usually the use cases provide a clear picture which phases are targeted, this does not necessarily imply that the approach would be unsuitable for other phases such as for “lifetime” (e.g. BARTOLOMEI [2007], WILDS [2008], MIKAELIAN ET AL. [2012]).

[118] Identifying the best performing baseline design is important as final results could wrongly indicate suitable flexible design concepts although yet unconsidered but existing baseline designs might perform even better.

The phase of generating flexible design concepts, especially by the use of matrix-based methodologies, has had little focus in research so far. Flexibility, i.e. the selection of change strategies (Transitions) and Change Enablers, is usually performed “ad hoc” without considering how these flexibilities are obtained [MIKAELIAN ET AL. 2012]. As indicated by CARDIN ET AL. [2012] so far DSM methods have focused mostly on switching flexibility between product variants, but do not consider other flexibility strategies that exist. KOH ET AL. [2012] emphasize the identification of the most suitable “change options” that address possible Transitions for design phases; however, Change Enablers to facilitate those changes are not further addressed. MIKAELIAN ET AL. [2012] offer the only matrix-based methodology that emphasizes the integrated identification of suitable Transitions (“type”) and Change Enablers (“mechanism”). However, the MDM only supports the phase of concept generation without explicitly dealing with the steps leading to flexibility.

Most flexible design concept evaluations use “real option valuations” for large scale systems as a means to quantify the value of flexible design concepts facing challenges when performance parameters cannot be clearly assigned to monetary payback functions [SCHRIEVERHOFF 2014, p. 6]. Additionally, the valuation of flexible design concepts can cause a lot of effort, especially if a large amount of design alternatives is addressed simultaneously.

Table 3-5 Comparison of matrix-based methodologies for identification of FDOs



		CLARKSON ET AL. [2004]	KOH ET AL. [2012]	KOH ET AL. [2013]	KALLIGEROS [2006]	SUH ET AL. [2007]	BARTOLOMEI [2007]	WILDS [2008]	MIKAELIAN ET AL. [2012]	HU & CARDIN [2015]	FDO Methodology
Lifecycle perspective on flexibility	Flexibility of a design under development	x	x	x	x	x	x	x			
	Flexibility of a design after fielding - Runtime adaptability								x		
	Flexibility of a design after fielding - Lifetime adaptability									x	x
Baseline design	Initial design basis	(x)	(x)	(x)	(x)	(x)	(x)	(x)	(x)	x	x
Uncertainty recognition	Uncertainty and scenario				(x)	(x)	'x'	x	(x)	x	x
Concept generation: Identification of Change Objects	Direct change instigating objects (Change Objects)	(x)	x	(x)	x	x	'x'	x	(x)	x	x
	Direct change propagation (direct change influence)	x	x	x	x	x	'x'	x		x	x
	Indirect change propagation	x	x	x				x		x	x
	Prioritization of Change Objects	x		x	x	x	'x'	x	(x)	x	x
Concept generation: Generation of Flexible Design Concepts	Change Strategies (Transition)		x			(x)	(x)	(x)	x	(x)	x
	Change Enabler			(x)		(x)	(x)	(x)	x	(x)	x
Design space exploration: Concept evaluation and decision-making	Qualitative design concept evaluation		x								x
	Quantitative design concept evaluation					x	(x)		x	x	

▨	Matrix-based contribution
x	Core of methodology
'x'	Addressed / brief documentation
(x)	"Ad hoc" consideration
	Not accounted for

Although all approaches are partially matrix-based, none of them represents a matrix-based “end-to-end” approach. Hereby the quantification by defined metrics (e.g. for change propagation, flexible design concept) often plays a more important role than a clear guidance to identify FDOs[119]. Also, the focus of current matrix-based approaches lies on the processing of empirically derived data that is then used for analysis in the absence of domain experts. It thereby ignores the available tacit knowledge of domain experts and required application flexibility in industrial settings and projects.

The need for addressing the phase of concept generation is explicitly highlighted by CARDIN [2013] considering phase 3 of the reference taxonomy of procedures (Figure 3-1) as a “rich environment for novel research contributions”. In this regard HU & CARDIN [2015] also add that “nowadays, many researchers realize that where/how to generate flexibility in engineering systems is an important and challenging task”.

Hence, the suggested FDO Methodology in this work emphasizes two main aspects which to the best knowledge of the author have had little focus so far and are visualized in Table 3-5. They reflect the two anticipated research contributions introduced in section 1.3.3:

1. Provide a matrix-based “end-to-end” methodology which facilitates the identification of FDOs by integration of domain experts in tender-based development projects. The methodology should be able to embed systematized empirical data and heuristics which guide the user interactively in systematically identifying uncertainties, affected system constituents for which suitable flexible design concepts are identified and flexible design solutions.
2. Emphasize the neglected phase of “flexible design concept generation” as an integrated part of the matrix-based methodology for the identification of FDOs by use of operators and heuristics regarding Transitions and Change Enablers.

Based on the second research contribution, the following section provides an overview of the state-of-the-art regarding “Transitions” and “Change Enablers” which are the basis for forthcoming work.

3.3 Flexible design concept generation

As addressed in section 2.4.3 whereas real options “on” projects consider the future “flexibility”, real options “in” projects address the technical domain of engineers by accounting for the “enablers of flexibility”. MIKAELIAN ET AL. [2011] refer to former as “type”, which belongs to the domain of managerial decision makers and to latter as “mechanism” which is the domain of engineers. This organizational distribution of decision-making, in turn, hinders a holistic consideration as decisions are made within each “silo” leading to suboptimal solutions. Both MIKAELIAN ET AL. [2011] and CARDIN [2014] recognize the need of an integrated perspective to generate better results on flexible design. Hence, MIKAELIAN ET AL. [2011] suggest defining “real options” as a <Mechanism, Type> tuple disambiguating the terminology by offering a single frame of reference. Both entities of that tuple represent design variables that together with the Change Object allow flexible design concept generation. Figure 3-3 illustrates the concept of integrating Transitions and Change Enablers basing on ALLAVERDI ET AL.

---

[119] For instance, BARTOLOMEI [2007] provides the ES-MDM domains and dependencies without offering clear guidance on the paths to follow.

[2014]. Hereby, Change Enablers are intended to reduce the incurred transition costs[120] which include both the time and money spent on the change path[121] between prior and post states.

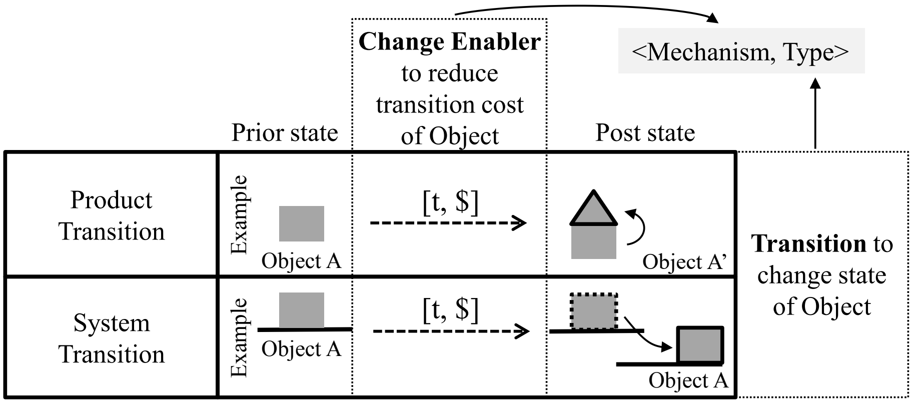


Figure 3-3 Integrated perspective of Transitions and Change Enablers for generation of flexible design concepts (adapted from Allaverdi et al. [2014])

In the following sections, both contributing entities to generate flexible design concepts are addressed separately. Whereas section 3.3.1 systematizes Transitions, section 3.3.2 addresses both the abstract Change Enabler principles and the more specific Change Enabler guidelines based on relevant literature. Each of the two sections conclude with the potential contributions that are to be addressed by the FDO Methodology.

3.3.1 Transitions

According to Ross et al. [2008], a change can be defined as "the transition over time of a system to an altered state". The focus is on "initiated changes" from external [Jarratt et al. 2011] in response to either value losses due to performance changes when changing use contexts and/or drops due to higher customer expectations as highlighted in section 1.2.4. As illustrated in Figure 1-7 by actively changing the system paths, post states of higher performance and, hence, also higher value can be attained.

Literature offers various definitions on Transitions which refer to the same phenomenon in similar ways. Table 3-6 summarizes the relevant ones, grouped by the academic fields they address. Baldwin & Clark [2000, p. 123] regard them as operators of modular designs enabling alternative evolutionary paths for the structure during development. Hernández [2003, pp. 43–46] focuses on fielded manufacturing systems and factories by separating Transitions from the less severe structure coupling of technical systems (also section 2.4.2). In the field of engineering systems, Transitions are mainly regarded as options for projects of

---

[120] "Transition costs" are introduced as "switching costs" may suggest that they only target "switching" of entire Change Objects. Instead, "transition costs" imply that the costs depend on the type of Transition.

[121] Note that as shown in section 2.4.1, Ross et al. [2008] refer to the change path taken as a "change mechanism" which includes both the time and money spent, which has a completely different meaning than "mechanism" defined by Mikaelian et al. [2011] who refer to "Change Enablers".

fielded systems that can be exercised in the future for technical, or even broader, socio-technical systems. Ross et al. [2008], in contrast, regard Transitions within the trade-space network of designs where various paths at different utility and costs can be taken.

Table 3-6 Definition of "Transition" across literature

	Reference	Reference term	Definition of Transitions
Engineering design	BALDWIN & CLARK [2000, p. 123]	Modular operators	Modular operators are "changes that can be imagined in a modular structure [...]. They provide a (parsimonious) list of things that designers can do to a modular system".
Manufacturing & factory planning	WIENDAHL ET AL. [2015, p. 100] based on HERNANDEZ [2003, pp. 43-46]	Transformation	"Transformations change not only the relation of the elements [structure coupling], but also their qualities and functions up until the point that new structures and systems are created."
Engineering systems	TRIGEORGIS [1996, p. 1]	Real options	Real options "to alter its initial operating strategy in order to capitalize on favorable future opportunities or to react so as to mitigate losses".
	WANG & NEUFVILLE [2005]	Real options "on" projects	"Real options "on" projects are financial options taken on technical things, treating technology itself as a black box."
	MIKEALIAN ET AL. [2011]	(Real options) type	"A real option type refers to an action or decision that may be exercised by the owner of the real option.The "type" is therefore representative of the future flexibility."
	CARDIN 2014 HU & CARDIN 2015	Flexible (design) strategy	"The flexible design strategies [...] are akin to real options and offer different ways to change and adapt the system in the face of uncertainty."
	ROSS ET AL. [2008]	(State) transition	"Change can be defined as the transition over time of a system to an altered state."

The characteristics of those Transitions can differ amongst various criteria that are highlighted in the following:

- Multiple enterprise views: As described in section 3.1.2, Transitions can be subject to multiple enterprise views[122] [Mikaelian et al. 2011]. For instance, by embedding modularity (product view of Change Enabler) the component provides the option of being reused in a future design (product view), provides a different function during system operation (process view) or the option to customize for market expansion (strategy view).

---

[122] Mikaelian et al. [2011] introduce eight enterprise views that apply for the tuple <Mechanism, Type>: Strategy, Policy, Organization, Process, Product, Service, Knowledge, IT.

- Transition interdependencies: Transitions can be performed in different combinations [TRIGEORGIS 1996, p. 3; BALDWIN & CLARK 2000, p. 123; MIKAELIAN ET AL. 2011; NILCHIANI & HASTINGS 2007]. They may be performed in sequence to "generate different evolutionary paths for the structure" [BALDWIN & CLARK 2000, p. 123]. Additionally, Transitions can also act as Change Enablers for other Transitions, often in a chain of Transitions representing "options on an option" which are also referred to as "compound options" [COPELAND & ANTIKAROV 2001, pp. 12–13; MIKAELIAN ET AL. 2011].
- Relations to Objects / system: Transitions can take different forms depending on the Object / system [CARDIN 2014; HEGER [2007, p. 70] which is a result of individual system behavior[123] [BALDWIN & CLARK 2000, p. 146].
- Relations to Change Enablers: Transitions and Change Enablers are related to each other and are interdependent [CARDIN 2014]. Consequently, their combinations must be considered as indicated by MIKAELIAN ET AL. [2011] who consider the following four main combinations of mechanisms M (Change Enablers) and types T (Transitions)[124]: M_1:T_1, M_1:T_n, M_n:T_1 and M_n:T_n.
- Level of abstraction: Transitions vary in their level of detail, thereby, also in their range of applicability. Whereas they may be defined as generic operators[125] describing "simple" operations (e.g. BALDWIN & CLARK [2000, p. 123]) or "real options" (e.g. TRIGEORGIS [1996, pp. 2–3]), they may also be expressed uniquely for the context of application. Due to the large scope possibilities of latter, they are usually provided as examples in literature (e.g. MIKAELIAN ET AL. [2011].

In the following only the generic sets of Transitions are introduced that can be directly applied or stimulate strategy generation for the particular context of application.

In engineering design BALDWIN & CLARK [2000] address the power of "modular design" and "design rules"[126] relating to their value by a retrospective look on design evolution in the computer industry and the application of certain design principles. According to BALDWIN & CLARK [2000, p. 12] "modularity dramatically alters the mechanism by which designs can change". Architectural changes can be performed to generate new modular design and task structures by the use of six "modular operators" [BALDWIN & CLARK 2000, pp. 123–146]: (1) "Splitting" a design (and its tasks) into modules, (2) "Substituting" one module for another (3)

---

[123] BALDWIN & CLARK [2000, p. 146]: "The nature and number of operators pertaining to a complex system is inherently an empirical question. One must look, in detail, at how the systems in question actually behave, to know what operators it is useful to define."

[124] Where M_n or T_n require multiple mechanisms or options respectively.

[125] According to BALDWIN & CLARK [2000, p. 129] within the context of complex adaptive systems "operators are actions that change existing structures into new structures in well-defined ways. They are like verbs in a language or functions in mathematics: by their powers of conversion […], they can define a set of trajectories, paths, or routes by which the system can change and grow more complex."

[126] The design rules are collections of modules that dictate the design of the other modules in the system.

"Augmenting" by adding a new module to the system, (4) "Excluding" a module from the system, (5) "Inverting" to create new design rules to consolidate redundant activities into single modules and (6) "Porting" a module to another system, thereby, linking systems via common modules. Those modular operators can be combined and sequenced to attain all desired evolutionary paths for the design and task structures.

PONN & LINDEMANN [2011] focus on the effective and efficient concept development and design of technical products. In contrast to BALDWIN & CLARK [2000], they define operators solely[127] for the systematic variation of functions in a flow-oriented functional model differentiating amongst eight different types [PONN & LINDEMANN 2011, p. 337]: (1) "Omit" functions, (2) "Add" functions, (3) "Interchange" functions, (4) "Series connection" of identical functions, (5) "Parallel connection" of functions, (6) "Cyclic connection" of functions, (7) "Integration" of functions and (8) "Separation" of functions. Although those operators do not focus on the physical domain of Objects specifically, they still represent generally applicable or transferable change strategies.

In contrast, HILDEBRAND ET AL. [2005] emphasize the benefits of modularity by suggesting a systematic approach for a change-oriented design of factories in order to reduce both the effort for the identification of Change Objects and concept generation addressing "extended flexibility" as introduced in section 2.4.2. The effort of the following operations should be reduced without disturbing the ongoing factory operations [HILDEBRAND ET AL. 2005, p. 25]: (1) "Integrate" modules thereby "extend" factory structures, (2) "Separate" modules thereby "reduce" factory structures and (3) "Substitute" modules thereby "qualitatively change" factory structures.

Instead, in the field of engineering systems "real options" are addressed which go beyond the Transitions of product or design changes of technical systems. In particular TRIGEORGIS [1996] focuses on real options "on" projects which concern the valuation of possible investment opportunities. In this regard TRIGEORGIS [1996, pp. 2–3] introduces seven real options that can be applied. They are a mix of "call" and "put" options (also section 2.4.3): (1) "Option to defer" capital investment until favorable market conditions arise, (2) "Time-to-build option" referring to staging the deployment of assets instead of inserting all capacity at once, (3) "Option to alter operating scale" by expanding or contracting output production capacity or resource utilization with halts or restarts in extreme cases, (4) "Option to abandon" a project permanently and realize the resale value of assets, (5) "Option to switch" by changing the output and/or input mix of the facility, (6) "Growth options" referring to early investments (e.g. R&D) to capitalize on future growth opportunities (e.g. new products) and (7) "Multiple interacting options" referring to a combination of various options, thereby, generating synergies amongst them.

---

[127] PONN & LINDEMANN [2011, pp. 397–413] also address the physical domain focusing on the "systematic variation of design" by providing a procedure for variation and a checklist of properties with design parameters (e.g. form, position, number) and the characteristics to be varied (e.g. inside / outside for "position"). However, their focus is not on the available operations for those physical changes (e.g. "increase" number, size). An exception represents the general "inversion of characteristics" where operators are defined (e.g. negation, exchange, mirror) that, however, are not relevant as change strategies for this context of application.

Whereas many of the real options occur naturally (e.g. to defer investment) others may be planned or build at some extra cost (e.g. to expand capacity).

COPELAND & ANTIKAROV [2001, pp. 12–21] provide the following modifications to TRIGEORGIS [1996]: Here the real option "alter operating scale" is split into the options "expand" and "contract". In that context, also "compound" options are introduced as "options on options", i.e. the consideration of each option as a dependent option of previous options which corresponds to the "staging option" by TRIGEORGIS [1996]. Beyond TRIGEORGIS [1996], COPELAND & ANTIKAROV [2001] addresses the "option to extend" the life of an asset and "rainbow options" that are driven by multiple sources of uncertainty where the option depends on two or more underlying variables [COPELAND & ANTIKAROV 2001, p. 13]. In contrast to TRIGEORGIS [1996], the "corporate growth option" and "multiple interacting real options" are not addressed explicitly. AMRAM & KULATILAKA [2000] address those real options similarly, however, misses emphasizing "rainbow options".

Based on those traditional real options, several authors apply them on specific problems: For instance, MIKAELIAN ET AL. [2011] provide examples on real option tuples that are applied across the enterprise architecture with types such as "expand collaboration" or "allocate resources in later project" together with their corresponding Change Enabler counterparts. NILCHIANI & HASTINGS [2007] apply real options exemplary for the domain of space systems. Hereby they refer to them as "responses to change in value delivery for a space system" which are introduced together with the underlying "conditions", i.e. reasons for change. Those "responses to changes" are still high-level and become concrete due to their affiliation to those conditions (e.g. "a partial fixable failure happens", "an increasing market demand exists"). They include Transitions such as to "fix", "reconfigure", "relocate", "extend / terminate lifetime", "expand", "contract", and "upgrade" a space system. NILCHIANI & HASTINGS [2007] emphasize that a system may need combinations of the above or even custom-made responses.

On the one hand, the provided operators do not specifically target fielded or physical systems (such as BALDWIN & CLARK [2000] and PONN & LINDEMANN [2011]) or are very limited in scope (e.g. HILDEBRAND ET AL. [2005]). On the other hand, as discussed in AARLE [2013, pp. 12–14] real options address Transitions from a project perspective that either aim for operating activities of one project (e.g. option to defer, abandon, contract) or take a strategic perspective addressing one or multiple projects where real options can initiate new projects (compound options). A broken-down and comprehensive set of specific options describing the alternative and complementary technical operations that must be accounted for when performing larger system upgrades are not targeted. Especially with the envisioned embedment of Transitions into a matrix-based methodology, there is a need to address a set of specific Transitions that are also compatible.

In the following, the second entity for concept generation is introduced by highlighting relevant literature in this regard.

3.3.2 Change Enablers

As highlighted by MIKAELIAN ET AL. [2011], the identification and implementation of Change Enablers are "increasingly important in efforts to actively seek flexibility for managing uncertainties”. Change Enablers have various definitions across literature although they all share key characteristics. Table 3-7 depicts important definitions from literature arising from the fields of “Manufacturing and factory planning” and “Systems engineering / Engineering systems” respectively.

Table 3-7 Definition of “Change Enabler” across literature

	Reference	Reference term	Definition of Change Enablers
Manufacturing & factory planning	HERNÁNDEZ [2003, p. 54]	Change enabler (homogenized in WIENDAHL ET AL. [2015]) Before also referred to as: - Changeability enabler (e.g. WIENDAHL ET AL. 2007) - Transformation enabler (e.g. NYHUIS ET AL. [2007])	“A change enabler characterizes an individual, non-directional, available feature of a change object to change. By its existence, mode of action and specification change enablers contribute significantly to the overall task fulfillment of change. The characteristics of the change enabler has a direct positive or negative impact on the object and, hence, indirectly on the changeability of the factory as a whole."
	WIENDAHL ET AL. [2007]		"A factory that is designed to be changeable must have certain inherent features or properties that will be called change(ability) enablers. They enable the physical and logical objects of a factory to change their capability towards a predefined objective in a predefined time."
	NYHUIS ET AL. [2008. p. 26]		“In order to ensure a manufacturing system’s ability to respond to change drivers or changes of receptors* respectively […], a production system requires features that enable change. These features are referred to as change enablers.”
Systems engineering / Engineering systems	FRICKE & SCHULZ [2005]	Principles	"The Principles** are enablers for the realization of changeability."
	WANG & DE NEUFVILLE [2005]	Real options "in" projects	"Real options "in" projects concern design features built into the project or system […]. They are options created by changing the actual design of the technical system."
	MIKAELIAN ET AL. [2011]	Mechanism	"A mechanism is defined as an action, decision or entity that enables a real option. The mechanism can therefore be interpreted as a source of flexibility."
	CARDIN [2014]	Enabler	“The enabler determines the instantiation of the flexibility in the design, and how it is managed […]. It represents what is done to the physical infrastructure design and management to provide and use the flexibility in operations."
	ROSS ET AL. [2008]	Path enablers	"Path enabling variables differ from design variables in that design variables are generated in order to create value, while path enablers are generated in order to create or enhance changeability. Real options and path enabling variables are similar in that both factors allow for a system change, and may not contribute to system value if left unused."

* Receptors refer to changes of the product such as the product itself, lot size, quality, etc.
** High-level Change Enablers

As observed in and complemented from SCHLATHER [2015, p. 36], Change Enablers can be differentiated according to different criteria such as:

- Multiple enterprise views: As shown for Transitions, Change Enablers can also be subject to multiple enterprise views [MIKAELIAN ET AL. 2011]. This is also reflected by HERNÁNDEZ [2003, p. 66] who differentiates amongst “technical”, “organizational” and “spatial” domains.
- Change Enabler interdependencies: Change Enablers affect each other either positively or negatively as indicated by FRICKE & SCHULZ [2005] or NYHUIS ET AL. [2008, p. 27]. Additionally, Change Enablers may not only facilitate changes of Change Objects directly but be indirectly required by primary Change Enablers [NYHUIS ET AL. 2008, p. 27; MIKAELIAN ET AL. 2012]. In dependence on the introduced “compound options” (section 3.3.1), “compound mechanisms” being a set of Change Enablers, may be required to enable a Transition [MIKAELIAN ET AL. 2011]. Similarly, HERNÁNDEZ [2003, p. 56] regards Change Enablers as individual properties of Objects which can be activated selectively by “targeted bundling” when changes are required.
- Relations to Objects / system: The suitability of Change Enablers depends on the addressed Object or system [HERNÁNDEZ 2003, p. 72; NYHUIS ET AL. 2005; CARDIN 2014]. Hence, HERNÁNDEZ [2003, p. 56] states that Change Enablers and Objects must be considered as combinations referring to them as “transformation building blocks”[128]. Change Enablers from different domains can be assigned to Change Objects on different hierarchical levels, e.g. on machine level or factory layout level [HERNÁNDEZ 2003, pp. 65–71].
- Relations to Transitions: as described in section 3.3.1
- Level of abstraction: Design guidance can be defined on different levels of abstraction [NOWACK 1997, pp. 50–62; VAN WIE 2002, p. 67; BISCHOF 2010, p. 85]. This also applies to design guidance for flexible design embodied by different hierarchical levels of “Change Enablers”. On the upper end, they can be considered as overarching “principles” [FRICKE & SCHULZ 2005] or “patterns of mechanisms” [MIKAELIAN ET AL. 2011] that enable change. On the lower end, they represent specific, detailed and prescriptive recommendations that themselves vary in their level of abstraction and can be assigned to those superordinate categories (e.g. BISCHOF [2010, pp. 83–107]).

Based on this last criterion, Change Enablers are differentiated in the following by providing an extensive overview of general Change Enabler principles and relevant representatives of Change Enabler guidelines.

Change Enabler principles

As highlighted in BISCHOF [2010, p. 89], guidelines can only be applied effectively when developers have easy, context sensitive access. Especially with a large number of guidelines a simple access is challenging; hence, in order to provide a quick overview and ease handling, its number should be limited by clustering [BISCHOF 2010, p. 89]. “Design principles”, which

---

[128] This term is a translation by WIENDAHL ET AL. [2007] who refer to the original term “Wandlungsbausteine” (ger.) by HERNÁNDEZ [2003, p. 56].

represent "general laws concerning a natural phenomenon or behavior of the system" [NOWACK 1997, p. 60], can facilitate a systematization of those guidelines. In the context of flexible design they provide a means to catalog Change Enabler guidelines fostering their "systematic application in new contexts and scenarios, similar to methods such as TRIZ and design patterns" [MIKAELIAN ET AL. 2011].

Prior work on DSM-based FDO identification focused primarily on modular designs despite the fact that not all Change Enablers actually stem from modularity [MIKAELIAN ET AL. 2012]. Various authors in their respective academic fields of research provide a whole range of Change Enabler principles that can also facilitate change and should be accounted for.

Table 3-8 summarizes the range of Change Enabler principles with respect to the corresponding author(s).

Table 3-8 Change Enabler principles across relevant literature of different academic fields

			Easy (Dis-) Assembly	Adjustability approach	Autarky	Autonomy	Automatability	Buffering	**Compatibility**	Convertibility	Customization	(Interface) Decoupling (approach)	Decentralization	Diagnosability	**Exchangeability**	Expandability and reducibility	Extended use	Handleability	**Ideality / Simplicity**	**Independence**	Inherent flexibility	Interconnectivity	(Dis-)Integrability	**Mobility**	Modularity (approach) / Encapsulation	(Function- and utilization) Neutrality	Nonhierarchical integration	Over-engineering	Parts reduction approach	Pretestability	Redundancy	**Scalability**	Spatial approach	Standardization	Staging	**Universality**	Miscellaneous	Object-specific changeability potential
High end Change Enablers with similarities / aggregation of other Change Enablers	**Universality**			o				o									o				o	o				o		o			o					■		
	Scalability															o																■	o					
	Mobility																o	o						■														
	Independence				o															■																		
	Ideality / Simplicity											o							■																			
	Exchangeability		o												■								o															
	Compatibility								■													o	o											o				
Engineering design and systems	QURESHI ET AL. [2006]			x								x													x								x					
	KEESE ET AL. [2007]			x								x													x				x				x					
	BISCHOF [2010]		x									x					x				x				x			x						x				
	FRICKE & SCHULZ [2005]					(x)							(x)						x	x			(x)		x		(x)				(x)	(x)						
	MIKAELIAN ET AL. [2011]							x																	x						x				x			
Manufacturing & factory planning	HERNANDEZ [2003]															x						x	x	x	x	x												
	HILDEBRAND [2005]		(x)		(x)				(x)						x			(x)						x	(x)					(x)				(x)				
	WIENDAHL ET AL. [2007]	RMS								x	x			(x)									(x)		(x)							x						
		RAS					x			x	x			(x)									(x)	x	(x)							x						
		TRF							x															x	x							x				x		
	HEGER [2007]	P-CPT									x			x		x						x	x	x	x	x								x			x	
		D-CPT							x															x	x	x						x		(x)		x		x

x Primary Change Enabler principles
(x) Secondary / extending Change Enabler principles

If explicit from literature, primary Change Enabler principles are differentiated from secondary or extending ones. As those Change Enabler principles partly have similar meanings across authors, Table 3-8 (top) illustrates overlaps for higher end Change Enabler principles[129] based

---

[129] A further confrontation amongst all Change Enabler principles is difficult: On the one hand, often only definitions without specific Change Enabler guidelines are available. On the other hand, Change Enabler principles often contain a mix of guidelines for each Change Enabler principle which, in turn, could be attributed to a range of Change Enabler principles addressed by other authors.

on their definitions[130] which are provided by appendix 11.2. This can be either due to similarities and/or due to aggregating subordinate Change Enablers (Table 3-8).

The primary focus of Change Enablers in the field of engineering design is on specific design guidelines for application. However, certain authors assign those design guidelines to superior categories corresponding to the addressed Change Enabler principles as a means of systematization: QURESHI ET AL. [2006] analyzed patents of the United States patent repository by use of the CMEA methodology and derived 17 representative guidelines[131] on flexible design of products that face product evolution. Those guidelines could be divided into four main principles to attain flexibility: “modularity approach”, “spatial approach”, “interface decoupling approach” and “adjustability approach”. They provide “instructions at progressively increasing levels of generalization” [QURESHI ET AL. 2006].

KEESE ET AL. [2007] build upon the work of QURESHI ET AL. [2006] and, additionally, perform an empirical study (section 3.2.1) to analyze 11 electro-mechanical consumer products to derive a merged list of guidelines. The guidelines from QURESHI ET AL. [2006] were partially rephrased to attain maximum clarity and new guidelines added resulting in a total of 24. This resulted in the additional principle “parts reduction approach”.

Based on an extensive study from literature, direct experiences of practicing developers and established design practices of engineering organizations, BISCHOF [2010, pp. 83–107] defines guidelines to support the identification of flexible, and as being very interdependent, robust designs for changing environments. A total of 34 design guidelines is derived that can be clustered to six categories: “decoupling and modularization”[132], “inherent flexibility”, “easy (dis-)assembly”, “standardization”, “extended use” and “over-engineering”.

FRICKE & SCHULZ [2005] address incorporating changeability into a system architecture when releasing a new version or derivative but, additionally, also when upgrading already fielded systems. They define four aspects of changeability namely “flexibility”, “adaptability”, “robustness” and “agility” as introduced in section 2.4.1. They differentiate between basic and extending principles where latter supports the former ones. Whereas basic principles (ideality / simplicity, independence, modularity / encapsulation) support all aspects of changeability, the six extending principles (e.g. scalability, redundancy) only address specific aspects of changeability. FRICKE & SCHULZ [2005] claim that although targeting product systems, the suggested principles are applicable to any type of system (e.g. processes, organizations).

MIKAELIAN ET AL. [2011] introduce a framework for holistic consideration of real options in an enterprise context where real options represent the already discussed <Mechanism, Type> tuples (section 3.2.1). Change Enabler principles are referred to as “patterns of mechanisms”

---

[130] Despite definitions and only if available, specific Change Enabler guidelines helped to further understand the meaning of those Change Enabler principles.

[131] Note that QURESHI ET AL. [2006] refer to those guidelines as “principles”; “principles” as defined in this work are referred to as “approaches” in their work.

[132] Split into two separate categories in Table 3-8.

such as “modularity”, “redundancy”, “buffering” and “staging”[133] which, as the type of real options (Transitions), can be instantiated for the relevant context of application. Those “patterns of mechanisms” may be specific to single views or applicable to multiple enterprise views.

Manufacturing & factory planning provides a rich field for Change Enabler principles and, by focusing on only changeability of products and systems after fielding (section 2.4.2), they have high relevancy for this work. HERNÁNDEZ [2003, p. 54] focuses on Change Enablers as facilitators of changeability in factory planning which imply the factory’s system characteristics of dynamics, complexity and connectivity. According to HERNÁNDEZ [2003, p. 54] the following six Change Enablers, which correspond to the higher-level principles, can be defined: “mobility”, “expandability and reducibility”, “modularity”, “function- and utilization neutrality”, “interconnectivity” and “(dis-)integrability”. They facilitate organizational, technical and spatial changes of Objects [HERNÁNDEZ 2003, p. 57] on all four hierarchical levels of a factory[134] [HERNÁNDEZ 2003, pp. 71–74]. Guidelines are deduced for each transformation building block, i.e. each Change Object-Change Enabler combination [HERNÁNDEZ 2003, pp. 75–82], however, at a still high abstraction level of both Change Enablers and Objects.

HILDEBRAND ET AL. [2005, pp. 36–81] introduce the two main principles “exchangeability” and “mobility” which are supported by various interdependent underlying principles: former is supported by mainly “modularity”, “compatibility”, “autarky”, “(dis-) assembly” and “pre-testability”. “Mobility” addresses primarily “handleability”, i.e. the unimpeded transport of the Object; however, in this case it also addresses the initiation and finalization of the Object handling process by accounting for its “(dis-) assembly” [HILDEBRAND ET AL. 2005, pp. 65–77]. This “handleability” must especially be ensured by accounting for the infrastructural conditions such as a lack of space in the factory (e.g. HILDEBRAND ET AL. [2005, p. 67]). The “standardization” of interfaces, in turn, is considered to be both relevant for the “exchangeability” and “mobility” of Change Objects. Specific design guidelines[135] are successively introduced in HILDEBRAND ET AL. [2005, pp. 81–128].

WIENDAHL ET AL. [2007] systematize Change Enablers facilitating both physical and logical Objects of a factory that may satisfy the needs of changeability on different hierarchical levels. Change Enablers of physical Objects can relate to a Reconfigurable Manufacturing System (RMS) on manufacturing level, Reconfigurable Assembly System (RAS) on assembly level or a Transformable Factory (TRF) on factory level. RMSs are marked by six core reconfigurable characteristics as defined in KOREN & ULSOY [2002] addressing both software and hardware components. “Customization”, “scalability”, “convertibility” are identified as primary Change Enablers; in contrast, “modularity”, “integrability” and “diagnosability” represent supporting Change Enablers. RASs include two additional Change Enablers according to WIENDAHL ET AL. [2007]: On the one hand, “mobility” is needed to reconfigure single stations or modules of

---

[133] In traditional real options literature “staging” represents a real option type, i.e. a Transition as shown in section 3.3.1.

[134] From highest to lowest level of the factory: (1) Factory, (2) production- and logistics area, (3) production- and logistic systems and (4) single workstation.

[135] As those guidelines are not explicit, however, they are not further considered.

an assembly system or even move the system to another location. On the other hand, as assembly operations can often be automated, “automatability” allows for adapting the ratio of manual and automated work content. At last for TRFs, the Change Enablers “universality”, “scalability”, “modularity”, “mobility” and “compatibility” apply which strongly overlap with the Change Enabler definitions by HERNÁNDEZ [2003, p. 54] and correspond to the definitions in WIENDAHL & HERNÁNDEZ [2006]. The Change Enablers defined by WIENDAHL ET AL. [2007] for TRFs are also considered by various other authors addressing changeability on factory level (e.g. NYHUIS ET AL. [2005], NYHUIS ET AL. [2007], HARTUNG ET AL. [2012]).

HEGER [2007] derives Change Enabler principles based on an empirical study that validates an already preliminary set from literature. HEGER [2007, pp. 22–25] bases upon Change Enabler suggestions by other authors, especially HERNÁNDEZ [2003] and literature related to KOREN & ULSOY [2002], to generate a preliminary set of Change Enabler principles[136] [HEGER 2007, pp. 76–78], called a “preliminary changeability potential type”[137] (P-CPT) represented in Table 3-8. The P-CPT represents one dimension in a search space that also includes the other two dimensions “type of Objects” and “feature types” [HEGER 2007, p. 74] to systematically identify “changeability potential features”[138], i.e. design variables such as weight, dimension or system architecture, that can influence the P-CPTs in the search space. This search was supported by use of literature, experiences from projects and domain experts [HEGER 2007, p. 83] ending up with the identification of 232 changeability potential features [HEGER 2007, p. 76]. In the subsequent bottom-up exercise, the assignment of those features to those P-CPTs revealed their relevancy leading to the identification of revised “detected changeability potential types” [139] (D-CPTs). As visualized in Table 3-8 this final set includes: “compatibility”, “mobility”, “modularity”, “neutrality”, “scalability”, “standardization”, “universality” and “object-specific changeability potential”, with the last principle representing a depository for features when only a very low number of feature types could be assigned [HEGER 2007, p. 78]. P-CPTs were removed (e.g. diagnosability) if the number of suitable features was low and only secondary[140]. Consequently, the P-CPT “standardization” was kept as a new D-CPT as it includes a very high number of secondary contributions.

The overview of the addressed Change Enabler principles in Table 3-8 suggests that the Change Enabler principle “modularity” is always accounted for independently from the academic fields and authors and, thereby, confirms the dominancy in research when addressing flexible design in general. However, other Change Enabler principles dominate as well, especially when accounting for the highlighted corresponding definitions such as for “universality”. Certain

---

[136] HEGER [2007, pp. 74–75] emphasizes that as completeness of those P-CPTs cannot be assured, the group “miscellaneous” is added acting as a placeholder.

[137] ger.: vorläufige Wandlungspotentialart

[138] ger.: Wandlungspotentialmerkmal

[139] ger.: ermittelte Wandlungspotentialart.

[140] Each “changeability potential feature” was assigned to one P-CPT (primary contribution) but could, in addition, also be assigned to another less important P-CPT if applicable (secondary contribution).

principles also dominate only in certain academic fields such as “mobility” in the field of “manufacturing & factory planning”.

Guidance on selecting the right flexibility goes beyond the high-level Change Enabler principles. The following provides an overview on alternative guidelines for flexible design.

Change Enabler guidelines

Guidelines are “principles put forward that set standards or determine a course of action” [NOWACK 1997, p. 61] and stand in contrast to “rigid prescriptions” as they must be adapted to specific problem situations [PAHL ET AL. 2007, p. 125]. They represent heuristics which are abstractions of experience being “trusted, nonanalytic guidelines for treating complex, inherently unbounded, ill-structured problems” [MAIER & RECHTIN 2009, p. 41]. Guidelines embody “a recommended action that is not guaranteed to work although it generally prescribes a useful action for some condition” [VAN WIE 2002, p. 66]. In the context of architecture design guidelines require a prior search for tacit, product based knowledge of architecture design which is then transformed into a meaningful set of design guidelines [VAN WIE 2002, p. 71]. In the end the generated design guidelines provide “prescriptive recommendation[s] for a context sensitive course of action to address a design issue” [NOWACK 1997, p. 62]. According to VAN WIE [2002, p. 67] those design guidelines can differ in their level of abstraction: Whereas a low level of abstraction eases execution, it hinders generalizing those guidelines and, especially due to its higher number and increasing context-dependency, makes it harder to maintain.

As already emphasized previously, various authors introduce Change Enabler principles together with the related prescriptive design guidelines. Based in the works embedded in Table 3-8, this applies especially to: QURESHI ET AL. [2006], KEESE ET AL. [2007], BISCHOF [2010, pp. 83–107], HERNÁNDEZ [2003, pp. 75–82] and HEGER [2007, pp. 164–191].

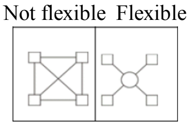
Additionally, by adopting the TRF Change Enabler principles of WIENDAHL ET AL. [2007], HARTUNG ET AL. [2012] define 37 underlying criteria (such as “pretestability”[141] being an important aspect of Change Enabler principle “modularity”) with specific characteristics and, if applicable, example cases for enhancing the understanding. Based on an empirical study and without referring to any superordinate Change Enabler principles, PALANI RAJAN ET AL. [2005] suggest six guidelines to improve flexibility of product design.

Table 3-9 depicts one typical design guideline each for the most common Change Enabler principle “modularity” based on the introduced references.

---

[141] Note that the exemplary focus in the paper of HARTUNG ET AL. [2012] is on the criterion “degree of connection” which belongs to the Change Enabler principle “mobility”. For better comparison of design guidelines across modularity-related guidelines in Table 3-9, however, the design guideline “pretestability” is shown.

Table 3-9 Exemplary design guidelines for Change Enabler principle "modularity"

	Reference	Guideline	Supplementary guideline information	
Engineering design	PALANI RAJAN ET AL. [2005]	Modularizing the design leads to more product flexibility. As the design becomes more integrated, it becomes more inflexible for redesign.		
	QURESHI ET AL. [2006]	Using a different module to carry out each different function.		
	KEESE ET AL. [2007]	Using separate modules to carry out functions that are not closely related.		
	BISCHOF [2010, pp. 94-95]	Minimize the internal connections. Use bus systems.	Example / abstract illustration 	Longer verbal explanation Minimizing the internal connections and making use of bus systems allows easy exchange of product parts during the whole lifecycle. The less a part or a module is connected with other parts of the product, the less the exchange or change of this part affects the rest of the product negatively. This way later changes can be implemented easier.
Manufacturing & factory planning	HERNANDEZ [2003, p. 80]	Standardized, pre-tested, autonomous units (plug and produce).		
	HEGER [2007, p. 165]	System architecture: the functions of the facility are realized in physically independent and standardized modules.	Target achievement here: qualitative not fulfilled sporadically fulfilled partially fulfilled mostly fulfilled fulfilled	Partial potential 0% 25% 50% 75% 100%
	HARTUNG ET AL. [2012]	Pretestability: Possibility of diagnosing, tuning, gauging, testing, etc. before exchange of means of production (integration into the system).	Characteristics (incl. example cases if possible) 1. Testing only possible during standstill of system 2, Testing when running system 3, Testing of partial functions without integration 4, Testing of basic functions without integration 5, Entire pretestability outside of manufacturing-/ assembly line	Transformed value 0 2,5 5 7,5 10 ↓ Increasing changeability

The subject of reference addressed by the guideline may differ across views (e.g. technical, organization) and within them (e.g. technical view with focus on "product", "production facility", "plant", etc.). The guideline usually contains prescriptive texts at different levels of abstraction. For instance, design guidelines by Palani Rajan et al. [2005] have a rather high level of abstraction and are more solution neutral in contrast to e.g. Heger [2007, pp. 164–191] who provides more specific design guidelines which also results in a higher number of guidelines for each Change Enabler principle[142]. Bischof [2010, pp. 91–92] also adds additional explanatory text and illustrations demonstrating unfavorable and favorable applications to ensure a proper, unambiguous understanding and application of the guideline by the user. Heger [2007, pp. 164–191] provides next to short guideline descriptions, a means for evaluating the fulfillment of current designs by providing performance characteristics at different levels of changeability that are either qualitative or quantitative in nature. Similarly,

---

[142] As could be observed, the level of abstraction differs even across design guidelines of the same authors which is not further addressed however.

HARTUNG ET AL. [2012] define those performance characteristics by combining verbal statements and numbers for the different levels of changeability. Where applicable, HARTUNG ET AL. [2012] also provide example cases to support the decision-making by users.

As BISCHOF [2010, pp. 209–211] shows and builds upon, various guidelines related to the addressed field of “design for flexibility” (e.g. “modularization”) exist. According to best knowledge of the author, however, further works within the field of flexible design do not provide comprehensive lists of design guidelines, especially as they usually focus on various aspects of products and systems and/or often target “flexibility of products during development” only: For instance, for VAN WIE [2002] “flexibility guidelines” represent only a subset of the targeted general architecture guidelines. MÖRTL [2002, pp. 105–108] who suggests various guidelines related to durable and upgradable products differentiates several perspectives (strategic decision-making, design, process of change, general) where the extent of “design guidelines” is rather limited and unspecific. Hence, a main contribution in this work lies on deducing specific Change Enabler guidelines on flexible design by addressing physical Change Objects of offshore drilling rigs, hence, contributing to the underrepresented field of plant engineering (section 2.1). The design guidelines should be defined in such a way that they can be suitably integrated into the matrix-based FDO Methodology.

4. Proposed FDO models and Procedural Model

The FDO Methodology consists of three different and interrelated models that all contribute to the fulfillment of objectives defined in section 1.3. Section 4.1 introduces those three models and elaborates on their interdependencies. Section 4.2 describes the general Procedural Model of the FDO Methodology in detail as it represents the starting point of the FDO Methodology development and the more specific FDO requirements. The process of their identification and the final results are presented in section 4.3.

4.1 Models for identification of FDOs

As discussed in section 3.1.1, the FDO Procedural Model bases upon CARDIN [2014]. It describes the main steps and iterations for identifying FDOs consisting of three main stages. In each of those stages different aspects of Flexible Design Opportunities (FDOs) are identified:

- Identification of Change Objects (stage I): At this stage, based on a selected reference design, the most relevant Objects for embedding flexible design are chosen that are then confronted with project-specific reasons for change. This results in the identification of project-relevant Change Objects if the underlying System Requirements cannot be met. Change Objects lie within the solution space[143], i.e. "include those elements that can be directly designed, changed, and implemented by the stakeholder(s)" [DE WECK ET AL. 2011, p. 98].
- Generation of Flexible Design Concepts (stage II): At this stage Flexible Design Concepts, i.e. the combination of Change Objects and suitable design variables consisting of "Transitions" and "Change Enablers" (section 3.3) are identified that ease the process of future changes.
- Determination of Flexible Design Solutions & Integration (stage III): At this last stage those Flexible Design Concepts are assessed and only the most performing and consistent ones are considered further and combined, whereas the other ones are discarded. Those Flexible Design Solutions can then be integrated into the initially chosen reference design.

As shown in Figure 4-1, the FDO Data Model is the second model that is part of the methodology.

---

[143] As the subject of investigation is a Drilling System Supplier, it mainly refers to drilling systems that are always or, depending on the project, sometimes part of the delivery.

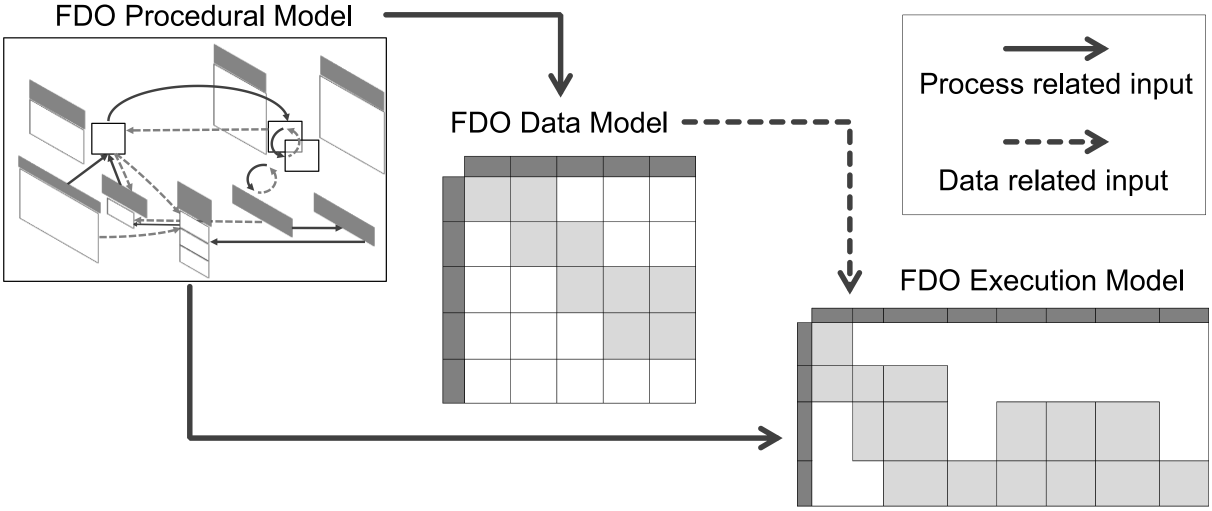


Figure 4-1 Models and their relations contributing to FDO Methodology

It represents a systematized and master[144] database containing relevant industry-specific and company-specific elements and relations that have been evaluated across domain experts. The main domains and dependency types of the FDO Data Model are based on the individual steps at each stage of the FDO Procedural Model and are represented in a matrix overview (section 5.1). It consists of matrices linking the same or different domains with each other. Each domain is made up of individual elements which are interlinked with other elements by "relations" following the dependency type (e.g. "affects") of the particular matrix. The embedded data represents valid but only potentially relevant elements and relations varying from project to project (e.g. due to different customer preferences, operational environment). The FDO Execution Model builds both upon the FDO Procedural Model consisting of multiple representations of the single represented matrices and inherits data from the FDO Data Model to allow a directed and traceable identification of FDOs (section 6). It can be realized in a tool which can be used by engineers during different projects in order to support the identification of FDOs. Based on the Procedural Model potential elements and relations are accounted for in two ways:

- Potential elements of domains: Based on a filter mechanism[145] supported by supplementary methods (section 7) only a relevant subset of existing elements is fed into the FDO Execution Model. Hence, depending on the boundary conditions, the size of the model and its constituents vary.
- Potential relations across elements: Testing the relevancy of potential relations across imported elements is performed on an individual basis during application of the FDO

---

[144] In this application context "master" refers to a database with all the available data that feeds a subset to the actual application model (FDO Execution Model).

[145] Although the filter can theoretically be applied to elements of all domains, the domain of "Objects" is considered to be most relevant to filter as it is subject to strong variation across projects and represents the baseline for flexible design. Based on an "Upgrade Risk Portfolio" (section 7.1), the number of elements can be limited to the most relevant ones.

Execution Model or even during the post assessment once tentative selections are pursued (in "FDO EM Report").

In contrast to the generic FDO Procedural Model, most data from the FDO Data Model is considered to be application specific[146] as boundary conditions differ strongly across application fields [ALLAVERDI ET AL. 2015]. This also applies to the FDO Execution Model that inherits industry specific information from the FDO Data Model. Nevertheless, some of the data may also apply to other similar fields of application such as "Transitions" or "Change Enablers", hence, are also considered research contributions (section 1.3.3); elements of the domain "Change Drivers", "System Requirements" and "Objects", however, are strongly application context dependent. The overall FDO Methodology is certainly applicable to other industries with similar boundary conditions (section 1.3.2).

The FDO Methodology is an interactive support as it involves many types of interactions[147] [BLESSING & CHAKRABARTI 2009, p. 163]. It requires user interaction when running the FDO Execution Model, during assessment and decision-making based on the FDO EM Report (section 6.4) and when applying the FDO Facilitators (section 7) that support the build-up, maintenance of the FDO Data Model and the identification of FDOs.

4.2 FDO Procedural Model

The FDO Procedural Model extends the set of the introduced "end-to-end" procedural models of section 3.1. As highlighted in section 4.1, it represents the basis for the FDO Data Model and FDO Execution Model by focusing on a specific aspect of the design project, namely the identification of FDOs. It is prescriptive in nature with a clear audience (sales engineers in tender phase) and applicable to an industrial section, namely the offshore drilling industry, although it might be equally applicable for other industries that share similar boundary conditions (section 1.3.2). The FDO Procedural Model bases upon the "Taxonomy of procedures to support the design of engineering systems for flexibility" by CARDIN [2014] which is introduced in section 3.1.1. It is developed to make it fit to and account for the previously mentioned market and corporate boundary conditions. It is considered to be "project-focused", i.e. supporting and improving the management of the design project, project portfolio or company [CLARKSON & ECKERT 2005, p. 41]. If implemented correctly, it is to improve the performance in specific aspects of a project, namely the successful offer of flexible systems that are to increase the lifecycle value of system users as highlighted in section 1.3.1.

The FDO Procedural Model represents different stages that have to be traversed to allow the identification of high-performing FDOs. It is intended that iterations are primarily performed between stages and not within stages. Nevertheless, certain activities such as the identification of the reference design might induce certain activities before the next stage can be attained. Hence, the FDO Procedural Model is stage-based in nature; nevertheless, certain specific acti-

---

[146] Here: application field of drilling system.

[147] Opposed to an automated support where interactions are mostly received from the support with some replies at the beginning and end of the interaction [BLESSING & CHAKRABARTI 2009, p. 163].

vities that are not further elaborated on in detail (e.g. systematic search of reference design), might be required additionally. The prescription of those activities, however, would limit the application context of the procedural model and, consequently, is not the focus of the formal description of this methodology. It is assumed that those activities are in place as a prerequisite to apply the procedure[148]. Iterations between the defined stages and steps are highlighted in section 4.2.1.

The identification of FDOs within the FDO Procedural Model can be separated into three main stages as shown in Figure 4-2. The left side marks the need for action by supporting the identification of Change Objects. Once those Objects are determined, the second stage (Figure 4-2, right top) deals with the generation of Flexible Design Concepts which consists of determined Change Objects and the available combinations of Transitions and Change Enablers. Subsequently, the third stage (Figure 4-2, right low) concerns the determination of Flexible Design Solutions by assessing those Flexible Design Concepts followed by combining and integrating them into the initial reference design. Being in line with NEUFVILLE & SCHOLTES [2011, pp. 99–127] the emphasis in this last phase lies upon the efficient short-listing and selection of candidate designs. As section 4.2.2 will show, consistent selections within and across stages of the FDO Procedural Model are pursued to ensure satisfactory results which is why those stages / their subordinate steps are represented as layers that are connected in series or in parallel in Figure 4-2.

---

[148] Those activities are most relevant in stages of the FDO Procedural Model that are not directly integrated into the FDO Execution Model, hence, represent aspects that go beyond the matrix-based approach (e.g. selection of reference design, FDO assessment & decision-making).

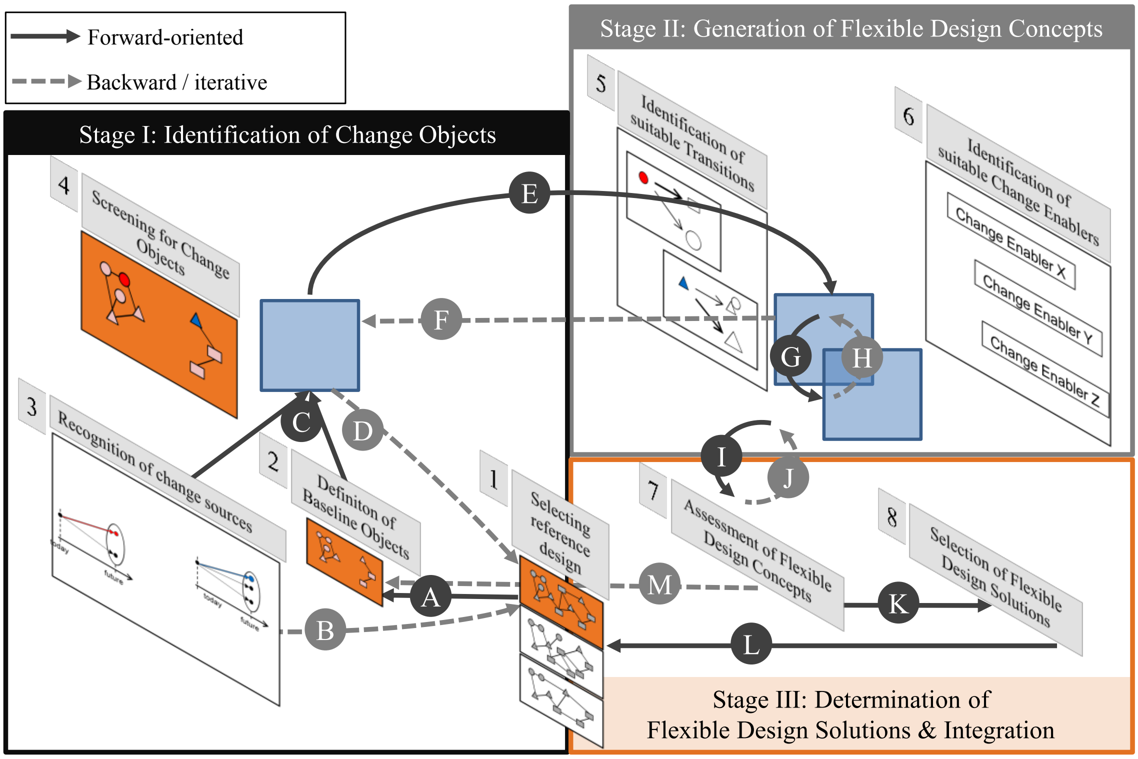


Figure 4-2 FDO Procedural Model with the three main stages and subordinate steps

In section 4.2.1 the FDO Procedural Model is elaborated on while referring to Figure 4-2. The focus lies upon a description of each stage and underlying steps. Based on the introduced FDO Procedural Model, the value and potential of providing consistency across steps and stages is emphasized in section 4.2.2.

4.2.1 Main stages in FDO Procedural Model

Identification of Change Objects: Determining Baseline Objects

In line with the corporate boundary conditions (section 1.3.2) and for attaining a more efficient process, a reference design is selected as starting point for new offers (step 1). It reduces the risk of delivering malfunctioning systems and supports a more efficient handling of projects. Similar designs are usually created by modifying the existing designs based on similar but different requirements [GU ET AL. 2009]. In this context of application, the reference design consists of a modified initial design basis requiring the following main activities:

- Determination of an already existing / delivered suitable hull design, drilling systems and system layout to minimize design changes due to customer specifications
- Modification of drilling system design including products and bulk items (in section 5.3.3 referred to as “Objects”) to meet individual customer specifications
- Modification of drilling system configuration (layout) to meet individual customer specifications

The outcome of those activities is a tentative solution without systematically identified FDOs that can, however, already include flexible[149] Objects. Oftentimes those Objects then do not become Change Objects as they already sufficiently handle future changes without requiring additional Change Enablers.

The reference design also includes Objects that might not be part of the solution space[150]. Those Objects are usually not imported as they cannot be influenced but might be relevant if, for instance, various System Suppliers cooperate to establish an integrated solution for the customer.

Next to that, the reference design may include Objects that are irrelevant for embedding flexibility in the first place. Hence, based on the Objects of the reference design (A), the general need for making those Objects flexible is assessed and irrelevant Objects are removed ending up with the flexibility relevant “Baseline Objects” (step 2); thereby, the degree of filtering may strongly dependent on the customer[151]. That filter works by having defined upgrade risks[152] for Objects allowing to discard Objects that lie below certain criticality values (section 7.1). In contrast to products[153], Objects that represent bulk items (e.g. piping, electrical cabling) and are mostly affected indirectly due to change propagation are always imported. They can hardly be filtered out beforehand as they are usually spread across the rig and integrated to various other Objects.

The defined Baseline Objects are considered further when addressing the identification of FDOs.

Identification of Change Objects: Recognition of change sources

At this stage the underlying factors for the potential change of Objects, so-called “change sources”, are identified represented by both the system-external Change Drivers and the system-related System Requirements (step 3). As introduced in section 2.2.1 and defined in section 5.3.1, Change Drivers represent both the uncertain underlying causes (root causes) and the resulting causes which lead to a non-fulfillment of System Requirements and, hence, drive the system change. They represent known uncertainties or knowable ones (knowable unk-unks) that must be converted beforehand as illustrated in section 2.2.1. They will be resolved in the future and come from outside the system such as oil price fluctuations, Health Safety Environment (HSE) requirement changes, etc. They also “represent uncertainty sources that are known

---

[149] As explained in section 2.4.4 this also includes robust designs.

[150] I.e. Objects that cannot be affected by the System Supplier. Note that this can vary from project to project or across the lifecycle.

[151] Hence, in contrast to a parallel reduction of the ES-MDM to only relevant subgraphs when the change scenario is known [WILDS 2008, p. 48], this allows condensing the field to a more relevant set for the customer before the change scenario is addressed.

[152] Resulting from the average likelihood and impact of the upgrade.

[153] A differentiation of Objects can be found in section 2.5.2 and, in more detail for this context of application, in section 5.3.3.

to engineers to have significantly impact on anticipated lifecycle performance” [CARDIN ET AL. 2012].

In this application context, a System Requirement, basing upon section 2.5.1 and anticipated for section 5.3.2, represents the capability of a system that can be validated and that must be met or possessed by a system to solve a customer problem or to achieve a customer objective. If met by the system, it provides both value[154] and utility[155] to the customer or system user.

As emphasized in DE WECK ET AL. [2007], the “key is that for exogenous uncertainties, these have to be projected into the system architecture and design embodiment to identify hardware and software components that are most likely to be changed in the future as a function of the exogenous uncertainties”. Hence, those Change Drivers constitute a cause-and-effect network of factors that can be uncertain and whose changes can affect certain System Requirements that, in turn, can affect physical Objects[156]. Change Drivers can be identified systematically by determining the relevant factors and building a representative and consistent scenario as introduced in section 2.2.2. The directly affected System Requirements and the ones that are affected indirectly by other System Requirements (e.g. “hydraulic power capacity” requires “electric power capacity”) are the output of step 3.

Iterations may be required (B) when the identified scenario results in the identification of entirely new System Requirements[157] / capabilities that were not accounted for when determining the reference design in step 1 [158]. Objects of dedicated capability would have been omitted when selecting the reference design as future scenarios were not yet accounted for and, consequently, are also not part of the imported Baseline Objects (e.g. MPD dedicated drilling systems if MPD is to be a new capability in the future). If reference designs from previous projects cannot be found with such a capability, Object placeholders must be added to the existing Baseline Objects (step 2) to ensure that flexibility for those Objects is at all considered.

At the next stage, it must be determined if the defined Baseline Objects (step 2) are significantly affected by the changing System Requirements that result from recognition of change sources (step 3).

---

[154] What it is worth when requirements are fulfilled.

[155] What you get out of the value of the system.

[156] Software components as potential “Change Objects” are not considered in this work.

[157] As will be later referred to: Cap$_{\mathrm{I}}$ System Requirements.

[158] Note that the recognition of change sources is usually not accounted for when identifying the initial reference design (step 1) as other factors dominate that stage in the industry (price, certain and immediate functionality, reusability of already delivered systems, etc.). However, if the priority level of design for flexibility were to raise in the future, the selection of the reference design (step 1) could be an outcome of change source recognition (step 2). Thereby, this iteration could be avoided.

Identification of Change Objects: Screening for Change Objects

The directly and indirectly affected System Requirements are now confronted with Baseline Objects (C). Each Baseline Object represents a potential Change Object, i.e. an Object where a change of a System Requirement may lead to its non-fulfillment. This non-fulfillment indicates a “Change Trigger”, thus, the Change Object would have to be changed to still run within the allowed ranges.

Three different types of Change Triggers could be confirmed when performing and processing results from semi-structured interviews (section 5.2) and performing a final expert evaluation of the FDO Methodology (section 8.3). The Change Trigger[159] alternatives are provided in Figure 4-3 and base upon observations made in semi-structured interviews (section 5.2) and a differentiation of change deviations made by CONRAT [1997, pp. 21–25].

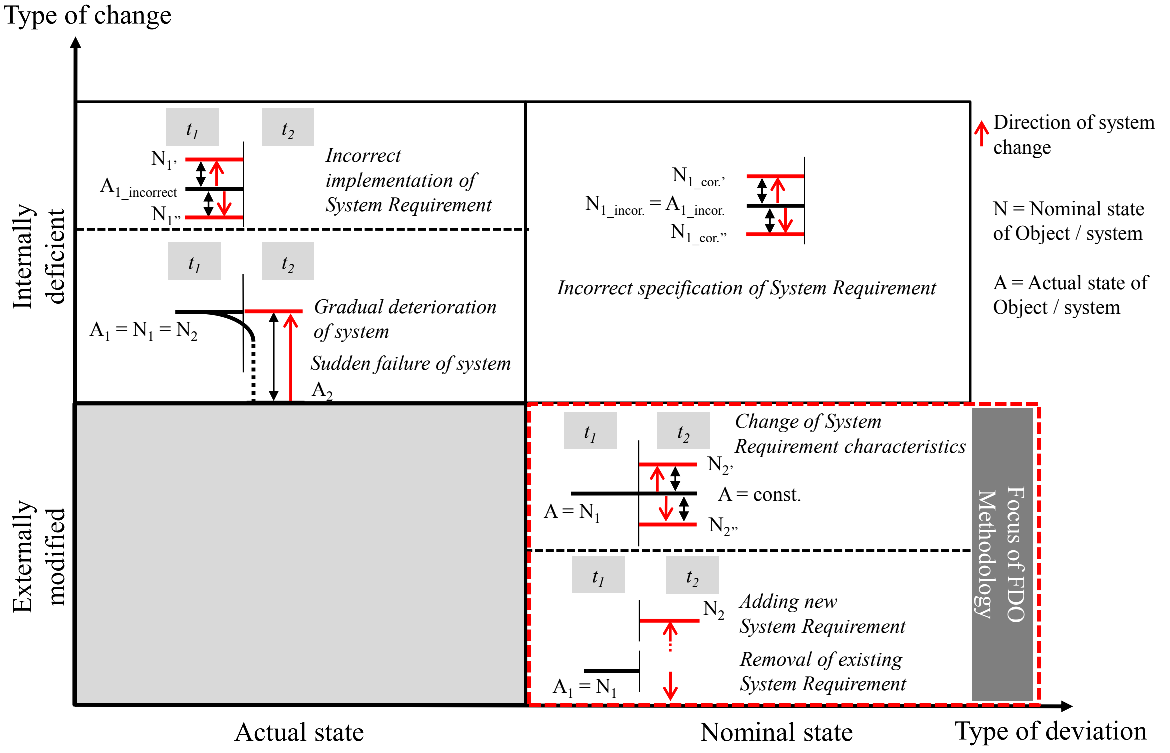


Figure 4-3 Change Trigger alternatives and focus in FDO Methodology

The three different types of Change Triggers can be differentiated based on “type of deviation” and “type of change”. “Type of deviation” refers to the fact that the Change Trigger can be either caused by a deviation of the actual state (e.g. deterioration of system) or of the nominal state (e.g. change of a System Requirement) after fielding the system. In contrast, the “type of change” refers to the fact that the change is “externally modified” or that the change is not modified but deficient either from the very beginning or due to deterioration across the life-cycle. ECKERT ET AL. [2004] differentiate “type of change” similarly between “initiated chan-

---

[159] MEKDECI ET AL. [2012] also refer to “change perturbations” as disturbances and disruptions both internal and external to the system which coincides with the definition of Change Triggers in this work.

ges" arising from outside a source and "emergent changes" arising caused by the state of the design. In the following those three different states are emphasized:

- Actual state deviation, internally deficient type of change: The Change Trigger is caused by not fulfilling the actual state from the very beginning due to an incorrect implementation of the System Requirement or due to a gradual deterioration or sudden failure of the system after fielding of the system.
- Nominal state deviation, internally deficient type of change: The Change Trigger is caused by an initial incorrect specification of the System Requirement.
- Nominal state deviation, externally modified type of change: The Change Trigger can be caused by a change of certain characteristics (e.g. capacity) or by adding / removing a System Requirement / a new capability where the reasons for change are exogenous and do not come from the system itself.

The last of those Change Trigger types is related to the addressed exogenous uncertainty whose systematic identification is to be supported with the FDO Methodology. In step 4 it focuses on the latter group by searching for affected Baseline Objects (Change Objects) based on the previously affected and identified System Requirements. The relevancy of changes, however, must be checked individually. Sufficient design margins, as discussed in ECKERT ET AL. [2012], might be considered to avoid Change Triggers in the first place.

If there is a high number of Change Objects where System Requirements remain unfulfilled, hence, require flexibility, it may be necessary to reconsider the initially selected reference designs and the defined Baseline Objects (D) to avoid a too wide and even superfluous focus when continuing with the identification of FDOs. The following actions may apply:

- There may be other reference designs and Baseline Objects that can better deal with the defined scenarios. In this case, the initially selected reference design in step 1 should be substituted with a more suitable one. This may result in avoiding Change Triggers in the first place or, if Baseline Objects are to be changed, changes to be performed at much lower efforts.
- The modifications of the original reference design in step 1 to better meet customer specifications may have increased the sensitivity of those Object for future changes (e.g. modification from skid to crane solutions makes it more sensitive to wind loads). Hence, the modification of the reference design should be reversed (e.g. keep skid solution) or applied in such a way that the sensitivity for change is reduced (e.g. change to over-dimensioned cranes that are already part of the product portfolio).
- The criticality value in the upgrade risk portfolio of step 2 can be increased further in addition or next to the reconsideration of reference designs (step 1) so that less Baseline Objects are considered in the first place.

Only considering direct dependent relationships between elements without considering indirect dependencies may ignore valuable opportunities to embed flexibility [HU & CARDIN 2015]. Hence, as section 3.2 illustrates, changes, may not only represent "planned changes" triggered by exogenous uncertainty but also be induced by change propagation [KOH ET AL. 2013]. This applies when Objects are coupled, especially when coupled physically, and a change made to one Object[160] requires the change of another Object in order for the overall product to work correctly [ULRICH 1995].

Consequently, Change Objects might not only be directly affected by changes of System Requirements but also by physical changes when propagation across Objects occur. This "change propagation", however, depends on the selected Transition (step 5) which is attributed to the second stage of the FDO Procedural Model. For instance, an "Entire Replacement" of an Object is more likely to have physical implications on the surrounding than a "Partial Replacement" of an Object. Consequently, an iteration[161] between the second and first stage is required to identify indirectly affected Objects (F) based on the selected Transition.

Those identified Change Objects are now transferred to stage II (E) to generate Flexible Design Concepts.

Generation of Flexible Design Concepts

Based on the identified Change Objects, the relevant Transition can now be selected (step 5). As introduced in section 3.3.1, they represent change strategies to be performed on physical Change Objects to make them re-fulfill any violated System Requirements. As section 5.3.5 will show, Transitions are always considered in relation to the entire Change Object. For instance, the change might be related to an "Entire Replacement" or "Relocating" of the Change Object. The suitable Transition always depends upon the Change Object itself.

Change Enablers, introduced in section 3.3.2, are inherent features or properties that enable the physical Change Objects to facilitate Transitions in a time and cost efficient manner after the system has been fielded. "Modularity" or "mobility" are only two examples of the underlying principles those Change Enablers can be attributed to as will be shown in section 5.3.4. The selected Change Object and Transition are both transferred (G) to step 6 for finalizing the generation of the Flexible Design Concept. Here the suitable Change Enablers are selected. Change Enablers might also require other specific Change Enablers as a prerequisite, i.e. cannot be embedded if other Change Enablers are not in place (section 5.1).

Both Transitions and Change Enablers represent design variables to generate Flexible Design Concepts for the previously defined Change Objects. The integrated perspective of those design variables and the means for generating valid combinations are highlighted in section 5.1. Two alternative approaches for generating Flexible Design Concepts exist that are highlighted in the following:

- Transition-driven approach: The Change Enablers are selected (step 6) based on previously identified Transitions for each Change Object (step 5) that are locked, i.e. are not subject to change once specified in step 5. This allows to consider change propagation immediately (F). Oftentimes, however, a single selection is difficult due to the Change Object being affected by different System Requirements (e.g. change of "hoisting capacity" and "degree

---

[160] The degree to which change propagates through a product depends on the complexity of the Object itself [CLARKSON ET AL. 2004].

[161] The scope of this iteration strongly depends on the system layout of the reference design.

of Derrick wind shielding" affecting crane A) or by other Change Objects (e.g. change of "Drillstring Compensation System" causing change of crane A) where suitable Transitions vary (e.g. Partial vs. Entire Replacement). Hence, in step 5 Transitions[162] must either be homogenized by compromising on one specific Transition for the Change Object (e.g. crane A only prepares for Entire Replacement) or by differentiating each Change Object and splitting it into multiple ones (e.g. crane A_1, crane A_2, etc.), thereby, allowing different Transitions for each Change Object (Partial Replacement for crane A_1, Entire Replacement for crane A_2). By feeding the alternative Flexible Design Concepts to stage III (I), they are assessed (step 7) and provide the basis for decision-making (K). The best performing Flexible Design Concepts are then determined (step 8) which represent or can be combined to "Flexible Design Solutions". The Transition-driven approach is recommended when upgrade preferences are well-established, upgrades have a fixed schedule and/or strong time pressure in projects exists.

- Enabler-driven approach: In this approach Transitions (step 5) and Change Enablers (step 6) are regarded simultaneously which results in a strongly iterative process (G, H). This allows the identification of best performing combinations of Transitions and Change Enablers for the identified Change Object. Transitions are now considered to be resettable design variables that can vary for a specific Change Object in search for the best Change Enabler-Transition combinations. However, to attain a single Transition which is required for the consideration of change propagation (F), an intermediate assessment (step 7) takes place to decide on the best Transition(s) with regards to the interdependent Change Enablers for the Change Object. In contrast to the Transition-driven approach where the Transition is defined from the very beginning, the Enabler-driven approach requires to go back to stage II after the assessment (J). Based on the assessment results, the most suitable Transition(s) can now be selected for the Change Object (step 5). As before, this can be either done by a "homogenization", i.e. determining a single Transition, or, by splitting-up the Change Object into different instances, thereby, allowing to choose a set of suitable Transitions. This is the basis for identifying downstream Objects that are affected by change propagation (F). Those indirectly affected Change Objects, in turn, would now be subject to the same iterative process until no more (relevant) Change Objects exist. The Enabler-driven approach is recommended when high-performing solutions should be embedded and/or there is sufficient time in projects as the process is more time-consuming than the Transition-driven approach.

The process of assessment and decision-making represents the next and last stage of the FDO Procedural Model.

---

[162] Section 6.1 will discuss in detail how the "homogenization of Transitions" and "splitting of Change Objects" is realized in the FDO Methodology.

Determination of Flexible Design Solutions & Integration

When applying the Transition-driven approach, the assessment of Flexible Design Concepts (step 7) is performed sequentially without returning to stage II. In contrast, when applying the Enabler-driven approach, the selection of the final suitable Transition(s) bases upon the outcome of the intermediate assessment: The Transition(s) that contributes best to the Flexible Design Concept is then selected in stage II.

The challenge of the assessment and decision-making at this stage is the high number[163] and the high[164] but also heterogeneous[165] level of abstraction of Flexible Design Concepts. Details on the assessment and decision-making are presented in section 6.4.2 as it strongly depends on the results of the applied FDO Execution Model.

Flexible Design Concepts of high performance are filtered and integrated to Flexible Design Solutions (step 8) with highly complementary Change Enablers. As the number of solutions should now be significantly reduced to a set that can be handled, a quantitative design space exploration could be performed subsequently (not part of the FDO Methodology and, hence, not visualized in Figure 4-2). The high-performing Flexible Design Solutions can then be integrated into the reference design (L).

At this conceptual stage a reiteration represents the most desirable iteration cycle next to no iteration at all [SUH 1990, p. 32]. As there might still be insufficient solutions for each Change Object, initially neglected Baseline Objects may be reconsidered by lowering the critical risk and by rerunning the FDO Methodology (M). Less critical Change Objects might still be worthwhile to embed flexibility as they may generate more value across the lifecycle.

The FDO Data Model, and subsequently, the FDO Execution Model, builds upon consistency of the available choices across different stages of the FDO Procedural Model which is presented in the next section.

4.2.2 Initial proposition of providing consistency across FDO steps

By running semi-structured interviews and continuous support evaluations, it could be observed that the selections across various steps and stages of the FDO Procedural Model were strongly interdependent. The selection of one element usually limits the available subsequent options and vice versa. Hence, only certain combinations within and across different stages, represented as layers connected in series or in parallel in Figure 4-4, are valid or technically consistent.

---

[163] The number of Flexible Design Concepts to be assessed is usually very high. Especially when considering the “Enabler-driven approach”, for various Change Objects a number of Transitions and Change Enablers can be selected each representing a Flexible Design Concept.

[164] Flexible Design Concepts are still at a quite high level of abstraction making an assessment difficult.

[165] Some of the Flexible Design Concepts are well-established and already physically available (e.g. lifting lugs) making an assessment on value and additional effort easier. Others (e.g. modular system) might still need development and reference values on added value and additional effort are missing.

Figure 4-4 depicts a simplified demonstration example[166] where only certain Baseline Objects are affected by relevant change sources (stage I). It also demonstrates the interdependency of Change Objects, Transitions and Change Enablers which only form Flexible Design Concepts when being consistent to each other (stage II). Based on the limited relations of domain elements across those steps, various consistent Flexible Design Concepts can be developed[167] that can then be assessed and result in high-performing Flexible Design Solutions[168].

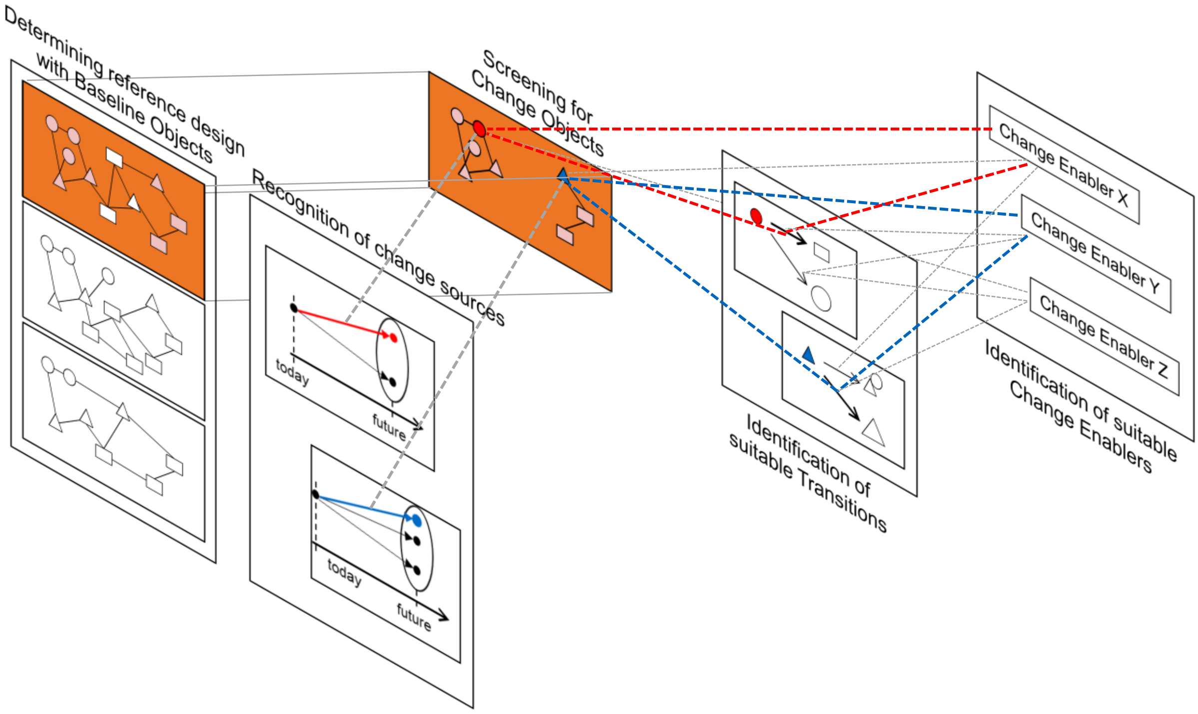


Figure 4-4 Technical consistency across FDO steps and stages

As highlighted in section 3.1.3, matrix-based approaches strongly support the fulfillment of (basic) FDO requirements and are especially suitable for visualizing those interdependencies in a compact format and support an application. Hence, in order to benefit from the existing technical consistencies during application, the data, i.e. the elements and potential relations, must be mapped and stored in a predefined data model (FDO Data Model) before being applied in the FDO Execution Model.

In the following the iterative process of identifying FDO requirements for the development and evaluation of the FDO Methodology is presented. This is followed by showing the results of that process.

---

[166] A differentiation between Change Drivers and System Requirements is not further considered in this example.

[167] In this example, each Change Object has only one valid Flexible Design Concept.

[168] Stage III is not visualized in Figure 4-4.

4.3 FDO requirements identification and specification

Section 4.3.1 demonstrates the iterative process of identifying FDO requirements. Section 4.3.2 then shows the final FDO requirements that guide the development of the methodology and also represent criteria against which the entire FDO Methodology is evaluated.

4.3.1 Process of identifying FDO requirements

The process of identifying FDOs is represented in Figure 4-5 together with an enumeration for each of the addressed activities. As section 1.3.3 has shown, the basic requirements of the FDO Methodology (1) are based on the industry-specific boundary conditions which were determined with the research methods discussed in section 1.4. They represent the starting basis for the development of the FDO Methodology. In the early phases of FDO Methodology development (2), in particular when developing the FDO Procedural Model, tentative proposals on the FDO process supported the definition of FDO requirements as the required building blocks of the methodology became clearer.

In order to fulfill those basic requirements and as highlighted in section 3.2, matrix-based methods were considered contributory to fulfill those basic requirements, hence, were selected as core reference methods of the FDO Methodology and, due to that concretization, also contributed to a breakdown into FDO requirements (3). Especially the input generated from semi-structured interviews on mini cases to build the FDO Data Model (4) emphasized in section 5.2 and informal interviews (5) further facilitated the generation and validation of FDO requirements. All inputs that affected the formulation of FDO requirements had to be analyzed for suitability first (6). Especially as the run interviews were usually not dedicated for determining FDO requirements from experts explicitly but were a result of implicit indications during interviews, it also became necessary to interpret relevant statements and translate them to FDO requirements (6).

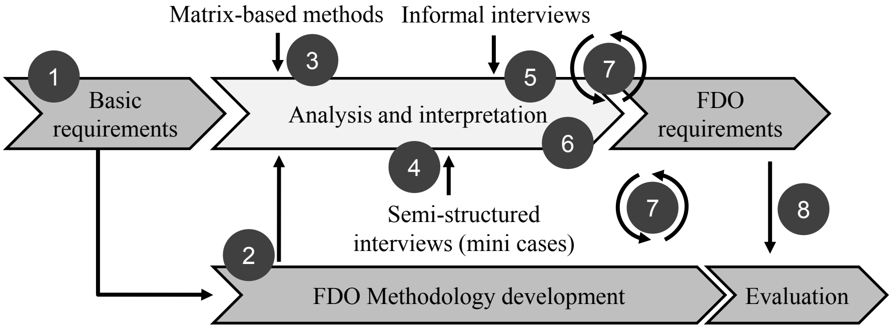


Figure 4-5 Process of identifying FDO requirements

Once tentative FDO requirements were defined, they were iteratively adjusted (7) based on further informal interviews or insights during the development of the FDO Methodology.

Finally, by completing the development of the FDO Methodology those FDO requirements represented the final criteria against which the final results were evaluated against (8) also reflected in section 8.3.

Hence, the generated FDO requirements based on initially defined basic requirements and knowledge gained during the development of the FDO Methodology and analysis / interpretation of the FDO requirements. This was favorable due to mainly two reasons: On the one hand, it provided clear and sufficient focus to develop the FDO Methodology from the start without locking oneself and compromising on suboptimal methods. On the other hand, it provided sufficient flexibility to allow for mutual adjustments of both FDO Methodology and FDO requirements based on the increasing knowledge and status of the development. This allowed their continuous convergence which, in the end, is also mirrored in the satisfactory fulfillment of FDO requirements (section 8.3.3).

In the following the final FDO requirements are presented.

4.3.2 Suggested FDO requirements

As the previous section illustrated, the superior basic requirements from section 1.3.3 were deduced gradually and iteratively based on the basic requirements and in parallel to the development of the FDO Methodology. A total of 23 FDO requirements were identified that are also listed in appendix 11.4. Hence, although they are considered to be solution neutral, they build upon an increasing concretization of the FDO Methodology.

BR I: Identification of effective FDOs

The identification of effective FDOs aims at the effective limitation and reduction to a relevant problem and solution space[169] while supporting the identification of relevant Flexible Design Concepts and Solutions within the determined solution space for both System Supplier and user. It includes the following requirements:

- R1, Ability to identify the relevant problem and solution space: The methodology should support the identification of only relevant change sources (Change Drivers, System Requirements) and Objects on the drilling rig.
- R2, Ability to identify technically feasible solutions: The methodology should allow the identification of only those Flexible Design Concepts that are technically feasible.
- R3, Ability to identify high-performing solutions: The methodology should allow the identification of the best performing Flexible Design Concepts beyond its feasibility, i.e. solutions of high value and/or high value-effort ratio.
- R4, Ability to reduce to effective and relevant solutions: The methodology should allow a systematic reduction of available solutions to an effective and relevant set (relevant together with "R7").

---

[169] The "solution space" includes only those elements that can be directly designed, changed and implemented by the stakeholder(s); the "problem space", on the other hand, includes elements that could be directly or indirectly affected by the proposed system solution or have an exogenous influence on the chosen solution [DE WECK ET AL. 2011, p. 98].

- R5, Ability to reduce risk of offering non-profitable solutions from System Supplier's perspective: By using the methodology, the System Supplier should reduce the risk of offering Flexible Design Solutions that are non-profitable due to e.g. new and yet unproven offers, embedment of flexibility at System Supplier's cost, etc.

Flexible Design might be effective locally. However, as MIKAELIAN ET AL. [2011] emphasize, a localized synthesis usually leads to flexibility candidates within silos being avoided by introducing a framework that allows a holistic consideration which are addressed as requirements in the following section.

BR II: Comprehensive identification of FDOs

The comprehensive identification of FDOs is necessary for filling in essential gaps on needs not articulated by the customer (e.g. emphasized in ROSS & RHODES [2007]) and extending the available sets of Flexible Design Concepts to generate better Flexible Design Solutions:

- R6, Comprehensive identification of change sources and Objects: The methodology should allow accounting for explicitly articulated but also non-articulated change sources (Change Drivers, System Requirements) and Objects by the customer.
- R7, Comprehensive generation and representation of Flexible Design Concepts: The methodology should allow a comprehensive identification and representation of Flexible Design Concepts including suitable Transitions and Change Enablers for the identified Change Objects.

The customer acts as the final decision-maker and, hence, must be accounted for when applying the FDO Methodology. As illustrated in section 1.3.3, it is the last other basic requirement next to BR II of aspect 1 to contribute to the core requirement BR I.

BR III: Customer-oriented identification of FDOs

The customer-oriented identification of FDOs accounts for identifying a customer-relevant problem space, solution space and Flexible Design Concepts resulting in Flexible Design Solutions that meet customer expectations:

- R8, Customer-dependent decision-making on relevant problem and solution space: The type of change sources (Change Drivers, System Requirements) and relevant Objects depend on the customer and must be accounted for during decision-making.
- R9, Customer-dependent decision-making on solutions: The selection of suitable Flexible Design Concepts and Flexible Design Solutions for the selected Change Objects depend on the customer and must be accounted for during decision-making.

The efficient identification of FDOs is considered to be important when considering the time constraints under which solutions have to be found and decisions are made.

BR IV: Efficient identification of FDOs

The efficient identification of FDOs is considered to be important in order to reduce the threshold of applying the FDO Methodology in the first place. At the same the FDO Methodology must meet the time and resource constraints as a prerequisite to provide quality results:

- R10, Efficient identification of Baseline Objects: The Baseline Objects, i.e. the Objects that represent the design basis before flexibility is even considered, should be identified in a time- and resource-efficient manner.
- R11, Efficient identification of change sources and Objects: The identification of change sources (Change Drivers, System Requirements) and the affected Change Objects should be performed in a time- and resource-efficient manner.
- R12, Efficient identification of Flexible Design Concepts and Solutions: The identification of Flexible Design Concepts and Flexible Design Solutions for the identified Change Objects should be performed in a time- and resource-efficient manner.

The usability of the FDO Methodology is the next basic requirement to be addressed.

BR V: Appropriate usability for engineers

The appropriate usability for engineers are relevant both with regards to the actual threshold of users to apply the methodology in the first place and, if being used, applying the methodology correctly. The following requirements are considered to be important:

- R13, Non-ambiguous and clear comprehension: The methodology and its constituents can be unmistakably comprehended by its users. Despite achieving better results, it also helps engineers and decision-makers to be more confident about those results.
- R14, Simple traceability of selections and decisions: The selections and decisions within the methodology are transparent and can easily be traced back.
- R15, Homogeneity of and within approach[170]: The methodology represents one integrated approach for both identifications of Change Objects and generation of Flexible Design Concepts.
- R16, Ease of application: The application of the methodology is easily understood and performable.
- R17, Ease of managing models during execution: The methodology should provide the means to easily adapt, integrate and remove data when being applied.

A flexible application of the methodology is considered to be of especially high importance under the boundary conditions it is to be used (section 1.3.2). As illustrated in section 1.3.3, it is the last other basic requirement next to BR V of aspect 2 to contribute to the core requirement BR IV.

---

[170] I.e. switching between different application models is to be avoided or limited.

BR VI: Flexible application of FDO Methodology

The flexible application of the FDO Methodology is essential for reducing the threshold of applying the methodology under varying boundary conditions and enabling the situation-dependent adequate identification of FDOs that suits those boundary conditions. This is embodied by the following requirements:

- R18, Alternative entry or exit points: The methodology should allow the user to enter or exit the model at different stages or steps.
- R19, Ability of omitting or postponing step(s) and iteration(s): The methodology should allow the user skipping certain steps and iterations. This also includes delaying decisions such as the selection of Transitions to later phases of the methodology.
- R20, Ability of changing direction of identification: The methodology should allow the user the identification of change sources and Change Objects by following different directions through the model being able to identify causally related and unarticulated prior upstream causes and downstream elements that follow causality.
- R21, Scalability of complexity and comprehensiveness: The methodology should be able to scale both the complexity of the model and the degree of comprehensiveness.

Despite the requirements that address the execution of the FDO Methodology, the prior and intermediate phases of building and maintaining the model database should also be accounted for which coincides with aspect III as section 1.3.3 illustrated.

BR VII: Efficient build-up and maintenance of database

The efficient build-up and maintenance of the database should reduce the threshold as well as the overall effort of incorporating the FDO Methodology due to time and resource savings in the build-up and maintenance of the model:

- R22, Efficient build-up of database: The build-up of the initial database should be performed in a time-and resource-efficient manner.
- R23, Efficient maintenance of database: The maintenance of the database, after the first build-up and in between application periods, should be performed in a time-and resource-efficient manner.

As section 4.3.1 illustrated, the FDO requirements are relevant with regards to continuously guiding and reflecting the development of the FDO Methodology; however, they also represent criteria for the methodology’s evaluation presented in section 8.3.

In the following, details and background information on the other model of the FDO Methodology introduced in section 4.1, namely the FDO Data Model, is presented.

5. FDO Data Model

Based on the FDO Procedural Model (section 4.2.1) and the need for consistency within and across stages (section 4.2.2), the suitability of matrix-based approaches to support the identification of FDOs is recognized.

In the following section 5.1 a meta-model of the FDO Data Model is introduced by highlighting the main domains and dependency types required for the identification of FDOs which guides the process of data elicitation, processing and verification. This process is described in detail in section 5.2. which focuses on the case-based semi-structured interviews, the main research method for populating the FDO Data Model. This is followed by presenting the results in section 5.3 on the FDO constituents and categories of each of the five domains.

The processing of data and the results for this chapter were strongly supported and covered by the theses of CARATHANASSIS [2015] and SCHLATHER [2015]. For the embedment into the overall research context and FDO Methodology minor adjustments of those results were performed.

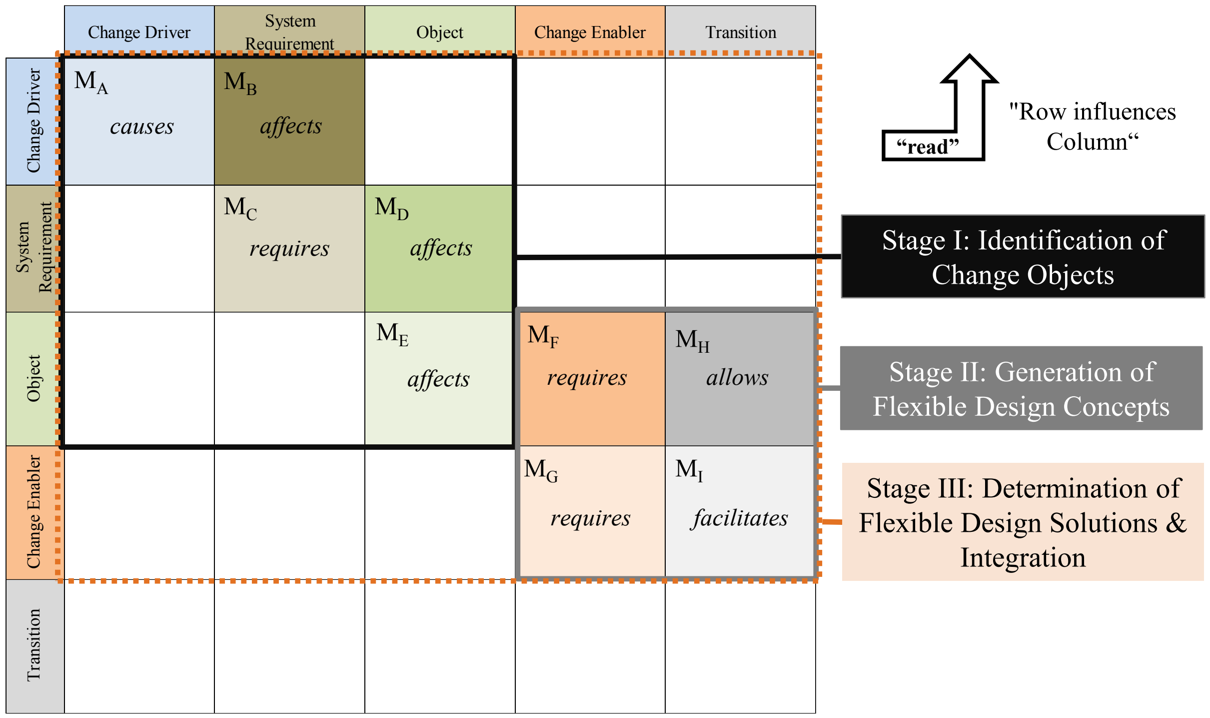
5.1 MDM-based meta-model

The FDO Procedural Model and the visualization of technical consistency in section 4.2.2 depicts that for the identification of Change Objects and the generation of Flexible Design Concepts various domains and type of dependencies are required which were already briefly addressed in section 2.5.2. According to LINDEMANN ET AL. [2009, p. 23], the number of components, dependencies and variants are important characteristics of complexity. LINDEMANN ET AL. [2009, p. 62] state that the system's complexity can lead to two challenges which are illustrated with respect to the FDO Methodology:

On the one hand, a "design problem" exists defined by the challenge of determining Change Objects and new Flexible Design Concepts based on the various combinatory options that exist. A proactive approach of identifying suitable FDOs and highlighting the consequences should be emphasized from the beginning to avoid iterations and setting the basis for generating high-performing solutions in the end.

On the other hand, a handling problem exists where ongoing adaptations such as changing selections during application of the FDO Methodology generate problems to control the complexity. Even if those changes are clear and by themselves not complex in nature, system dependencies may lead to subsequent changes that are implicit and usually cannot be anticipated leading to both losses in efficiency and effectiveness. This might result in missing out on risks such as by the negative consequences of change propagation but also on new opportunities that arise by such adaptations (e.g. changes of "Transitions" allow the selection of new and potentially even better Change Enablers). Hence, as highlighted in LINDEMANN ET AL. [2009, p. 63] for better handling system designers need a manual that contains information about impact chains or the consequence of selections and adaptations.

As section 3.1.3 demonstrated, matrix-based methods contribute significantly to the fulfillment of basic requirements. By applying structural complexity management, complex systems can better cope with the above addressed design and handling problems. The scope of consideration can be defined in a Multiple-Domain Matrix (MDM) also introduced in section 3.2.1 and illustrated as a meta-model in Figure 5-1. The meta-model systematizes and collects relevant domains and dependency types and puts these into a common framework [KREIMEYER 2010, p. 109]. As highlighted in KOH ET AL. [2012], various entities and dependencies can exist when using matrix-based approaches. Hence, this requires to develop supports with specifically defined domains and dependency types which in this context of application follow the FDO Procedural Model presented in section 4.2.1.



	Change Driver	System Requirement	Object	Change Enabler	Transition
Change Driver	M_A *causes*	M_B *affects*			
System Requirement		M_C *requires*	M_D *affects*		
Object			M_E *affects*	M_F *requires*	M_H *allows*
Change Enabler				M_G *requires*	M_I *facilitates*
Transition					

Figure 5-1 FDO Data Model as MDM-based meta-model

As highlighted in section 1.4 the applicable domains and dependency types and the underlying elements and relations result from an iterative process[171] through the application of various research methods, especially the case-based semi-structured interviews (section 5.2.1). As depicted in Figure 5-1 the following five domains are relevant with regards to the identification of FDOs: Change Driver, System Requirement, Object, Change Enabler and Transition. As illustrated in section 2.5.2 Change Drivers belong to the environment of the technical system, hence, are part of the system context[172]. All other domains belong to the technical system and, consequently, with their elements and relationships make up the system architecture. The FDO Data Model covers stages I and II of the FDO Procedural Model and, indirectly, sets the basis for stage III.

---

[171] Iterations are often necessary for practical applications [LINDEMANN ET AL. 2009, p. 63].

[172] BARTOLOMEI [2007, p. 73] also defines "system drivers" in the ES-MDM which lie outside of the system boundary as Figure 11-8 highlights.

The “Object” domain contains all possible Objects that could be fed as Baseline Objects[173] when identifying FDOs. It is the central domain as it:

- Connects it with the steps of change source recognition by determining the System Requirements and the underlying Change Drivers which enable the identification of Change Objects[174]
- Represents the basis for the identification of suitable Transitions and Change Enablers as only by knowing the Change Objects, Flexible Design Concepts can be generated

This MDM consists of four DSMs and five DMMs. It includes the dependency types that, as highlighted in section 4.1, only represent potential relations across elements, i.e. require a confirmation in the respective application context as illustrated in section 6.4.1. In the following both the DSMs and DMMs of stage I, i.e. the identification of Change Objects, and stage II, the generation of Flexible Design Concepts, are described successively by providing one illustrative example for each of those matrices. Readers who already would a like to have a deeper look on those matrices are recommended to look at the FDO Execution Model[175] for the use case described in section 8.1.3.

For the first stage of identifying FDOs, namely the identification of Change Objects, the following matrices exist (Figure 5-1) of which M_D and M_E can be subject to Change Triggers which were introduced in section 4.2.1:

- M_A: A Change Driver can “cause” other Change Drivers that in turn affect certain System Requirements (M_B). For instance, the Change Driver “change of oil price” might affect the Change Driver “change of operating area” both being external to the system of concern.
- M_B: A Change Driver can “affect” certain System Requirements. For instance, a customer “demand for improved ergonomics” might affect the System Requirement “direct line of sight”, i.e. a better view on the drilling systems and operations.
- M_C: A System Requirement may “require” another System Requirement to be fulfilled as a prerequisite. For instance, a change in “lifting capacity” requires the consideration of “hydraulic power capacity” and, consequently, also of “electric power capacity” in the first place. Latter can be showstoppers if they are not prepared for or able to be changed.

---

[173] Note that the steps leading to and the identification of Baseline Objects itself (step 1 and 2) are considered as input to the FDO Execution Model. The selection in step 2 is supported by the Upgrade Risk Portfolio, an FDO Facilitator, that is emphasized in section 7.1.

[174] Similarly, KALLIGEROS [2006, pp. 60–61] differentiates for the identification of platform and customized components between “exogenous factors”, “functional requirements” and “design variables” which correspond similarly to “Change Drivers”, “System Requirements” and “Objects” in this context of application.

[175] As will be discussed in section 6.1, the FDO Execution Model consists of multiple representations of matrices, hence, the reader is advised to look at the represented matrices M_A – M_G in section 8.1.3 and/or appendix 11.7.4. As the Transition-dependent matrices M_H and M_I are superposed with M_D/M_E and M_F in the FDO Execution Model (section 6.1), they are introduced separately in appendix 11.7.2.

- M_D: A System Requirement usually “affects” an Object to become an instigating Change Object. This Change Trigger can occur when a System Requirement belonging to an Object is not fulfilled anymore (e.g. “hook load capacity” affects the Object “Topdrive”) or when System Requirements could imply physical impacts due to movements[176] (e.g. changes of “tubular handling principles”, i.e. how tubulars such as drill pipes, casings, etc. are handled might affect the “Drillstring Compensator” physically).
- M_E: A Change Object “affects” another Object (Change Trigger) when Objects have a physical impact on other Objects due to change, also referred to as “change propagation” (section 3.2). For instance, changes of the Drillers Control Cabin may affect the “Derrick (structure)” physically. Hence, in addition to M_D, M_E represents another way of generating Change Objects.

Flexible Design Concepts build upon the identified Change Objects from M_D and M_E, respectively. M_F and M_G should include only those relations in the FDO Data Model that are profitable or feasible from a System Supplier’s perspective. The matrices related to stage II, the generation of Flexible Design Concepts, are shown in the following:

- M_F: As highlighted in section 3.3.2, Change Enablers and Objects must be considered integrated [Hernández 2003, p. 56], where each combination is referred to as a “transformation building block” [Wiendahl et al. 2007]. Hence, an Object “requires” Change Enablers that contribute to the effectiveness and efficiency of physical change. For instance, a (Gantry) crane (Change Object) can be changed and handled at more ease if its sub-assemblies were equipped with lifting lugs or pad-eyes (Change Enabler).
- M_G: As emphasized in section 3.3.2, Change Enablers affect each other (e.g. Fricke & Schulz [2005]) and may “require” other Change Enablers as a prerequisite [Nyhuis et al. 2008, p. 27]. They provide a platform for other Change Enablers (mechanisms), thereby indirectly enabling Transitions (type of real options) [Mikaelian et al. 2012]. Hence, overlooking a “Prerequisite Change Enabler” might lead to not being able to exercise the initially selected Change Enabler which then represents a bad investment despite its suitability when considered isolated[177]. For instance, the embedment of the previously mentioned “lifting lugs” for increased mobility (initial Change Enabler) usually requires “available space for better accessibility” (Prerequisite Change Enabler) where “lifting lugs” are considered to be a bad investment if there is a lack of accessibility.
- M_H: As discussed in section 3.3.1 (e.g. Cardin [2014], Heger [2007, p. 70]), an Object only “allows” certain Transitions depending on the function, build-up of the Object and system constraints. For instance, the Object “Topdrive” cannot be “relocated” (Transition) as it has to remain at well center and within the Derrick structure to fulfill its function(s).

---

[176] M_E, in contrast, only covers physical changes between Objects that are statically connected.

[177] This can be translated into a bad performance of this Change Enabler as it cannot be used for what it is intended for.

- M_I: A Change Enabler "facilitates" only certain Transitions. For instance, pre-installing a structure base for a Change Object usually does not ease the Transition "Partial Replacement", i.e. the removal and integration of the Object's sub-assemblies. The empirical data indicates a "M_n:T_n" relationship between Change Enablers and Transitions which represents the most general case of the mapping alternatives suggested by MIKAELIAN ET AL. [2011] introduced in section 3.3.1.

Although, as highlighted by MIKAELIAN ET AL. [2011] and emphasized in section 3.3.1, Transitions (or "real option types") can enable other Transitions, i.e. "an option on an option" which are also referred to as "compound options", empirical data and evaluation has not provided an applicable case and need for this research, hence, was not pursued further. This also applies to the DMM "System Requirement-Transition" where certain relationships could be identified (e.g. the relation of adding a new capability (System Requirement) and the need of "adding" a new Object (Transition)) but due to this exception hardly justify the build-up of a dedicated DMM as a whole. This is resolved by categorizing System Requirements (section 5.3.2) and the use of constraints (section 7.3).

The MDM-based meta-model represents the basis for both defining the system (section 5.3) and the application of the FDO Methodology in the FDO Execution Model (section 6).

Prior to introducing the constituents of the model in section 5.3, the focus in the following is on the research approach to identify those constituents.

5.2 FDO data elicitation, processing and verification

In section 5.2.1 the basis for the semi-structured interviews and a classification of this research method is provided. This is followed by section 5.2.2 which elaborates on the steps of processing the elicited data and verifying results based on another run of expert interviews.

5.2.1 Case-based expert interviews

Throughout the study various research methods were used to develop and evaluate the FDO Methodology (section 1.4). The core research method, however, is represented by semi-structured interviews. The main objective of running those interviews was to gain understanding of the phenomena related to the domain elements and the relations[178] between them as highlighted in section 4.2.2. The end result was not intended to be a complete model but only an initial FDO Data Model that is applicable for use while, based on the high level of concretization, allows making specific iterative improvements on the FDO requirements (section 4.3.1) and, hence, the FDO Methodology itself. The following description bases upon ALLAVERDI ET AL. [2015] describing the process of data acquisition in detail.

Interviewing is regarded especially useful for understanding complex systems that are not easy to simulate or that include many different stakeholders, actors and systems [SUMMERS & ECKERT 2013]. At the same time the database was lacking most of the information required for

---

[178] Both relations within and across domains were addressed.

meeting the objectives mentioned above. The overview in Table 5-1 classifies the applied research method when running interviews based on criteria defined by SUMMERS & ECKERT [2013].

Table 5-1 Classification of expert interviews [adapted from Allaverdi et al. 2015]

Interviewing as a research method	
Purpose of research study	Understanding
Purpose of interview	Core
Additional methods for mini cases	Document archival analysis
Context of study	(Upstream) Oil & Gas
	Complex systems

Interview participants	
Organization	- 1 company: Drilling System Supplier (topside) - various divisions covering different parts of product portfolio
Interviewee	- approx. 20 experts on Lifecycle Engineering - individual interviews
Relationship between interviewer and interviewee	Interviewer employed in organization
Interviewer (number)	single interviewer

Interview process data	
Interview	on-site at corresponding division
Type of interview	- semi-structured - based on specific cases (past, present) - close precious, prompting
Supplemental material	- introductory presentation to research / educational training - audio recording - interview worksheet (content immediately verified during note taking)
Duration interview	- 2,0 - 3,0 hrs/session (effective) - 35 sessions - duration depending on complexity, scope and knowledge of interviewees on the addressed mini case

A study within the organization of one Drilling System Supplier was conducted by focusing on upgrade relevant Objects that possessed significant differences amongst each other. By addressing product families[179] as the targeted Objects of investigation, a sufficiently high level of abstraction was attained limiting the number of accounted Objects of the portfolio while neglecting inconsiderable deviations[180] of product variants with regards to upgrade relevant aspects (e.g. suitable Change Enablers, Transitions). The Upgrade Risk Portfolio (section 7.1) to support the identification of Baseline Objects in the FDO Methodology (section 4.2.1) was initially built for and used in the context of those case-based interviews to prioritize most relevant product families. Based on the defined criticality of Objects, the relevant product families and the order of addressing them were determined. Those critical Objects were now confronted with existing upgrade projects of the past or present to concretize the interviews around specific cases (“mini case”). The interviews were run for each “mini case” independently by going through a reference questionnaire (appendix 11.5) while allowing for iterations and encouraging discussions. Although Change Objects were usually only assigned to one “mini case”, in some cases the Object was confronted with different projects to account for major new

---

[179] Only equipment related product families were considered as a starting point (not bulk items).

[180] The performed interviews showed that the statements always apply within the same product family.

insights that were announced in advance by the interviewees (e.g. new “mini case” for the same Object leading to completely different Change Enablers).

Each “mini case” used the same procedure following four different categories of questions. After the first pilot interviews in the early phases, questions were removed, combined or modified in order to improve the execution of the interviews and increase the quality of the results. Besides a category of questions for eliciting general information on the upgrade project and Change Objects (“main data”), questions were also targeting the different stages and, subsequently, five domains introduced in section 5.1, including an initial assessment of Change Enablers that make up the Change Enabler Value-Effort Portfolio (section 7.4). Despite project-specific questions, questions regarding the generalization of statements were raised to provide details on the transferability and applicability of statements to other cases and circumstances (e.g. reassuring applicability of Object in “mini case” for entire product family). Questions also concerned receiving background information both as a means to understand the context of the data when being processed while providing insights affecting the FDO requirements and methodology as a whole. The full list of questions attributed to the four categories can be found in appendix 11.5.

A series of interviews was held at different sites of the Drilling System Supplier under investigation as each site had its own product lines contributing to the entire product portfolio. There mostly experts[181] on Lifecycle Engineering (LCE) were interviewed that were both familiar with the addressed product families while having detailed knowledge on those upgrade projects. 35 interview sessions were performed resulting in 35 documented “mini cases” on critical Objects.

Based on the core research method and other complementary methods (section 1.4), the data for the FDO Data Model was processed and verified displayed in the next section.

5.2.2 Complementary data and activities

The case-based interviews contributed majorly to building the FDO Data Model as a whole, i.e. for both stages of the FDO Procedural Model. The questions concerning stage I provided project specific insights on relevant elements and relations leading towards the identification of Change Objects. In contrast, questions related to stage II focused on providing rigorousness on Flexible Design Concepts by introducing a high number of embedded and recommended Change Enablers. Consequently, whereas the case-based approach contributed to generate a large amount of Flexible Design Concepts based on specific projects, this rigorousness was rather limited[182] for System Requirements and especially Change Drivers. Hence, to extend the scope on elements for stage I, complementary methods were used to widen the data basis on relevant elements in the offshore drilling industry. Based on the research approach and methods of section 1.4, this included using the results from both RC and DC-I stages such as the obser-

---

[181] In few cases product or project responsibles were interviewed if they were familiar with the case under investigation.

[182] As only the case relevant change sources were identified which were partially also redundant.

vations made in trainings on drilling systems and operations, the long-term participatory observation of an Operator-dominated system development project, the informal interviews and an additional document archival analysis on technical specifications for heterogeneous tender projects.

The processing, completion and verification of data related to the phase of “Identification of Change Objects” (stage I) and “Generating Flexible Design Concepts” (stage II) required certain activities to get useful results from the raw data. Carathanassis [2015, pp. 51–75] and Schlather [2015, pp. 52–96] describe those activities for stage I and II respectively. Table 5-2 provides a general overview of the performed activities[183] which has parallels to the more general procedure for “Qualitative Knowledge Construction” (QKC) suggested by Bartolomei [2007, pp. 97–102] when building the ES-MDM introduced in section 3.2.1.

Table 5-2 Activities related to processing, data extension and verification of data

	Type of activity	Change Driver	System Requirement	Object	Change Enabler	Transition
I, Data processing	A systematic and continuous aggregation of redundant domain elements and relations	x	x		x	
	An abstraction of individual domain elements to a suitable level	x	x		x	
	A reassignment of domain elements to other domains based on a more specific domain definition	x	x			
	A categorization of domain elements (section 5.3)	x	x	x	x	
	Definition of consistent syntax for all domain elements (section 5.3)	x	x		x	
II, Data completion on relations	Expert-supported building of new causal chains (relations) based on the verified domain elements	x	x	x		
	A systematic extension of relations by Object classes (section 7.2)			x	x	x
III, Expert verification	Systematic and continuous expert verification of the domain elements, categories and relations	x	x	x	x	x

As the case-based interviews only provided a subset of relations that are to be embedded into the FDO Data Model, relations had to be completed separately. In a separate workshop with domain experts and based on an initial prioritization of Change Drivers, sample causal chains were identified individually for stage I. Despite improving the FDO Methodology and showing its applicability (support evaluation), it represented the basis for applying the methodology from the beginning to the end[184] on verified real-world data and run the expert evaluation of the methodology. Besides the data gathered from the case-based interviews, change propagation (M_G) was not specifically targeted during the completion process.

Stage II was reaching out for a more complete model beyond depicting its applicability. As highlighted in section 1.3.3, the “Generation of Flexible Design Concepts” had a special focus within the framework of the FDO Methodology. Despite the lack of research and the research contribution of this work, practical reasons motivated a higher density in stage II due to:

---

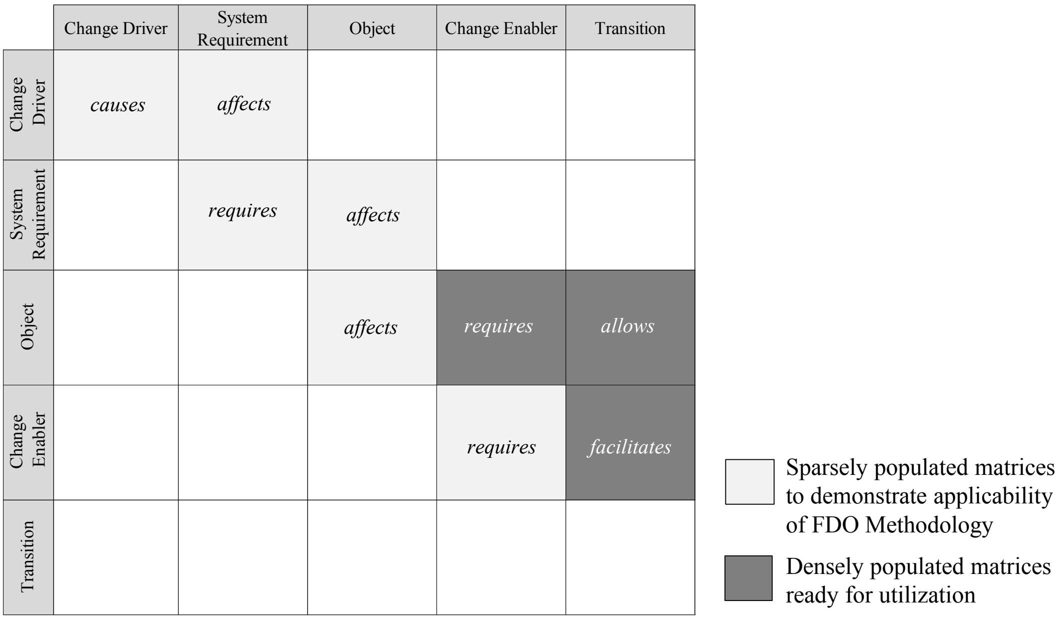
[183] This process was highly iterative and could deviate from the intended order.

[184] More sample causal chains were gathered for stage I of the FDO Methodology than were actually used for the use case and expert evaluation (section 8).

- More knowledge of potential system users on affected Change Objects by certain change sources (stage I) than on how they can be enabled by flexible design (stage II)
- Incomplete stage II would question the overall value added by the FDO Methodology as it requires supporting the generation of Flexible Design Concepts

Stage II realized the systematic completion of relations without running individual paths but by generating Object classes that shared common properties (section 7.2). This allowed assigning Change Enablers and Transitions to new Objects where relations had already been known for Objects of the same class. M_G was not addressed in that context and, hence, bases upon the case-based interviews only. Both the elements and relations were subject to an extensive verification process by domain experts.

As is shown schematically in Figure 5-2, the FDO Data Model of stage I is populated sparsely whereas stage II, especially due to generating Object classes, is mostly densely populated[185]. Densely populated matrices, however, do not ensure completeness as is explained in section 7.2.1, but allow an application of random selections (e.g. any Change Object can be selected for generating useful Flexible Design Concepts). In contrast, sparsely populated matrices must demonstrate the application of the FDO Methodology based on a small number of interrelated elements and specific cases (e.g. only certain instigating Change Drivers usable for demonstrating tracing across domains).



	Change Driver	System Requirement	Object	Change Enabler	Transition
Change Driver	*causes*	*affects*			
System Requirement		*requires*	*affects*		
Object			*affects*	*requires*	*allows*
Change Enabler				*requires*	*facilitates*
Transition					

☐ Sparsely populated matrices to demonstrate applicability of FDO Methodology

■ Densely populated matrices ready for utilization

Figure 5-2 Population density of relations in FDO Data Model

Overall, taking into account the boundary conditions and the large amount of data required for the development of the FDO Methodology, this procedure is considered to be satisfactory. On the one hand, by collecting, processing, completing and verifying data, enough knowledge was

---

[185] The only exception is matrix “M_G” which solely bases upon the results of case-based interviews.

available to develop, apply and evaluate the FDO Methodology. On the other hand, by performing those activities with an enhanced focus on stage II, the core aspect of the FDO Methodology, namely flexible design, could be targeted addressing especially the second research contribution, i.e. the operators and heuristics for the generation of Flexible Design Concepts as defined in section 1.3.3 and 3.2.2.

Based on that FDO Data Model, the FDO Execution Model is run. In the following the domains that make up the FDO Data Model are presented.

5.3 Main domains of FDO Data Model

The following sections introduce the constituents for each of the five domains. Each of the domains are built up similarly by providing a general definition, a syntax[186] or other expressions for the constituents to be applied in the FDO Data and Execution Model, a categorization within each domain and, partially, statistical distributions on the individual constituents and (sub-) categories based the available empirical data.

5.3.1 Change Driver

Based on the various definitions and the classifications provided in section 2.2.1, Change Drivers are defined as follows in the course of this work:

Change Drivers are both the root and resulting causes which can lead to a non-fulfillment of System Requirements and, hence, drive the system change. They include both "known unknowns" and "knowable unknowns" that act exogenously on the technical system.

Based on this definition and by considering causality, Change Drivers are both the underlying causes, i.e. the initial reasons for change and the subsequent causes which lie downstream causing other Change Drivers[187] to occur. Change Drivers across this causal chain must end up affecting System Requirements to be of relevancy and, hence, represent the underlying reason for the change of an Object. The Change Drivers that are of concern are uncertain to occur; however, the existence of those uncertainties is either known (articulated needs by customer) or knowable (unarticulated needs by customer) where latter can be converted to known unknowns by use of the methodology (section 2.2.2). Unlike System Requirements, Change Drivers are independent of the technical system and affect it from exterior. As expressed by HERNÁNDEZ [2003, p. 110], they represent "non-steerable factors" of the global and corporate environment and are the basis for change scenarios discussed in section 6.3.2.

As discussed in section 5.2.2, certain activities had to be performed with the available raw data. Each domain should have uniquely defined domain elements to form a consistent and homogenous group that facilitates comprehension and avoids misunderstandings. As the defini-

---

[186] A syntax is applicable to the domains "Change Driver", "System Requirement" and "Change Enabler".

[187] Gaps or "jumps" over Change Drivers in the cause-and-effect network are possible as indirect relationships may have been confused with direct ones / forgotten during the elicitation process. This motivates an iterative and incremental improvement of the FDO Data Model in the long-run.

tion of domain elements is to connect domains in the FDO Data Model and the FDO Execution Model, developing a suitable syntax required the consideration of the defined dependency types and domains that the Change Driver domain is related to.

Based on CARATHANASSIS [2015, pp. 55–56], the following syntax rule was considered and proven to be applicable:

<Type of change><Subject of change>

Thereby, the first part of the syntax refers to the type of change. The second part refers the subject that is to be changed outside of the technical system (section 2.5.2). Based on this general syntax three alternative formulations were defined:

- "Change of": e.g. "Change of rate of penetration"[188]. It represents the most common formulation as it is generic enough to be applicable across different cases and specific enough to describe relations to other domain elements. Mostly they can be regarded as "must changes"[189] [CONRAT 1997, pp. 52–53] in the causal network as they usually cannot be prevented or ignored and, hence, are permanently valid causalities.
- Alternatively, the change can be formulated more specifically to avoid misunderstandings. "Depletion of formation" or "In-and outsourcing of well services" are examples that concretize the type of change. As for the "change of" syntax, they usually represent permanently valid causalities.
- "Demand for": e.g. "Demand for mud logging". They are usually the last Change Drivers in the causal network of this domain causing either other "demand of" Change Drivers or affecting specific elements of the "System Requirement" domain. They indicate explicit customer requests and, hence, as being strongly dependent on the preferences of the decision-maker can be interpreted as "can changes" opposed to the permanently valid "must changes" from before.

After having systematized the empirical data according to those three alternative formulations, CARATHANASSIS [2015, pp. 56–60] assigns those Change Drivers to certain superordinate categories. They base upon the classification of DE WECK ET AL. [2007] introduced in section 2.2.1, however, are condensed to only the relevant ones based on the elements from the data:

- Use Context: Change Drivers related to the way a product is used and the conditions under which it has to operate. It is related to changes in modes of operation and circumstances.
- Economic Context: Change Drivers that include availability and, especially, efficiency related customer requests mostly representing subsets of the defined "market context". They are based on economic interests[190] across the value chain.

---

[188] The rate of penetration by which the formation can be drilled changes.

[189] Although CONRAT [1997, pp. 52–53] refers to changes of physical products, this type of change is similarly applicable to Change Drivers.

[190] Safety, for instance, although being also of interest for the customer, does not belong to the economic but belongs to the "Legal Context" (Health Safety Environment (HSE)).

- Legal Context (HSE): It includes Change Drivers which emerge from superior political decisions leading to certain HSE regulations in legal areas of operations or are defined by rig owner or operator specific HSE rules[191]. They represent a subset of the “Political & Cultural Context”.
- System Context: Change Drivers related to uncertain lifecycle properties, technical obsolescence and control of wear & tear of the system. They correspond to “Product Context”.

Subcategories represent an intermediate level of categorization between specific Change Drivers and the introduced generic main categories. Besides its purpose of further systematizing Change Drivers, this level of concretization allows the targeted prompting[192] of new Change Drivers when building scenarios (section 6.3.2). Table 5-3 illustrates the fifteen identified subcategories that are assigned to the four main categories and provides domain specific examples of Change Drivers for each of them.

Table 5-3 Systematization of Change Drivers in subcategories

Use Context	**Operational Environment**	**Metocean Conditions**	**Formation & Well Conditions**	**Well Planning**	**Operational Flexibility**	**Operational Method**
	e.g. Change of Operations From Harsh to Benign Environment	*e.g. Change of Wind Loads*	*e.g. Change of Well Pressure & Temperature (e.g. HPHT)*	*e.g. Change of Measured Depth (MD)*	*e.g. Change of 3rd Party Equipment*	*e.g. Demand for Managed Pressure Drilling*
Economic Context	**Operational Availability**	**Operational Efficiency**	**Time Efficiency**	**Cost Efficiency**		
	e.g. Demand for Increased Operational Weather Window	*e.g. Demand for Increased Riser & BOP / X-Mass Tree Running Efficiency*	*e.g. Demand for Redundancy of Critical Drilling System*	*e.g. Demand for Maintenance/ Repair Costs Reduction*		
Legal Context (HSE)	**Safety Environment**	**Waste & Emission Management**				
	e.g. Demand for Reduced Manual Handling (Handsfree operations)	*e.g. Change of Waste Storage*				
System Context	**Lifecycle Properties**	**Technical Obsolescence**	**Wear & Tear**			
	e.g. Demand for Improved Ergonomy	*e.g. Demand for Increased Automation Level*	*e.g. Change of Utilization of Drilling System*			

A total of 78 Change Drivers could be identified. Although those Change Drivers only represent one snapshot and perspective based on the chosen research methods and boundary conditions

---

[191] Regulations are the rules which are authorized by the government and are part of an act to control people from doing anything not permissible by law. Instead, rules are a set of instructions that are part of that regulation meant for individuals and organizations to tell them what to do and what not to do [SURBHI 2016].

[192] Prompting new Change Drivers by asking about the relevancy of each Change Driver subcategory.

(organization, people, country, etc.), the relative contribution to the categories and subcategories indicates a tendency of the dominating Change Drivers in this context of application.

Figure 5-3 highlights the assignment of single Change Drivers to sub-categories and categories based on the available data. The figure suggests that the largest group of relevant uncertainties to prepare for in the future are related to “Use Context” headed by “Operational Flexibility”, i.e. preparing for potential operational changes such as “changes of well services” or “changes of rig crew constellations”, etc. The distribution does not provide any indication of the risk of emergence of each Change Driver. Hence, it is supposable that subcategories and categories that constitute very few Change Drivers are still very important as they are likely to occur in the future and/or have a strong impact.

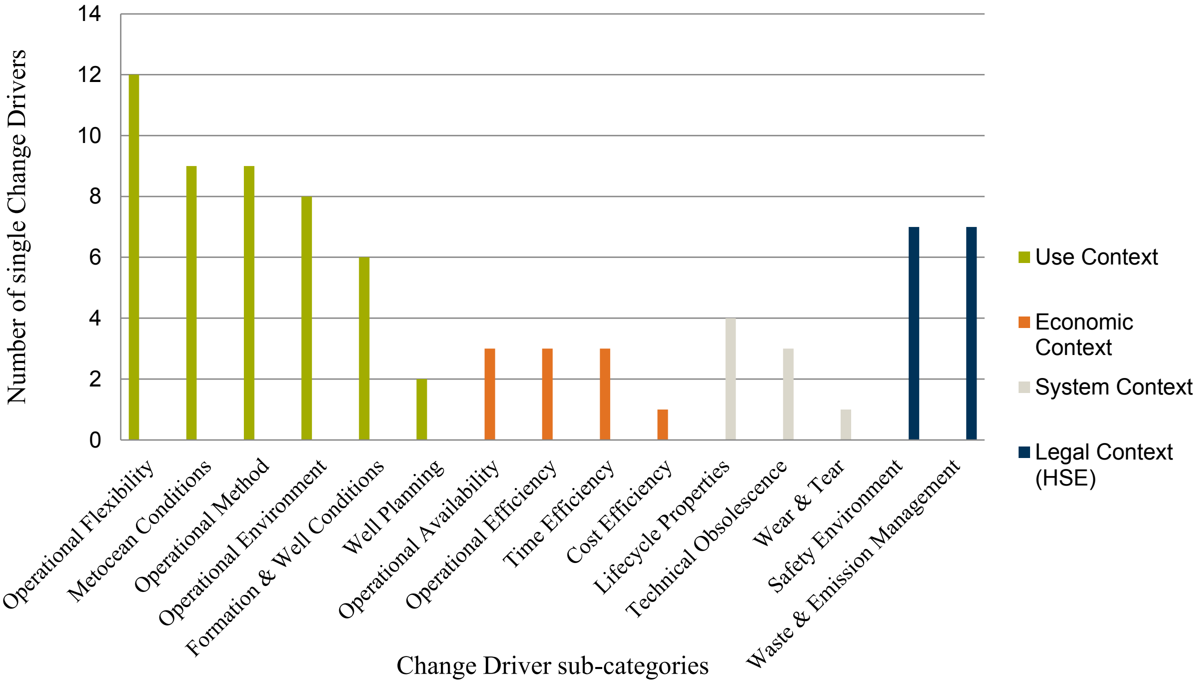


Figure 5-3 Contribution of Change Drivers to categories and sub-categories

The next domain to be discussed is the domain of “System Requirements”.

5.3.2 System Requirement

System Requirements can be deduced from the known or knowable Change Drivers. Section 2.5.1 provides insights into the definition and constituents of system requirements which are especially based on IEEE 1233 [1996, pp. 11–12]. Based on that the specific definition of System Requirements for the FDO Methodology are derived:

A System Requirement is a statement of system capability that is qualified by measurable conditions and bounded by constraints that can be validated. If met or possessed by a (drilling) system, it solves a customer problem or achieves a customer objective which, in turn, provides value and utility to the customer or system user.

Based on this definition, System Requirements define a capability with measurable conditions and constraints that are related to the system. Based on the insights from section 2.5.1, the three constituents can be elaborated on for this context of application:

- "Capabilities" describe the ability of the system to perform a function (e.g. the ability of "Managed Pressure Drilling") or the existence of a feature (e.g. having CE certified equipment). Capabilities alone can have binary attributes on a nominal scale (no, yes) describing if the capability is required or not.
- "Conditions" either describe the manner of how a function is fulfilled (e.g. methods such as alternative Heavy Equipment Guiding Principles) or parameters within allowable borders for functions or features (e.g. changes in Mud Storage (volume)). Hence, conditions can be provided quantitatively by a continuous or discrete scale of values[193]. For the other cases, conditions can be expressed qualitatively by ordinal scales or by categorical variables where there is no intrinsic ordering (e.g. Tubular Connection Making Method).
- "Constraints" indicate externally imposed borders under which functions or features have to be fulfilled (e.g. specific "Tubular Specifications", limits in "Indoor Toxic Fumes Exposure"). The same scales apply as for conditions[194]. Identically also categorical variables may apply.

Based on this definition the following syntax of a System Requirement was defined:

<System Requirement><[Capability],[Condition],[Constraint]>

where the first part represents the description of the capability and the second part specifies if it concerns the existence of that capability or a related condition or constraint of that capability. The following three syntaxes exemplify each of the three alternatives:

- Offline Standbuilding [Capability]: The ability of parallel offline standbuilding when performing drilling operations.
- Marine Riser Handling Principles [Condition]: The method of how marine risers are handled.
- Working Temperature [Constraint]: The allowed temperature upper and lower bound under which the rig crew and drilling systems operate.

The System Requirements of concern are only those that face significant uncertainty and can potentially trigger changes of Objects by changes of their characteristics or by introducing a

---

[193] Although theoretically possible, based on the data a discrete scale does neither apply for conditions nor constraints.

[194] Note that "specifications" that are imposed on the system (e.g. BOP Specifications) represent an aggregation of different attributes (e.g. dimensions, weight) and are not further differentiated. A further differentiation, however, may be required if only subsets of System Requirements (e.g. weight and not dimensions) are affected by Change Drivers / upstream System Requirements and/or when the impact on other Objects depends on those attributes. Hence, a further differentiation of domain elements may be considered but was not further pursuit in this work due to practical reasons.

new capability as highlighted in Figure 4-3. Those System Requirements can be differentiated further: In line with the system theoretical considerations of section 2.5.2, system internal dependencies exist that can be separated into spaces of different degrees of influence. According to DE WECK ET AL. [2011, pp. 97–101], the system can be divided into three different spaces as illustrated in Figure 5-4. Elements, i.e. System Requirements, within the boundary are part of the system; elements[195] outside of the boundary belong the environment or context.

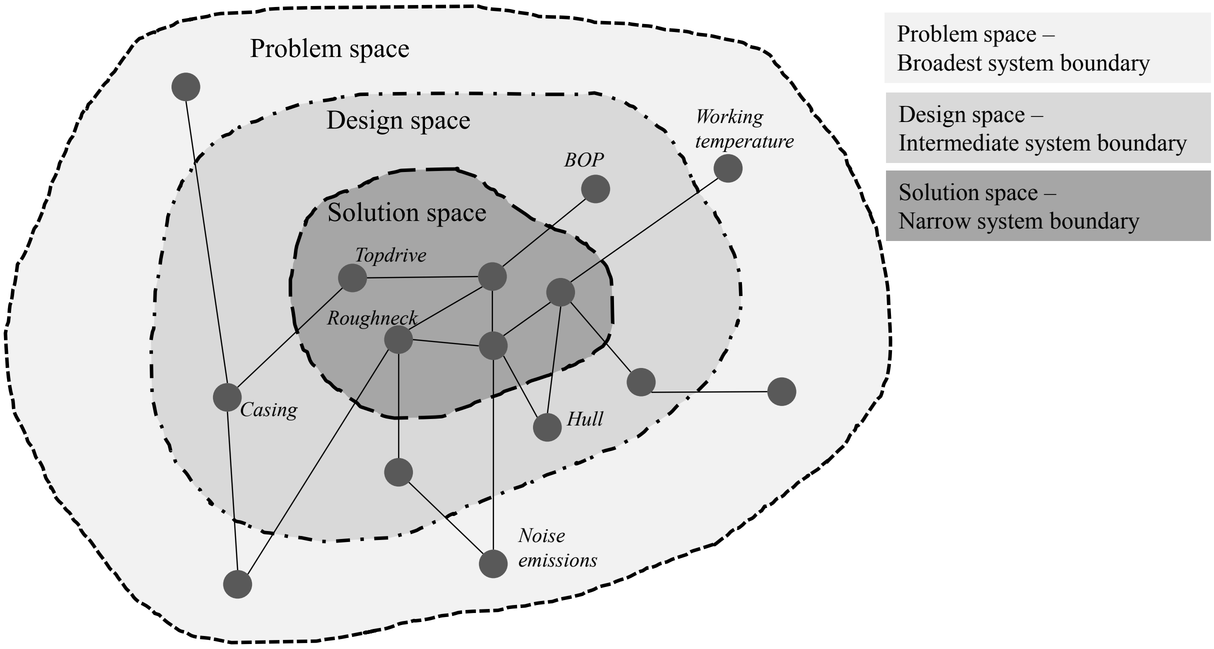


Figure 5-4 Definition of system boundary [adapted from de Weck et al. 2011]

In this application context, the different spaces represent the alternative origins of System Requirements. The solution space reflects the space that can be directly designed, changed, and implemented by the stakeholder(s) [DE WECK ET AL. 2011, p. 98], hence, that is under control of the System Supplier of concern. The design space includes also other elements that could be part of the solution, however, cannot be affected as they are not the scope of the concerned stakeholder[196] and usually involve other contributors to the system. The problem space, the broadest system boundary, includes all types of System Requirements, also those, that only affect the design space exogenously. Whereas changes of capability and conditions can be interpreted as requirement changes within the solution space (i.e. System Requirements that can be influenced by the System Supplier), exogenous influences on the solution space represent constraining System Requirements that define the lower and upper bound for the System Supplier. Similar to DE WECK ET AL. [2011, pp. 97–101], HERNÁNDEZ [2003, pp. 109–111]

---

[195] Note that elements of the context are not "Change Drivers" but System Requirements that require a relation to the system and cannot be affected by design (e.g. noise emissions).

[196] As noted in KOH ET AL. [2012], system boundaries may be porous when changes of elements within the system boundary have wider implications. This may require analysis to capture the wider implications of changes that go beyond those boundaries, i.e. accounting for system elements that are outside of solution space and in the design space.

refers to those system boundaries as influencing areas of manageable and non-manageable factors in a factory.

Figure 5-5 depicts the derived six different categories of System Requirements that could be differentiated based on the consolidated data. Besides accounting for the origin of System Requirements, the general characteristics of System Requirements allow further differentiation of capabilities and conditions that are subject to change within the design space (Figure 5-5, left). Capabilities address the ability to perform a function (Cap$_1$) or the existence of a feature (Cap$_2$). Conditions address the manner of how functions are fulfilled (Cond$_1$) or the parameters for features or functions within the allowable borders (Cond$_2$). Two different constraints can affect the solution space (Figure 5-5, right): On the one hand, elements of the design space can act upon elements of the solution space (Const$_1$). On the other hand, constraints can act externally from the problem space (Const$_2$).

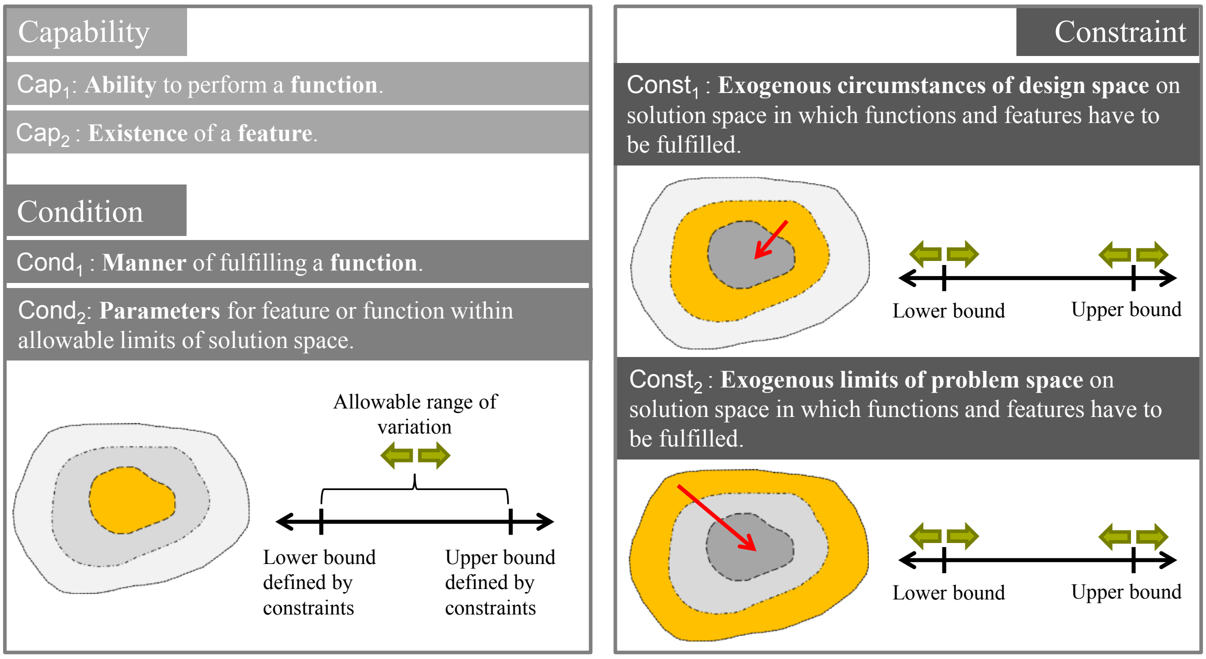


Figure 5-5 Categories of System Requirements

Figure 5-6 shows the number of relevant System Requirements assigned to those six categories. It indicates that Cap$_1$, i.e. adding[197] a new a functional capability, and Cond$_2$, changing parameters within the allowable range of variation, represent the most dominating System Requirements that could face change in the future. As for Change Drivers, those results only provide an indication as they are limited to the specific boundary conditions of the offshore drilling industry, the corporate context and the applied research methods.

---

[197] Although "removing" is also possible usually "adding" is meant.

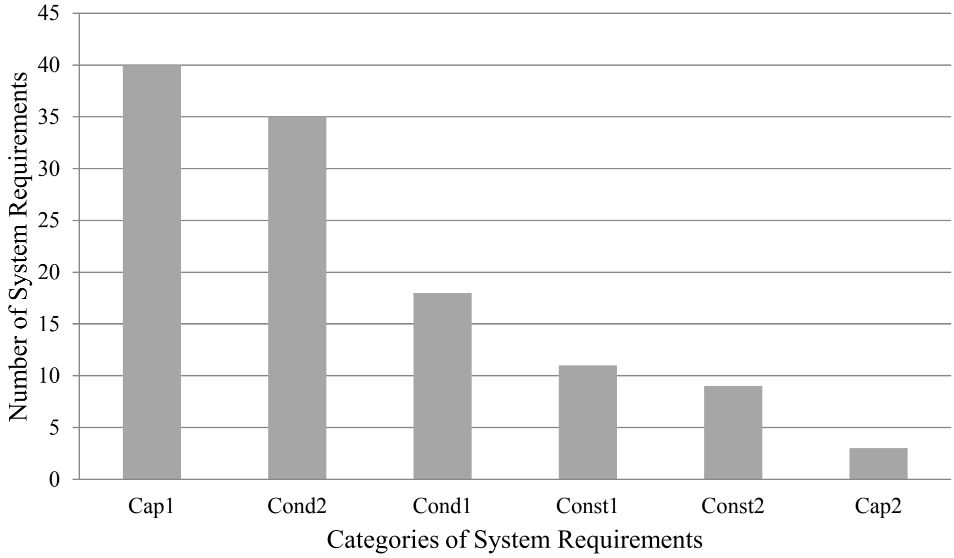


Figure 5-6 Number of System Requirements related to the six different categories

Despite the systematization of the System Requirements domain and transparent-making of the most dominating ones, this differentiation has also implications[198] on the execution of the FDO Methodology. One important implication relates to the possibility of "adding" an entirely new functional capability: When accounting for new functional capabilities (Cap_1) that were not considered when selecting the reference design (step 1 in FDO Procedural Model), an iteration (iteration "B" in FDO Procedural Model) to the reference designs might be required to either select another reference design with Objects containing that capability or by including "project neutral" Objects to the existing reference design as "Object placeholders" that can then be optionally "added" as "Change Objects" if needed[199].

The next section focuses on the Objects domain that is strongly related to the domain of System Requirements.

5.3.3 Object

The "Object" domain contains all possible Objects of the reference design that could be fed as Baseline Objects (step 2 in FDO Procedural Model). As highlighted in section 5.1 it is the central domain as it is both relevant with regards to the identification of Change Objects and the generation of Flexible Design Concepts by considering suitable Transitions and Change Enablers for those Change Objects. In line with the definition by BARTOLOMEI ET AL. [2012], the Object domain "represents the technical domain or the physical components of the system". Within the FDO Methodology Objects are defined as follows:

---

[198] Other implications and benefits from that categorization shall be subject to further research.

[199] The FDO Execution Model always requires a reference (Baseline Object) to change the design from. If there is no Baseline Objects available for the new capability, those Objects remain unconsidered and, hence, can never be "added" (Transition "3") to the system and prepared for. i.e. enabled with flexibility.

Objects are physical constituents of the drilling system that can be influenced by the System Supplier, i.e. belong to the solution space. If the Baseline Object in the Object domain does not fulfill the System Requirement, a Change Trigger occurs and the Object becomes a Change Object.

Although System Requirements could theoretically also affect software related constituents in the Object domain, which, in turn, could be enabled, in this application context the focus lies solely upon identifying and enabling physical Objects that are within the scope of the System Supplier and are considered to have the largest potential to avoid value losses across the lifecycle as highlighted in section 1.2.3.

As pointed out by HERNÁNDEZ [2003, pp. 65–66] defining the search space of Objects is important for the identification of Change Objects as it ensures a comprehensive identification of system constituents at different levels of detail. As CLARKSON ET AL. [2004] indicate, generating a product model requires a careful balance between the level of detail and the subsequent cost of populating the model. Hence, this also strongly applies to the build-up of the FDO Data Model.

As emphasized in section 2.5.2 and with regards to system theoretical considerations, the system can be decomposed into subsystems at different levels of abstraction with a "is part of relationship" implying a nested hierarchy. Based on SCHLATHER [2015, pp. 48–53] the search space can be defined according to this hierarchy of the system where the relevant Objects are assigned to different hierarchical levels (Figure 5-7). This hierarchy includes the underlying systems for the constituents of the Objects domain, the potential Change Objects of concern and also "Enabler Reference Objects" which belong to the domain of "Change Enablers" being introduced in section 5.3.4.

On system level the drilling system constitutes the solution space of the System Supplier. It belongs to the overall system, the superordinate drilling rig, and can be broken down into various subsystems. As section 2.5.2 already highlighted more generally, the drilling system can mainly be differentiated into "drilling equipment" that represent products contributing to the drilling process (e.g. drilling machines, cranes, chutes, cabins, etc.) and bulk items with a passive function which mainly include:

- Structure: load-carrying structure (e.g. drillfloor structure, moonpool structure) and hull rooms that that are part of the hull structure (e.g. equipment rooms)
- Flowing systems: flowing systems refer to all pipes, tubes and ducting elements that are part of the drilling system and conduct hydraulic and pneumatic media (e.g. hydraulic piping, HVAC ducting)
- Electrical cabling: electrical cabling refers to all cables conducting electrical power and information (power cables, data communication cables)

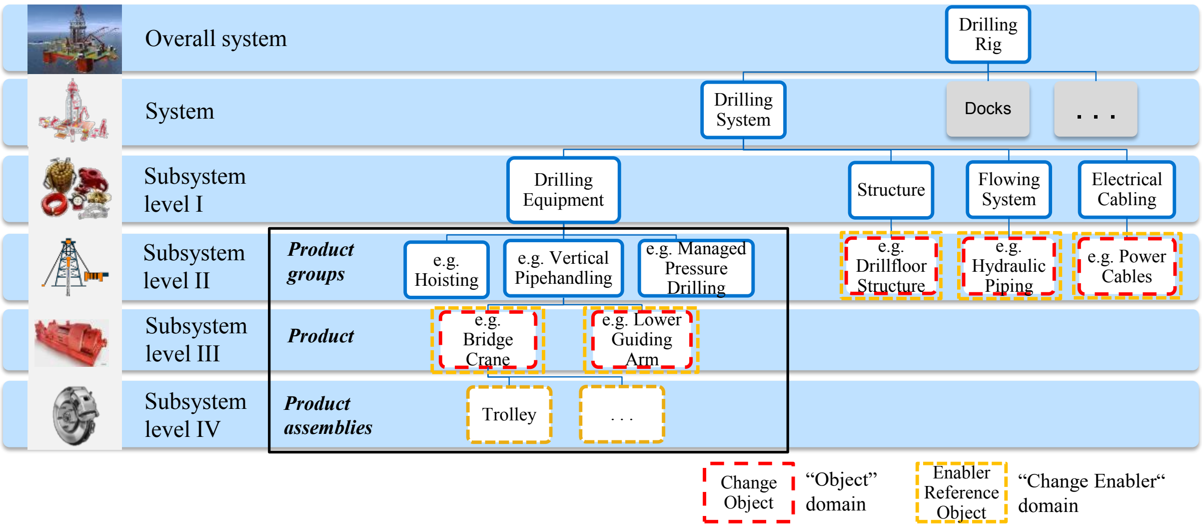


Figure 5-7 Hierarchy of drilling system for identification of FDOs

Drilling equipment can be further differentiated in product groups that contribute to a drilling process by fulfilling a specific superordinate function (e.g. vertical pipehandling, hoisting, rotating) or can be assigned to a characteristic location of operation (e.g. drillfloor). The level below represents the product level[200] where the constituents of the Objects domain are represented in addition to the bulk items on subsystem level II. The scope of those Objects may differ (e.g. Roughneck vs. Drillstring Compensator) as core functionalities may be fulfilled by single equipment only or by a larger set of interacting decentralized equipment which only conjointly form a "product".

Within the FDO Methodology they may be imported various times[201] to differentiate multiple Objects that belong to the same product family (e.g. Roughneck product family) and are represented multiple times on the rig (e.g. Roughneck #1, #2, …). Product assemblies are assigned to the lowest hierarchical level consisting of product subsystems which are only relevant for Enabler Reference Objects discussed in section 5.3.4. They include also architectural elements that are part of the drilling system but not part of the load-carrying structure such as doors, windows, etc.

Bulk items can be sufficiently described on "subsystem level II". In contrast to "drilling equipment", "bulk items" usually represent Objects that are either affected directly and

---

[200] Note that, on the one hand, "product" refers to the type of Objects as defined in section 2.5.2 that are embodied by "drilling equipment" in this application context. On the other hand, "product" refers to a specific hierarchical level of "drilling equipment" as illustrated in Figure 5-7.

[201] Note that in the following, especially in the use case of section 8.1, each product is fed only once without differentiating different instances of that product further.

globally[202] (M_D) but mostly indirectly as a result of "drilling equipment" changes (M_E). Hence, bulk items are not defined and fed uniquely as Baseline Objects for products (e.g. "Roughneck Hydraulic Piping") but usually remain unspecific (e.g. "Hydraulic Piping") with a traceable affiliation due to their relation to Objects in the FDO Data Model in case of change propagation (M_E). In contrast to drilling equipment, bulk items are also not filtered according to their criticality (Upgrade Risk Portfolio) as they are usually affected in case of drilling equipment changes and, therefore, mostly indirectly making a prior anticipation of "upgrade risk" difficult. However, as bulk items remain unspecific, the number of imported bulk items is very limited and, hence, the need for a reduction of those Baseline Objects is also low.

The next section discusses the Change Enablers domain by using the definition of Enabler Reference Objects of this section.

5.3.4 Change Enabler

Based on the identified Change Objects, suitable Transitions shall be facilitated. The Change Enabler domain represents the main domain in stage II of the Procedural Model to generate Flexible Design Concepts. In this application context Change Enablers only relate to the product view (section 3.3.2) and are defined as follows:

Change Enablers are inherent features or properties embedded in physical Enabler Reference Objects to facilitate Transitions of physical Change Objects in a time and cost efficient manner after the system has been fielded, i.e. is in operation[203].

As highlighted in section 5.3.3, the Object domain considers physical constituents only. Change Enablers facilitate those physical Objects and are also embedded in physical Enabler Reference Objects which are discussed in detail in this section. Hence, software related solutions to ease future changes are not addressed in this domain. By easing the Transition between two states of the product or system, both the time spent and the costs of making those changes should be reduced for systems which are already in use.

In order to avoid ambiguousness while easing application, SCHLATHER [2015, p. 62] defines a syntax for Change Enablers as follows:

<Design guideline ID><Design guideline><Enabler Reference Object>

Those constituents have the following meaning[204]:

- A "design guideline" is a formal prescriptive description of what to do with the Enabler Reference Object. For clarity and systematization of design guidelines, each design guideline is assigned to a superior category of Change Enabler principles and defined by a clear

---

[202] In case of deviations, a further specification of bulk items might be required (e.g. "drillfloor" hydraulic piping).

[203] Basing upon the definition of flexibility by SALEH ET AL. [2003].

[204] Note that examples with that syntax can be found in Table 5-5 as the individual constituents require a thorough derivation first.

number which together form a unique design guideline ID[205] (e.g. "MOB_1" for a specific mobility-related design guideline).

- An "Enabler Reference Object" which defines the location of where the design guidelines are embedded as it oftentimes does not correspond to the Change Object that is to be facilitated. So far this differentiation has not been made, also not for the "transformation building blocks" defined by HERNÁNDEZ [2003, p. 56] introduced in section 3.3.2. However, based on the elicited data it is considered necessary to ensure a proper application of the defined design guidelines.

As demonstrated in section 3.3.2, Change Enablers can be defined on different levels of abstraction, divided into the general Change Enabler principles and the more specific design guidelines to ease the identification of FDOs. As emphasized by VAN WIE [2002, p. 67] and in section 3.3.2, the level of abstraction is a compromise leading to either an ease of application (low level of abstraction) or generalization independent from the context of application (high level of abstraction). Thus, based on the case-based interviews described in section 5.2, although a mostly context-independent applicability of design guidelines was pursued, their level of abstraction still varies depending on the danger of possible misunderstandings but also based on the level of concretization in the original data. Hence, whereas in some cases very specific design guidelines were synthetized, in other cases more general ones were generated that leave their users more degrees of freedom. As in some cases the more general design guidelines also contain the more specific ones, redundancies exist that, however, are dealt with by excluding redundant Change Enabler alternatives (section 7.5).

Literature-based design guidelines (section 3.3.2) only provided a basis of reference and comparison. SCHLATHER [2015, pp. 135–136] could illustrate an overlap of those design guidelines and the ones from literature, especially the ones with a rather high level of abstraction.

Based on the defined Change Enabler principles from literature (section 3.3.2), the design guidelines could be attributed clearly[206] to the following six Change Enabler principles: universality, modularity, mobility, scalability, compatibility and connectivity. The principles base especially on the five principle categories by WIENDAHL ET AL. [2007] and ELMARAGHY & WIENDAHL [2009] for a Transformable Factory (TRF) as shown in section 3.3.2. However, SCHLATHER [2015, p. 42] adds the principle "connectivity" for stronger dissociation from the principle "compatibility" and "modularity".

Based on SCHLATHER [2015, pp. 41–44] and section 3.3.2, the categories are defined as follows with respect to the FDO Methodology:

---

[205] The FDO Data Model and the FDO Execution Model only show the compressed form of the ID which can be looked up to identify the description of the associated design guideline.

[206] Other attempts of systematization (e.g. according to functionality such as "handling" (devices), goals such as weight reduction or specific subprinciples such as standardization / over-sizing) could not be defined for the whole set of design guidelines accordingly.

- Universality (UNI): “Universality” represents the characteristic of Objects to be dimensioned and designed to meet diverse tasks, demands, purposes and functions; to guarantee the independence of function and use, universality stipulates an over-dimensioning of Objects [ElMaraghy & Wiendahl 2009]. Strongly associated with “robustness”, it characterizes the system’s ability to be insensitive towards changing environments and deliver its intended functionality even under varying operating conditions without requiring physical changes from external [Fricke & Schulz 2005]. For instance, “universality” is embodied by over-dimensioning carrying structures or the pre-installation of parts (e.g. fundaments), supply pipes or prepared boreholes for attachment.
- Scalability (SCA): “Scalability” provides technical, spatial and personal extensibility [Wiendahl et al. 2007]. It serves to easily modify production capacity by adding or subtracting manufacturing resources (e.g. machines) and/or changing components of the system [Koren & Shpitalni 2011]. It is strongly related to universality as scalable Objects often need related system constituents to be universal to allow an expansion or reduction (e.g. sufficient deck space required for extension of crane system on deck).
- Modularity (MOD): “Modularity” relates to the compartmentalization of operational functions into units [Koren & Shpitalni 2011]. It fosters the ability to easily exchange uniform, autonomous, functional units or elements on different system levels [Nyhuis et al. 2008, p. 27]. As modules are autonomously acting units and elements, exchanges only have a partial impact on Change Objects and the surrounding [Hernández 2003, p. 55]. Standardized interfaces are often seen as part of modularity (e.g. ElMaraghy & Wiendahl [2009]), however, here are considered as prerequisites of modularity and covered separately by the Change Enabler “compatibility”.
- Mobility (MOB): “Mobility” describes the ability to change the location of Objects with least effort, which besides the possibility of motion, also includes the aspect of execution and applicability [Hartung et al. 2012]. It goes beyond the division of immobile and mobile items and covers all production and auxiliary facilities including buildings and building elements [Wiendahl et al. 2007]. In this application context, “mobility” covers both direct mobility by enabling Objects (e.g. through lifting lugs) but also indirect ones such as by easing the mobility of personnel through e.g. access baskets or manrider winches.
- Connectivity (CON): “Connectivity” refers to the type of (physical) connections within and across Change Objects. By identifying suitable force-, positive- and material-locking connections, the integration and disintegration of Objects is to be eased. It is separated from the Change Enabler principles “compatibility” and “modularity”.
- Compatibility (COM): “Compatibility” is to allow various interactions between Objects [Wiendahl et al. 2007]. Here the primary focus lies on the standardization of interfaces with the ability of interfaces to fit regarding material, information, power and media [Nyhuis et al. 2008, p. 27]. In this particular context, this is reflected in the standardization of e.g. ports, plugs or footprints towards certain drilling equipment.

As highlighted by SCHLATHER [2015, pp. 42–43] those six Change Enabler principles, especially the separation between modularity, connectivity and compatibility, allows a better differentiation amongst design guidelines during application while supporting the identification and development of Object classes (section 7.2.1).

On a more detailed level of abstraction, design guidelines represent the other main aspect of the Change Enabler's syntax. Similar to BISCHOF [2010, p. 92] and introduced in section 3.3.2, Change Enabler guidelines are described by a short verbal explanation:

<Action><Subject><Purpose (optional)>

Whereas the action relates to what is to be done with the Enabler Reference Object (e.g. "provide"), the subject refers to the aspect of enablement (e.g. space around object). The purpose provides an additional information what the Change Enabler is meant for. The purpose is added in some cases to avoid ambiguity and/or add precision. For instance, the extent of "providing space around object" differs significantly depending on if it is meant for "accessibility" or "spatial expansion". This ensures a better interpretation of those heuristics, that, as being applied with judgment [MAIER & RECHTIN 2009, p. 30], are more apt to be applied properly than without such an additional information.

To avoid further ambiguity, and shown exemplarily in Table 5-4 for the scalability-related design guideline "SCA_16: Assign dedicated areas on room ceiling for evolutionary development of piping, cabling and ducting", each guideline is integrated into a checklist categorized[207] according to the applicable Change Enabler principles. Based on common practice and the benefits of supplementary guideline information presented in section 3.3.2, the design constitutes of the design guideline ID, the presented short verbal explanation and an additional more detailed description.

Table 5-4 Checklist of design guidelines based on example "SCA_16"

SCA_16	**Assign dedicated areas on room ceiling for evolutionary development of piping, cabling and ducting**	The aim is to constrain changes over the lifetime to dedicated areas on the ceiling of the room that do not affect its surrounding as there are spatially separated from other Objects. This applies especially to bulk items such as piping, cabling, ducting that strongly develop across the lifecycle and due to that spatial separation would not affect other Objects.

The complete list with the identified 88 design guidelines[208] that bases solely on the consolidated data from the semi-structured interviews can be found in appendix 11.6. As demonstrated

---

[207] Design guidelines may sometimes be assigned to alternative Change Enabler principles. In this work, however, the assignment of design guidelines always follows the categorization made and described by SCHLATHER [2015, p. 58] that already allocated them to the most intuitive Change Enabler principles.

[208] To ensure consistency and clarity, the IDs, design guidelines and their descriptions are partially adapted from the originally synthesized design guidelines provided by SCHLATHER [2015]. Explanatory pictures are not provided as the modified descriptions should already ensure an unambiguous interpretation.

in SCHLATHER [2015, pp. 135–136], they have partially significant commonalities[209] with the design guidelines defined by other authors introduced in section 3.3.2.

The Enabler Reference Object, the other constituent of the Change Enabler syntax, can take various forms [SCHLATHER 2015, pp. 62–65]. Seven types of Enabler Reference Objects could be identified resulting from a compromise between a sufficiently precise description to avoid ambiguity while limiting the number of Enabler Reference Objects to an applicable set during application. They are illustrated in Table 5-5 together with additional explanations and examples[210].

Table 5-5 Alternative types of Enabler Reference Objects for Change Enabler definition

#	Ref. Object	Case	Example	Explanation
1	**Change Object**	The design measure needs to be embedded into the Change Object.	Roughneck | MOB_ 1: Equip with lifting lugs / pad-eyes for Object handling; ***Change Object***	The Change Object "Roughneck" is to be equipped with bolted or welded lifting lugs to ease its lifting or repositioning (e.g. entire replacement of Roughneck).
2	**Specific module of the Change Object**	The design measure needs to be embedded into a specific module of the Change Object.	Roughneck | MOB_ 1: Equip with lifting lugs / pad-eyes for Object handling; ***Change Object (Motor)***	The motor of the Change Object "Roughneck" is to be equipped with bolted or welded lifting lugs to ease its lifting or repositioning (e.g. partial replacement of Roughneck).
3	**Several modules of the Change Object**	The design measure can be embedded into several modules of the Change Object.	Operator chair | CON_6: Design quick connectors for Object modules; ***Change Object (Modules)***	Upgrading the Change Object "Operator Chair" (e.g. partial replacement) is facilitated by quick connectors on certain Operator Chair modules (e.g. joystick, screens, armrests).
4	**A specific other Object**	The design measure needs to be embedded into another specific Object.	Electrical Cabling | MOD_ 10: Decentralize supplying Objects in system; ***LIR***	Upgrading the Change Object "Electrical Cabling" (e.g. partial replacement) is facilitated by a "decentralization" of the specific supplying Object "Local Instrument Room" (referred to as "LIR") especially as cable segments become shorter.
5	**Objects interfacing the Change Object**	The design measure is not directly related to the Change Object but to the Objects "interfacing" the Change Object.	Hydraulic Piping | MOD_12: Reduce distance between connected Objects; ***Object***	Reducing the distance of connected Objects facilitates upgrading the Change Object "Hydraulic Piping" due to shorter pipe segments. It is related to the Objects connected by Hydraulic Piping (e.g. Hydraulic Power Unit (HPU) and Roughneck). They are simply referred to as "Object" and can be derived from the system architecture of the reference design.
6	**The room the Change Object is located in**	The design measure needs to be embedded into the (hull) room where the Object is located.	Shale Shaker | MOB_10: Provide pre-installed lifting gear on top of ceiling; ***Room***	Upgrading the Change Object "Shale Shaker" (e.g. entire replacement) is facilitated by auxiliary lifting equipment (pulleys) that are mounted on the ceiling of the (Shale Shaker) Room. A further differentiation of "Room" is not required as it can be derived from the system architecture of the reference design.
7	**The structure that directly supports the Change Object**	The design measure needs to be embedded into the structure that directly supports the Change Object.	BOP Crane | UNI_2: Oversize with regard to stress / load cases; ***Structure***	Upgrades on the Change Object "BOP Crane" (e.g. extension) are facilitated by over-sizing the "Structure" (e.g. changing wall thickness or material) supporting the BOP Crane. A further differentiation of "Structure" is not required as it can be derived from the system architecture of the reference design.

Whereas the Enabler Reference Object types 1-3 refer to the Change Objects or modules of it, Enabler Reference Object types 4-7 refer to other Objects. Enabler Reference Object types 6 and 7 represent exceptions referring to specific structure items, i.e. embedded hull rooms and support structures, that are repetitively used and whose affiliation can be derived from the

---

[209] Although possible, the extension to new and other literature-based design guidelines was not the focus.

[210] Note that in the example an additional "Change Object" is included at the beginning separated from the Change Enabler syntax by "|" to ensure better understanding. In the FDO Methodology (FDO Data Model, FDO Execution Model) this affiliation is evident from the element relations in matrix M_F.

affected Change Object and the system architecture of the selected reference design. Identically, the affiliation can be determined for Enabler Reference Object type 5.

As discussed in section 5.3.3. the search space embodied by the hierarchy of the drilling system for the identification of FDOs (Figure 5-7) does not only define hierarchies for potential Change Objects but also those of Enabler Reference Objects. Change Objects for Enabler Reference Objects 1, 4, 5, 6 and 7 can be identified on subsystem level III for equipment and subsystem level II for bulk items. In contrast to Change Objects, Enabler Reference Objects (type 2 and 3) may have to be specified for module(s) of Objects (subsystem level IV) to provide sufficient accuracy for correct application.

The collected Change Enablers, in particular the design guidelines, can be differentiated across different groups[211] according to the elicitation and processing activities described in section 5.2: Change Enablers that were already accounted for in the mini-case project (1), i.e. already part of the upgrade project, Change Enablers that were recommended but not embedded and, hence, could not be activated for the upgrade project under investigation (2) and those that were required for other Change Enablers as a prerequisite[212] (3). Next to that as a result of the subsequent verification, new Change Enablers were added or removed when verifying the consolidated data (4).

As indicated by SCHLATHER [2015, p. 98] recommended Change Enablers that were not yet embedded and of a high value-effort ratio (section 7.4) strongly encourage engineers to integrate them in future projects to ease changes. However, as in many cases those Change Enablers represent entirely new solutions of Objects (e.g. modular design of Object), they must often[213] face prior product development to be offered in the first place. Especially latter must then also be evaluated for their maturity during stage III of the FDO Methodology (section 4.2).

The next section elaborates on the domain of "Transitions" that is strongly interrelated to the domain of Change Enablers.

5.3.5 Transition

Transitions are represented in the last domain of the FDO Data Model. The Transition domain represents the second main domain in stage II of the Procedural Model to generate Flexible Design Concepts. In this application context Transitions only relate to the product view (section 3.3.1) and are defined as follows:

Transitions are externally imposed change strategies for physical Change Objects to make them re-fulfill any violated System Requirements.

---

[211] Any statistical distributions are not shown especially due to reasons of confidentiality and as they do not affect the outcome of the FDO Methodology.

[212] Covered by matrix M_G in FDO Data Model.

[213] Not all Change Enablers require separate product development efforts in order to be embedded (e.g. space around Object).

As introduced in section 3.3.1, Transitions represent an intended change of a system to an altered state as defined by ROSS ET AL. [2008]. In line with HERNÁNDEZ [2003, pp. 44–45] and WIENDAHL ET AL. [2015, pp. 99–100], those changes refer mainly to the radical change type of "transformation" rather than "structural coupling"[214]. Once System Requirements are not fulfilled due to external changes (Change Drivers) resulting in a Change Trigger (Figure 4-3), the Transition re-establishes the desired status-quo by use of an external change agent[215] [ROSS ET AL. 2008]. As highlighted by BALDWIN & CLARK [2000, p. 146], the nature and number of (Transition) operators to a system depends on the use context. Hence, although the literature-based Transitions of section 3.3.1 are used complementary to the empirical data, the case-based interviews are the primary source to derive Transitions that are relevant for this context of application.

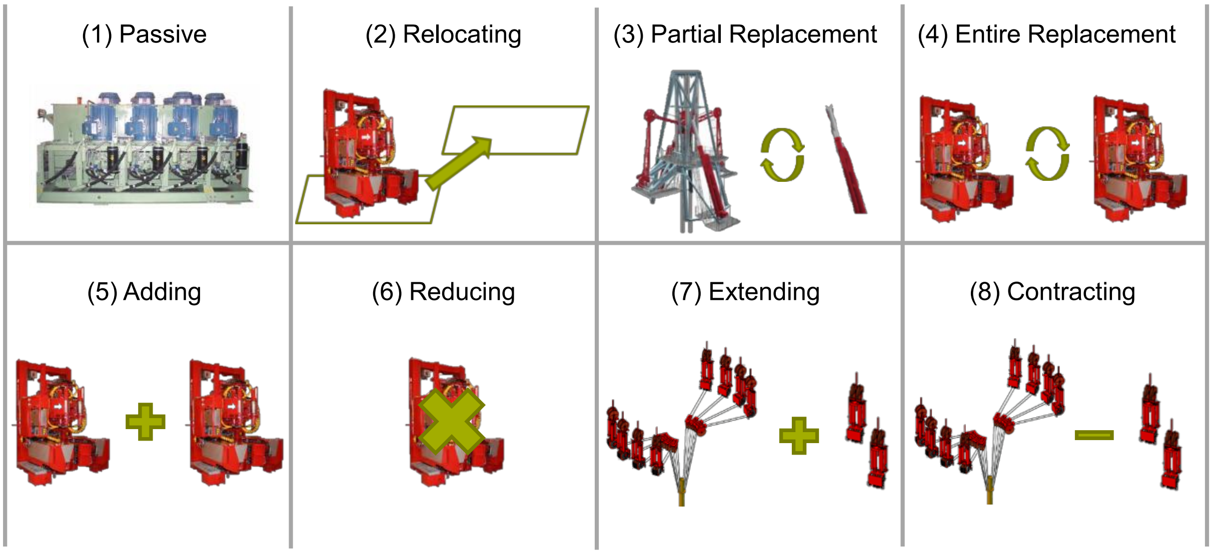
As demonstrated in section 3.3.2, Transitions can be defined at different levels of abstraction being very general (e.g. embodied by operators) or uniquely defined for a single case. The integration of Transitions into the FDO Execution Model favors a high-level definition of Transitions, namely operators, which are based on the context of application but allow reuse for those types of systems for identical purposes, namely the identification of FDOs. Based on the case-based semi-structured interviews (section 5.2), the following eight distinct operators could be identified (Figure 5-8). They are in line with the criteria for selecting "module operators" by BALDWIN & CLARK [2000, p. 130] introduced in section 3.3.1 as being "simple", "parsimonious", "complete", "faithful to underlying structure" and "verifiable by direct observation". This set of operators includes the "smallest number of elements and rules possible, but the total must be capable of explaining all cases that arise in the relevant domain" [BALDWIN & CLARK 2000, p. 130]. However, in contrast to module operators, those Transitions are not meant to be combinatory[216] (e.g. "substitution" only possible after "splitting") but regarded as standalone operators. They always refer to the hierarchical level of the Change Object under investigation, which is subsystem level III for drilling equipment and subsystem level II for bulk items (section 5.3.3).

---

[214] New structural coupling would only be applicable to the Transition "Relocating".

[215] External change agents represent flexibility-type changes according to ROSS ET AL. [2008] and FRICKE & SCHULZ [2005]. Here, they represent physical changes performed by humans assisted by machinery.

[216] Although theoretically, combinations of Transitions may exist (e.g. "Relocating" combined with "Partial Replacement"), the consideration of those "compound options" (section 3.3.1) is not pursuit further as there was no case demonstrating that need. Nevertheless, compound options could be handled by splitting Objects into instances with unique Transitions as shown in section 6.1. In contrast to the illustrated split-up, however, the Transitions would not represent alternative but always complementary Transitions when an upgrade occurs (e.g. not "Relocating" vs. "Partial Replacement" but "Relocating" & "Partial Replacement). Hence, they would also not belong to competing but complementary Flexible Design Concepts that, in the end, are integrated to the same Flexible Design Solution.



(1) Passive
(2) Relocating
(3) Partial Replacement
(4) Entire Replacement
(5) Adding
(6) Reducing
(7) Extending
(8) Contracting

Figure 5-8 Available Transitions for Change Objects [Schlather 2015, p. 60] shown exemplarily for drilling equipment (Images: MHWirth AS)

In contrast to the Transitions 2-8 which require changes performed by external agents, Transition 1 does not require any actions in response to changing System Requirements as it is meant to deliver its intended functionality under varying conditions of operation [Fricke & Schulz 2005]. This can mean, for instance, an over-dimensioning of hydraulic or electric power capacity, the over-dimensioning of deck sizes or excessive load capacities of structures preventing a Transition requiring external agents in the first place. This robustness, however, comes at a certain “cost” (e.g. higher investment, additional maintenance and costs, weight, etc.) allowing only an “adequate” performance [de Weck 2008] as highlighted in section 2.4.4. Nevertheless, robustness must be considered integrated with the other flexibility-related Transitions due to:

- The intention of comprehensiveness (BR II) which includes the consideration of rigid, robust or flexible solutions to avoid bias of selecting flexible solutions at less performance
- Limits in being able to change designs by either the nature of the Object (e.g. load carrying structures) or by being outside of the System Supplier’s solution space
- Strong interdependency of purely flexible and robust Change Enablers where a lack of robustness might act as a showstopper for exercising embedded flexibility in the first place[217]

The relocation of Change Objects (Transition 2) refers to a change of its position and/or system configuration on the rig. Although drilling systems mostly keep their initial configuration across their lifecycle, sometimes configuration changes might occur that are usually limited to single Objects[218].

---

[217] Proven by the existence of universality-related Prerequisite Change Enablers in M_G of the FDO Data Model.

[218] Due to the compact and constrained design of offshore drilling rigs (section 2.1), large-scale reconfigurations such as in production engineering are hardly possible and could not be confirmed within the scope of this research.

Replacements (Transition 3 and 4) may refer to certain larger subassemblies[219] such as a motor or gearbox (Partial Replacement) or to the entire Object (Entire Replacement). “Entire Replacements” of Change Objects may also be necessary when adding functionality or capacity. In contrast, major changes in subassemblies, e.g. due to modified functionality or capacity, are not considered to be a “Partial Replacement”. This operation is covered by an extension (Transition 7) or contraction of the Change Object (Transition 8).

In some cases, Objects are added to (Transition 5) or removed from the drilling system (Transition 6). “Adding” may also mean the inclusion of entirely new Objects that were not present on the rig before, usually when entirely new capabilities are added (e.g. Managed Pressure Drilling). Hence, whereas “Adding” is mostly a response to missing functionality, capacity or the need to increase performance, “Reducing” may be required due to excessive utility consumption, maintenance efforts, weight, etc. of idle or overdimensioned Objects[220].

“Extending” reflects the “partial adding” of subassemblies to the Object to meet functional or capacity related System Requirements (e.g. additional cross-bracings to Derrick structure, stronger and larger Derrick Drilling Machine motor). “Contracting” goes into the opposite direction mainly for the same reasons as “Reducing” but on a subsystem level.

As the scope of Objects, especially equipment-like ones, varies (section 5.3.3), Objects of smaller scope (e.g. consisting of only single machine such as a “Roughneck”) might be related to “Adding” or “Reducing” vs. Objects of larger decentralized scope that are usually “extended” or “contracted” by subassemblies (e.g. Drillstring Compensator that consists of various units).

The identified Transitions usually occur in response to epoch shifts (section 1.2.4) when various Objects are affected simultaneously, either directly or by change propagation. Depending on the transition path [ROSS ET AL. 2008] which depends on the preferences and circumstances, including the available resources, the selected Transitions for each Change Object might be synchronized or performed independently from each other.

Based on the case-based interviews and the eight introduced Transitions, Figure 5-9 illustrates the number of Change Enablers facilitating Transitions [SCHLATHER 2015, p. 107]. It summarizes the occurrences of matrix M_I in descending order.

---

[219] The modernization of components is not the direct focus of upgrades and considered to be “overhaul” (section 2.3).

[220] Either embedded consciously as a means of robustness or unintentionally due to insufficient planning.

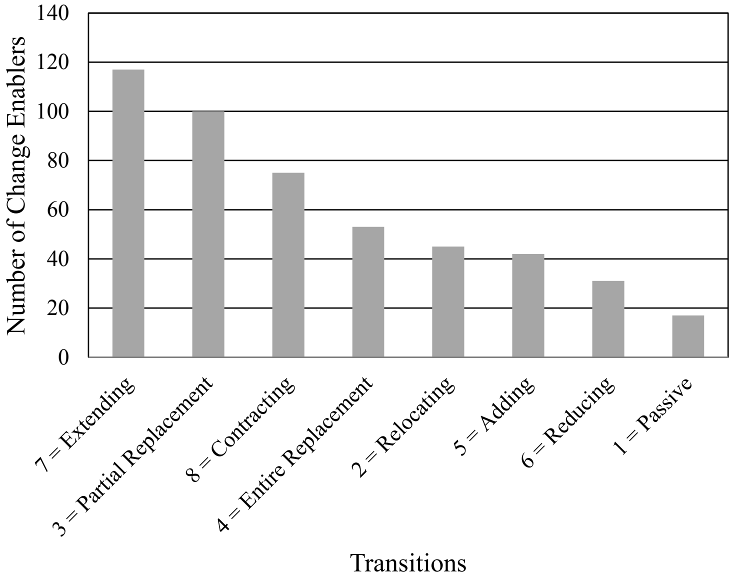


Figure 5-9 Number of Change Enablers facilitating Transitions (based on SCHLATHER *[2015, p. 107])*

It highlights that most Change Enablers do support the extension of Objects while the least Change Enablers facilitate the Transition “Passive”. Latter can be explained by the focus of interviews on flexibility-type Change Enablers and the fact that, in contrast to other Transitions, “Passive” usually refers some kind of over-dimensioning which limits the extent of possible Change Enablers. Hence, the distribution highlighted in Figure 5-9 can be both an indication for the nature of Transitions of which some are facilitated by many and some by only few means. However, they might also reflect gaps of supporting certain Transitions which might be closed by targeted initiatives in product development.

In the following the FDO Execution Model is presented.

6. FDO Execution Model

The FDO Execution Model bases upon the FDO Data Model and its constituents which have been introduced in the previous section and the FDO Procedural Model (section 4.2). Whereas the FDO Data Model represents the project-independent database, the FDO Execution Model represents the project-dependent application model of the FDO Methodology. It consists of only relevant FDO Baseline Objects for the project limiting the size of the FDO Execution Model.

Section 6.1 provides a general characterization of the FDO Execution Model where the main build-up is introduced. Section 6.2 displays the alternative and cumulative paths that can be run depending on the scope that is targeted. After highlighting the need, tracing and the systematic building of change scenarios is highlighted in section 6.3. Finally, section 6.4 shows how the assessment and decision-making is performed when running through the FDO Execution Model and, in addition, when entire Flexible Design Concepts are assessed and decided on which base upon a separate report based on the selections made.

6.1 Characterization of model

The FDO Execution Model consists of multiple representations of the defined FDO Data matrices[221] which were introduced in section 5.1. The sequence of those matrices presented in Figure 6-1 allows the systematic identification of FDOs following the three subsequent stages of the FDO Methodology: “Identification of Change Objects”, “Generation of Flexible Design Concepts” and, finally, based on a report of the FDO Execution Model the “Determination of Flexible Design Solutions & Integration”.

---

[221] The size of each matrix for this demonstration is random and may vary relatively to each other depending on the application context.

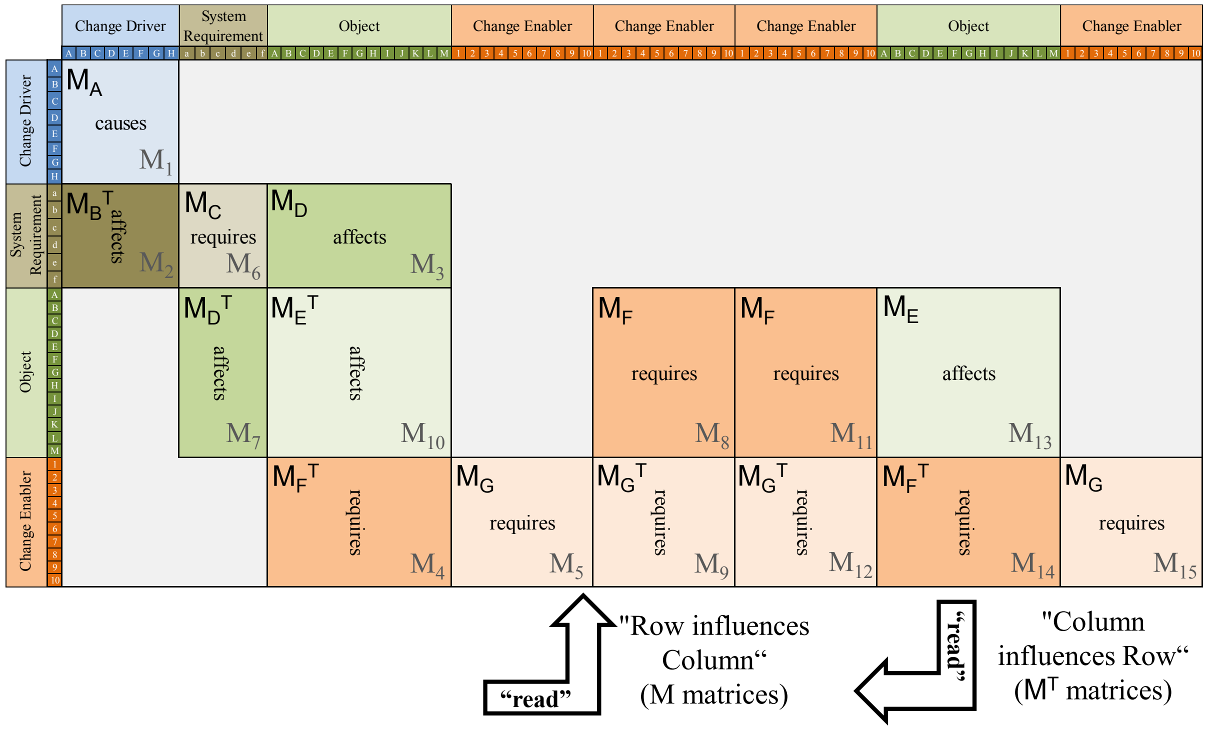


Figure 6-1 FDO Execution Model with original and transposed matrices

To allow a continuous and traceable approach for the identification of Change Objects and the generation of Flexible Design Concepts, the FDO Execution Model consists of originally oriented and transposed matrices that are run through in alternating directions. For instance, the basic path "Light" (section 6.2), consists of the alternately run through matrices M_1, M_2, M_3, M_4 and M_5 requiring a change of reading direction from matrix to matrix. Whereas originally oriented matrices are read as "Row influences Column", transposed matrices are read as "Column influences Row".

Matrices may be represented multiple times to account for the various possibilities of how the Objects can be affected and enabled while allowing an unambiguous representation of those results as a means for assessment. This is accounted for by the definition of singular matrix IDs that are required for clear referencing and tracking decisions in those matrices. For instance, the subordinate dependency type "System Requirement affects Objects" (M_D) is represented twice by the unique matrices M_3 and M_7. Those matrix IDs are defined according to the order of steps within and across each path.

M_H and M_I represent exceptions of the MDM-based meta-model which are not directly represented in the FDO Execution Model as matrices. They are added on top of certain represented matrices as additional selections[222] enabling the generation of Flexible Design Concepts (stage II). The generation of Flexible Design Concepts can be divided into the selections made in M_D/M_E and M_F respectively.

First, the selection in M_D/M_E is addressed. The selection with the "Transition-driven approach" is integrated by superposing M_H with matrices M_D or M_E which allows selecting only suitable

---

[222] In the Excel® based tool this is solved by drop-down menus.

Transitions for the identified Change Objects. Figure 6-2 shows the integration of allowable Transitions for the identified Change Object "C" where only Transition 1, 2, 4 and 6 can be selected.

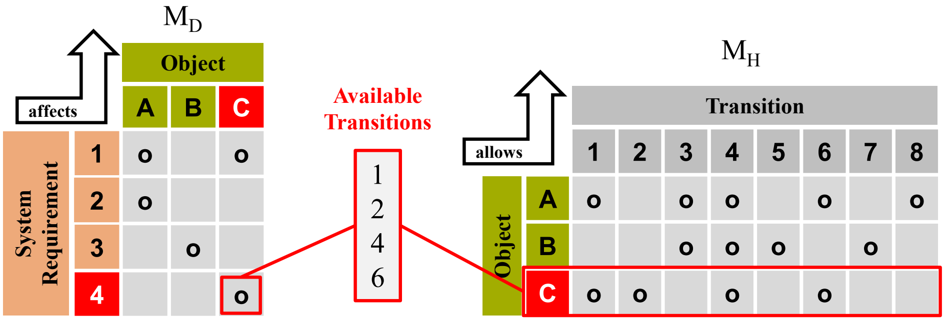


Figure 6-2 Exemplary superposition of matrix M_H on top of M_D

In the FDO Procedural Model the identification of Change Objects (step 4 in stage I) and suitable Transitions (step 5 in stage II) is represented separately. In contrast, the FDO Execution Model using a matrix-based approach performs it in a combined step, i.e. the selection of Change Objects is confirmed by the selection of the allowable Transition when performing the "Transition-driven approach". In this approach a potential influence might be regarded irrelevant being marked by symbol "!" which means that the Change Object is not pursued any further. If, in contrast, an "Enabler-driven approach" is selected, an "x" is selected for confirming the "Change Object" while postponing the decision-making on the suitable Transition to the next step when Change Enablers are considered. The same logic applies to matrix M_E which, however, is not represented separately in Figure 6-2.

In the second case matrices are superposed with M_F. In this case only those Transitions are represented that are both applicable to the Change Object (M_H) while, additionally, complying with the Change Enablers that are represented in M_I. Figure 6-3 depicts an example of the available Transitions for Object "C" when selecting Change Enablers "a" and "d". If Transitions have already been selected in M_D or M_E respectively when performing the Transition-driven approach, only rejections ("!") or confirmations with the selected Transition number are required. In this case Change Enablers that cannot be selected due to incompatible Transitions in M_I would not be shown in M_F. In contrast, when performing the Enabler-driven approach all available Transitions that comply with both M_H and M_I are shown as illustrated exemplarily in Figure 6-3. As a result, Change Object "C" could be facilitated with Change Enabler "a" allowing Transition 1, 2 and 4 and Change Enabler "d" allowing Transition 4 and 6.

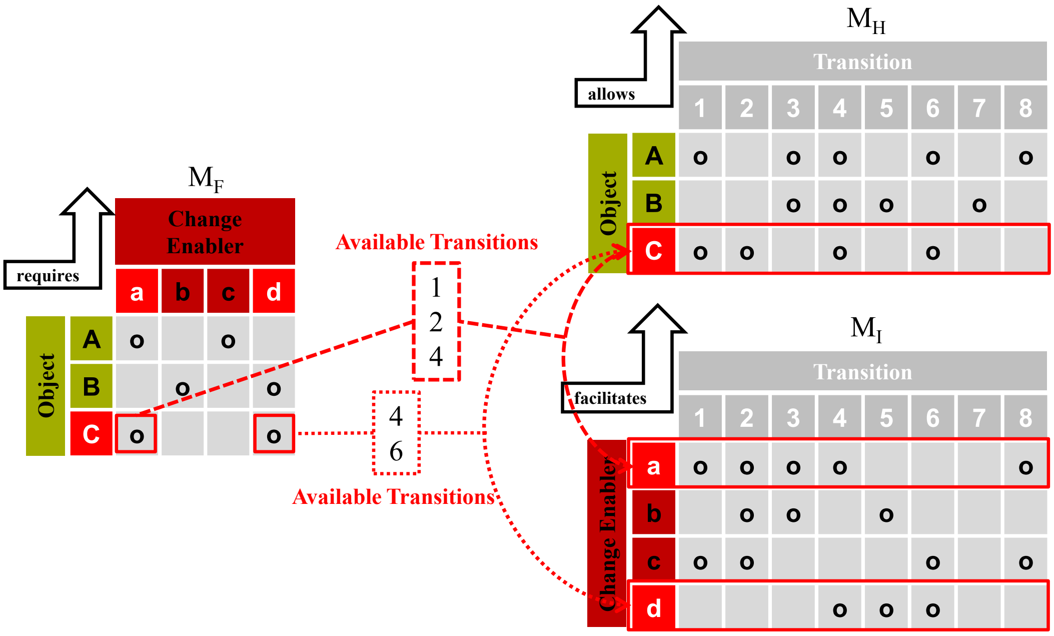


Figure 6-3 Superposition of matrix M_H and M_I for decision-making in M_F

In the FDO Execution Model the following selections are possible[223]:

- M_A: <o>, <x>
- M_B: <o>, <x>
- M_C: <o>, <x>
- M_D: <o>, $<!>_{12}$, $<x>_2$, $<\text{Transition \#}>_1$
- M_E: <o>, $<!>_{12}$, $<x>_2$, $<\text{Transition \#}>_1$
- M_F: <o>, $<!>_{12}$, $<\text{Transition \#}>_{12}$
- M_G: <o>, <!>, <x>

with

- <o> potential relation imported from the FDO Data Model
- <x> for confirming the relation
- <!> for rejecting the relation
- <Transition #> for confirming the relation with the according Transition
- $<\ldots>_1$ representing selections for the Transition-driven approach, $<\ldots>_2$ for the Enabler-driven approach and $<\ldots>_{12}$ for both

During the identification of change sources (M_A, M_B, M_C) only a small set of elements might actually be relevant; hence, in this case only relevant relations are confirmed while irrelevant ones are ignored, thus, the initial setting <o> can remain. In contrast, based on the identified directly and indirectly affected System Requirements, the identification of Change Objects and Change Enablers in M_D, M_E, M_F, M_G uses active rejection or confirmation of potential relations

---

[223] As already mentioned this is solved by drop-down menus in the Excel® based tool.

to make sure that both Change Objects and Change Enablers are all accounted for and documented. Selections in M_G must also be actively confirmed as they represent prerequisites for the selected Change Enablers in M_F and ignoring them could entail bad consequences when not being able to activate Change Enablers over the lifecycle.

As introduced in section 4.2.1, suitable Transitions must be clearly defined for each Change Object to consider their effects on other Objects (change propagation). Multiple System Requirements usually belong to a core scenario (section 6.3.2) that can affect the same Change Objects at different times[224]. Alternatively, multiple Change Objects may affect the same Objects through change propagation at different times. As preferences on Transitions may differ depending on the specific underlying reasons for change, certain measures must be in place to account for this matter[225]. For instance, both a change in the System Requirement "Tubular Handling Principles [Condition]" and "RGHD[226] Handling [Capability]" affect the Change Object "Riser Gantry Crane". However, it may be possible that the feasible Transition 1 (Passive) is preferred for one type of change reason, whereas Transition 4 (Entire Replacement) is preferred for the other one. Figure 6-4 depicts the alternatives to processing heterogeneous Transitions.

One alternative is making a compromise by homogenizing the Transitions, i.e. forcing the identical Transition upon the same Change Object. Alternatively, however, if such a compromise cannot be made, then the Change Object must be split into at least two instances to deal with it separately and result in a homogenous Transition for each Change Object instance (e.g. C_1, C_2 in Figure 6-4). Consequently, this also means that at least two separate Flexible Design Concepts for the Change Object are generated. For simplification, heterogeneous Transitions can be prevented in the first place by setting constraints between Transitions within and across matrices in advance (section 7.3) to avoid the need for a subsequent homogenization.

---

[224] Belonging to the same core scenario does not mean that both impacts occur simultaneously, hence, would require the same change.

[225] Those measures are only relevant if Change Objects are affected within the same matrix, i.e. a matrix with identical unique matrix IDs (e.g. M_3). If they are affected in a different matrix following a different path (e.g. M_7, M_{10}, M_{13}), then the Transition of the Change Object must not be the same across those matrices. In this case a homogenization or splitting the Object into instances would not be required.

[226] Riser Gas Handling Device.

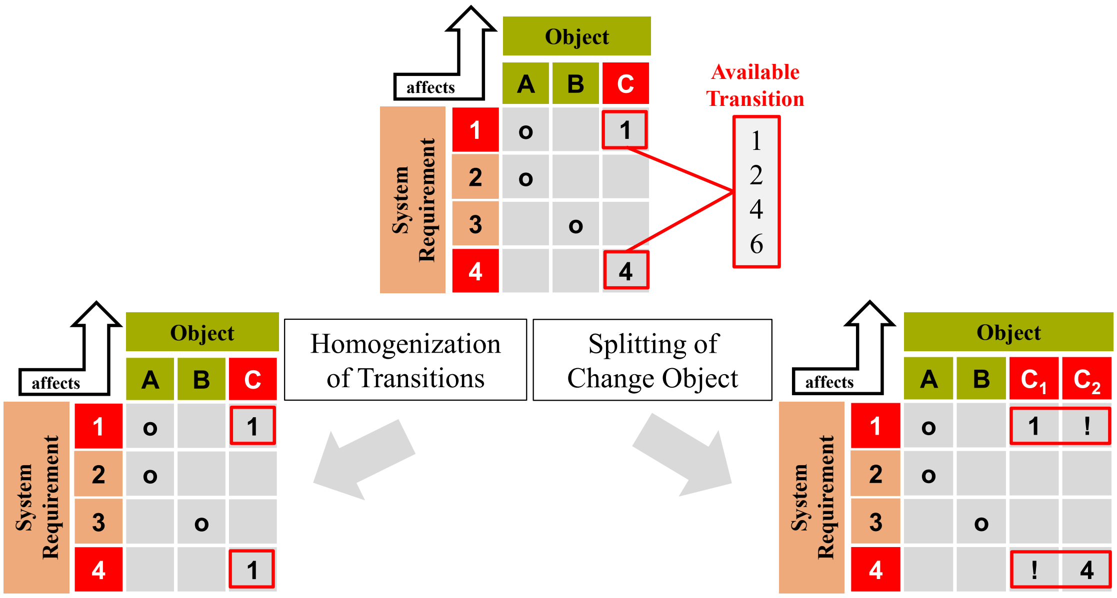


Figure 6-4 Alternatives to processing heterogeneous Transitions for same Change Objects (Example for M_D*)*

Although the processing of heterogeneous Transitions is illustrated for the Transition-driven approach where matrices M_D and M_E are affected, it is similarly applicable for the Enabler-driven approach[227] and can be performed in M_F. In latter case, however, heterogeneous Transitions across Objects do not exist because of accounting for the different change reasons, i.e. changing System Requirements and upstream Change Objects, but in order to generate alternative and best performing Change Enabler-Transition combinations for the Change Object. Hence, the decision on the Transition for the Change Object bases upon the performance of each Flexible Design Concept which requires an intermediate assessment (section 6.4.2). This, in turn, allows a homogenization of Transitions or a split-up of Change Objects which is the starting point for considering new Change Objects that are affected by change propagation (iteration "F" in FDO Procedural Model).

---

[227] Note that with the selection of the Enabler-driven approach, the user ignores the fact that the Object may require different Transitions due to different change reasons, i.e. changing System Requirements or upstream Change Objects. In this case Transitions of Change Objects are selected purely based on the performance of the Flexible Design Concept independently of which reasons for change actually apply. Hence, Flexible Design Concepts may be best with regards to the consideration of the Change Object-Change Enabler-Transition combination but not ideal if the reasons for change imply that another Transition would be more suitable. If different Transitions due to different change reasons are important to the user, then the Transition-driven approach must be chosen and a split-up of Change Objects into instances must already be performed in M_D/M_E. Depending on the number of generated Change Object instances and, consequently, the accounted for Transitions for the Change Object, this allows the identification of best performing Flexible Design Concepts while accounting for the reasons for change. Naturally, now Transitions that were irrelevant with regards to the change reasons, i.e. were not selected in M_D or M_E, respectively, are also not selectable in M_F and, therefore, do not contribute to the Flexible Design Concept.

6.2 Paths and scaling

The FDO Execution Model is scalable enabling to follow four cumulative paths when identifying FDOs. The scope of paths mostly depends on the individual market conditions that usually vary (BC5 – BC8) highlighted in section 1.3.2 and embodied by BR VI, the "Flexible application of the FDO Methodology". The paths build upon the prioritization scheme illustrated in Figure 6-5 and are discussed schematically before illustrating the actual application in the FDO Execution Model (Figure 6-6).

Generally, the prioritization scheme suggests that directly affected System Requirements are preferred over indirectly affected ones and that directly affected Change Objects are preferred over indirectly affected ones. Figure 6-5 shows that all paths undergo the identification of direct System Requirements and Change Objects (section A). The additional consideration of indirectly affected Systems Requirements (section B) only applies to paths II – IV. Path III and IV consider additionally the indirectly affected Change Objects, i.e. change propagation (section C) based on the directly affected System Requirements of section A. At last, path IV accounts for all four sections (A-D) including change propagation across Change Objects based on the impact of indirectly affected System Requirements (section D).

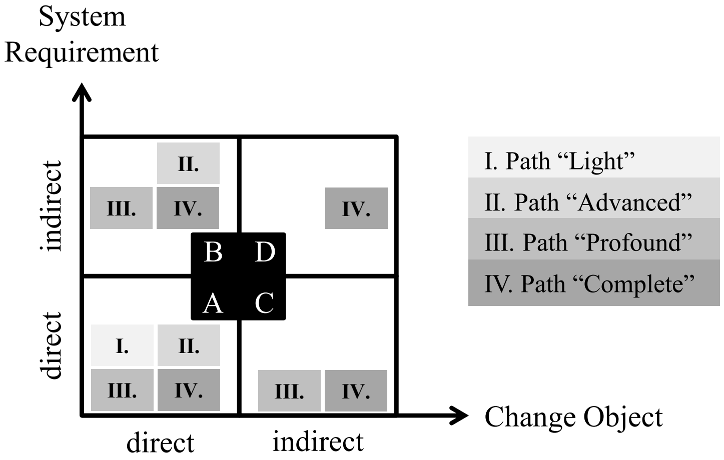


Figure 6-5 Prioritization scheme for additive paths

The gradual integration of paths in the FDO Execution Model is illustrated in Figure 6-6. The introduced paths include two different types of tracing[228]: "inter-domain tracing", i.e. identification of elements within DMMs, and "intra-domain tracing", i.e. the identification of elements within DSMs. Similar to the observation by WILDS [2008, p. 43], each step in the methodology focuses on specific submatrices which allows to spotlight user-relevant information while irrelevant information on less relevant paths can be omitted.

Path "Light" (Figure 6-6, upper left) represents the basis of running the FDO Execution Model. This allows the identification of directly affected System Requirements, related Change Objects

---

[228] As discussed in section 3.2, MDMs allow the systematic "tracing" of dependency chains within (DSMs) and across matrices (DMMs) in both directions of causality [LINDEMANN ET AL. 2009, p. 89].

and, together with the suitable Transitions[229], suitable Change Enablers. The identification of indirectly required Change Enablers (in M_G) is also accounted for as they must be considered simultaneously with M_F to identify suitable solutions. The consideration of Prerequisite Change Enablers (M_G) applies to all four paths.

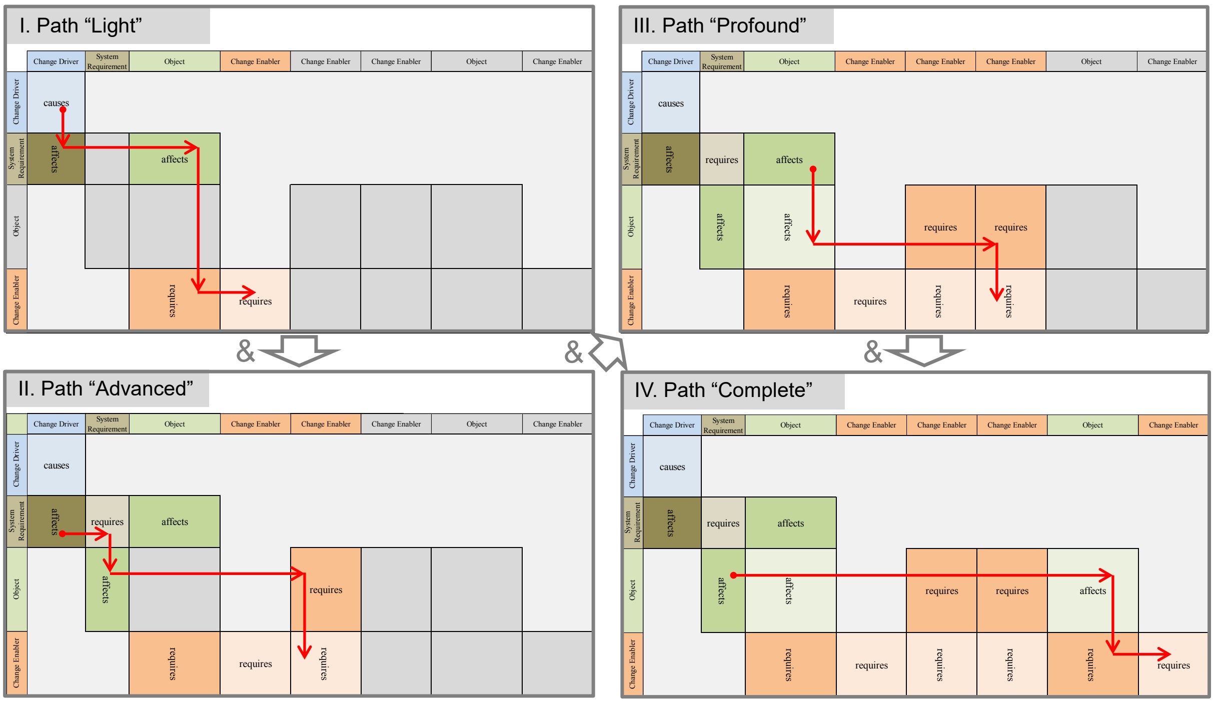


Figure 6-6 Tracing with scalable paths in FDO Execution Model

Path “Advanced” (Figure 6-6, lower left) builds upon the first path and identifies indirectly affected System Requirements, which in turn affects Objects also requiring Change Enablers and Prerequisite Change Enablers.

Path “Profound” (Figure 6-6, upper right) considers additionally to path “Advanced” physical change propagation, i.e. change due to physical changes of upgraded Objects. Based on the directly affected Change Objects by System Requirements, indirectly affected Objects are identified. For those Change Objects, Change Enablers and Prerequisite Change Enablers are determined.

For the last path change propagation of Change Objects are considered that are indirectly affected by System Requirements (Figure 6-6, lower right). As this path cumulates all possible paths of the FDO Execution Model, it is referred to as path “Complete”. As already highlighted in section 6.1, change propagations depend on the selection of Transitions that can be selected in M_D, M_E and M_F. Hence, a homogenization of Transitions or split-up of the Change Object into multiple instances with common Transitions is required.

Although accounting for indirect relationships of System Requirements first, before considering change propagation amongst Change Objects is the preferred order of consideration, an

---

[229] As discussed in section 6.1, Transitions are not explicitly shown in those matrices although they are accounted for in each of the paths.

individually different prioritization between path “Profound” and path “Advanced” is possible as both paths are independent from each other.

In reality the FDO Execution Model has a very large size to account for all relevant elements of the different domains. This can limit the usability of the model. Hence, an enhanced tool could be valuable by following a defined workflow (e.g. start with M_A, continuing and showing M_B when performing path “Light”) for the cumulative paths. This allows the isolated consideration of single matrices when jumping to subsequent or previous ones which fosters keeping the focus solely on the matrix under investigation. At the same time, different views may be relevant (e.g. only show change propagations, Change Objects affected by System Requirements > number x) that highlight certain aspects that are relevant to the user. Both workflows and views can limit the perceived complexity and support the usability of the model. Consequently, real world applications of the FDO Methodology should enable a division into separate workflows and views[230].

Section 6.3 focuses upon understanding the tracing capability in the FDO Execution Model and, strongly related to that, the ability to build change scenarios.

6.3 Tracing and change scenario building

Section 6.2 suggests a forward-oriented model for identifying FDOs which starts by identified Change Drivers and ends with the embedment of Change Enablers into relevant Change Objects. This downstream orientation, however, only depicts an “ideal” process which must be enhanced due to real-world boundary conditions when addressing the change scenario. Specifically, boundary conditions BC4 and BC6 presented in section 1.3.2 become relevant to consider in this context:

- BC4 addresses the “fragmented and incomplete articulation by customers regarding needs on flexible design”. The reasons usually lie in customers facing difficulties in expressing the need correctly, forgetting needs, being unaware of them or presuming that they were already accounted for or intentionally remain unmentioned to remain secret [ROSS & RHODES 2007].
- BC6 addresses the “variation of type and detail level of customer specifications”. This entails, on the one hand, heterogeneous forms of communicating specifications varying between oral vs. written or brief vs. detailed statements and, naturally, different manners and forms of describing the same issue. On the other hand, the addressed domains of the articulated needs may vary (e.g. articulated Change Driver vs. Change Object) or needs may even be expressed across various domains simultaneously (e.g. Change Driver & Change Object). The reasons lie especially in the “variation of stakeholder constellations and tender conditions during system development” (BC5).

---

[230] The Excel® based tool for representing the FDO Methodology in this work does not have those capabilities, i.e. following certain workflows or establishing certain views, as the primary purpose of this tool was to evaluate the FDO Methodology and not the incorporation in real-world settings.

Consequently, there is a demand for systematically identifying the underlying reasons of articulated needs on future changes which in turn might pinpoint to new relevant domain elements. However, in order to enable tracing of FDOs in the first place a proper identification of initial elements by a previous translation and decomposition of articulated needs is required to deal with heterogeneously provided information.

Section 6.3.1 emphasizes the preparation of input for the FDO Execution Model which focuses on the derivation of initiating elements. Based on that, alternative tracing techniques are introduced. Section 6.3.2 builds upon those introduced techniques to present a process for building a comprehensive change scenario. Finally, in section 6.3.3, the alternative tracing techniques are applied in the FDO Execution Model emphasizing the differences amongst matrices.

6.3.1 Tracing and Back-Tracing based on initial data

As discussed in section 1.1.2, an initial rig concept is generated in the tender phase between ITT (Invitation to Tender) and contract award to ensure a technically feasible and economically realistic offer. It is before or during that phase that flexible design is addressed as major changes after contract awards are hardly feasible.

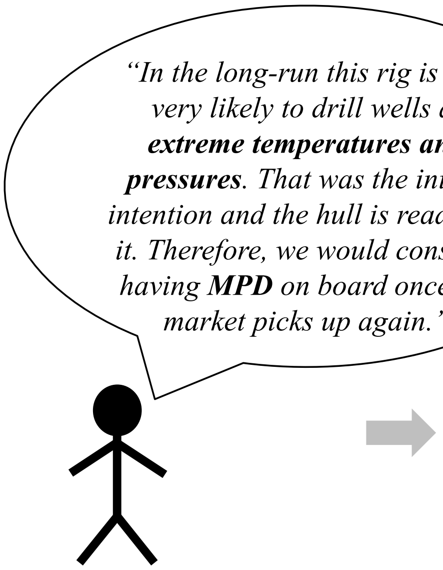
Due to the strong variation in type and detail level of the customer specifications (BC6), customer input can often not be directly transferred to constituents of the FDO Execution Model. Consequently, based on customer requests for future change, a decomposition, translation and assignment to existing constituents of the model (domains, elements) must take place. Those customer requests can be formulated in various forms (oral or written in tender specifications, bill of material, etc.). They can be assigned to the domains[231] “Change Driver”, “System Requirement” and “Object” and matched to pre-defined and best matching domain elements. The articulated need might relate to only one particular element in one domain or various elements in identical or different domains. Consequently, articulated customer needs can lead to various instigating elements, the starting point for performing tracing in the FDO Execution Model.

Figure 6-7 illustrates an example of an orally articulated need[232]. The customer request is already clear and can be assigned to two different domains with one corresponding element in each of those domains without further decomposition and translation. Both elements represent articulated instigating elements which can be used for tracing (shown later).

---

[231] Customer requests for future change addressing the domain “Objects” often also include a Change Enabler as a suggested solution by the customer. Although this can be accounted for when building and assessing alternative Flexible Design Concepts, it does not represent an initiating element.

[232] The example is also the basis for the use case addressed in section 8.1.



	Articulated need	Corresponding FDO domain	Corresponding FDO element
I	"Extreme temperatures and pressures"	Change Driver	Change of Well Pressure & Temperature
II	"MPD"	System Requirement	Managed Pressure Drilling [Capability]

Figure 6-7 Processing of exemplary articulated need by customer

Building upon section 6.2, based on the articulated needs by the customer, the process of tracing is extended to increase the comprehensive identification of FDOs which contributes to the fulfillment of BR II and R6 in particular:

- "Tracing"[233] as the forward-oriented identification of FDOs based on an instigating element. It concerns the identification of relevant downstream elements in the direction of causality and, as highlighted in section 6.2, addressing both DMMs (inter-domain tracing) and DSMs (intra-domain tracing).
- "Back-Tracing" as the backward-oriented identification of FDOs based on an instigating element. In contrast to "Tracing", it addresses the reversal of the tracing direction by going against causality which facilitates the identification of upstream elements. As for "Tracing", "Back-Tracing" applies to both DMMs and DSMs.

Despite the identified articulated needs and as ROSS & RHODES [2007] emphasize, the goal of the designer (System Supplier) must be to identify as much of the unarticulated needs as possible, or, at least make the system able to meet them when they are revealed or discovered.

Back-Tracing pursues the former goal by enabling the identification of the underlying reasons of change which, in turn, might affect other elements that would not have been identified by downstream analysis of a predefined causal chain. Depending on the domain of the instigating element, the need and scope of Back-Tracing varies. For instance, corresponding FDO elements in the domain "Change Driver" usually relate to less effort by Back-Tracing as only intra-domain tracing is needed. In contrast, extensive Back-Tracing efforts (intra-domain, inter-domain) are needed when the corresponding FDO elements represent Change Objects as, in addition, the domains "System Requirement" and "Change Driver" must be run through rever-

---

[233] "Tracing" with a capital "T" indicates a forward oriented direction of the tracing technique.

sely. Based on the example in Figure 6-7, Figure 6-8 demonstrates the benefit of Back-Tracing and Tracing in a graph of a random causal network[234].

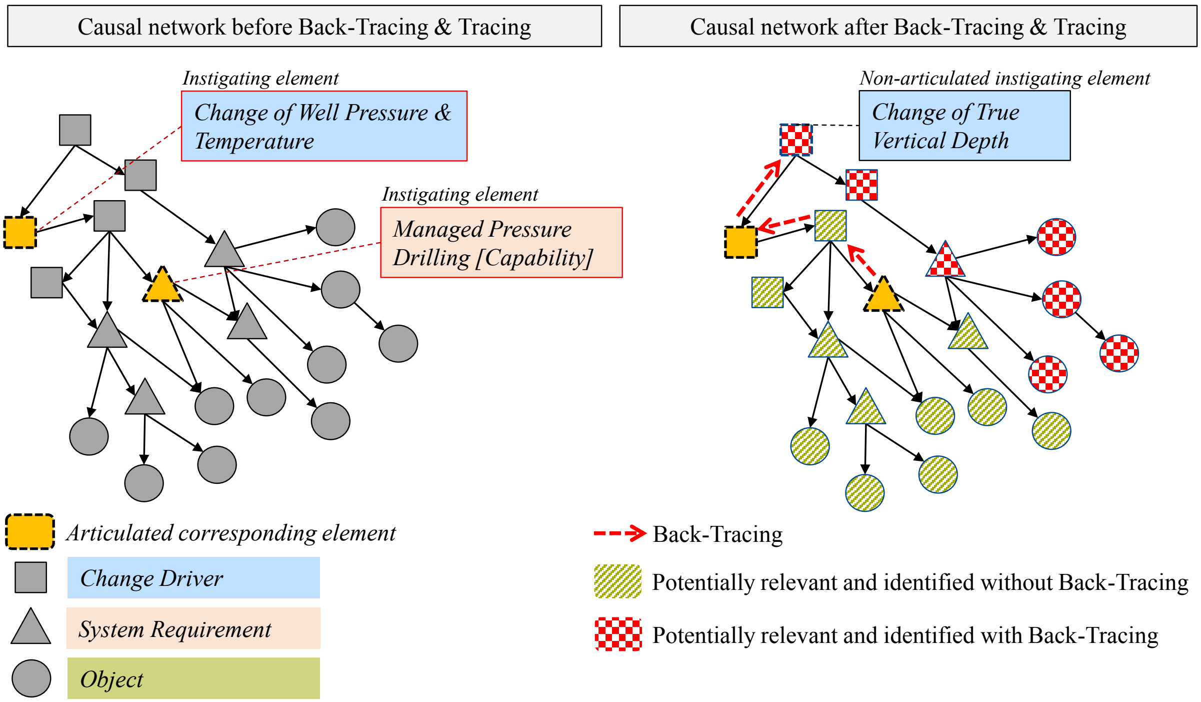


Figure 6-8 Benefit of Back-Tracing in exemplary causal network

Based on two articulated needs in different domains, which represent the initiating elements for the analysis, an initial Tracing would only allow the identification of downstream elements. Back-Tracing, in contrast, allows the identification of the underlying reasons upstream of the causal network, which in turn leads to the identification of new unarticulated initiating elements (Figure 6-8, right). If relevant, following the causal network downstream (Tracing) leads to completely new affected elements which in the end can result in otherwise unconsidered Change Objects. This, however, indicates missed opportunities as those Change Objects could be prepared for future changes by embedding Change Enablers.

In the following section 6.3.2 a process for the systematic building of scenarios is suggested that bases upon the introduced tracing techniques.

6.3.2 Gradual scenario building

The integration of articulated customer needs and the concept of tracing were introduced. However, for attaining comprehensiveness in change sources that are relevant to the customer, a systematic scenario building is required.

As introduced in section 2.2.2, a scenario is a generally understandable description of a possible future that builds upon a complex network of influencing factors [GAUSEMEIER ET AL. 2001, p.

---

[234] Causal relationships of elements besides the named ones are random and only for demonstration.

82]. By defining certain articulated instigating elements and performing tracing through the built network, various partial scenarios can be built and integrated to a final core scenario. This scenario is a representation of relevant elements and their attributes. Hence, scenario building targets a comprehensive representation of consistent[235] or independent[236] future scenarios that the customer is interested to prepare for[237]. This, however, requires following a process for building that scenario gradually as shown in Figure 6-9.

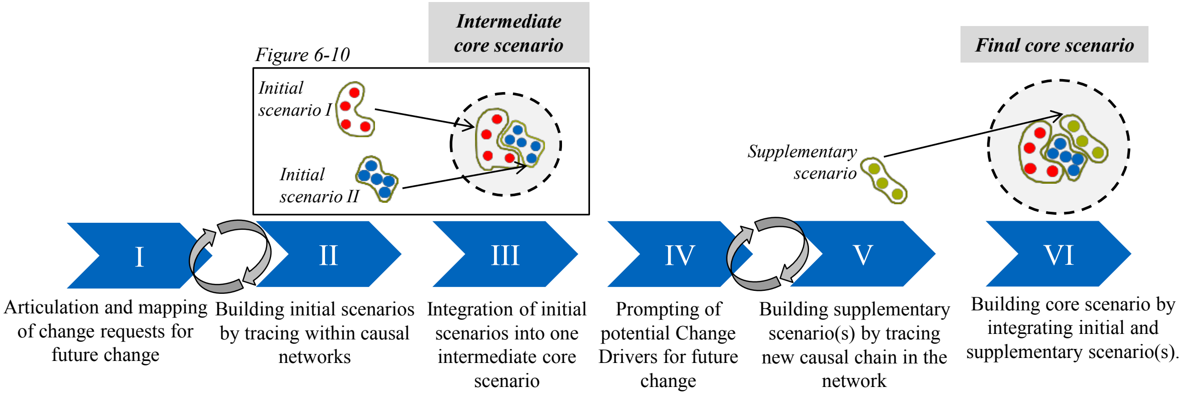


Figure 6-9 Process of gradual scenario building

As shown in section 6.3.1, Change Drivers, System Requirements or even Change Objects can be deduced directly from articulated customer needs referring to potential change requests in the future and, hence, represent instigating elements in the causal network (step I). Following that causal network by Back-Tracing and Tracing from those instigating elements, an initial scenario[238], a causal network of relevant Change Drivers, can be built (step II). As detailed in Figure 6-10 by highlighting especially the build-up of the initial scenario I, those scenarios must not only account for the Change Drivers (attributes) but also include the direction and magnitude of change that those elements will face which is shown by the anticipated future characteristics (e.g. increase of True Vertical Depth to 30000 ft). As defined by GAUSEMEIER ET AL. [2001, p. 92], those characteristics can be either quantitative or qualitative. As highlighted in Figure 6-9, steps I and II are performed iteratively to allow building scenarios that are causally independent and, hence, belong to different initial scenarios which are less likely to occur simultaneously in the future. Those initial scenarios are then integrated to a consistent intermediate core scenario (step III).

---

[235] Referring to a likely combined occurrence of those scenarios.

[236] Referring to an independent occurrence of those scenarios.

[237] Does not mean the generation of alternative scenarios for different possible futures which is referred to as “future robust planning” according to HERNÁNDEZ [2003, p. 101].

[238] The initial, supplementary and final core scenarios contain elements of the Change Driver domain only.

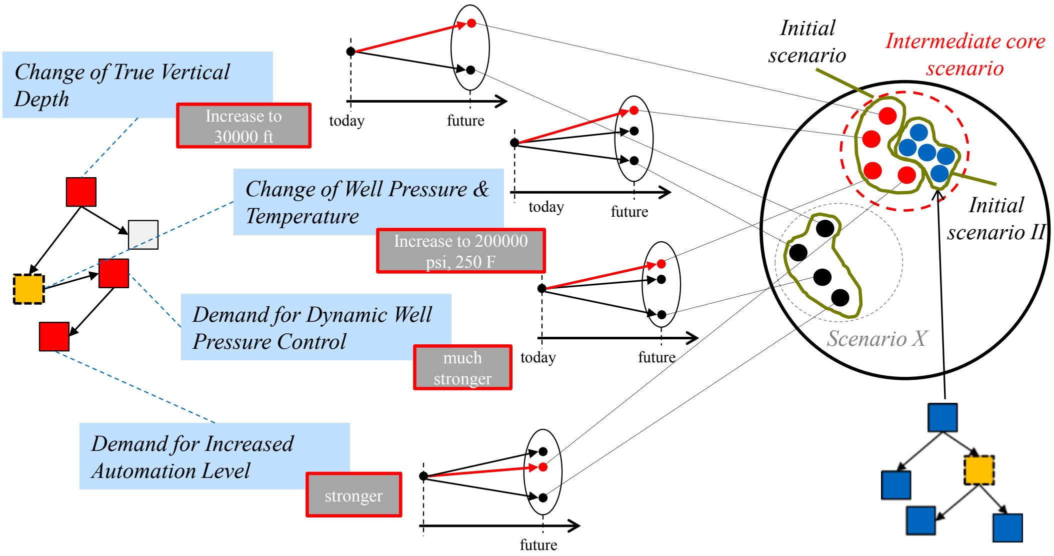


Figure 6-10 Building initial scenarios and integration to intermediate core scenario

Additionally, and only if the boundary conditions allow for it[239], in step IV further Change Drivers can be prompted from the customer by actively addressing specific categories and subcategories of Change Drivers (Table 5-3), questioning their relevancy and eliciting instigating elements. If being independent from the initial scenarios, those Change Drivers then belong to supplementary scenarios as they are not explicitly articulated by the customer but built by prompting the instigating elements. Hence, a new causal chain based on those instigating elements is built by tracing (step V). As for steps I and II, steps IV and V can also be iterative as illustrated in Figure 6-9 possibly leading to more supplementary scenarios. The new supplementary scenario(s) are then added to the intermediate core scenario to represent the final core scenario (step VI). As the intermediate core scenario, this final core scenario does not represent a simultaneously occurring and consistent future scenario but is an agglomeration of all potential scenarios that are relevant to account for and can be handled by the System Supplier. Hence, for future considerations the different partial scenarios (initial, supplementary) should still be considered separately and gradually as their importance varies and Flexible Design Concepts might only target the most important partial scenarios in the end.

Thus, in contrast to “future robust planning”, the presented scenario building does not consider alternative developments of Change Drivers. In line with HERNÁNDEZ [2003, p. 101], it rather targets “focused planning” as only one future development makes up an initial or supplementary scenario. However, nevertheless multiple scenarios can occur, not due to alternative developments of Change Drivers, but as several initial and supplementary scenarios make up a final core scenario which usually occur independently from each other.

In the end, each partial scenario, initial or supplementary, should have Change Drivers that can be directly related to the System Requirement domain which is the basis for performing interdomain tracing. As discussed in section 6.2, tracing, however, is not only limited to stage I, the “Identification of Change Objects”, but also stage II, the “Generation of Flexible Design

---

[239] Otherwise intermediate core scenario represents final core scenario.

Concepts”. The following section presents the techniques of tracing within the entire FDO Execution Model.

6.3.3 Matrix-based tracing techniques

Figure 6-11 provides an overview of the matrices where Back-Tracing is relevant to consider. Whereas inter-domain Tracing applies to all possible DMMs explicitly represented in the FDO Execution Model (M_B, M_D, M_F), inter-domain Back-Tracing only applies to M_B and M_D in order to identify the underlying reasons for identified FDOs presented in the previous section. Inter-domain Back-Tracing from M_F is not considered to be relevant as suitable Change Enablers are deduced based on existing Change Objects and not vice versa.

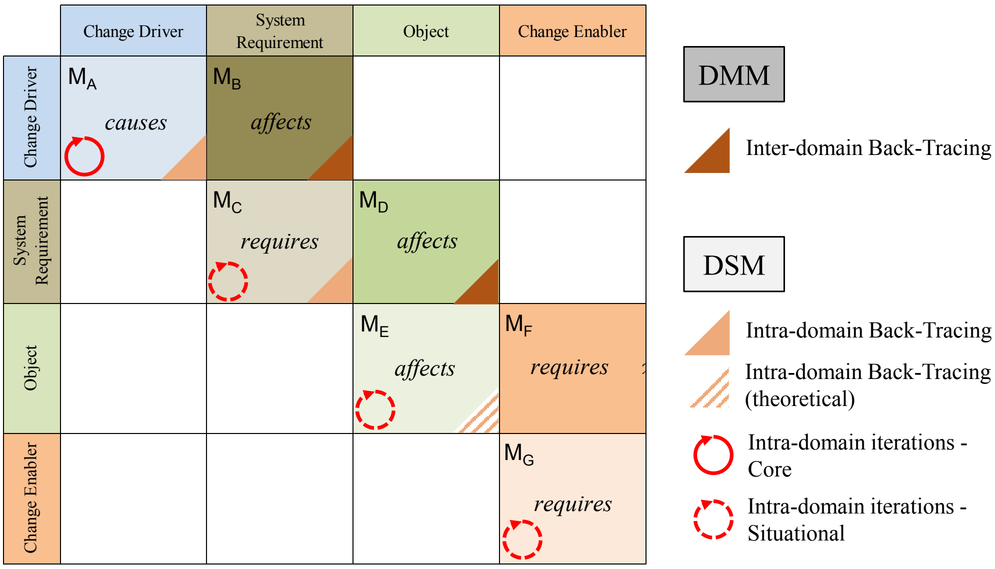


Figure 6-11 MDM representation[240] *of matrices for Back-Tracing and iterations in FDO Execution Model*

Intra-domain Tracing is relevant for all DSMs explicitly represented in the FDO Execution Model (M_A, M_C, M_E, M_G). Regarding intra-domain Back-Tracing, M_G is irrelevant as Change Enablers only consider downstream Prerequisite Change Enablers and not vice versa (Figure 6-11). M_E is theoretically a possible candidate for Back-Tracing to arrive at directly affected Change Objects by System Requirements based on articulated Change Objects affected by change propagation; however, as the document archival analysis on tender project specifications (section 1.4) suggests, articulated Change Objects as instigating elements usually refer to Change Objects directly affected by System Requirements[241] and not, indirectly, by change propagation. M_C represents a relevant DSM for Back-Tracing as an articulated System Requirement may be affected by another upstream System Requirement. The same applies to M_A where

---

[240] Note that in contrast Figure 5-1 the domain “Transition” and the related matrices are excluded as not explicitly represented in the FDO Execution Model.

[241] Requiring inter-domain Back-Tracing in M_D.

the articulated Change Driver is usually affected by upstream Change Drivers as illustrated in the example of Figure 6-8.

When introducing the paths of the FDO Execution Model in section 6.2, intra-domain Tracing only referred to direct relationships (e.g. System Requirement affects Object that only affects another Object). However, iterative identifications within DSMs can also exist in order to identify also higher degree of influences, i.e. indirect impacts within matrices M_A, M_C, M_E and M_G. As could be observed using the miscellaneous research methods (section 1.4) and especially the case-based interviews (section 5.2), a higher degree of propagations is mainly relevant for M_A. Elements identified in M_C, M_E and especially M_G are usually accounted for by addressing direct propagation changes only.

The lack of considering indirect change propagation in M_E bases upon the fact that changes of “drilling equipment” usually affect “bulk items” which represent adaptors. As illustrated by PONN & LINDEMANN [2011, p. 259] adaptors represent the embodiment of adaptor functions to adapt to other systems and circumstances; bulk items being “adaptive” are able to absorb[242] changes and drilling equipment being usually separated from other equipment through “bulk” reduces the effect of indirect change propagation. This can similarly be observed by CLARKSON ET AL. [2004] when investigating the case on “Westland Helicopters” (section 3.2.1) where “bulk” such as “cabling and piping” indicates the lowest risk of influencing other elements while having a high susceptibility to change, which, according to ECKERT ET AL. [2004] characterizes an absorber.

For M_G it could be observed that Prerequisite Change Enablers usually represent robust related (“Universality”) Change Enablers which often already represent highest order elements that do not require other ones; in some cases, however, those Change Enablers might require other robust related Change Enablers which indicates cases for indirect considerations in DSMs. Being very time consuming, the extent of applying intra-domain tracing in any of the four DSMs strongly depends on the application context and the boundary conditions (e.g. time constraints). Nevertheless, the FDO Execution Model is able to deal with indirect propagation in DSMs generally as illustrated later in this section.

The implementation of tracing techniques within matrices is now demonstrated on a subset of the FDO Execution Model. Figure 6-12 depicts the identification of Change Objects by indirectly affected System Requirements[243]. Based on this example both the downstream (Tracing) and the upstream (Back-Tracing) identification of FDOs are demonstrated.

---

[242] This may be highly different in integrated products where there is much more change propagation amongst multiplier and carrier elements.

[243] Representing subparts of path “Advanced”.

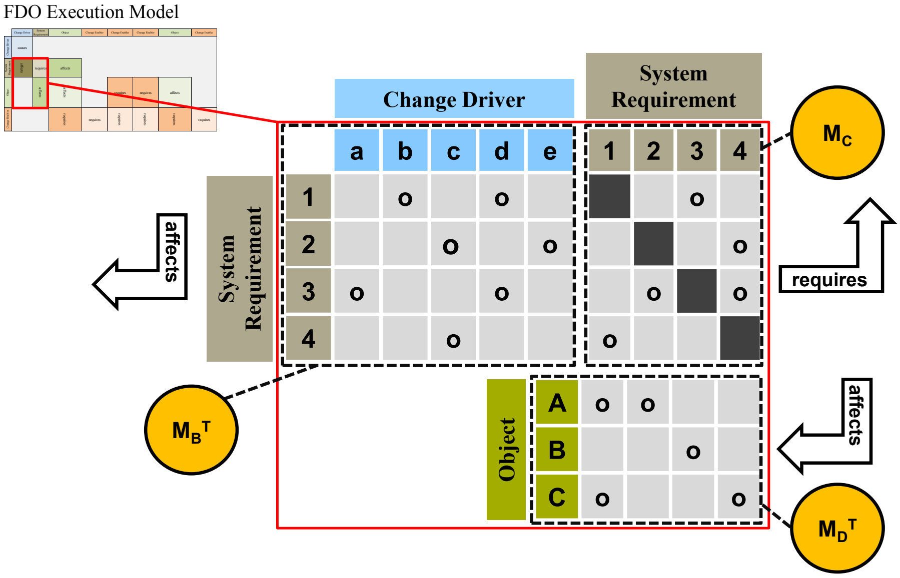


Figure 6-12 Subset of FDO Execution Model for demonstrating tracing technique

This subset contains the matrices M_B^T, M_C and M_D^T. Based on this subset of the FDO Execution Model the systematic identification of FDOs is performed. In this example the articulated need is expressed as a System Requirement ("2") representing the instigating element in M_C (Figure 6-13, top).

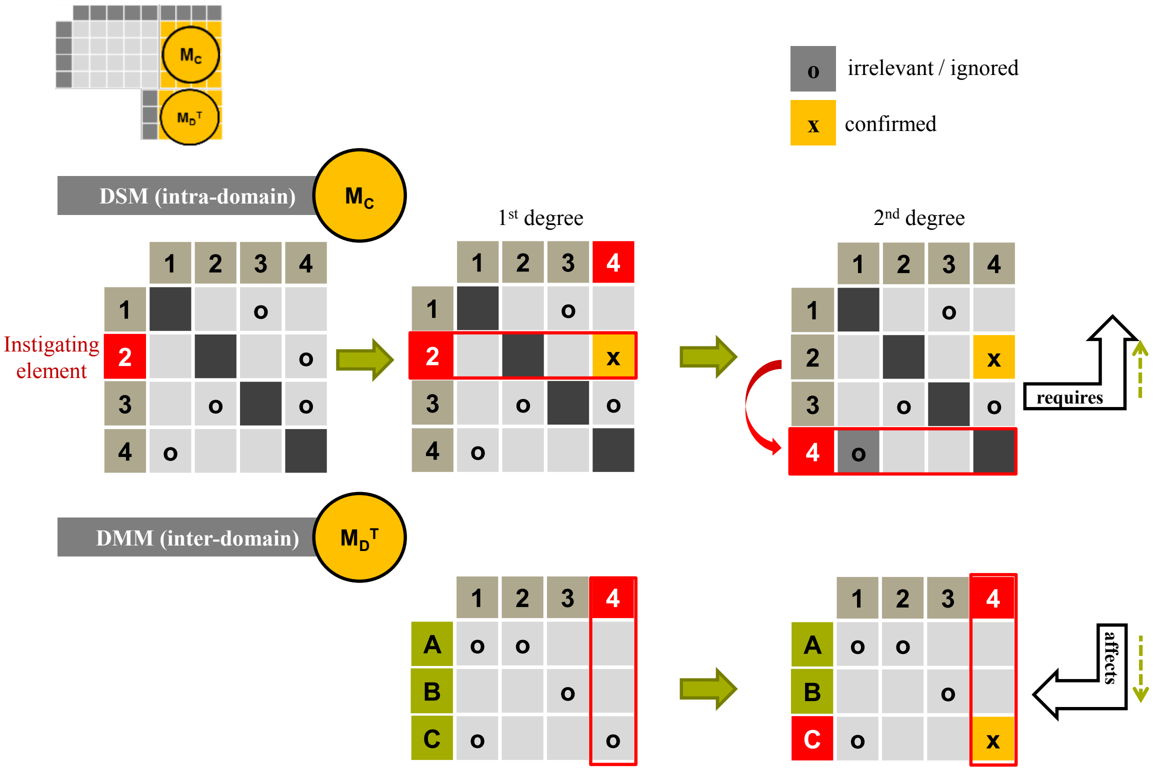


Figure 6-13 Tracing in the FDO Execution Model

Tracing the row of the same domain for indirectly affected System Requirements leads to the identification of System Requirement "4". The identification of further System Requirements that System Requirement “4” affects, requires screening the fourth row. In this case a potential relationship exists, but is irrelevant and can be ignored for this application context.

Based on the identified System Requirement “4”, its impact on Objects is investigated[244]. In this case the matrix is transposed (M_D^T), hence, Tracing must be performed by screening the columns (Figure 6-13, bottom). Object “C” is identified as a Change Object[245] failing to fulfill System Requirement “4” (Change Trigger). The identification of Change Enablers and Transitions or other Objects (change propagation) is not considered further.

Back-Tracing is demonstrated by identifying upstream elements of the instigating element, System Requirement “2”, by going against causality (Figure 6-14, top).

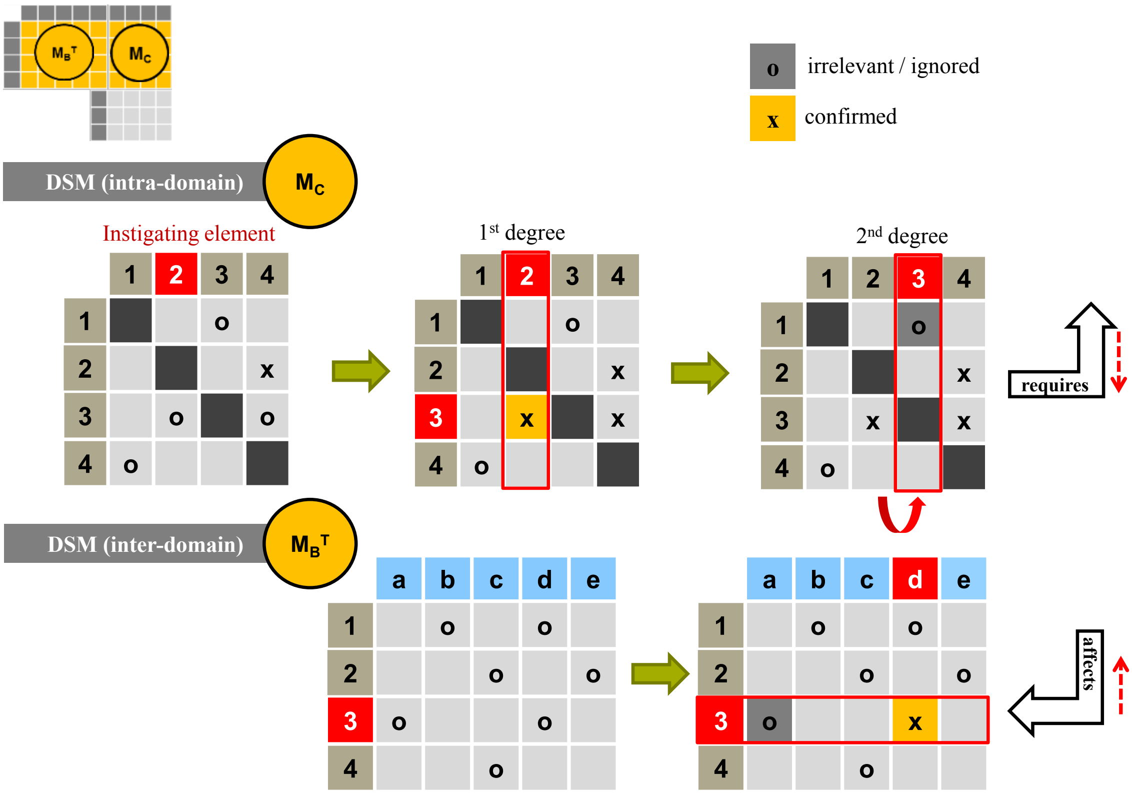


Figure 6-14 Back-Tracing in the FDO Execution Model

In this case column 2 is screened for an unarticulated upstream System Requirements that could have affected the articulated instigating element. System Requirement “3” is identified to affect System Requirement “2”. System Requirement “3”, in turn, is not considerably affected by any other System Requirement.

Based on the identified System Requirement “3”, now inter-domain Back-Tracing can be performed (Figure 6-14, bottom). M_B^T, a transposed matrix, requires the screening of the row

---

[244] The instigating element System Requirement “2” could also affect Object “A” directly, which, however, is not further pursued as this must be represented in M_D matrix M_3. However, in the example of Figure 6-12 and Figure 6-13, only M_D matrix M_7 is followed.

[245] Confirmation of relation by “x” which reflects an “Enabler-driven” approach (section 6.1).

in order to go against causality. In this case Change Driver “d” is confirmed to be the governing Change Driver. The identification of further Change Drivers in M_A (intra-domain) is not considered further. Table 6-1 summarizes the main aspects on Tracing and Back-Tracing in the FDO Execution Model. It concludes with an example by using actual elements and relations from the database.

Table 6-1 Main aspects for performing Tracing and Back-Tracing in FDO Execution Model (similar to CARATHANASSIS [2015, pp. 78–79])

	Tracing	Back-Tracing
Screening direction	• Row-wise in non-transposed matrices • Column-wise in transposed matrices	• Column-wise in non-transposed matrices • Row-wise in transposed matrices
Goal	Identification of “affected” elements by starting with articulated instigating element and identifying subsequent elements (downstream)	Identification of preceding elements affecting the articulated instigating element (upstream)
Key question	Which relevant elements affect other elements? (active form of question)	By which elements are the relevant elements affected? (passive form of question)
Example	Does “*Managed Pressure Drilling [Capability]*“ *affect “Topside Surveillance [Condition]”*? (Intra-domain Tracing in DSM matrix M_C)	Is “*Managed Pressure Drilling [Capability]*“ affected by “*Demand For Dynamic Well Pressure Control”*? (Inter-domain Back-Tracing in DMM matrix M_B)

Although tracing techniques in the FDO Execution Model are highlighted in this section by focusing on stage I, the “Identification of Change Objects”, they also apply to stage II, the “Generation of Flexible Design Concepts” in matrices M_F and M_G. However, as shown in Figure 6-11, for stage II only forward oriented Tracing is of relevancy.

Tracing, in general, leads to the identification of Change Objects, which in turn, should lead to the definition of suitable Flexible Design Concepts. However, already during the selection of elements and, finally, when deriving high-performing Flexible Design Solutions that are to be embedded into the reference design, an assessment must be performed that is the basis for decision-making.

6.4 FDO assessment and decision-making

The assessment and decision-making is considered twofold in the FDO Methodology being presented in the following sections: On the one hand, it is already addressed when running through stage I and II in the FDO Execution Model as potential relations might not be applicable or relevant in the particular project context, hence, do not require further consideration (section 6.4.1). On the other hand, the assessment and decision-making relates to the already specified Flexible Design Concepts (stage III) which are exported to a separate report based on the selections in the FDO Execution Model and based on which the Flexible Design Solutions are deduced (section 6.4.2).

6.4.1 Continuous assessment and decision-making in stage I and II

During the selection process of Change Objects and Flexible Design Concepts, pre-defined relations have to be confirmed or rejected depending on their applicability and relevancy. Figure 6-15 demonstrates the criteria and the project context categories that are relevant for decision-making.

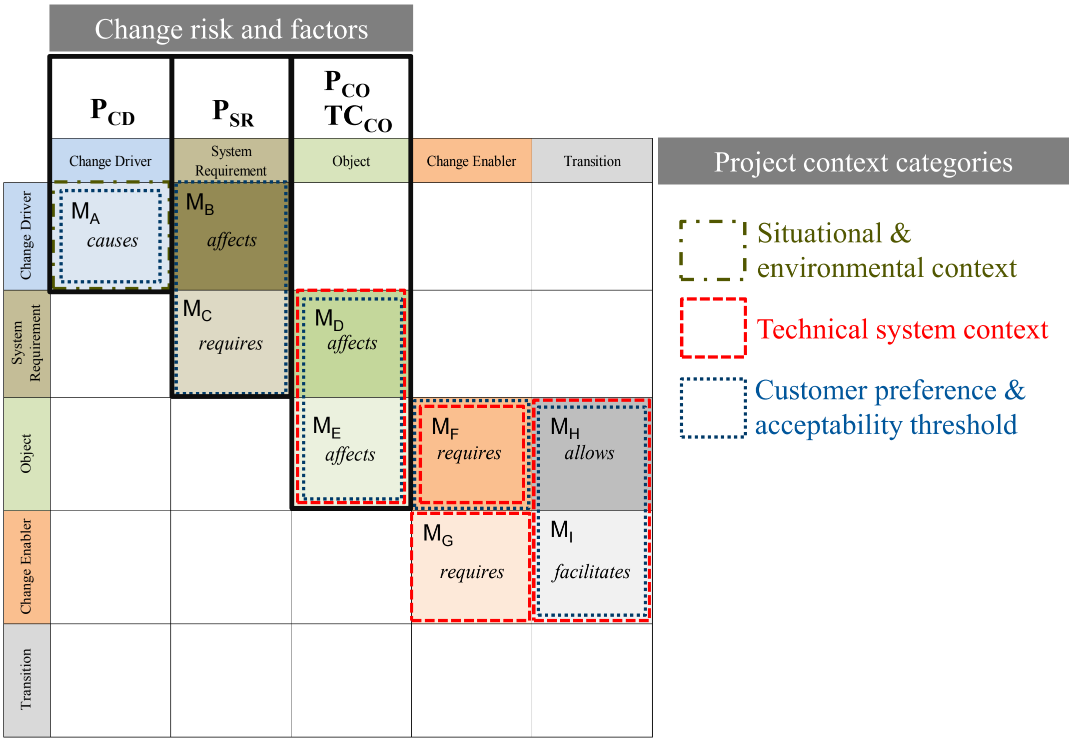


Figure 6-15 Change risk factors and project context categories for FDO Execution Model

Change risk and factors

The identification of Change Objects (stage I) depends on certain criteria which already have been highlighted by various authors (e.g. SUH ET AL. [2007], BARTOLOMEI [2007], HU & CARDIN [2015]) and were introduced in section 3.2.1. They concern both the probability and (switching) cost of changes. The values of those criteria are set based on the information that is provided by the specific project of concern (e.g. specific uncertainties, system architecture, project boundary conditions) and, hence, must be determined when running the FDO Execution Model. Based on the example of Figure 6-8, a subgraph of an initial scenario is created (Figure 6-16) to demonstrate the identification when Tracing[246] the model. Hereby, the potential relations are confirmed node by node independently of the associated domain.

Through Tracing in M_A the potential relations between Change Drivers are checked by considering their probability of occurrence (P_{CD}). As shown in Figure 6-16, the probability of the instigating element ($P_{CD\_a}=0.5$), i.e. the presumed root cause for the initial or supplementary scenario to occur, is put on the element itself. The other probabilities within M_A concern the

---

[246] Back-Tracing works the same way in the opposite direction.

relations between Change Drivers represented by P_{CD_ab}. In this case the relation is always true when Change Driver “a” occurs and, hence, the probability of P_{CD_ab} equals 1.

Next, the relevancy of System Requirements is investigated in M_B and M_C. As Change Driver “b” is related to System Requirement “1”, it represents a “demand for” Change Driver (section 5.3.1). The probability of impact of this Change Driver on System Requirements in M_B determines if this System Requirement is considered further based on the addressed scenario. As Figure 6-16 shows, System Requirement “1” is affected with the probability of 0.6 (P_{SR_b1}), hence, is considered further. In this example, the indirectly affected System Requirement “2” is also considered further with a P_{SR_12} of 0.7.

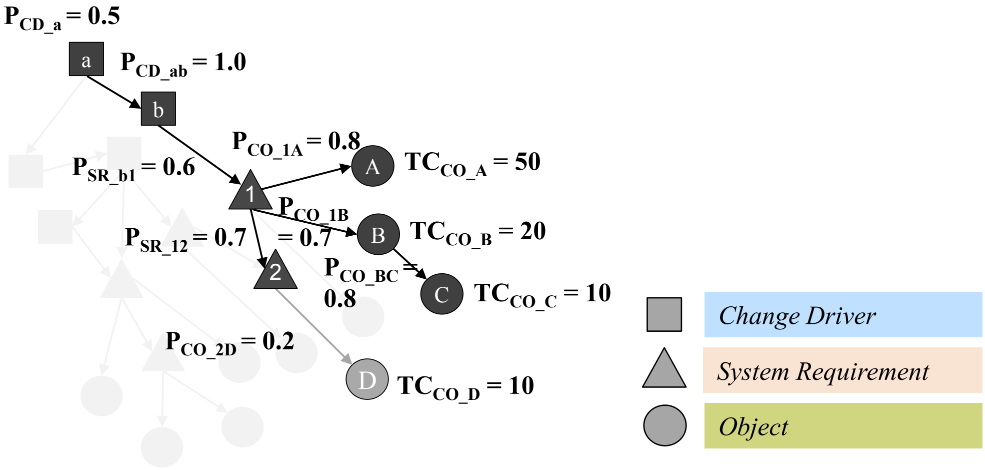


Figure 6-16 Subgraph as example for decision-making when Tracing FDO Execution Model

In M_D Change Objects are identified based on the underlying System Requirements. The probability coincides with the probability of the Change Trigger occurring, i.e. when design margins of Objects do not suffice and, hence, Objects will require change (section 4.2.1). The same applies to M_E where the reasons for change, however, lie system internally due to change propagation (e.g. Object B affecting Object C). The high values of P_{CO_1A}, P_{CO_1B} and P_{CO_BC} indicate that it is quite likely that the Objects require change. In contrast, the probability of System Requirement “2” on Object D (P_{CO_2D}) is rather low.

Besides the addressed probability of change that was sufficient to identify relevant Change Drivers in M_A or System Requirements in M_B or M_C, the transition cost of Objects (TC_{CO}) (introduced in section 3.3) must also be considered when addressing the risk of change in M_D and M_E. They play an important role “since decision-makers may not want to pay more in the initial design phase to enable flexibility if the system with standard design components can change easily in the future” [Hu & Cardin 2015]. In that regard, as defined by Hu & Cardin [2015], “risk susceptibility” can help determining the change strategy, i.e. the choice between keeping a fixed, rigid design or, alternatively, embedding changeability by either flexible or robust design (section 3.2.1). The “node by node” assessment and decision-making in the FDO Execution Model leads to differences to the suggested risk susceptibility by Hu & Cardin [2015]: On the one hand, any upstream probabilities and, hence, the calculation of a “posterior probability” of the Object of concern is not considered as those upstream probabilities have been already accounted for before when leading to the consideration of this Object. On the other hand, the selection of the Object of concern does not consider the downstream risk and, hence $R^{Generated}$, as this would require anticipating the effects of change propagation across various nodes that are still to be addressed when running the methodology. Consequently, only the incoming change $R^{Received}$ of the Object of concern is targeted that is sufficient and accounts for the probability of change and the transition cost[247]:

$$R_{CO}^{Received} = P_{CO} \times TC_{CO} \qquad (6\text{-}1)$$

For Object A that is to perform an "Entire Replacement", the following risk is determined:

$$R_{CO\_1A}^{Received} = P_{CO\_1A} \times TC_{CO\_A} = 0.8 \times 50 = 40 \qquad (6\text{-}2)$$

The same calculation can be made for Object B, C and D. Based on customer preferences and acceptability thresholds, due to its low value Object D can be rejected, thus, is not considered to be a Change Object. In contrast, Objects A, B and C are considered to be Change Objects and, thus, are also considered further during stage II of FDO identification.

As the transition costs TC_{CO} depend on the actual Transition that is to be performed and prepared for, the "Entire Replacement" and the high TC_{CO} may never apply in the future and, hence, overestimate the need for flexible design. For instance, a "Partial Replacement" usually entails much lower transition costs in comparison and a rigid design may still be sufficient to cope with such a change in the future. The differentiation of Transitions when estimating transition costs, however, can only be done when running the Transition-driven approach as Change Objects and Transitions are selected simultaneously here. In contrast, when running the Enabler-driven approach, Transitions are selected independently after Change Objects are already selected. In this case the TC_{CO} must account for the worst-case change, i.e. when the entire Object is to be replaced.

Additionally, as more than one initial or complementary scenario might contribute to the overall core scenario, Change Drivers, System Requirements and Change Objects may be affected multiple times which has an amplifying effect on the relevancy of those elements as the total probability of impact and change is increased. Practically, this implies that elements that were rejected in previous runs of the FDO Execution Model, may suddenly become relevant as the total probability has significantly increased.

Due to the "node by node" assessment and decision-making based on the individual project conditions, the large number of elements to be assessed and the gradual consideration of scenarios, a formal analysis based on pre-determined values would be less feasible and also counterproductive compared to accounting for the existing experience of engineers and their capability of making sophisticated decisions. Thus, the selection of elements is performed when running the methodology by a "quick estimation when analyzing product properties" as suggested by LINDEMANN [2005, p. 304] by accounting for change risk implicitly. This is opposed to the more time consuming approaches introduced in section 3.2.1, that usually base their decisions on explicit pre-calculated numbers for specific use cases.

---

[247] The cost of change could also be normalized with respect to the maximum value of each Object which is not demonstrated here.

The strength of the criteria, its perception and, thus, the implications, strongly depend on the boundary conditions of the project. Consequently, the project context categories are discussed in the following.

Project context categories

The boundary conditions of the project of concern can strongly affect the strength of change risk. Generally high change probabilities between elements and high transition costs of Objects indicate that they are considered further. However, the perception depends on the decision-maker as customer preferences and individual acceptability thresholds differ as highlighted by ROSS ET AL. [2008]. Consequently, they also represent project-specific boundary conditions that must be considered node by node for decision-making.

Those three project context categories are elaborated further:

- Situational & environmental context: There are situational and environmental reasons why relations may not exist or differ in strength. For instance, despite the potential relation that exists, a "change of operating area" may not or only very unlikely cause severe "changes of water depth" as customers may only aim for certain operating areas which have minor water depth changes in their location surrounding.
- Technical system context: The relevancy of potential relations depends on the system architecture of the initial reference design. Potential physical changes that are generally relevant, may not be applicable to the specific system of concern. For instance, a Drillers Control Cabin (DCC) of the selected reference design in the methodology may not be integrated or have interfaces to the Derrick structure and, hence, a future extension would not affect that structure physically.
- Customer preference & acceptability threshold: Despite a valid situational & environmental context and technical context of the potential relations, customer preferences vary and lead to different acceptability thresholds. For instance, Object D of Figure 6-16 may be considered further by other decision-makers if acceptability thresholds were lower. Additionally, the weighting of the two risk factors may vary, where, for instance, decision-makers prioritize the probability of change over the transition cost of the Object. As the following shows, preferences and acceptability thresholds must also be considered for stage II of the FDO Execution Model when Transitions and Change Enablers are determined.

The applicable boundary conditions vary with each matrix (Figure 6-15). Outermost boxes represent primary accounted project contexts, whereas secondary ones apply when going inwards.

Whereas situational & environmental context dependent boundary conditions apply to M_A only, technical system context dependent boundary conditions become relevant with the physical consideration of FDOs addressing matrices M_D and further. In particular, in M_D technical system context is relevant when physical impacts exist due to movements as explained in section 5.1 (e.g. changes of "Tubular handling principles" might affect the "Drillstring Compensator"). Here the impact depends on the project-specific reference design. The technical system context is also relevant for M_E as change propagation also varies depending on the reference design.

In matrix M_F customer preferences are considered to be primary boundary conditions as technical system context dependencies are explicitly covered by matrix M_G which can only be checked ones a preferred Change Enabler is selected in M_F. For instance, if “lifting lugs” are confirmed as a preferred Change Enabler of a customer in M_F, they might still be subject to system constraints (e.g. space above lifting point) which are handled separately in M_G. Prerequisite Change Enablers in M_G cannot be rejected as they always represent indispensable relations if required within technical system context. Only if the relations in M_G are fulfilled in the reference design (e.g. sufficient space above lifting point) the initially selected Change Enabler in M_F (lifting lugs) is also applicable. This implies iteration(s) between M_F and M_G to facilitate a selection. Both M_H and M_I still depend primarily on the technical system context as project-specific constraints may exist.

The next section deals with the intermediate and final assessment of Flexible Design Concepts (section 4.2.1) to generate Flexible Design Solutions represented by stage III in the FDO Methodology.

6.4.2 Assessment and decision-making in stage III

FDO EM Report Structure

The selections performed in the FDO Execution Model are not suited for post-assessment and decision-making on the generated Flexible Design Concepts as information is neither condensed nor comparable in that format. In order to get the results into a suitable form, all confirmed selections are transferred to a table, the FDO EM Report, which is shown in Table 6-2[248]. The report highlights both the key features of the Flexible Design Concept and the applicable change sources. The first two stages are displayed in reverse order as the focus lies on rating Flexible Design Concepts where change sources only provide the context for those concepts. Hence, the FDO EM Report facilitates decision-making especially by providing transparency and ability to trace back previous selections[249] realizing especially FDO requirement R14. Each row represents a specific Flexible Design Concept based on a unique combination[250] of Change Object, Transition and Change Enabler. They are organized according to their domains and subdivided according to the matrices of selection.

The first part defines the Object by highlighting the class the Change Object belongs to implying the same Change Enablers and Transitions for the constituents of that class (section 7.2.1). This reference helps to systematize the table according to Objects with similar proper-

---

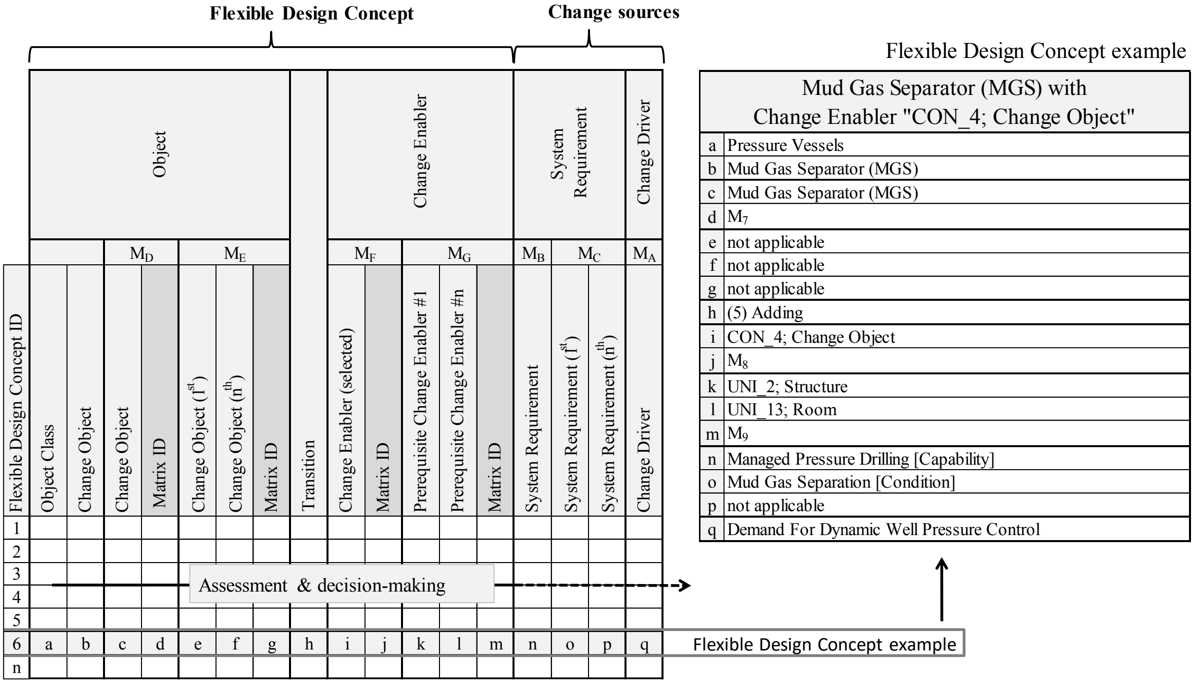
[248] Table 6-2 also provides an example of a Flexible Design Concept for the Change Object “MGS” with Change Enabler “CON_4; Change Object” as is selected for the intermediate assessment of section 8.1.4.

[249] This is especially relevant when FDO selections and assessment are performed by diverse people.

[250] Identical Flexible Design Concepts with different change sources must only be considered once for assessment and decision-making.

ties. The Change Object represents the Object that is affected and is to be enabled. As the Change Objects originate from one of the M_D or M_E matrices, additional IDs are provided for better transparency (e.g. M_7 for M_D). Change Objects derived from change propagations of higher degrees (nth) in M_E are visualized by separate columns[251]. The Transition is followed by a specification of the Change Enabler. Columns related to M_F show the desired Change Enabler whereas M_G related columns show all Prerequisite Change Enablers that have to be in place[252].

Table 6-2 FDO EM Report with Flexible Design Concept example



	Object							Transition	Change Enabler					System Requirement			Change Driver
			M_D		M_E				M_F		M_G			M_B	M_C		M_A
Flexible Design Concept ID	Object Class	Change Object	Change Object	Matrix ID	Change Object (1st)	Change Object (nth)	Matrix ID	Transition	Change Enabler (selected)	Matrix ID	Prerequisite Change Enabler #1	Prerequisite Change Enabler #n	Matrix ID	System Requirement	System Requirement (1st)	System Requirement (nth)	Change Driver
1																	
2																	
3																	
4																	
5																	
6	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q
n																	

Mud Gas Separator (MGS) with Change Enabler "CON_4; Change Object"	
a	Pressure Vessels
b	Mud Gas Separator (MGS)
c	Mud Gas Separator (MGS)
d	M_7
e	not applicable
f	not applicable
g	not applicable
h	(5) Adding
i	CON_4; Change Object
j	M_8
k	UNI_2; Structure
l	UNI_13; Room
m	M_9
n	Managed Pressure Drilling [Capability]
o	Mud Gas Separation [Condition]
p	not applicable
q	Demand For Dynamic Well Pressure Control

System Requirements that are directly affected by Change Drivers refer to M_B. As Change Objects might originate from indirectly affected System Requirements, first and higher order (nth) elements are depicted in M_C. The last column shows the Change Driver domain with the decisive Change Driver[253] that directly affects the System Requirement domain.

As highlighted in Table 6-2, unique Change Object-Transition-Change Enabler combinations, represent a “Flexible Design Concept”. It must be assessed individually as each Change Object can be subject to different suitable Transitions and Change Enablers (section 3.3). Consequently, the initial table usually consists of various Flexible Design Concepts for each Change Object. However, after the assessment and decision-making, each Change Object should only have identical Transitions and best performing Change Enablers. As illustrated in section 6.1, a Change Object may need to be split into different instances, i.e. own rows, if a homogenization

---

[251] Note that in Table 6-2, Change Object nth only represents a placeholder for the suitable number of columns.

[252] Prerequisite Change Enablers of higher degrees (nth) are not emphasized in this work.

[253] Showing higher order Change Drivers (towards root cause) are not considered to be advantageous with regards to transparency.

of Transitions cannot be attained without splitting[254]. Irrelevant Flexible Design Concepts are removed by striking each row[255].

The final solution ("Flexible Design Solution") for each Change Object might be a combination of various Flexible Design Concepts (rows) with different best performing Change Enablers. Flexible Design Concepts should be consistent amongst each other being ensured by applying the "Change Enabler Consistency Matrix" introduced in section 7.5.

The process of assessment and decision-making is elaborated on in the following.

Process of assessment and decision-making

The Flexible Design Concepts that are assessed and require decision-making are not yet physical in nature opposed to the subsequent phase of embodiment design[256] and, thus, subject to uncertainty during assessment. Additionally, the high number of Flexible Design Concepts makes a thorough quantitative assessment less feasible.

Consequently, a stage-based qualitative assessment is preferred (Figure 6-17) that supports the gradual containment of solutions especially under the boundary conditions presented in section 1.3.2. The process applies to both the intermediate and final assessment of Flexible Design Concepts.

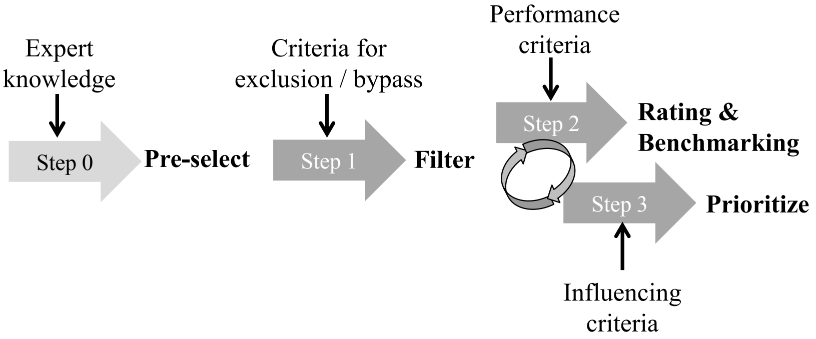


Figure 6-17 Assessment and decision-making process

The pre-step (step 0) accounts for possible knowledge by domain experts who can easily discard Flexible Design Concepts that should not be pursued further. This reduction can be subdivided into:

---

[254] The split must be performed in the FDO Execution Model itself ending up in at least another row in the FDO EM Report.

[255] As for the documentation of requirements lists [LINDEMANN 2005, pp. 108–113], for documenting the decision-making less suitable Flexible Design Concepts are not deleted.

[256] "Embodiment design is the part of the design process in which, starting from the principle solution or concept of a technical product, the design is developed in accordance with technical and economic criteria and in the light of further information, to the point where subsequent detail design can lead directly to production" [PAHL ET AL. 2007, p. 227].

- Reduction of Transitions: The number of Flexible Design Concepts can be reduced by homogenizing Transitions[257] (section 4.2.1).
- Reduction of Change Enablers: The number of Flexible Design Concepts can be reduced by identifying least performing Change Enablers which are then discarded.

In step 1 an absolute assessment of the remaining Flexible Design Concepts is performed based on criteria related to technical risk and the perspective of a System Supplier. Especially based on informal interviews, case-based interviews and their evaluations, the following criteria were derived:

- "Technology Readiness Levels (TRLs)" describing the state of the art of a given technology and providing a baseline from which maturity is gauged and advancement defined [NASA 2007, pp. 296–298]. TRLs are defined on a scale from 1 (basic principles) to 9, with latter reflecting the most mature and already fielded technology. The threshold for discarding Flexible Design Concepts is set individually.
- "Feasibility of incorporation in project" concerns the successful delivery of the pursued flexible design under the boundary conditions of the project, especially acknowledging its time and economic constraints. For instance, Flexible Design Concepts with lower TRLs might still be acceptable in projects with extended feasibility periods such as in system development projects that are "Operator-dominated" (section 1.1.2).
- Fulfillment of applicable "Prerequisite Change Enablers", i.e. those Change Enablers that are not explicitly selected (M_G) but are required for the selected ones in M_F. As discussed in the previous section, they may not be applicable in the technical system context of concern and be ignored. If they must but cannot be met, however, the selected Change Enablers in M_F must also be excluded from the beginning.
- Fulfillment of "Must Change Enablers" which are prerequisites for the exercise of specific Transitions in the first place[258]. Whereas Prerequisite Change Enablers are required to allow using the originally defined Change Enablers selected in M_F, Must Change Enablers allow the defined Transitions to be performed in the first place. Hence, under those circumstances and in contrast to the three above criteria, Must Change Enablers are most prioritized and bypass further assessments (step 2 and 3).

In step 2 a relative assessment is performed comparing the performance of the remaining Flexible Design Concepts of each Change Object amongst each other by using the Baseline Object as a reference.

FRICKE & SCHULZ [2005] emphasize the trade-off to be made between the cost of changeability with higher design and manufacturing efforts due to incorporating changeability and the cost

---

[257] If Transitions can already be reduced to one type by experts, the intermediate assessment can stop as its primary objective is the homogenization of Transitions or split-up of Change Objects if required. The Flexible Design Concepts of those Objects would then undergo a final assessment.

[258] SCHLATHER [2015, p. 131] resumes that certain Change Enablers cannot be renounced (e.g. provide space around Objects) as they would hinder exercising a desired Transition (e.g. "Adding" a new Object).

of changing a system architecture imposed by higher effort to change the system architecture across the lifecycle due to not incorporating changeability. GREDEN [2005, pp. 71–74] emphasizes that the additional "upfront effort" represents the "initial cost" that should be smaller than the "option value". Similarly, ROSS ET AL. [2008] display this trade-off in a "Cost-Utility space" confronting the resources required (cost) and value delivered (utility) for the systems to identify those at highest utility at a given cost or those of lowest cost at a given utility. In line with HILDEBRAND ET AL. [2005, p. 51], the scope of adequate design[259] must be determined based on balancing the additional efforts (upfront effort) against the benefits of less efforts (upgrade efforts) and potential operational disturbances of such changes (operational effort & losses). Based on a prior differentiation of flexibility related costs by ALLAVERDI ET AL. [2014] and the performed interviews and evaluations, the following governing performance criteria of the three superordinate categories could be derived for the assessment in step 2 (Figure 6-18).

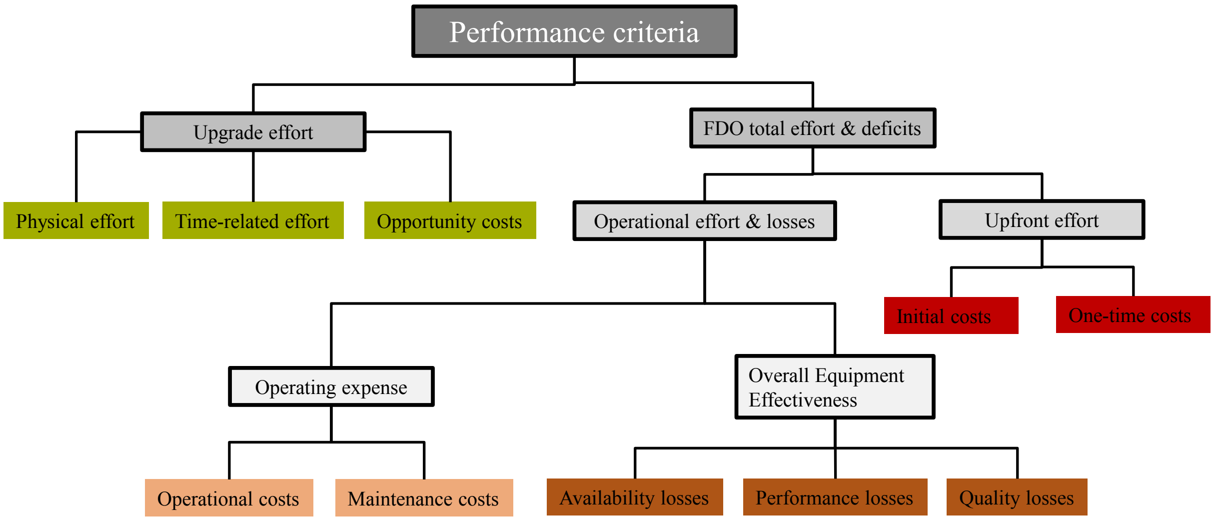


Figure 6-18 Performance criteria for assessment of Flexible Design Concepts in step 2

Each performance category consists of:

- Upgrade effort: This category refers to the "exercise costs" of an upgrade and targets the benefits from incorporating flexibility. Savings can be attributed to less physical effort related to reductions in capital e.g. required material, required machines. It also consists of reductions in time-related effort by spending less time or manpower on changes. Especially a subsequent reduction of opportunity costs[260], which represent implicit costs due to lost opportunities during the period of changes, can also be decreased when reducing the time spent. They can be a highly governing factor as shown in section 1.2.2.

---

[259] Although the focus of HILDEBRAND ET AL. [2005, p. 51] lies on "exchangeability", in particular, it is equally relevant for all Transitions.

[260] Opportunity costs refer to the lost benefit due to not selecting the best rated alternative of all available course of actions [THOMMEN & ACHLEITNER 1998, p. 134].

- Upfront effort: Usually incorporating flexibility leads to an increase in upfront effort [FRICKE & SCHULZ 2005]. One contribution is the increased initial costs due to higher design and manufacturing efforts. However, it may also include implicit opportunity costs such as by attributing additional space for future changes that cannot be used otherwise or only sub-optimally. Next to that upgrade efforts also imply higher one-time costs related to delivery time, transportation, integration and installation of the drilling system, commissioning, personnel and staff training, certification, etc.

In contrast to upgrade and upfront efforts, the category “Operational effort & losses” emphasizes changes in performance during operation. Although in this case neither a positive nor negative impact can be predefined across the board, flexible design may lead to significant performance changes that require a consideration.

- Operating expense: The embedment of flexible design may affect operational costs (energy, supply, disposal, wages for operating staff, recertification costs, etc.) or maintenance costs (service, inspection, repair, etc.).
- Overall Equipment Effectiveness (OEE): Despite the above operating expenses, significant changes might also be attributed to runtime losses during operations such as defined by OEE [HANSEN 2002]. Three types of losses contribute to OEE. This includes the consideration of “availability losses” which in this context of application are mainly related to the time of equipment setup and adjustment or equipment failure and breakdown. “Performance losses” relate to idling and minor stop losses (e.g. due to disturbance of handshakes between machines) or reduced speed losses. “Quality losses” might relate to newly introduced or avoidance of defects, damage of equipment or tangibles. It may also include changes in safety hazards and HSE compliance on the rig.

As already highlighted in section 6.4.1 and ROSS ET AL. [2008], each customer or decision-maker will have an individual acceptability threshold[261] for time and money spent for enacting change. Hence, as preferences strongly vary amongst customers and the methodology shall account for customer-dependent decision-making on solutions (R 9) also during intermediate and final assessment, performance criteria are weighted. A progressive weighting (1,3,9) is suggested, which in contrast to a linear weighting, implies a disproportional increase compared to its importance; thereby, alternatives that seem to be comparable at first sight can be better differentiated [LINDEMANN 2005, p. 184]. The rating itself is performed between “-3” and “+3” differentiating 7 different stages of relative performance[262]. The dependency between rating and performance can be represented as a function (utility function) which accounts for the subjectivity of the rating and marks a reference point for the assessment [LINDEMANN 2005, p. 186]. Those utility functions may be straight proportional, progressive or regressive.

---

[261] “Filtered outdegree”, in that context, reflects the number of alternatives that are available for the particular decision-maker.

[262] The evaluative case study by SCHLATHER [2015, pp. 108–131] indicated that a differentiation of seven rating stages is suitable.

Figure 6-19 exemplifies an assessment of a Flexible Design Concept for the performance category “upfront effort”. The weighted and normalized sum illustrates a slightly higher “upfront effort” than its rigid Baseline Object. It is assigned to the performance profile in Figure 6-19 together with the separately rated two other performance categories of that Flexible Design Concept (calculation not visualized). Whereas the “Operational effort and losses” are comparable, the “upgrade effort” is much lower compared to the rigid Baseline Object.

As shown by Hu & Cardin [2015], a ranking can be a meaningful way to improve the expected lifecycle performance of the system under uncertainty. Hence, if different Flexible Design Concepts exist, each of them would usually have a different profile, performance rating and, based on that, also ranking compared to other Flexible Design Concepts. The underlying performance rating is derived by adding up the performance ratings of each performance category (e.g. upgrade effort) for each Flexible Design Concept (Figure 6-19). Although the performance ranking supports decision-making, a comparison of the performance profiles of different Flexible Design Concepts should also be considered before decision-making. Intuitively, the performance categories that are assigned more to the left of the profile, indicating lower efforts and losses, are more favorable than the ones attributed to the right. Hence, as can be seen both from the performance rating and performance profile in the example of Figure 6-19, the benefits of the Flexible Design Concept outperform the rigid peer which makes it preferable.

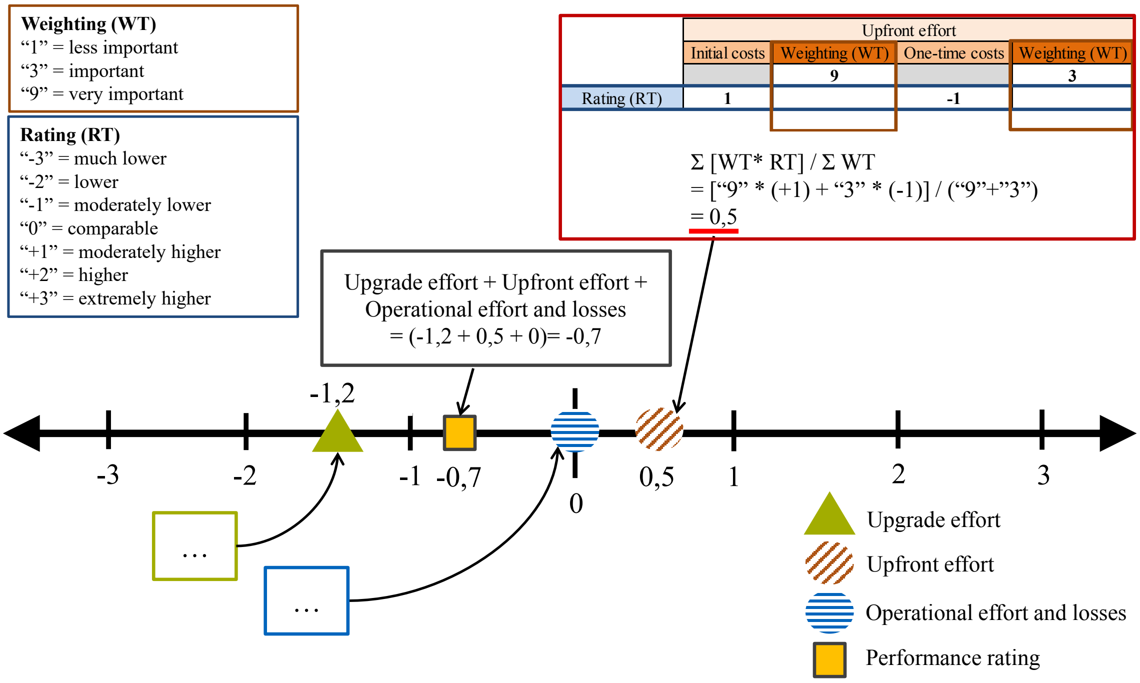


Figure 6-19 Assessment of a Flexible Design Concept by rating and performance profile

As Suh et al. [2007] constitute with a higher frequency of changes occurring and use of a particular flexibility, the value of that flexibility strongly increases as switching or transition costs of rigid designs are frequently undershot. Thus, besides the performance rating and profiles of Flexible Design Concepts, it must also be accounted for that Change Enablers vary in their usage frequency across the lifecycle (step 3) which indirectly affects its performance when considering two main types of changes:

- Frequency of upgrades across lifecycle
- Frequency of maintenance, repair and overhaul activities[263] across lifecycle

In addition to considering the usage frequency of the addressed Change Object and Transition, the total amount also includes usage by other Objects and different purposes[264]. An increased frequency of Change Enabler usage positively affects the performance category "upgrade effort" across the lifecycle. Depending on which activity is facilitated (e.g. upgrade vs. repair) the positive impact varies. The consideration of usage frequency is not explicitly accounted for during the rating of the Flexible Design Concept (step 2) and not visualized in the performance profile. Nevertheless, it allows reconsidering the rating and, finally, ranking of the Flexible Design Concepts and, thereby, supports decision-making.

Based on the assessment and a comparison of Flexible Design Concepts, underperforming ones are removed. As highlighted in section 3.3.2, however, a combination of multiple flexibilities ("compound mechanisms") improves the overall performance. Hence, if desired by the customer and if consistent amongst each other (section 7.5), multiple high-performing Flexible Design Concepts of the same Object are integrated to one solution. The assessment and decision-making is repeated for Flexible Design Concepts of other Change Objects. All Flexible Design Solutions can then be implemented into the initial reference design. As highlighted in section 4.2.1, in case of insufficient Flexible Design Solutions a reselection of Baseline Objects can be performed which restarts the process of FDO identification.

The presented FDO Methodology supports the identification of Flexible Design Solutions. However, without additional support, it would insufficiently fulfill important FDO requirements which, in turn, would challenge the practical application of the methodology. Consequently, FDO Facilitators are introduced which represent complementary methods that should be integrated into the methodology to meet those requirements.

---

[263] As shown in section 2.3, maintenance, repair and overhaul activities are not targeted with the FDO Methodology. However, various Change Enablers meant for upgrades can also support those activities. Neglecting those benefits could falsify the overall value of Flexible Design Concepts.

[264] Although often the only beneficiary is the addressed Change Object, sometimes Changes Enablers can support other types of Objects and rig changes that were not explicitly targeted initially.

7. FDO Facilitators

The build-up and maintenance of the FDO Data Model as well as the running of the FDO Execution Model have a high complexity and cause significant effort. In order to better meet the FDO requirements, FDO Facilitators are introduced which facilitate the FDO Methodology in different phases (Figure 7-1).

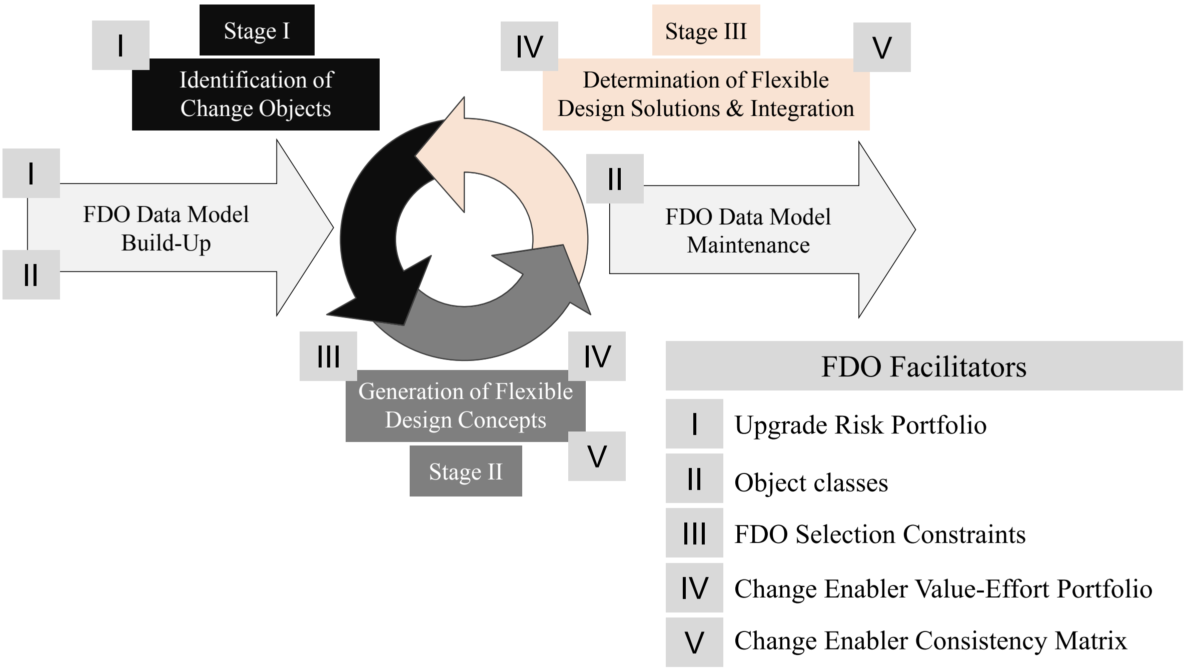


Figure 7-1 FDO Facilitators for different phases of the FDO Methodology

The initial phase, the FDO Data Model build-up, is supported by the "Upgrade Risk Portfolio" (section 7.1) in order to prioritize Objects that should be targeted in the case-based interviews (section 5.2.1). Those Objects are assigned to Object classes (section 7.2) that ease the building of the FDO Data Model. Latter also support the long-term maintenance of the model after it has been built.

The exercise of the FDO Execution Model is supported by various means in the three consecutive stages of the FDO Methodology: the identification of Change Objects, the generation of Flexible Design Concepts and the determination of Flexible Design Solutions that are integrated into the reference design. First, the identification of Change Objects is supported by the "Upgrade Risk Portfolio" which besides building the FDO Data Model also helps identifying the relevant Baseline Objects when running the FDO Methodology. The generation of Flexible Design Concepts in the FDO Execution Model is supported by pre-defined constraints amongst selections (section 7.3). This stage is also supported by a Change Enabler Value-Effort Portfolio (section 7.4) that visualizes the cost-benefit of Change Enablers and the Change Enabler Consistency Matrix (section 7.5) that supports the identification of non-redundant and feasible solutions. Although the two latter methods mainly refer to stage III, they *can already support decision-making when running the FDO Execution Model and, hence, reduce efforts beforehand.*

Besides the FDO Selection Constraints, which belong directly to the FDO Execution Model and have only been built up exemplarily, all other FDO Facilitators[265]*were built up and verified for the product portfolio under investigation to have usable results while demonstrating its applicability.*

7.1 Upgrade Risk Portfolio

The Upgrade Risk Portfolio contributes to limiting the considered Objects when building up the FDO Data Model. It helps setting priorities which Objects to pursue first when running interviews for data elicitation. As performed during the semi-structured interviews, most critical Objects are addressed first followed by less critical ones. In combination with the generation of Object classes (section 7.2), this allows an efficient and effective build-up of the FDO Data Model. Next to that, the FDO Data Model consists of various Objects that could potentially be imported into the FDO Execution Model. Importing all Objects would strongly increase the complexity and effort of identifying Change Objects as more Objects must be screened for and, most likely, less relevant Flexible Design Solutions would be generated in the end. Thus, the Upgrade Risk Portfolio enables the decision-maker to address only the most critical Baseline Objects (step 2 in FDO Procedural Model) from the beginning.

Objects have a diverse risk for being upgraded, highlighted already by the introduced “change risks”[266] that are divided into probability of change and transition costs (section 6.4.1). As observed during the project-independent risk assessment of Objects before running the case-based semi-structured interviews (section 5.2.1), several of those Objects have a very low risk, hardly ever being considered as Change Objects when imported into the FDO Execution Model. The Upgrade Risk Portfolio allows the consideration of the Object’s relevancy before being imported and used in the FDO Execution Model. By limiting considered Objects to only the most relevant ones, this method limits complexity and establishes focus on most relevant Objects. As highlighted in section 4.2.1, for the risk assessment only drilling equipment related Objects are accounted for as bulk items are always imported into the FDO Execution Model. Those Objects are considered on subsystem level III (section 5.3.3) and represent product families as the case-based semi-structured interviews confirmed that a differentiation of variants is not necessary, i.e. does not change the position in the Upgrade Risk Portfolio.

---

[265] The established Change Enabler Consistency Matrix and the relations between Change Enablers could only be verified exemplarily.

[266] The change risk of the Object during the node by node assessment (section 6.4.1) and the project independent risk mapped in the “Upgrade Risk Portfolio” are not necessarily identical. During the node by node assessment the probability of change is done individually for each project, scenario and upstream node. Additionally, the node by node assessment does neither account for downstream change propagation nor the impact due to time losses during those changes / upgrades as both would require a more systemic consideration beyond the addressed node.

The Upgrade Risk Portfolio shares the attributes of a common risk portfolio dividing risk into the two categories “likelihood” and “impact” which both address average values in line with the risk management theory and change prediction method by CLARKSON & ECKERT [2005]. The “likelihood of upgrade” concerns the average probability of Objects to be changed represented by the approximate frequency of yearly physical upgrades [ALLAVERDI ET AL. 2015]. It also accounts for yearly upgrade inquiries of customers that have not been performed and were withdrawn for various reasons.

The “impact of change” concerns the average direct cost impact on Change Objects when changed (transition cost) but also the induced cost impact by change propagation of downstream Objects and the impact of rig downtime[267] when changes of the Change Object have to be performed.

The assessment for building the Upgrade Risk Portfolio was purely based on an average of typical projects and interviewees’ experience. Only medium and larger scale upgrades above a critical monetary value were accounted for to highlight the most relevant Objects and cases for embedding flexibility. Each of the contributing aspects of “impact”, such as “impact by change propagation”, was acquired separately for each Object to be calculated to an overall average value in the end. The individual ratings for both “likelihood of change” and “impact of change” run on a scale that goes from 1 to 10.

Figure 7-2 is a schematic and exemplary visualization[268] of the Upgrade Risk Portfolio. It depicts sample Objects with varying likelihood and impact. The hyperbola represents lines of equal risk. The visualized line of critical risk separates Objects that are imported as Baseline Objects into the FDO Execution Model from those that are not imported due to a low upgrade risk. The line is set individually when running the FDO Methodology due to varying boundary conditions (e.g. time constraints) and acceptability thresholds of customers / decision-makers. As highlighted in section 4.2, this filter may be reduced if solutions remain unsatisfactory (iteration “M” in FDO Procedural Model). This should result in Flexible Design Solutions of less critical Change Objects but with higher lifecycle performance compared to Baseline Objects.

---

[267] Rig downtime refers to losses where the rigs are unable to operate which strongly affects Operator and especially Drilling Contractor.

[268] The actual Upgrade Risk Portfolio cannot be put into the appendix due to reasons of confidentiality.

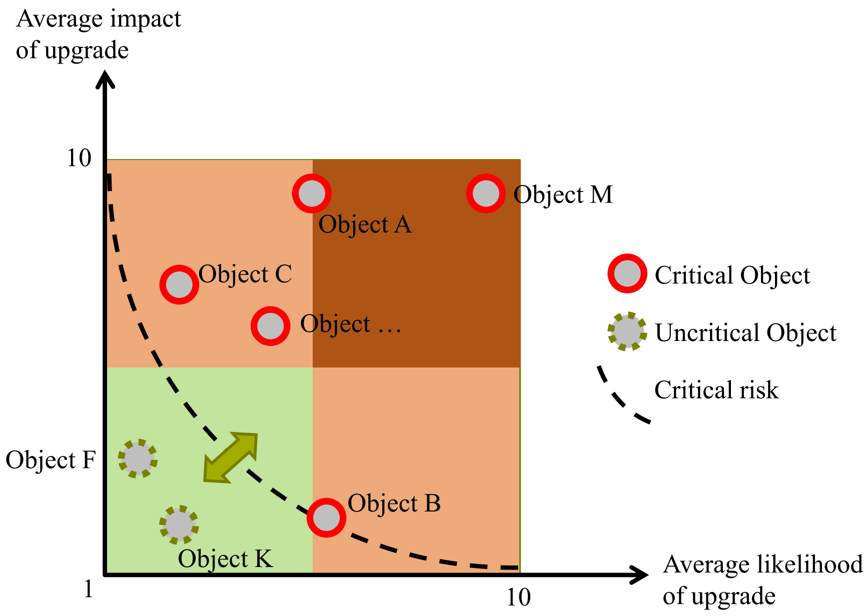


Figure 7-2 Upgrade Risk Portfolio

As highlighted by KOH ET AL. [2013] for the critical Objects it is "imperative to make these system components more changeable so as to improve the overall changeability of the system". Whereas the impact can be reduced by flexible design measures, the likelihood of change can be reduced by embedding robust measures which are only regarded complementary to the targeted flexible measures in the FDO Methodology as described in section 2.4.4.

Together with the Upgrade Risk Portfolio, the Object classes are relevant to ease the build-up of the FDO Data Model. They are introduced in the following.

7.2 Object classes

In section 7.2.1 the underlying criteria and the results on Object classes are presented. They build strongly on the work and results of SCHLATHER [2015]. This is followed by section 7.2.2 where those Object classes are applied and their value is demonstrated.

7.2.1 Generating Object classes

Section 5.2.2 highlighted the reasons for a densely populated FDO Data Model that targets the stage of concept generation. Attaining suitable combinations of Change Objects and Change Enablers (M_F) or Transitions (M_H), respectively, can be done individually for single Change Objects or, more efficiently, by transferring knowledge of known suitable combinations to other Objects. As shown at the beginning of chapter 7, thereby the build-up (R22) and maintenance of the FDO Data Model (R23) can be supported.

The basis for building those Object classes builds upon two assumptions:

- Different types of Objects require different Change Enablers / Transitions[269]
- Objects that share certain properties require alike Change Enablers / Transitions

Consequently, Object classes target building groups of Objects which can be enabled equally (M_F) or require the same Transitions (M_H). In that context, SCHLATHER [2015, pp. 70–77] focuses on understanding the relations between Change Objects and Change Enablers. On the one hand, the analysis focuses on the data from the case-based interviews (section 5.2.1) by focusing on the identified Change Enablers of Change Objects, contextual information for better understanding (e.g. upgrade process) and Object-specific product information (e.g. technical drawings). On the other hand, the analysis bases upon literature to identify the criteria behind a suitability of Change Enablers to certain Change Objects. This included accounting for product properties on different hierarchical levels (functional, working principle, physical level) as suggested by PONN & LINDEMANN [2011] and the criteria for the "classification of technical systems" introduced by HUBKA [1984, pp. 82–96]. Based on the data and the criteria from literature, SCHLATHER [2015, p. 75] synthetized a limited set of Object properties[270] upon which Object classes with akin properties were then generated. In line with LINDEMANN [2005, p. 160], those Object properties are made up of two property constituents[271], namely an "attribute" and a specific "characteristic"[272]. The Object properties, including attributes and exemplary characteristics from the data, are shown in the following:

- Function, e.g. rotate, apply torque, drill
- Type of operand, e.g. tubular
- Main assemblies, e.g. swivel, gearbox, motor
- Powering principle, e.g. hydraulic, pneumatic, passive
- Geometry, e.g. block, barrel
- Degree of complexity, e.g. high
- Size, e.g. big
- Weight, e.g. heavy
- Structural arrangement[273]

---

[269] Building Object classes with identical Transitions was not targeted from the beginning and resulted from the data of the case-based interviews and the subsequent evaluation.

[270] Properties that change due to boundary conditions (e.g. position) were not considered as they represented an unstable set of criteria that allows Objects to switch between Object classes.

[271] As highlighted by BIRKHOFER & WAELDELE [2008], the English translation of "Eigenschaften" (ger.) and its two constituents can be ambiguous. Hence, the suggested separation into "attributes" and "characteristics" may have different meanings across literature.

[272] LINDEMANN [2005, p. 160] refers to "Eigenschaften" (ger.) that consist of "Merkmale" (ger.) and "Ausprägungen" (ger.).

[273] Added to the existing set of properties after the verification of the generated Object classes as an important Object property was missing.

Similar to the introduced utility functions in section 6.4.2, the properties “size” and “weight” were assigned to quantitative values (e.g. small size equals 1m^3) to reduce subjectivity. Whereas some attributes of Objects can have various characteristics (e.g. property of Object “Mud Hopper” with attribute “function” has both the characteristic “feed” and “mix”), other Object properties are always unique for a Change Object[274], i.e. Object attributes can only be assigned to a single characteristic. A non-redundant and unambiguous terminology of characteristics was established (e.g. function “guide” excluding alternative expressions such as “route” or “lead”) to allow a clear and unique assignment of Objects to Object classes. In order to avoid too many Object classes while still ensuring a suitable assignment of Change Enablers to Change Objects, a minimum correspondence[275] of properties across Objects (e.g. corresponding in same function, operand, size, etc.) had to be in place. Based on the commonalities across Objects (e.g. Object “Drillers Control Cabin” and “Local Instrument Room”) and the elicited data on suitable Change Enablers for certain Change Objects from the case-based interviews, new Objects that were not yet addressed could now be assigned to the generated Object classes (e.g. Object class “Containers”, “Pressure Vessels”, “Manifolds”, etc.). Table 7-1 illustrates the Object class “Container” generated by SCHLATHER [2015] with a full correspondence of properties across Objects.

Table 7-1 Exemplary Object class “Container” defined by SCHLATHER [2015]

	Container			
	Drillers Control Cabin	Local Instrument Room	Local Electrical Room	Other Drilling System Containers
Function	Protect, Surround	Protect, Surround	Protect, Surround	Protect, Surround
Type of operand	People, Equipment	People, Equipment	People, Equipment	People, Equipment
Main assemblies	Walls, Ceiling, Floor	Walls, Ceiling, Floor	Walls, Ceiling, Floor	Walls, Ceiling, Floor
Powering principle	not applicable	not applicable	not applicable	not applicable
Geometry	Box	Box	Box	Box
Degree of complexity	Medium	Medium	Medium	Medium
Size (range)	Medium	Medium	Medium	Medium
Weight (range)	Medium	Medium	Medium	Medium

Based on the case-based interviews and the technical documentation the applicability of Object classes could also be demonstrated for Transitions (M_H) as shown by SCHLATHER [2015, pp. 81–82]. The suitability of the generated Object classes together with the newly assigned Objects were verified regarding Change Enablers and Transitions. Based on this verification the suitability of Object classes and the assigned Objects could mostly be confirmed. Exceptions were handled by individual markings, splitting of Objects and Object classes or adding the attribute “structural arrangement” that was missing initially [SCHLATHER 2015, pp. 89–96]. Table 7-2 illustrates the Object class “Container” together with the assigned Objects, Change Enablers and Transitions.

---

[274] Single assignments apply to the attributes “powering principle”, “degree of complexity”, “size” and “weight”.

[275] A correspondence of at least five out the eight Object properties was targeted to fit into an Object class.

Table 7-2 Exemplary Object class "Container" with suitable Change Enablers and Transitions defined by SCHLATHER *[2015]*

Object class	Objects	Change Enablers	Transitions
Containers	- Drillers Control Cabin - Local Instrument Room - Local Electrical Room - Other Drilling System Containers	UNI_1: Design with regard to geometry and available space; Change Object	1; 3; 4; 7; 8
		UNI_3: Oversize entry and exit areas spatially for easing removal / installation of Objects; Change Object	
		UNI_13: Provide space around Object for better accessibility; Room	
		SCA_4: Provide space around Object for spatial expansion; Room	
		SCA_5: Design non-load carrying separation walls for easing their changes or removal; Change Object	
		MOD_3: Aim for differential / modular design for (dis-)assembly and extension / reduction; Change Object	
		MOD_15: Limit integration of Objects into surrounding structure; Change Object	
		MOD_16: Integrate Objects into compatible other Objects; -	
		CON_4: Use bolts instead of welding for Object fixation; Change Object	
		CON_8: Use bolts instead of welding for Object internal connections; Change Object	
		CON_14: Design detachable bolted hatch in (room) structure for better accessibility; Change Object	
		COM_3: Design for standardized replacement parts / sub-assemblies; Change Object	
		COM_6: Use standardized interfaces between Objects and their modules; Change Object	

In the end a total of 36 Object classes[276] were generated [SCHLATHER 2015, pp. 112–114]. Each Object class contains only those Change Enablers that were initially assigned to Objects of that class during case-based interviews. However, certain Change Enablers might also be valid for other classes that were not explicitly mentioned for Objects of that class. Additionally, some Change Enablers may be independent from the properties defined for Object classes, i.e. do not fulfill the first assumption that "different types of Objects require different Change Enablers". Hence, some suggested Change Enablers are generally applicable making them suitable for various Object classes. The differentiation[277] between those generally applicable and the Object-class specific Change Enablers is also considered as one of the contributions of the FDO Methodology (section 8.2, C16).

7.2.2 Applying Object classes

Object classes primarily target a reduction of efforts related to the building and maintenance of the FDO Data Model. However, they also enhance the quality of the data in the FDO Data Model. Figure 7-3 summarizes the various contributions of Object classes. Effort related benefits targeting the build-up of the initial FDO Model are marked by E_1, E_2 and E_3. Effort related benefits concerning the maintenance of the FDO Data Model relate to E_4, E_5 and E_6. Benefits that concern the quality of the results, independently if for build-up or maintenance, are indicated by Q_1 and Q_2.

---

[276] This excludes a "class" which is not built based on "Object properties" and includes miscellaneous equipment lying outside of the System Supplier's scope (3rd party) and/or is very uncritical.

[277] The differentiation between the general and very specific Change Enablers could only be performed for parts of the database as highlighted by SCHLATHER [2015, pp. 99–100].

As discussed in section 7.2.1, Object classes are both applicable for Change Enablers (M_F) and Transitions (M_H). Consequently, the benefits highlighted in Figure 7-3 are relevant for both types of matrices[278].

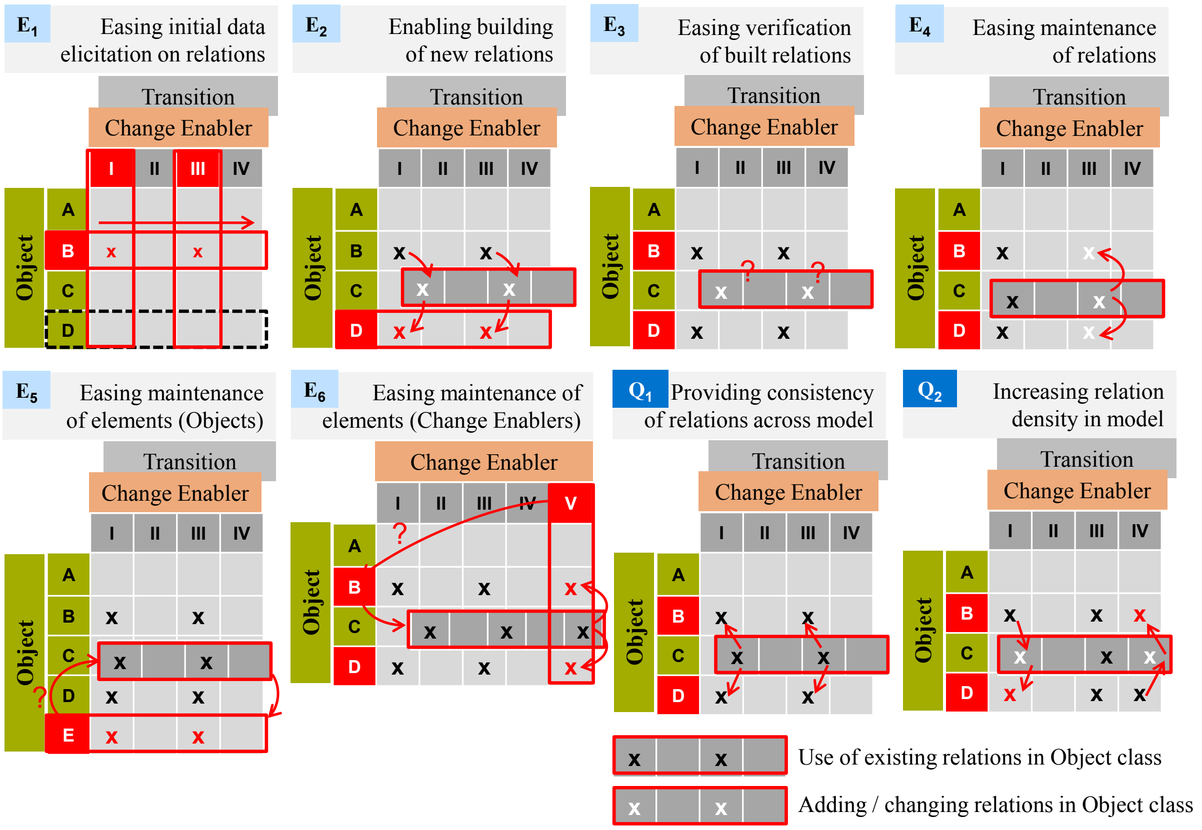


Figure 7-3 Contributions of Object classes

E_1 supports the elicitation of relations by targeting only critical Objects (section 7.1) of a specific Object class that have a satisfactory track record in projects and can be acquired at more ease (Object B in E_1); in this manner, Objects of the same class with hardly any available information (Object D in E_1) do not have to be elicited explicitly. Instead, as illustrated in E_2, based on the gained information in E_1, the elicited relations of Object B can easily be transferred to akin Objects (Object D in E_2) that share certain Object properties and, hence, belong to the same Object class. During the initial build-up, verifications of assigned relations (E_3) can easily be performed for the entire Object class (e.g. central removal or adding of relations, removal of Objects from class, splitting of class). E_1, E_2 and E_3 highlight the contributions of Object classes to generate the densely-populated matrices M_F and M_H of the FDO Data Model (Figure 5-2).

The maintenance of Objects can also be performed centrally by adding or removing relations to and from the class which automatically affects the relations of individual Objects in that class (E_4). In the long run, also new elements are likely to be added to the model: New Objects (Object E in E_5) profit from the already existing Object classes. If Object properties correspond, the added Object E can be assigned to the Object class and, thereby, inherit relations from that

---

[278] The only exception is E_6 where Object classes contribute to M_F only.

Object class (E_5). This also applies to new Change Enablers being added (E_6). However, new Change Enablers (Change Enabler V in E_6) must first be assigned to suitable Objects (e.g. a specific crane (Object B) that would highly benefit from that Change Enabler). Next, the Object class of Object B could then adopt that new Change Enabler. As a result, all Objects that belong to that class, including also Object D (e.g. another crane) could also be facilitated by Change Enabler V in the future[279].

Additionally, the quality of the results is ensured by two contributions of Object classes which apply to both the initial build-up and maintenance of the FDO Data Model: First, Object classes ensure the consistency of relations across the model as akin Objects inherit relations from the centrally stored Object class (Q_1), i.e. relations are and remain equal across Objects of the same class[280]. Secondly, a higher density of relations is usually achieved if Change Enablers or Transitions are elicited for more than one Object of the same class (in Q_2 Object D with new relation to Change Enabler / Transition I and Object B with new relation to Change Enabler / Transition IV). This is due to the fact that interviewees oftentimes miss out on certain Change Enablers or Transitions[281] when discussing relevant Objects for specific (upgrade project) cases. Hence, through elicitations of relations for different Objects in the same class and a subsequent aggregation of those relations, the density of M_H and M_F can be increased[282] (Q_2).

Naturally, despite its value, those Object classes do not replace regular plausibility checks and verifications as Objects might not be sufficiently akin to the intended class, there may exist exceptions for certain relations in that class or the provided data might be disproved by another case or person.

7.3 FDO Selection Constraints

Flexible Design Concepts of Change Objects can be generated by a large amount of Transition and Change Enabler alternatives. The selection of Flexible Design Concepts can be time consuming. There are also multiple paths how the identical Object can be affected and enabled (section 6.2). Hence, interdependencies within and across matrices of selections may become overwhelming to control for the user.

This motivates the use of constraints within and across matrices summarized in Table 7-3 to ensure consistency of results while avoiding redundant and time-consuming efforts during selection and assessment of Flexible Design Concepts (stage II and III in FDO Procedural Model). By setting constraints the user can focus solely on the selection process without being concerned about related prior and subsequent selections.

As shown in Table 7-3, within and across matrices of M_D and M_E, constraints are set between Transitions which are only relevant for the Transition-driven approach (TD). As announced in

---

[279] Naturally, the newly added Change Enabler might be suitable for various Object classes.

[280] As discussed in section 7.2.1 exceptions exist.

[281] Missing out on Transitions is less likely as only 8 predefined elements exist.

[282] The suitability across Objects in that class must be verified and might require a marking if exceptions exist.

section 6.1, the automatic homogenization once a selection is made represents a compromise as different reasons for change (System Requirement, Change Object) may actually lead to different favorable Transitions. Another relevant constraint in M_D concerns the restricted types of Transitions that are available when a new System Requirement (capability) is added. Latter constraint also applies when the Transition is selected in M_F (Enabler-driven approach (ED)). Furthermore, within and across matrices M_F, the "Change Enabler Consistency Matrix" (section 7.5) can be integrated as constraints to avoid inconsistent Change Enablers selections for the identical Change Object. In M_G matrices of all identical Flexible Design Concepts, i.e. identical combinations of Change Object, Transition, Change Enabler must also have the identical Prerequisite Change Enablers[283] selected. At last, double allocations of identical Change Enablers required in M_G should be avoided by constraints prohibiting a redundant selection in M_F. This avoids performing an assessment for a Flexible Design Concept whose Change Enabler must be in place anyway for another Change Enabler selected in M_F.

Table 7-3 FDO Selection Constraints in FDO Execution Model

	Matrix type	Matrix ID	Within matrix	Across matrices
Stage II: Generation of Flexible Design Concepts	M_D	M_3, M_7	• Homogenization of Transitions (compromise): same Transition for identical Object affected by different System Requirements (TD) • If new capability is added: only Transition "1" (Passive) and "2" (Adding) available (TD)	Example Figure 7-4 • Homogenization of Transitions (compromise): same Transition for identical Object affected by different System Requirements (TD)
	M_E	M_{10}, M_{13}	• Homogenization of Transitions (compromise): same Transition for identical Object affected by different Change Object (TD)	• Homogenization of Transitions (compromise): same Transition for identical Object affected by different Change Object (TD)
	M_F	M_4, M_8, M_{11}, M_{14}	• If new capability is added: only Transition "1" (Passive) and "2" (Adding) available (ED) • Compatibility of selected Change Enablers based on "Change Enabler Consistency Matrix"	• Compatibility of selected Change Enablers based on "Change Enabler Consistency Matrix" • Avoiding double allocation of Change Enablers for identical Objects in M_F and M_G
	M_G	M_5, M_9, M_{12}, M_{15}	/	• Same selection ("x") or rejection ("!") of prerequisite Change Enablers for identical Flexible Design Concepts • Avoiding double allocation of Change Enablers for identical Objects in M_F and M_G

TD: Transition-driven; ED: Enabler-driven

Figure 7-4 illustrates the application of constraints by using the exemplary excerpt of the FDO Execution Model in Figure 6-12 extended by M_3. The example illustrates a constraint for M_D across matrices (M_3 and M_7) setting same Transitions for identical Change Objects when performing the Transition-driven approach. In this case Change Object "C" (e.g. "Derrick

---

[283] This can be critical for bulk items (e.g. piping) as they are usually not identical but belong to different areas / Objects on the rig.

Drilling Machine") is affected both directly by changes of System Requirement "4" (e.g. hydraulic power capacity) and by System Requirement "1" (e.g. electric power capacity). However, as System Requirement 1 is not affected by Change Driver "c" but is required by System Requirement 4 (hydraulic power capacity), Object "C" is identified in two different matrices, namely in both M_3 and M_7. As Transition "3" is selected in M_3[284] (e.g. replacement of the Derrick Drilling Machine motor) when performing path "Light" first, the selection in M_7 should be identical by default using constraints.

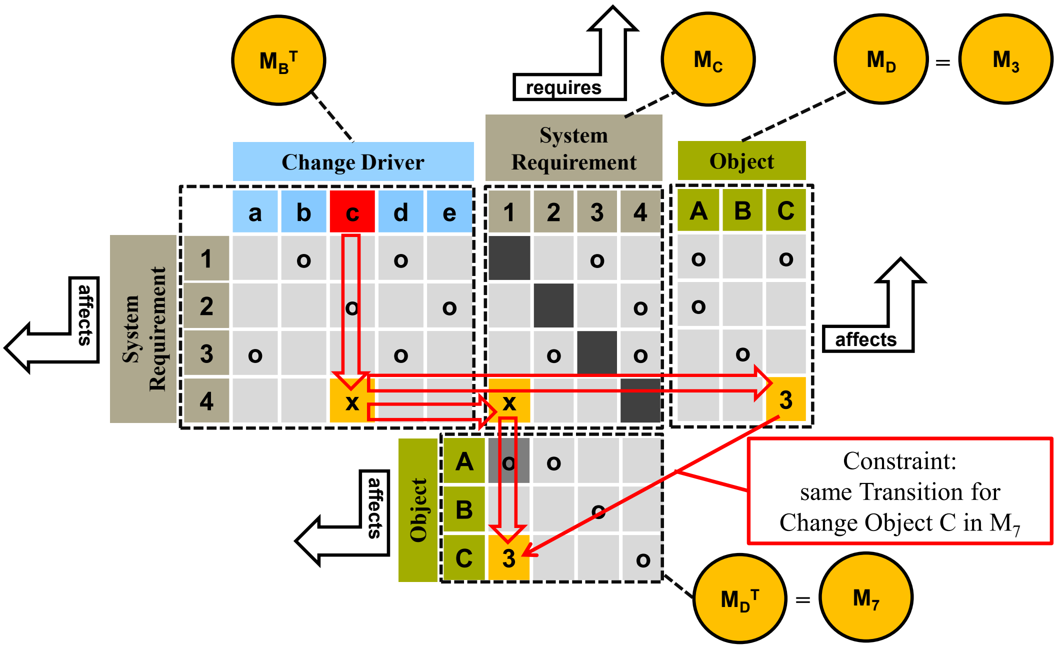


Figure 7-4 Example for illustrating benefit of constraint in FDO Execution Model

Hence, in this example constraints across matrices ensure that Change Object C, the Derrick Drilling Machine, adopts the identical Transition independently of how it is affected. Thereby, a homogenization is already performed without the user having to choose between the Transition alternatives. This represents a compromise as the ideal Transition might differ depending on the type of impact, i.e. if affected by changes of hydraulic power capacity or electric power capacity.

7.4 Change Enabler Value-Effort Portfolio

Both the generation of Flexible Design Concepts (stage II) and the determination of Flexible Design Solutions (stage III) can be extensive as a lot of Change Objects exist that are compatible with various Change Enablers. However, preferences and acceptability thresholds for flexible design vary strongly across customers as discussed by e.g. BROWNING & HONOUR [2008] and ROSS ET AL. [2008]. Hence, accounting for heterogeneous preferences on Change Enablers is

---

[284] Naturally, both fields are not the same if one of those fields is not affected in the first place (e.g. Objects affected by System Requirement "4" but not by "1"). In this case the field in M_7 would be set to "!" whereas in M_3 the Object would have the desired Transition "3".

important to limit iterations and efforts, especially when considering the strong time-pressures that typical tender projects are exposed to (section 1.1.2). At the same time offers that do not meet customer needs are usually punished directly by losing bids and, hence, may even deteriorate bid success rates of System Suppliers when introducing flexible design.

Change Enablers[285] can vary both in absolute value and value-effort ratios. In this application context, "value" only refers to the savings in "upgrade effort", i.e. a reduction of transition costs, whereas "effort" refers to the additional "upfront effort" that is required to incorporate those Change Enablers. In order to ensure a consistent outcome of the assessment, the four alternative performance ratings referred to specific quantifiable characteristics when Change Enablers were assessed during the case-based interviews (section 5.2.1) illustrated in Table 7-4. As can be seen the major underlying criteria of assessment were focusing solely on time-related aspects as they govern the ratings while easing the process of assessment.

The ratings were averaged when rated multiple times across "mini-cases" and then assigned to the Change Enabler Value-Effort Portfolio. As discussed by SCHLATHER [2015, p. 102], however, despite Change Enablers being suggested and assessed multiple times and by different assessors, deviations in ratings have been very limited.

Table 7-4 Performance ratings for specifying value and effort of Change Enablers

		Value - Upgrade effort savings	Effort - Additional upfront effort
1	Low	almost none (minutes to an hour)	almost none (minutes to an hour)
2	Average	some hours until a day	some hours until a day
3	High	days until a week	days until a week
4	Very high	few until many weeks	few until many weeks

Despite the low sample size when performing the assessment in case-based interviews, the ratings provide a first indication of the value-effort ratios of Change Enablers. Figure 7-5 is a schematic and exemplary visualization of that portfolio used by SCHLATHER [2015, p. 103] to assign specific Change Enablers based on the case-based interviews.

---

[285] Note that Change Enablers were considered without a specific Enabler Reference Object in mind; that means that only design guidelines were rated.

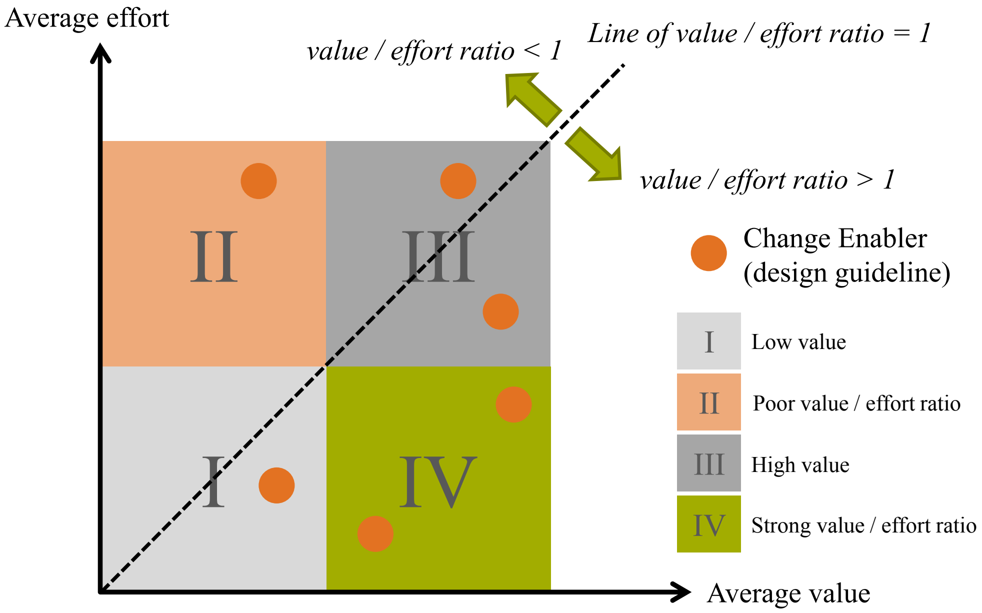


Figure 7-5 Change Enabler Value-Effort Portfolio (adapted from Schlather 2015, p. 103)

The diagonal indicates equal value / effort values. Thus, Change Enablers with ratings below the diagonal are preferable to the ones above. Basing upon SCHLATHER [2015, p. 104], the portfolio in Figure 7-5 can be divided further into four sections with the following characteristics:

- Section I: Although having rather low value, there may be other reasons of customers preferring those Change Enablers. Preferences related to value that is not covered by the portfolio, especially the category of “operational effort & losses” (section 6.4.2) such as “additional safety” or “less maintenance costs” can be governing. Section I may also cover Prerequisite Change Enablers that are not directly preferred and selected but required by preferred high value / effort Change Enablers.
- Section II: Section II represents the least favorable area in the portfolio. Nevertheless, similarly to section I, other reasons may contribute to a consideration of Change Enablers despite the low value / effort ratio.
- Section III: Section III represents Change Enablers of high value but also high effort indicating a high risk of investment if Change Enablers are not exercised across their lifetime. Typically, those Change Enablers are beneficial for customers that are also system users or who can directly benefit from those Change Enablers across the lifecycle.
- Section IV: Section IV contains Change Enablers with the highest value-effort ratios. They are preferable amongst most customers as upfront efforts and, hence, risk of investment is rather low. Those Change Enablers also represent opportunities from a System Supplier’s perspective where Change Enablers can be embedded for customers at no charges with positive effects for both system users and System Suppliers: On the one hand, it enables system users to perform upgrades in the first place and at low efforts. On the other hand, System Suppliers benefit from selling new or modified services which otherwise may not have been realized.

The Change Enabler Value-Effort Portfolio can support the continuous assessment and decision-making of Change Enablers in M_F directly or, indirectly, by considering the additional Prerequisite Change Enablers in M_G. Once selected, it supports the determination of Flexible Design Solutions by rating the selected Change Enablers in step 2 of the assessment and decision-making process (Figure 6-17).

7.5 Change Enabler Consistency Matrix

Each Change Object can usually choose between various Change Enablers in M_F. Besides the consistency across domains that is accounted for in the FDO Methodology (section 4.2.2) and, in particular, the FDO Data Model (section 5.1), Change Enablers[286] may also affect each other negatively as discussed in section 3.3.2. This may be due to the following reasons and has the following implications:

- Compatibility: The inconsistency appears due to a goal conflict of Change Enablers which, in turn, implicates an avoidance of a simultaneous embedment. For instance, the design guideline SCA_14 “Design wider and less compact for easing extension or embedment of modules” is a goal conflict to design guideline MOB_9 which aims for “compact design for enhancing mobility”.
- Redundancy: The inconsistency arises due to the fulfillment of the same function or contributing similarly to meeting the goal[287]. They are redundant to each other and represent alternatives which, if embedded, usually[288] reflect unnecessary investments or do not provide any additional value. For instance, the design guideline SCA_16 “Assign dedicated areas on room ceiling for evolutionary development of piping, cabling and ducting” is redundant to design guideline MOD_13 “Assign area and interfaces to specific additional piping, cabling and ducting”.

Consequently, a significant reduction of irrelevant Change Enablers can take place by confronting them in a matrix. The consistency matrix explores the agreeability of elements amongst each other, uncovers contradictions and goal conflicts and allows deducing consistent combinations of elements [LINDEMANN 2005, p. 276]. Figure 7-6 is a schematic and exemplary visualization of that consistency matrix. Two types of inconsistencies exist being indicated by:

- “I” for Change Enablers that are incompatible to each other
- “R” for redundant Change Enablers that should not be embedded simultaneously

All other pairs are not inconsistent to each other, hence, can theoretically be combined. Beyond the clear incompatibilities and redundancies, however, positive and negative synergies may

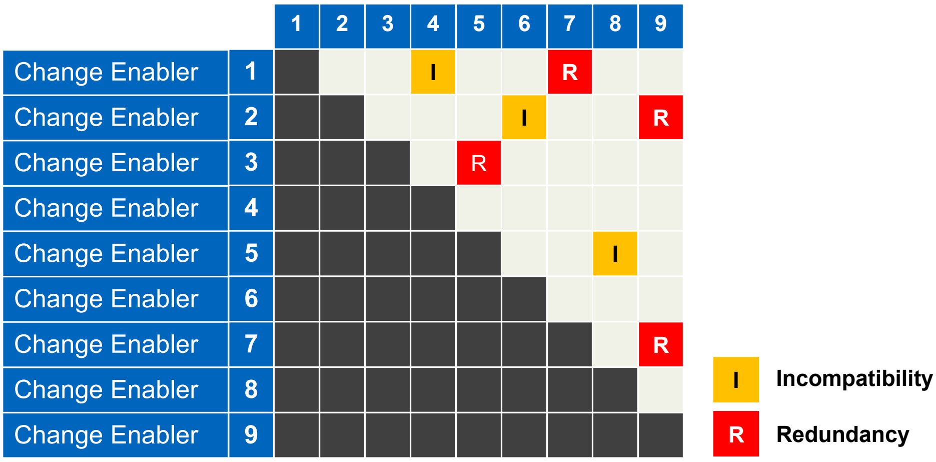
---

[286] Although inconsistencies amongst Change Enablers are defined across “design guidelines”, they equally apply to “Change Enablers” with Enabler Reference Objects included.

[287] As discussed in section 5.3.4, however, this may also be due to the heterogeneous level of concretization of design guidelines, where more general ones include aspects of more specific ones, hence, represent alternatives to each other. The user is then obliged to determine if the more general or the more specific one should be selected.

[288] Can be ignored if redundancy of Change Enablers is desired.

exist. The strength and existence of those synergies, however, strongly depend on the type of Objects and technical system context as discussed in section 6.4.1. For instance, increasing the number of Objects to multiple ones with lower capacities (SCA_9) may reduce the weight of the now subdivided single Objects (MOB_7) or have no impact at all (e.g. if Object was already modularized in the first place). Hence, as the "synergy" of Change Enablers can hardly be described on the rather abstract level of Change Enabler (guidelines) and decisions become rather intuitive once the Object and the reference system are known when applying the FDO Methodology for a project, only generally applicable incompatibilities and redundancies are represented in the Change Enabler Consistency Matrix.



		1	2	3	4	5	6	7	8	9
Change Enabler	1	■			I			R		
Change Enabler	2	■	■				I			R
Change Enabler	3	■	■	■		R				
Change Enabler	4	■	■	■	■					
Change Enabler	5	■	■	■	■	■			I	
Change Enabler	6	■	■	■	■	■	■			
Change Enabler	7	■	■	■	■	■	■	■		R
Change Enabler	8	■	■	■	■	■	■	■	■	
Change Enabler	9	■	■	■	■	■	■	■	■	■

I **Incompatibility**
R **Redundancy**

Figure 7-6 Change Enabler Consistency Matrix

The Change Enabler Consistency Matrix can be embedded by integrating inconsistencies as constraints in M_F matrices in stage II as illustrated in section 7.3. Once certain Change Enablers are selected for Change Objects, inconsistent ones are prevented from selections. In this case a prior overview of suitable similar Change Enablers is advantageous for the user before an initial selection as certain Flexible Design Concepts are locked and cannot be selected although competing Change Enablers may turn out to have a better value / effort ratio. The consideration of inconsistencies as constraints may also only include one of the two inconsistency types, i.e. either "R" or "I" where accounting for either of them is postponed to stage III.

Alternatively, the selection of Change Enablers may not be desired to be limited from the beginning. Preventing inconsistent Flexible Design Solutions in the end is ensured by a full subsequent assessment in stage III when the "rating & benchmarking" of Flexible Design Concepts is performed (section 6.4.2). In contrast to using constraints, here the "Change Enabler Consistency Matrix" is used explicitly. By comparing Change Enablers inconsistent ones are removed to keep only the best of the two Flexible Design Concepts.

Although postponing the consideration of inconsistencies to stage III can lead to better global results due to relative comparison before elimination, it is more time consuming compared to the constraint-based use of the Change Enabler Consistency Matrix.

Based on the presented FDO Methodology, the evaluation of the methodology is now presented in the next section.

8. Application and evaluation of FDO Methodology

Performing an evaluation of a design support is essential because its effects can only be assumed while developing the support; it is aimed at obtaining a proof-of-concept [BLESSING & CHAKRABARTI 2009, p. 182]. Support evaluation[289] was regularly performed during the development of the overall methodology and for subparts of the FDO Methodology both by the researcher and by using evaluators. Due to constraints in resources, only an initial final evaluation is performed to indicate applicability, usability and usefulness of the design support.

In this chapter, first an industrially relevant use case of the offshore drilling industry is presented (section 8.1). This is followed by illustrating the theoretical contributions of the FDO Methodology to the fulfillment of the deduced FDO requirements (section 8.2). Both the application in the use case and the theoretical contributions of the FDO Methodology form the basis for evaluating the FDO Methodology by domain experts (section 8.3). Section 8.4 provides a reflection and conclusion based on the performed evaluation.

8.1 Use case: MPD capability on drillship

Section 1.1.4 motivated this research by illustrating that Managed Pressure Drilling (MPD) is a highly uncertain yet beneficial drilling method in the offshore drilling industry that requires a systematic approach for identifying FDOs. Consequently, the FDO Methodology is applied on this use case.

In the following section 8.1.1 a general understanding of the MPD drilling process, drilling systems and the use case are provided. Next, the initial situation and preparation before running the FDO Execution Model is presented (section 8.1.2). The FDO execution is then run for the two cumulative paths “Light” and “Advanced” (section 8.1.3). Finally, an intermediate assessment of Flexible Design Concepts based on the exported FDO EM Reports is provided that are run before further paths related to change propagation of Change Objects are considered (section 8.1.4).

8.1.1 Use case basis

MPD drilling process and use case

Conventional drilling is performed under atmospheric pressure by drilling fluid exiting the top of the wellbore through a diverter which guides the flow to a flowline. The flowline leads the gaseous drilling fluid to the Mud Gas Separator (MGS) which separates the gas from the liquid. Solid control equipment such as the Shale Shaker separates the fluid from solid rocks and after treatment the purified mud can be re-injected into the wellbore again.

---

[289] Support evaluation involves continuous testing during development of the design support to ensure that it can be evaluated in the end.

In a stable state of drilling when circulating mud, the bottom-hole pressure P_{BH} in the wellbore equals the hydraulic pressure (P_{Hyd}) and the dynamic pressure due to annular friction (P_{AF}). When the circulation is stopped due to e.g. making up drillpipes on the rig, P_{BH} exceeds P_{Hyd} which can cause an influx that affects the drilling efficiency as the influx has to be circulated out of the well. Those well control incidents come in addition to the repeating "Kick-stuck-kick-stuck" scenarios triggered by lost circulation, stuck pipe and wellbore instability. They all contribute to non-productive time (NPT) on the rig [MALLOY 2007].

In contrast to conventional drilling, MPD is realized by a closed vessel, i.e. fluids exiting the borehole are not exposed to the atmosphere. Additional to the static hydraulic pressure (P_{Hyd}) and the dynamic pressure (P_{AF}), a back pressure (P_{Back}) can be applied flexibly to the closed system. Hereby the annular pressure profile can be controlled better while enabling instant reactions in case of pressure changes. Especially in complex formations with narrow pressure margins[290], MPD can significantly reduce NPT by better controlling P_{BH}.

The following functionalities and systems are required to facilitate MPD operations.

MPD systems and main functionality

Most of the equipment for MPD operations corresponds to the ones for conventional drilling (e.g. hoisting, rotating, tubular handling). They require, if at all, minor modifications if being upgraded to a rig with MPD capability. Nevertheless, by integrating this new capability also dedicated equipment must be installed especially related to well control and mud circulation systems.

In order to ensure a pressurized circulation of drilling fluid the Riser Gas Handling Device (RGHD) is attached to the riser string below the telescopic joint of the riser. The RGHD consists of two main components in the upper riser package: the Riser Drilling Device (RDD) and the Flowspool. The Riser Drilling Device (RDD) consisting of highly resistant and lubricated rubber sealing elements provides an active seal on the drillstring containing annulus pressure while allowing the drillstring to rotate. To prevent the RDD from excessive wear, a Seal Integrity Circuit (SIC) on the topside of the rig circulates synthetic fluid from tanks to the rubber seal via hoses and back. The mud returns are prevented from bypassing the RDD and are run through a Flowspool and the attached hoses (return lines) back to the rig.

Through pipes the mud return then enters the Buffer Manifold which merges the flows. The flow then enters the "Coriolis Meter"[291] where the mass flow rate is measured. Subsequently, it then enters the Pressure Control Manifold which consists of chokes that can be flexibly closed if the mud flow decreases to increase the backpressure P_{Back}. In case of a sudden backpressure loss (e.g. late response of closing chokes), the backpressure remains lost until flow resumption

---

[290] Introduced in section 1.1.4: Means the delta between formation pore pressure and fracture pressure which prevails in mature fields with already highly depleted wells or areas with a strong overburden of seawater, i.e. especially in deeper waters.

[291] In this case the "Coriolis Meter" is not considered as a separate Object but as an integrated module of the "Pressure Control Manifold".

of the well or additional pressure by another source [FREDERICKS & REITSMA 2006]. One such source can be a “Back Pressure Pump” (not visualized in Figure 8-1) which represents an automated on-demand pump to ensure sufficient fluid supply and, thereby, prevent unwanted backpressure losses in the first place or reestablish backpressure once lost.

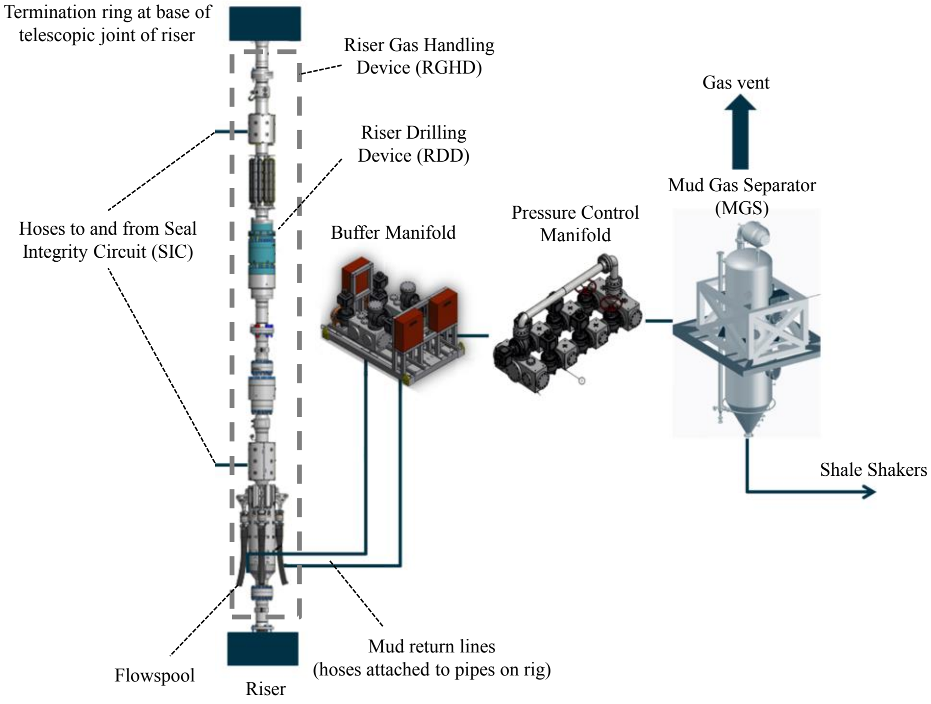


Figure 8-1 Build-up of typical MPD system (adapted from MHWirth AS [2014])

The Pressure Control Manifold then diverts the mud return to the drill floor going through a Mud Gas Separator[292] (MGS) from which large portions of gas are removed and released (gas vent). The mud return then runs through Shale Shakers to get rid of large cuttings and continues to be cleaned and treated with additives before being re-injected into the mud circuit again.

8.1.2 Initial situation and preparation

The use case bases upon a long-term run tender in an Operator-dominated system development (section 1.1.2) for a drillship that is run collaboratively between drilling contractor and oil company[293]. That project addresses the need for drilling operations in increasingly tougher conditions as fields mature and more challenging operating environments are selected. Those environments are usually in deep water (up to 10000 ft) and drilling depth (up to 40000 ft) with the rig and drilling systems being exposed to extreme reservoir pressures and temperatures. The

---

[292] The MGS for MPD must be able to handle much higher gas returns due to the higher flow rates and operations close to pore pressure. Hence, it is referred to as UMGS (Ultra High Rate Mud Gas Separator).

[293] Details are modified as they are irrelevant for the application of the methodology and subject to confidentiality. This project does not coincide with the project where “participatory observation” was performed (section 1.4).

deep water also increases the seawater overburden leading to narrow pressure windows which complicates conventional drilling due to frequent “Kick-stuck-kick-stuck” scenarios. This, in turn, has a negative impact on NPT as highlighted in section 8.1.1. The objective of the rig is to foster efficient and safe drilling operations with the ability of performing well completion and intervention operations.

The assumed circumstances of the project are such that the main technical specifications of the hull design are already set and now System Suppliers compete in this tender to provide suitable drilling systems to meet those technical specifications. Due to a large drop in oil price recently and a negative outlook, drilling operations in deep water have become less likely in the near future. Nevertheless, the drillship is still considered to be built but the customer considers a change of scope that is not embodied in the initial technical specifications. As highlighted in Figure 6-7, the customer expresses the following need:

“In the long-run this rig is still very likely to drill wells at extreme temperatures and pressures. That was the initial intention and the hull is ready for it. Therefore, we would consider having MPD on board once the market picks up again.”

Compared to the initial technical specifications, the customer now considers to postpone the investment and to prepare the drillship for a potential change in the future due to the arisen uncertainty of requiring MPD capability. The customer would like to know the implications of such a decision.

The application of the FDO Methodology on this use case bases upon the steps for the FDO Procedural Model (FDO PM) illustrated in Figure 4-2. Initially, the technical specifications are compared to already delivered drilling systems that were placed on similar hulls. Despite the limited track record on projects meeting those extreme technical specifications, the most suitable reference design of a drillship is selected (step 1 in FDO PM). The boundary conditions, especially the customers being also the system users and the long-time horizon of the tender project, allow the selection of a more comprehensive set of Baseline Objects. By using the Upgrade Risk Portfolio (section 7.1), only the least upgrade critical Objects (criticality of 1) are filtered out from the defined reference design. The rest of the drilling equipment and all bulk items represent the imported Baseline Objects that are now considered in the FDO Execution Model (step 2 in FDO PM). As the main uncertainty addresses “adding a new capability” which usually requires additional dedicated Objects, it must be checked if MPD dedicated Objects are already part of the reference design and imported as Baseline Objects (iteration “B” in FDO PM). In this case the reference design already includes the customer articulated MPD capability, hence, no additional Baseline Objects must be added.

Although an extensive data elicitation and validation was performed to build the FDO Data Model with all MPD relevant elements[294] (section 5.2.2), the identification of FDOs only considers a subset of the data and application in this use case: A full scope model and application cannot be incorporated due to reasons of confidentiality. However, it would also exceed the needs for demonstrating the basic functionality of the FDO Methodology, especially as being used as a demonstrator for the expert evaluation.

---

[294] The Object classes generated by SCHLATHER [2015] also already include Objects with MPD capability.

Concretely, the reduction of data has the following implications:

- More potential Change Objects exist in the FDO Data Model that are not all represented in the FDO Execution Model (stage I)
- More suitable Change Enablers exist to facilitate Change Objects that are not represented in the FDO Execution Model (stage II)

Despite the reduced scope of the data model, also the described scope of the application is reduced to the following:

- Only the paths "Light" and "Advanced" are elaborated on (stage I, II). A possible end result for all paths when running the FDO Execution Model is represented in appendix 11.7.5.
- Only the intermediate assessment of the identified Flexible Design Concepts for one Change Object are shown illustrating both the homogenization of Transitions and the deduction of a Flexible Design Solution (stage III)

In the following section the identification of FDOs of stage I and II are shown using the FDO Execution Model.

8.1.3 Identification of Change Objects and Flexible Design Concepts

For the demonstration in a use case all matrices of the FDO Execution Model were reduced to a representative subset of the FDO Data Model both for stage I and II of the FDO Execution Model (Figure 8-2). The imported elements in the FDO Execution Model are described in detail in appendix 11.7.1. As the Transition-dependent matrices M_H and M_I are superposed with M_D/M_E and M_F in the FDO Execution Model (section 6.1), they are introduced separately in appendix 11.7.2. Figure 8-2 is shown enlarged in appendix 11.7.4.

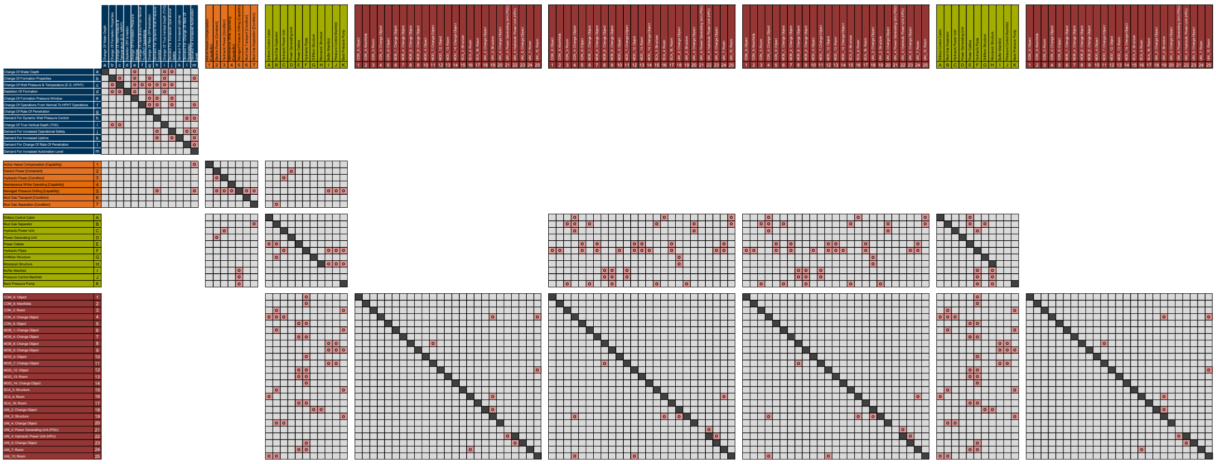


Figure 8-2 FDO Execution Model in use case (enlarged model shown in appendix 11.7.4)

In stage I the reduced matrix M_A* is entirely verified and represents a densely populated and MPD relevant section of the sparsely populated matrix M_A of Figure 5-2. M_B, M_C and M_D are reduced to M_B*, M_C* and M_D* with only seven relevant System Requirements in this application context. They still represent only sparsely populated matrices in the FDO Execution

Model, i.e. even more influences on System Requirement or Objects, are possible than the ones that are mapped. The same applies to M_E that is reduced to M_E* with only 11 Objects.

Stage II, the generation of Flexible Design Concepts, is represented by densely populated matrices with the exception of M_G* as illustrated in Figure 5-2. M_F and, hence, M_F* represents a densely-populated matrix due to the application of verified Object classes. However, a full factorial consideration would certainly lead to discovering further suitable combinations[295] as discussed in section 7.2.1. Finally, M_H and M_I also represent dense and entirely verified relations that are not explicitly represented as matrices in the FDO Execution Model as discussed in section 6.1. In the following those matrices are referred to by singular matrix IDs as also discussed in section 6.1 (e.g. M_3* and M_7* for M_D*).

The identification of FDOs in stage I and II is performed by continuous assessment and decision-making (section 6.4.1). Thereby, for the identification in stage I, change risk factors are accounted for as discussed in section 6.4.1. The relevancy of potential relations in both stages I and II depend on the project context categories where “customer preference & acceptability thresholds”[296] govern the final decision-making. Additionally, both in stages I and II, FDO Facilitators are applied to ease selections (section 7). Note that the use case is run by referring to three different types of “steps”:

- “FDO PM steps 1-8” refer to the FDO Procedural Model (FDO PM) of Figure 4-2
- “Steps I-VI” refer to the gradual scenario building of Figure 6-9
- “FDO EM steps 1-x” refer to individual steps in the FDO Execution Model (FDO EM) of this use case

Path “Light”

As shown in section 6.2, path “Light” represents the basic path of the FDO Execution Model by identifying directly affected System Requirements, Change Objects and Change Enablers. As part of “Recognition of change sources” (step 3 in FDO PM), the process of scenario building is applied (section 6.3.2). In step I (Figure 6-9) the core statements of the articulated need by the customer are assigned to the corresponding FDO domains and elements. As already depicted in Figure 6-7, “extreme temperatures and pressures” can be assigned to the Change Driver “Change of Well Pressure & Temperature” in the database. “MPD” refers to the System Requirement “Managed Pressure Drilling [Capability]” which can also be found in the database.

In step II of scenario building the causal network in the FDO Execution Model is traced by using the articulated need on future change (Figure 8-3). Based on System Requirement “5”, (Managed Pressure Drilling [Capability]) the causal network is back-traced (step 1 in FDO EM) following the guidance for inter-domain and intra-domain tracing (Table 6-1). The Change

---

[295] Each Object class would have to be checked against all Change Enablers. Yet undiscovered suitability would then be inherited to the Objects of the Object class.

[296] Hence, decisions may differ. In this use case, it indicates a typical decision-making under the boundary conditions of the project.

Drivers are selected based on high P_{CD} and customer specific acceptability thresholds. Change Driver “h” (Demand for Dynamic Well Pressure Control) is identified as the underlying reason for a change in System Requirement “5”. Further Back-Tracing (step 2 in FDO EM) leads to the identification of other Change Drivers that are relevant in this context: “Demand For Increased Uptime” (k) and “Change Of Well Pressure & Temperature” (c). Latter also represents the other articulated corresponding FDO element. Hence, it belongs to the same initial scenario as it appears in the same causal chain as the other articulated corresponding FDO element.

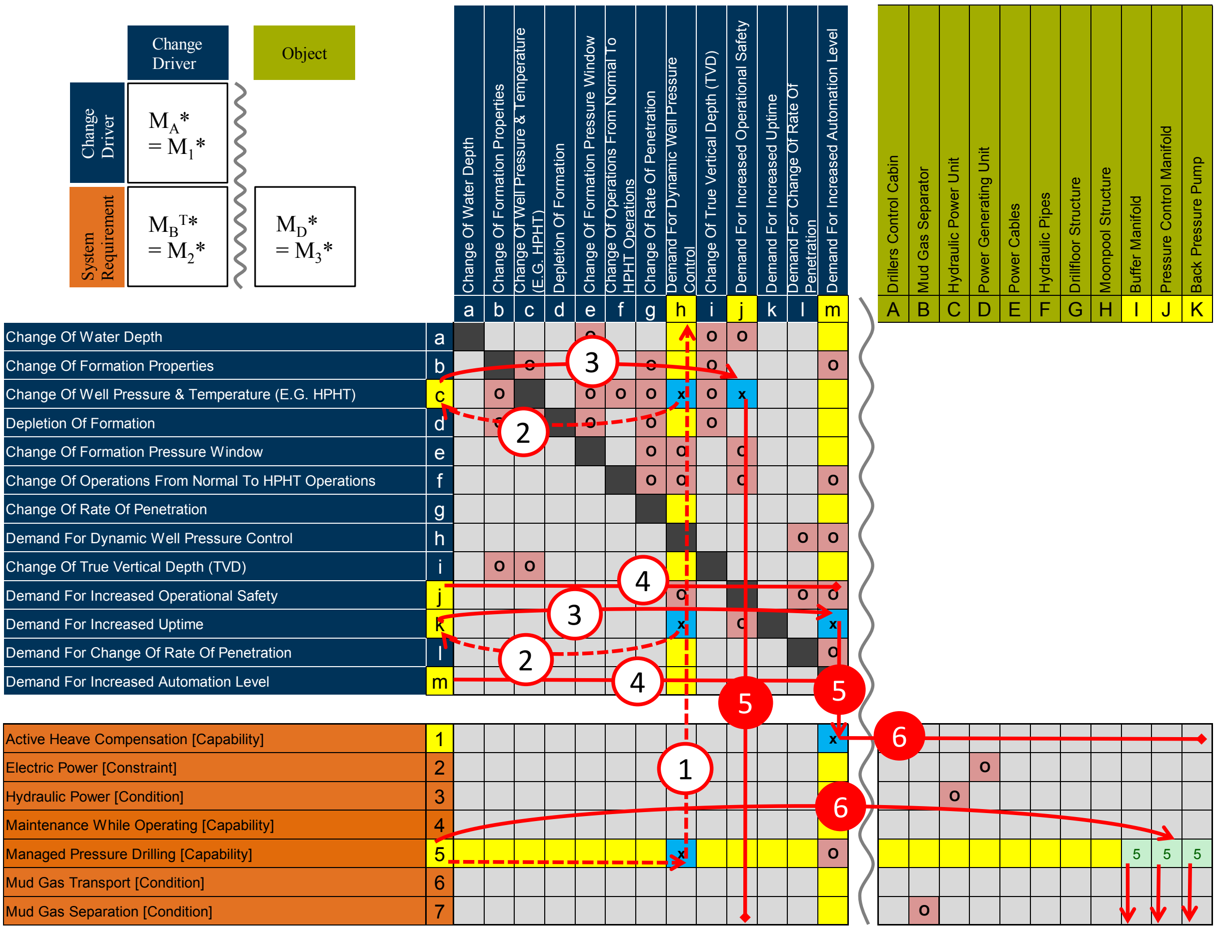


Figure 8-3 Path “Light”: Scenario building and identification of Change Objects in FDO Execution Model

Further Back-Tracing is stopped as the gained results are considered sufficient starting points for further Tracing. Based on the two indirectly identified Change Drivers c and k in M_1^*, the new Change Drivers “j” (Demand For Increased Operational Safety) and “m” (Demand For Increased Automation Level) are selected (step 3 in FDO EM). As both are directly connected to M_2^* and further Tracing in M_1^* (step 4 in FDO EM) leads to no or only irrelevant results[297],

---

[297] In M_1^* the affected Change Driver “m” has an empty row and Change Driver “j” does not cause any other relevant Change Drivers in that row. As argued in section 6.1 although those potential Change Drivers are not selected, irrelevant relations are not marked by <!> but ignored during the identification of change sources, i.e. the initial setting <o> remains. The reason is that in this phase of selections only a small set of elements may actually

the process of building the "initial scenario" is stopped. In line with the process of scenario building (Figure 6-9), this initial scenario also represents:

- An "intermediate core scenario" (step III) as the articulated statement by the customer is the only statement available and both corresponding FDO elements belong to the same causal chain
- A "final core scenario" as no prompting was applied to generate any supplementary scenarios, i.e. steps IV-VI are omitted

Based on the two new Change Drivers "j" and "m", inter-domain Tracing is performed to identify further, not yet articulated System Requirements (step 5 in FDO EM). The confirmation of potential relations is based on a high P_{SR} and customer specific acceptability thresholds. In this reduced matrix M_2*, Change Driver "j" has no impact on other System Requirements. In contrast Change Driver "m" affects System Requirement "1" (Active Heave Compensation [Capability]).

Based on the defined System Requirements and the imported Baseline Objects in the FDO Execution Model, Objects are screened for relevancy (step 4 in FDO PM). Change Objects are identified based on estimating $R^{Received}$ which indicates the risk of change for the node under investigation (section 6.4.1). Partially, decision-making depends on the technical context and, in all cases, on the customer preference and acceptability thresholds.

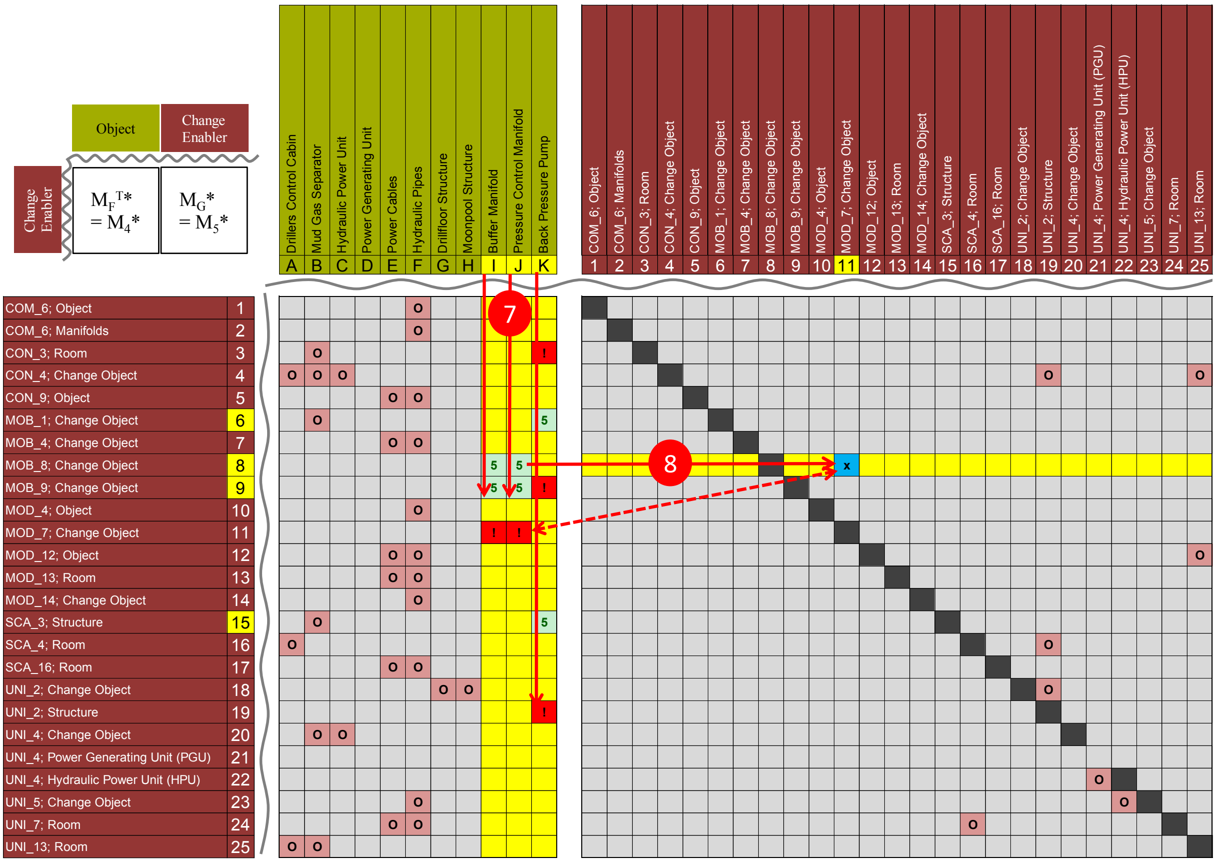
In M_3* no Change Objects are identified by System Requirement "1" (step 6 in FDO EM). Based on the articulated System Requirement "5" (Managed Pressure Drilling [Capability]) Change Objects are identified in M_3* by Tracing (also step 5 in FDO EM). In M_3* the Objects "I" (Buffer Manifold), "J" (Pressure Control Manifold) and "K" (Back Pressure Pump) are selected as Change Objects, hence, are input for stage II, the generation of Flexible Design Concepts. It is decided that Transitions are determined without the consideration of Change Enablers. Hence, in M_3* the identification of Change Objects (step 4 in FDO PM) and Transitions (step 5 in FDO PM) is performed in conjunction representing a "Transition-driven approach" (section 4.2.1).

As a new capability is added, the MPD dedicated Objects can either be added or be installed from the beginning (Passive); this limited set of Transitions can be defined by constraints within matrix M_3* as discussed in section 7.3. In this case "Adding" those three Objects (Transition "5") is the preferred option that is feasible in the system context.

Followed by the identification of Change Objects and their Transitions, suitable Change Enablers must now be identified (step 6 in FDO PM). As shown in Figure 8-4 based on customer preferences, Change Enablers are selected in M_4* (step 7 in FDO EM). As Object "I" and "J" belong to the same Object class "Manifold", they also allow for the same Change Enablers for easing upgrades.

---

be relevant and a confirmation of each potential element in the usually large matrix is considered to be counterproductive.



		Drillers Control Cabin A	Mud Gas Separator B	Hydraulic Power Unit C	Power Generating Unit D	Power Cables E	Hydraulic Pipes F	Drillfloor Structure G	Moonpool Structure H	Buffer Manifold I	Pressure Control Manifold J	Back Pressure Pump K	COM_6; Object 1	COM_6; Manifolds 2	CON_3; Room 3	CON_4; Change Object 4	CON_9; Object 5	MOB_1; Change Object 6	MOB_4; Change Object 7	MOB_8; Change Object 8	MOB_9; Change Object 9	MOD_4; Object 10	MOD_7; Change Object 11	MOD_12; Object 12	MOD_13; Room 13	MOD_14; Change Object 14	SCA_3; Structure 15	SCA_4; Room 16	SCA_16; Room 17	UNI_2; Change Object 18	UNI_2; Structure 19	UNI_4; Change Object 20	UNI_4; Power Generating Unit (PGU) 21	UNI_4; Hydraulic Power Unit (HPU) 22	UNI_5; Change Object 23	UNI_7; Room 24	UNI_13; Room 25
COM_6; Object	1						o						■																								
COM_6; Manifolds	2						o							■																							
CON_3; Room	3		o									!			■																						
CON_4; Change Object	4	o	o	o												■															o							o
CON_9; Object	5					o	o										■																				
MOB_1; Change Object	6		o									5						■																			
MOB_4; Change Object	7					o	o												■																		
MOB_8; Change Object	8									5	5									■			x														
MOB_9; Change Object	9									5	5	!									■																
MOD_4; Object	10						o															■															
MOD_7; Change Object	11									!	!												■														
MOD_12; Object	12					o	o																	■													o
MOD_13; Room	13					o	o																		■												
MOD_14; Change Object	14						o																			■											
SCA_3; Structure	15		o									5															■										
SCA_4; Room	16	o																										■			o						
SCA_16; Room	17					o	o																						■								
UNI_2; Change Object	18							o	o																					■	o						
UNI_2; Structure	19											!																			■						
UNI_4; Change Object	20		o	o																												■					
UNI_4; Power Generating Unit (PGU)	21																																				
UNI_4; Hydraulic Power Unit (HPU)	22																																o	■			
UNI_5; Change Object	23						o																											o	■		
UNI_7; Room	24					o	o																					o								■	
UNI_13; Room	25	o	o																																		■

Figure 8-4 Path "Light": Generation of Flexible Design Concepts in FDO Execution Model

The following Change Enablers are available for the two types of manifolds in M_4*:

- "8": "MOB_8; Change Object" with MOB_8 "Equip with single lifting lug on centralized frame for ease of handling"
- "9": "MOB_9; Change Object" with MOB_9 "Aim for compact design for enhancing mobility"
- "11": "MOD_7; Change Object" with MOD_7 "Design single centralized frame"

Change Enabler "8" has a very advantageous value-effort ratio[298] by being represented in "Section IV" of Figure 7-5. As M_5* indicates in step 8 (FDO EM), Change Enabler "8" also requires Change Enabler "11" as a prerequisite. Latter accounts for the system context under which Change Enabler "8" can be embedded in the first place. The total value-effort ratio is still considered to be acceptable and hence, both Change Enabler "8" in M_4* and Change Enabler "11" are selected in M_5*. Change Enabler "9", in contrast, has a value effort ratio < 1 (Section III in Figure 7-5). However, the high value still makes this Change Enabler attractive and the development of more compact manifolds likely. Hence, Change Enabler "9" is also selected. Change Enabler "11" in M_4*, in contrast, is already embedded as a Prerequisite

---

[298] Note that only the sections of allocation in the portfolio and not the exact value-effort ratios are provided in this work due to reasons of confidentiality.

Change Enabler for the selected Change Enabler “8”. Hence, to avoid double allocation, constraints prohibit its selection in M_4* as discussed in section 7.3.

The following Change Enablers are available for the Change Object “Back Pressure Pump”:

- “3“: CON_3; Room with CON_3 “Design detachable bolted hatch in (room) structure for removal / integration of Object”
- “6“: MOB_1; Change Object with MOB_1 “Equip with lifting lugs / pad-eyes for Object handling”
- “9“: MOB_9; Change Object with MOB_9 “Aim for compact design for enhancing mobility”
- “15“: SCA_3; Structure with SCA_3 “Pre-install structure base for easing subsequent integration of Objects”

Change Enabler “3” is not considered to be of much value as hatches are no option in the envisioned system layout[299] and has a rather low value (Section I in Figure 7-5). Change Enabler “6” is also allocated in Section I but with the minimum effort rating, Change Enabler “6” is considered further. As for the manifolds, the Back Pressure Pump could aim for Change Enabler “9” to enhance mobility. In this case, however, the effort of building the pump more compact is considered to be unjustified. Change Enabler “15” allocated in the favorable Section IV of Figure 7-5 is selected as the last Change Enabler for the Back Pressure Pump. A cross-check with the Change Enabler Consistency Matrix shows that all selected Change Enablers in M_4* are neither incompatible nor alternatives to each other. The identification of indirectly affected Objects based on the performed changes (Path “Profound”) is not further considered.

The Flexible Design Concepts of path “Light” are defined and exported to the FDO EM Report where assessment takes place (step 7 in FDO PM) that is required for determining Flexible Design Solutions (step 8 in FDO PM). The assessment and decision-making for those Flexible Design Concepts, however, is not further pursued. Due to the favorable boundary conditions and the desire for a more thorough analysis, however, FDOs are also selected by path “Advanced”.

Path “Advanced”

Path “Advanced” builds upon the first path and identifies indirectly affected System Requirements as shown in section 6.2 (step 3 in FDO PM). As for path “Light”, System Requirement “5” (Managed Pressure Drilling [Capability]) and the unarticulated System Requirement “1” (Active Heave Compensation [Capability]) represent the starting point for further Tracing illustrated as step 1 (FDO EM) in Figure 8-5.

---

[299] As shown in section 6.4.1, in M_F the “technical system context” and, hence, the reference design must be considered.

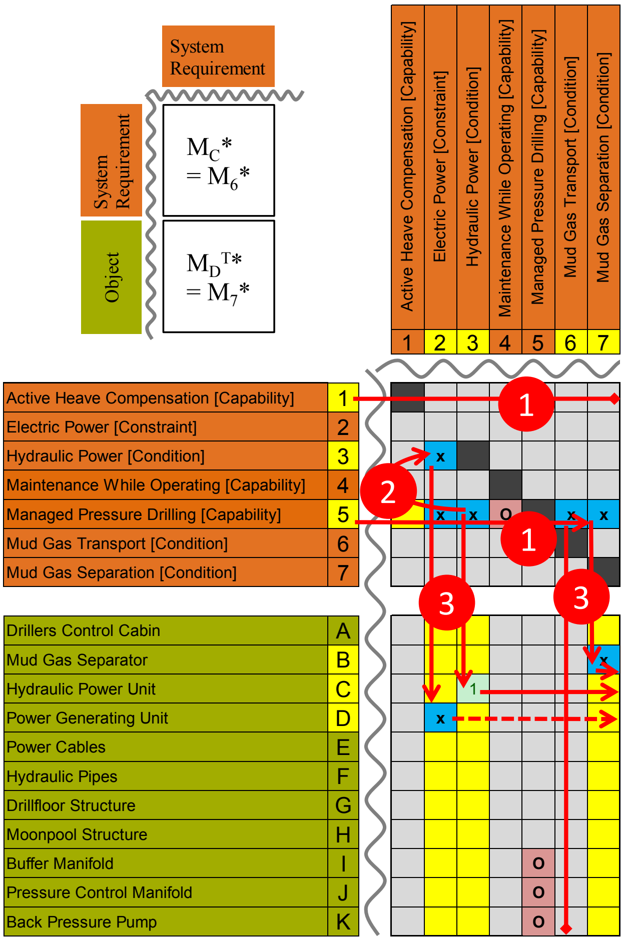


Figure 8-5 Path "Advanced": Identification of Change Objects in FDO Execution Model

As before the confirmation of potential relations is based on high P_{SR} and customer specific acceptability thresholds. System Requirement "1" does not affect any other System Requirements in M_6*. In contrast, System Requirement "5" has 5 potential impacts on other System Requirements. The embedment of "MPD capability" will certainly affect both System Requirement "2" (Electric Power [Constraint]) and "3" (Hydraulic Power [Condition]) as new equipment will be installed and has to be powered. Another System Requirement ("6") that is affected is the Mud Gas Transport [Condition], i.e. the transported mud gas flow rate and Mud Gas Separation [Condition] ("7"), i.e. the rate of gas separation from the mud return. The additional capacity increase is required for the additional gas that is returning from the formation due to operations close to pore pressure (section 8.1.1) while increasing the mud flow and, hence, the trapped gas, compared to conventional drilling. System Requirement "3", the additional hydraulic capacity, however, itself requires additional electric power capacity which may be limited[300] ("2"). This allocation requires intra-domain Back-Tracing and represents step 2 (FDO EM).

---

[300] In contrast to double attributions of Change Enablers, which are redundant and to be avoided by selection constraints (section 7.3), multiple selections of System Requirements, such as System Requirement "2", or Objects undermine the importance of those elements and indicate an even higher priority.

Based on those indirectly affected System Requirements Objects can now be traced in M_7* (step 4 in FDO PM). As for path "Light", Change Objects are identified based on an estimation of $R^{Received}$ (section 6.4.1). As shown in Figure 8-5, the Object "B" (Mud Gas Separator), "C" (Hydraulic Power Unit) and "D" (Power Generating Unit) are affected in step 3 (FDO EM). The Power Generating Unit and the underlying System Requirement, however, lie outside of the solution space, i.e. are not scope of the main System Supplier. Hence, no specific Transition (step 5 in FDO PM) is selected but the information on an impact is forwarded to other System Suppliers in charge which will have to agree on a flexible solution. In line with the customer preferences, the Hydraulic Power Unit is to be built robust without requiring changes in the future (Transition 1= "Passive"). Consequently, it can be specified together with the Change Object selection in M_7* (Transition-driven approach). In contrast, the Transition is still considered to be an undefined design variable in the Flexible Design Concept of the Mud Gas Separator. Therefore, it is only selected as a Change Object and the selection of the Transition is performed together with the Change Enabler in M_8* (step 6 in FDO PM) shown in Figure 8-6. It therefore represents an Enabler-driven approach.

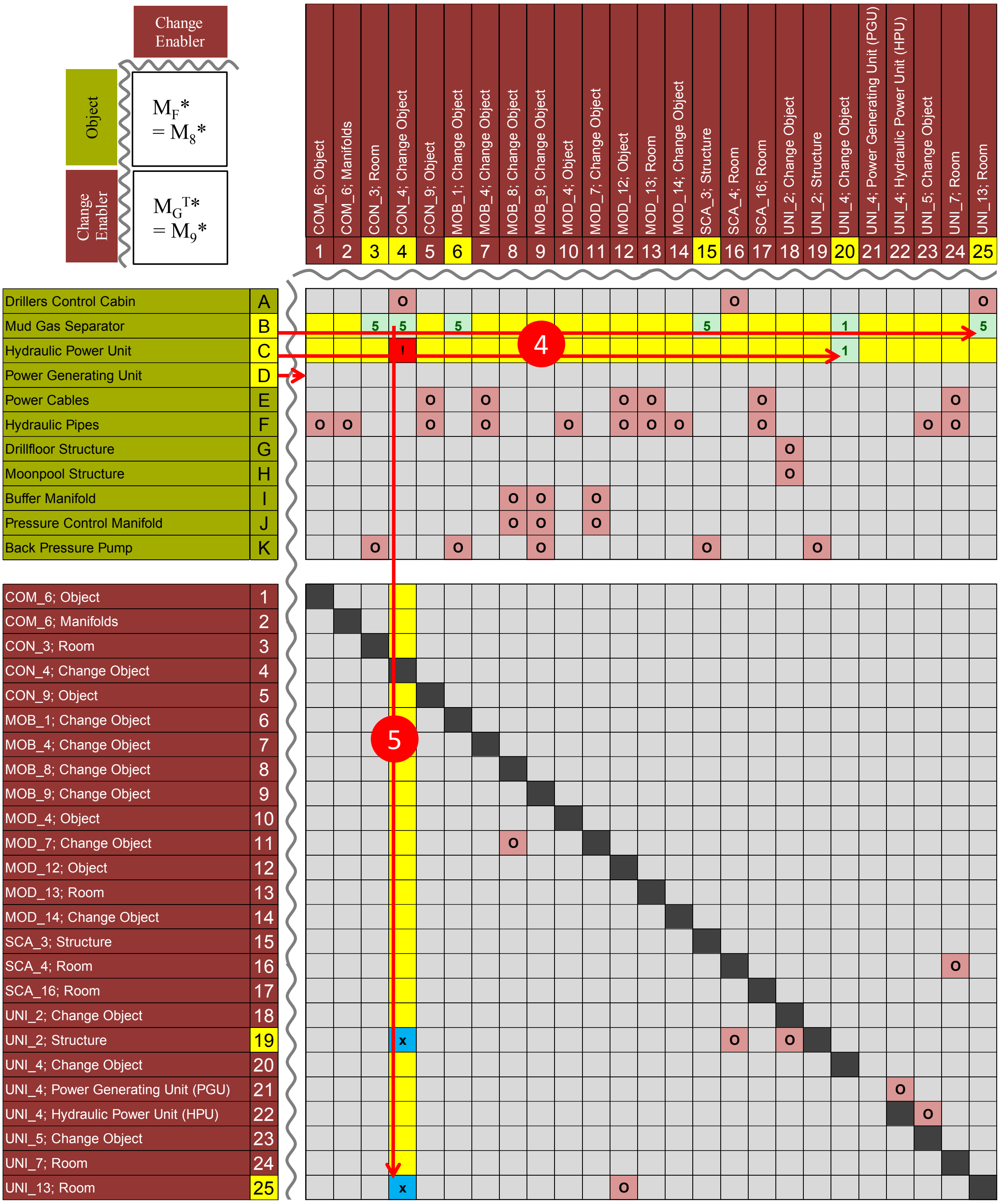
In M_8* the suitable Change Enablers are selected (step 4 in FDO EM) based on customer preferences and, if relevant, the system context. The Hydraulic Power Unit (Object "C") allows only the selection of Change Enabler "20" (UNI_4; Change Object) that also fits to the locked Transition selected in M_7*. Due to the chosen Enabler-driven approach, the Transition and Change Enablers for the MGS are selected simultaneously. Two[301] alternative Transitions are reasonable: Transition 1, "Passive", which requires no physical changes, and Transition 5, "Adding", by integrating an additional MGS to the existing one on the rig. As highlighted in section 6.1, however, both suitable Object-Transition (M_H) and Change Enabler-Transition (M_I) combinations must be accounted for.

The following Change Enablers are available for the Change Object "B" (MGS):

- "3": CON_3; Room with CON_3 "Design detachable bolted hatch in (room) structure for removal / integration of Object"
- "4": CON_4; Change Object with CON_4 "Use bolts instead of welding for Object fixation"
- "6": MOB_1; Change Object with MOB_1 "Equip with lifting lugs / pad-eyes for Object handling"
- "15": SCA_3; Structure with SCA_3 "Pre-install structure base for easing subsequent integration of Objects"
- "20": UNI_4; Change Object with UNI_4 "Oversize with regard to power / energy / capacity"
- "25": UNI_13; Room with "Provide space around Object for better accessibility"

---

[301] Whereas "Passive" refers to the integration of an "Ultra High Rate Mud Gas Separator" or "UMGS" right from the start, "Adding" refers to the need-based integration of an additional conventional MGS after fielding the rig.



		COM_6; Object 1	COM_6; Manifolds 2	CON_3; Room 3	CON_4; Change Object 4	CON_9; Object 5	MOB_1; Change Object 6	MOB_4; Change Object 7	MOB_8; Change Object 8	MOB_9; Change Object 9	MOD_4; Object 10	MOD_7; Change Object 11	MOD_12; Object 12	MOD_13; Room 13	MOD_14; Change Object 14	SCA_3; Structure 15	SCA_4; Room 16	SCA_16; Room 17	UNI_2; Change Object 18	UNI_2; Structure 19	UNI_4; Change Object 20	UNI_4; Power Generating Unit (PGU) 21	UNI_4; Hydraulic Power Unit (HPU) 22	UNI_5; Change Object 23	UNI_7; Room 24	UNI_13; Room 25
Drillers Control Cabin	A				o												o									o
Mud Gas Separator	B			5	5		5									5					1					5
Hydraulic Power Unit	C				!																1					
Power Generating Unit	D																									
Power Cables	E					o		o					o	o				o							o	
Hydraulic Pipes	F	o	o			o		o			o		o	o	o			o						o	o	
Drillfloor Structure	G																		o							
Moonpool Structure	H																		o							
Buffer Manifold	I								o	o		o														
Pressure Control Manifold	J								o	o		o														
Back Pressure Pump	K			o			o			o						o				o						
COM_6; Object	1	■																								
COM_6; Manifolds	2		■																							
CON_3; Room	3			■																						
CON_4; Change Object	4				■																					
CON_9; Object	5					■																				
MOB_1; Change Object	6						■																			
MOB_4; Change Object	7							■																		
MOB_8; Change Object	8								■																	
MOB_9; Change Object	9									■																
MOD_4; Object	10										■															
MOD_7; Change Object	11								o			■														
MOD_12; Object	12												■													
MOD_13; Room	13													■												
MOD_14; Change Object	14														■											
SCA_3; Structure	15															■										
SCA_4; Room	16																■								o	
SCA_16; Room	17																	■								
UNI_2; Change Object	18																		■							
UNI_2; Structure	19				x												o		o	■						
UNI_4; Change Object	20																				■					
UNI_4; Power Generating Unit (PGU)	21																					■	o			
UNI_4; Hydraulic Power Unit (HPU)	22																						■	o		
UNI_5; Change Object	23																							■		
UNI_7; Room	24																								■	
UNI_13; Room	25				x								o													■

Figure 8-6 Path "Advanced": Generation of Flexible Design Concepts in FDO Execution Model

All Change Enablers are selected for the MGS as they are suitable. Change Enablers "3" and "25" with the Enabler Reference Object "room" are suitable but, due to the system layout, "room" refers to an enclosed structure that can be opened from the top when the MGS is lifted into it. The following suitable Change Enabler-Transition combinations exist: Transition "Passive" only suits to Change Enabler "20" whereas the other Change Enablers are suitable for the Transition "Adding".

The consideration of those two Transitions for the same Change Object "B" (MGS), however, displays an internally not yet consistent Flexible Design Concept. A subsequent homogenization[302] of MGS Transitions is both needed for determining the identification of other Objects by change propagation[303] (M_E) and, in the end, for determining a final high-performing Flexible Design Solution. Hence, the Flexible Design Concepts are exported to FDO EM Reports and an intermediate assessment is performed (step 7 in FDO PM) to homogenize Transitions for the MGS and return to stage II of the Procedural Model to identify Change Objects affected by change propagation. The next section, however, focuses solely on the intermediate assessment (step 7 in FDO PM) and based on that on the selection of Flexible Design Solutions (step 8 in FDO PM) without considering change propagation.

8.1.4 Intermediate assessment of Flexible Design Concepts and selection of Flexible Design Solutions

The intermediate assessment is performed equally to the final assessment[304] except that next to providing a basis for Flexible Design Solutions (step 8 in FDO PM), results are again used for stage II to homogenize Transitions and then stage I to identify Objects affected by change propagation (iteration "F" in FDO PM). In this section, however, only the intermediate assessment and, based on that, the selection of Flexible Design Solutions is demonstrated for the MGS. It follows the assessment and decision-making process introduced in section 6.4.2 and Figure 6-17:

Based on the intermediate FDO EM Report[305], expert knowledge should be applied to homogenize Transitions. In this case "step 0" (Figure 6-17) is skipped and an absolute assessment using criteria for exclusion / bypass is performed (step 1):

All six Change Enabler alternatives had a positive track record in the past and, hence, a high TRL level. Especially due to the long feasibility phase of the considered tender project, a successful incorporation of the addressed Change Enablers is guaranteed under those constraints. As shown in step 5 (FDO EM) of Figure 8-6, two Prerequisite Change Enablers in M_G accounting for the system context are relevant to consider for Change Enabler "4" (CON_4; Change Object):

- "19": (UNI_2; Structure): "Oversize with regard to stress / load cases", i.e. a sufficient structural enforcement of the deck structure for allowing bolting
- "25": (UNI_13; Room): "Provide space around Object for better accessibility" to make sure that bolting can be performed in the first place

---

[302] Note that the alternative of splitting up the MGS into two instances (due to two possible Transitions) is not considered further.

[303] If Transition "1" is selected, no change propagation would occur as no change occurs.

[304] Both belong to step 7 in the FDO Procedural Model.

[305] The exported Flexible Design Concept for the Change Object "MGS" with Change Enabler "CON_4; Change Object" was already illustrated as an example in Table 6-2 of section 6.4.2.

According to experts the Prerequisite Change Enabler “25” (UNI_13; Room) represents a Must Change Enabler as it must be in place before another MGS can be added. Next to that a prior installation of a structure base is required to allow the subsequent integration of the MGS (SCA_3; Structure). However, both Change Enablers are obligatory only if “Adding” becomes the favorite Transition which, however, is not yet decided but the result of the intermediate assessment. Consequently, they must still be considered[306] for a performance rating as this could affect the decision-making on the Transition.

For benchmarking the Flexible Design Concepts an assessment is performed using performance criteria (step 2, Figure 6-17). Each criterion within the three main performance categories is weighted individually and progressively. Each Change Enabler is then rated for the applicable Change Object (here: MGS) and Transition (here: “Adding” or “Passive”) by comparing it to the Baseline Object, multiplied with the weighting and then being normalized (section 6.4.2). The calculation and results of the assessment can be found in appendix 11.7.3. Those results are added to the performance profile as shown in Figure 8-7. Based on the performance rating, the performance ranking of the Flexible Design Concepts can also be derived. As emphasized in section 6.4.2, although the performance rating and ranking supports decision-making, a comparison of the performance profiles of the different Flexible Design Concepts should also be considered before decision-making. A consideration of those profiles may deviate from decisions that are based solely on the performance rankings.

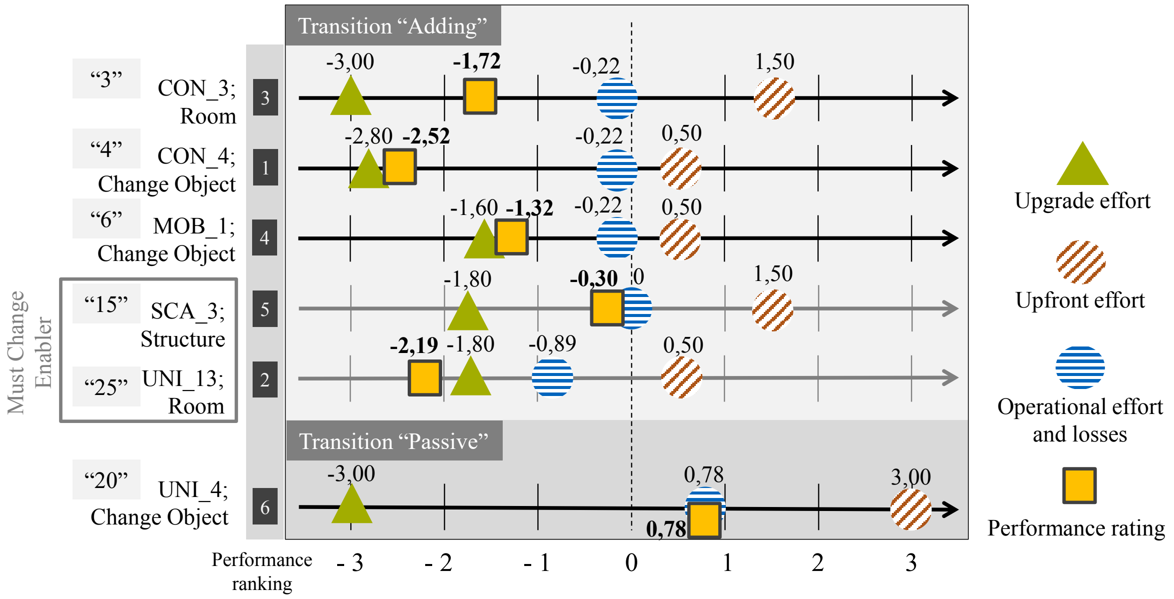


Figure 8-7 Performance profile of Flexible Design Concepts for MGS (calculation in appendix 11.7.3)

As the focus lies upon identifying the most suitable Transition for Flexible Design Concepts of the MGS, the set of Change Enablers for “Adding” the MGS are compared to the one for the Transition “Passive” (Figure 8-7). As can be seen Change Enabler “20” (UNI_4; Change Object) is both in the right (Upfront effort) and left corner of the chart (Upgrade effort). The

---

[306] If “Adding” the MGS were the only Transition, then both Change Enablers would not require a performance rating as they must be in place.

over-dimensioned MGS also has significant operational deficits compared to a fit-for-purpose rigid design especially due to the higher operational and maintenance costs. This observation is also reflected in the only positive, i.e. bad "operational effort and losses" rating and, hence, results in the weakest performance ranking of all Flexible Design Concepts. Its value is also strongly dependent on the usage frequency of the over-dimensioned MGS (step 3, Figure 6-17) which, if at all, is likely to be only once for the anticipated single upgrade across the lifecycle. As, in this case, the project customers also represent the system users benefiting directly from lower lifecycle costs, Change Enabler "20" (UNI_4; Change Object) is considered to be a suboptimal solution compared to the Flexible Design Concepts that consider "Adding" a MGS and is removed as a result. The Transition "Adding" is homogenized[307] for the Change Object MGS. Based on that, the other Flexible Design Concepts are further assessed to generate the best performing Flexible Design Solution(s) (step 8 in FDO PM).

All remaining Change Enablers for "Adding" a MGS have beneficial performance profiles and a high frequency of utilization as they can be used also for maintenance, repair or overhaul activities[308] (step 3, Figure 6-17). In particular, Change Enabler "3" (CON_3; Room) has a very high utilization rate as the hatch in the ceiling for removal / installation of the Object can also be used for other Objects for multiple purposes. Thus, besides the two obligatory Must Change Enablers whose performance rating now remains unconsidered, all remaining Change Enablers have satisfactory performance profiles and are, according to the Change Enabler Consistency Matrix, all consistent to each other. Hence, all remaining Flexible Design Concepts for the Change Object MGS, i.e. including Change Enabler "3", "4", "6", "15" and "25", are now integrated and result in a high-performing[309] Flexible Design Solution which can now be included into the reference design (iteration "L" in FDO PM).

As all Change Objects in the FDO Execution Model were set to unique Transitions, their change propagation can now be determined. Since the homogenization was performed as result of path "Advanced", change propagations based on those results could be identified by performing path "Complete". However, as change propagation across Objects only repeat the already presented aspects of the FDO Methodology, neither path "Profound" nor path "Complete" are pursued further. However, the complete run-through FDO Execution Model, which is also presented as part of the expert evaluation (section 8.3), is shown schematically with the run paths in Figure 8-8 and enlarged in appendix 11.7.5.

---

[307] This allows returning to stage I of the FDO Procedural Model to identify Change Objects affected by "Adding" the MGS in the future. Change propagation, however, is not considered further.

[308] This does not apply to Change Enabler "15" (SCA_3: Structure) which, however, is a Must Change Enabler when "Adding" the MGS.

[309] The overall performance of the Flexible Design Solution should now be significantly higher than that of the Baseline Design. Nevertheless, for assurance and quantification, an optional assessment of the Flexible Design Solution can be performed by using the already elicited data for each Flexible Design Concept and comparing the final result to the performance of the Baseline Design.

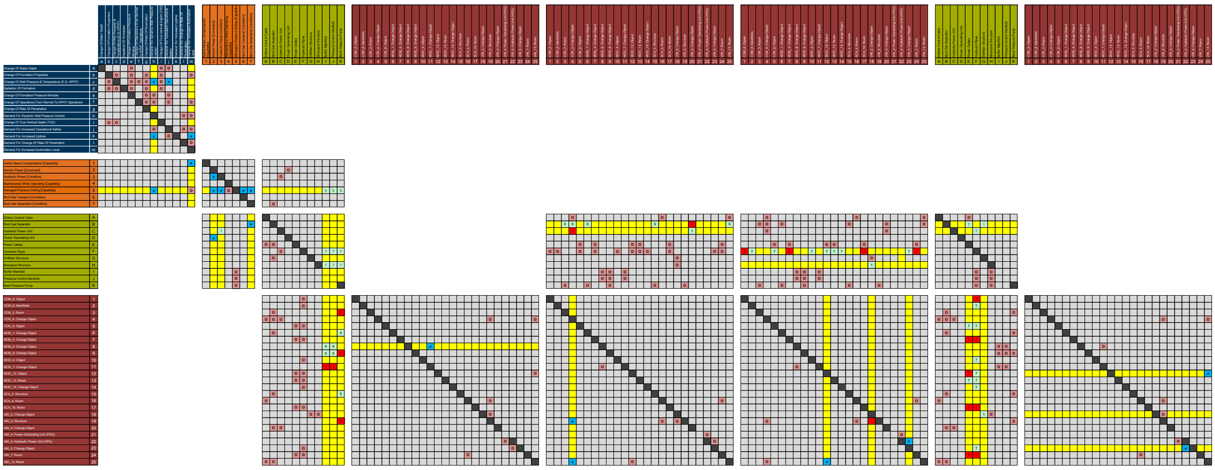


Figure 8-8 Completed FDO Execution Model (enlarged model shown in appendix 11.7.5)

In the following the theoretical contributions of how the FDO Methodology fulfills the FDO requirements are addressed.

8.2 Theoretical contributions to fulfillment of FDO requirements

The development of the FDO Methodology was guided by initially set basic requirements (section 1.3.3) which are based on the underlying market and corporate conditions of the industry (section 1.3.2). The FDO requirements were iteratively concretized while guiding the development of the FDO Methodology (section 4.3.1). This guidance is mirrored in the various contributions of the generated results to fulfill those FDO requirements.

In the following those contributions are condensed to a limited set which facilitates a clear[310] confrontation with the defined FDO requirements. Although each contribution can refer to multiple sections of this thesis, especially as they depend or build upon each other, only the main sections are highlighted in the following. The contributions can be divided into five main categories. The contributions in those categories are referred to when discussing the main contributions to research in section 9.2.2.

The first category, namely "FDO execution", focuses on contributions that affect the process of identifying FDOs:

- C1: "Matrix-based approach" which refers to the integration of a matrix-based application for the identification of FDOs using original and transposed matrices (section 6.1)
- C2: "Multiple paths in FDO Execution Model" enabling to follow four cumulative paths depending on the individual boundary conditions in each project (section 6.2.)
- C3: "Reference and baseline design basis" highlighting that the starting point for the identification of FDOs is based on previously proven designs (section 4.2)
- C4: "Tracing and Back-Tracing capability" fostering the identification of downstream elements and upstream elements based on articulated needs (section 6.3.1, 6.3.3)

---

[310] This is especially important as this confrontation is also used for the expert evaluation of the FDO Methodology.

- C5: "Gradual scenario building" emphasizing the step-by-step and case-dependent building of potential future changes to a final customer relevant scenario (section 6.3.2)
- C6: "Change trigger definition and application" focusing on uncertainty related Change Triggers that can be determined in matrices M_D and M_E (section 4.2.1, 5.1)
- C7: "Transition integration into FDO Execution Model" refers to the integration of Transitions[311] when generating Flexible Design Concepts (section 6.1)
- C8: "Transition vs. Enabler driven approach" accounting for Transitions as either boundary conditions or design variables (section 4.2.1)

The second main category focuses on the "Database" referring to contributions that concern the data the methodology builds upon:

- C9: "Pre-defined elements in domains" concerns the domain dependent and independent elements that are defined and verified for the five domains of the FDO Data Model (section 5)
- C10: "Pre-defined relations in matrices" concerns the specific relations within domains (DSMs) and across (DMMs) that are defined and verified (section 5.1, 5.2)
- C11: "Large scope of applicable change sources" emphasizing the extensive and diverse collection of specific Change Drivers and System Requirements (section 5.3.1, 5.3.2)
- C12: "Large scope of alternative design variables for possible Flexible Design Concepts" emphasizing the extensive and diverse collection of specific Objects, Change Enablers and Transitions (section 5.3.3, 5.3.4, 5.3.5)

The third main category "Definition & structuring" refers the imposed systematization concerning the overall FDO Methodology and its constituents:

- C13: "Split of FDO models" concerns the separation into a Procedural, Data and Execution Model that are interrelated (section 4.1)
- C14: "Syntax definition of domain elements" addresses the sentence structure of elements in domains that is defined by the application in the FDO Execution Model (section 5.3)
- C15: "Categorization and hierarchization of domain elements" refers to the horizontal and vertical systematization of domain elements (section 5.3.1, 5.3.2, 5.3.3, 5.3.4)
- C16: "Differentiation of general and specific Change Enablers" highlights the need for distinguishing Change Enablers that fit to specific Object classes and more generic Change Enablers that are applicable across many Object classes as they are not bound to specific properties of the Object (section 7.2.1)

The fourth main category addresses the "FDO assessment & decision-making" concerning contributions that facilitate the selection of Flexible Design Concepts and final solutions:

---

[311] Implemented as dropdowns in the Excel® tool of the FDO Execution Model.

- C17: “Continuous assessment and decision making” by permanent consideration of applicability and relevancy which is performed by accounting for risk factors and project context categories when confirming relations in the FDO Execution Model (section 6.4.1)
- C18: “Report-based assessment and decision-making” referring to the intermediate or final assessment and decision-making on tentative Flexible Design Concepts based on a separate output table (section 6.4.2)
- C19: “Criteria and stage-based assessment” referring to an intermediate or final assessment by gradual application of exclusion, performance and influencing criteria in each stage (section 6.4.2)
- C20: “Utility analysis and comparison of Flexible Design Concept performance” based on comprehensive performance criteria being weighted for rating alternative Flexible Design Concepts and confrontation of those results in performance profile (section 6.4.2)

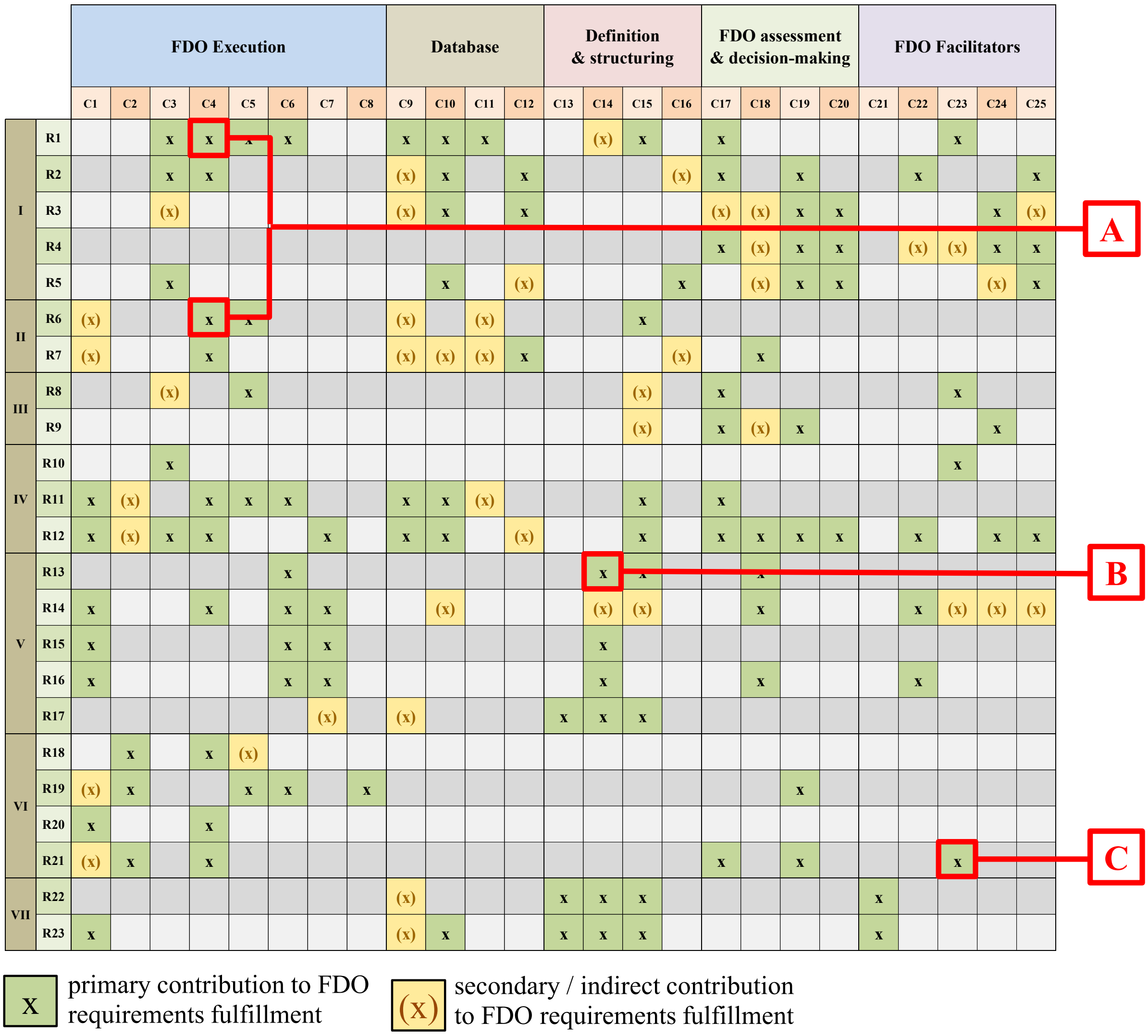
The fifth and last group, the “FDO Facilitators”, which are covered in chapter 7, focus on facilitating the FDO Methodology across the stages of build-up, execution and maintenance:

- C21: “Object classes” refer to the build-up of internally homogenous groups of Objects which require identical Change Enablers and allow identical Transitions (section 7.2)
- C22: “FDO Selection Constraints” sets constraints amongst selections within and across matrices to ensure consistency and validity (section 7.3)
- C23: “Upgrade Risk Portfolio” assigns Objects to a project unspecific risk of being upgraded ensuring that only critical Objects are accounted for when building Object classes and when running the FDO Methodology by identifying relevant Baseline Objects (section 7.1)
- C24: “Change Enabler Value-Effort Portfolio” assigns Change Enablers according to their estimated average value and effort supporting the identification of Change Enablers with high value or high value-effort ratios (section 7.4)
- C25: “Change Enabler Consistency Matrix” confronts Change Enablers with each other to highlight Change Enablers that are incompatible or redundant (section 7.5)

The contribution to specific requirements is highlighted and documented by confronting the contributions (columns) with System Requirements (rows) in Figure 8-9. Whereas primary contributions to meet FDO requirements are marked by “x”, secondary or indirect contributions are indicated by “(x)”. This documentation is the basis for the second phase of expert evaluation[312] (section 8.2).

---

[312] In the expert evaluation process (section 8.3) only the most important primary contributions are accounted for to make the evaluation process more efficient.



		FDO Execution								Database				Definition & structuring				FDO assessment & decision-making				FDO Facilitators				
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25
I	R1			x	x	x	x			x	x	x			(x)	x		x						x		
	R2			x	x					(x)	x		x				(x)	x		x			x			x
	R3			(x)						(x)	x		x					(x)	(x)	x	x				x	(x)
	R4																	x	(x)	x	x		(x)	(x)	x	x
	R5			x							x		(x)				x		(x)	x	x				(x)	x
II	R6	(x)			x	x				(x)		(x)				x										
	R7	(x)			x					(x)	(x)	(x)	x				(x)		x							
III	R8			(x)		x										(x)		x						x		
	R9															(x)		x	(x)	x					x	
IV	R10			x																				x		
	R11	x	(x)		x	x	x			x	x	(x)				x		x								
	R12	x	(x)	x	x			x		x	x		(x)			x		x	x	x	x		x		x	x
V	R13						x								x	x			x							
	R14	x			x		x	x			(x)				(x)	(x)			x				x	(x)	(x)	(x)
	R15	x					x	x							x											
	R16	x					x	x							x				x				x			
	R17							(x)		(x)				x	x	x										
VI	R18		x		x	(x)																				
	R19	(x)	x			x	x		x											x						
	R20	x			x																					
	R21	(x)	x		x													x		x				x		
VII	R22									(x)				x	x	x						x				
	R23	x								(x)	x			x	x	x						x				

x primary contribution to FDO requirements fulfillment

(x) secondary / indirect contribution to FDO requirements fulfillment

Figure 8-9 Contribution to fulfillment of FDO requirements

As the matrix shows each FDO requirement is addressed by more than one contribution. Three examples of primary contributions are highlighted for demonstration:

- Example "A": The FDO requirement R1, the "Ability to identify the relevant problem and solution space", is partially[313] fulfilled by the FDO contribution C4, namely the "Tracing and Back-Tracing capability". By tracing, relevant change sources can be confirmed and Change Objects identified. Those may not only represent articulated change sources / Change Objects which is why C4 also supports R6, the "Comprehensive identification of change sources and Objects".
- Example "B": The FDO requirement R13, the "Non-ambiguous and clear comprehension", is partially fulfilled by the FDO contribution "Syntax definition of domain elements" (C14).

---

[313] There are usually various contributions for the fulfillment of an FDO requirement which is illustrated by the multiple entries in each row of Figure 8-9.

As each domain has consistent and clearly defined domain elements, they can be easily understood and followed both in the FDO Data and Execution Model.

- Example "C": The FDO requirement R21, "Scalability of complexity and comprehensiveness", is partially fulfilled by the "Upgrade Risk Portfolio" (C23). By adjusting the line of critical risk in the portfolio, the number of considered Baseline Objects can be flexibly adjusted, affecting the scope of Baseline Objects to be screened in the first place.

The full evaluation sheet including a detailed representation of Figure 8-9 can be found in appendix 11.8. The next section addresses the process and results of the expert evaluation.

8.3 Final expert evaluation in industry

Both the demonstrator that was applied on the use case of section 8.1 and the theoretical contributions to the fulfillment of FDO requirements (section 8.2) are the basis for the expert evaluation that is run in the industry. In the following sections details on the expert evaluation are provided. First, details on the evaluation group and the general evaluation process are displayed (section 8.3.1). This is followed by presenting details on the process of each individual evaluation and the evaluation sheet that was used as the primary means of eliciting feedback on the FDO Methodology (section 8.3.2). In section 8.3.3 the results of the expert evaluation are presented which are divided into two parts: The first part addresses results on rating the validity of FDO requirements and their fulfillment by the FDO Methodology. The other part addresses related results from comments and group discussions. All results are analyzed and interpreted. In section 8.4 the evaluation process and the results are reflected and a conclusion on the FDO Methodology is made based on the performed expert evaluation.

8.3.1 Evaluation setting and process

In order to meet the specific evaluation strategy, the following aspects were important to address as suggested by BLESSING & CHAKRABARTI [2009, p. 207]:

- Type of user involvement: Both important users and stakeholders participate in the expert evaluation. They play a passive role as observers of the presented FDO Methodology and provide feedback. The configuration and size of the expert group were chosen in such a way that it supports group discussions while enabling an efficient execution.
- Setting: The use case applied for demonstrating the application of the methodology is performed on a real-life tender project that is slightly adapted. As stakeholders and users only represent observers of the methodology, the use case is presented simultaneously to the entire audience.
- Task: The FDO Methodology is applied on a real-life use case which depicts a potential late integration of the new capability "Managed Pressure Drilling" to an existing offshore drillship and the embedment of flexible design in very early design phases (section 8.1). The scope of this case is condensed and based on logically argued selections of the verified available data to demonstrate the application of the methodology sufficiently.

The evaluation was performed in one coherent time period at two different sites of the System Supplier in Norway. A total of four sessions were performed of which each lasted approx. 5 hours. In each session 2-4 evaluators attended with a total of 12 evaluators to be interviewed. In line with Blessing & Chakrabarti [2009, p. 209], those evaluators involved both users and other relevant stakeholders to obtain stronger statements about the support. They included senior engineers, senior advisors and managers from the lower and middle management in the organization. Table 8-1 gives an overview of the participants with respect to the evaluation sessions.

Table 8-1 Configuration of evaluators in evaluation sessions

Session	Status	Evaluator ID	Hierarchy	Role	Affiliation
I	Pilot evaluation & evaluation	1	Lower-Level Management	Manager	Research & Development
		2	Lower-Level Management	Manager	Research & Development
II	Evaluation	3	Functional	Senior Engineer	Tender - System Concept
		4	Functional	Senior Engineer	Tender - System Concept
		5	Lower-Level Management	Manager	Lifecycle Engineering
III		6	Functional	Senior Advisor	Tender - System Concept
		7	Lower-Level Management	Manager	Lifecycle Engineering
		8	Lower-Level Management	Manager	Lifecycle Engineering
IV		9	Functional	Senior Advisor	Research & Development
		10	Functional	Senior Engineer	Tender - System Concept
		11	Lower-Level Management	Manager	Tender - System Concept
		12	Middle-Level Management	Senior Manager	Tender - Business Development

Each of those evaluators has a technical background and can be attributed to three different fields of affiliation:

- The affiliation to “Tender” can be divided into two parts: Whereas “Business Development” handles the sales-related activities during tenders, the technical innovation and adaptation of system concepts is managed by the engineering division of “System Concept”. Both groups represent potential users of the FDO Methodology. Whereas “Business Development” with its direct contact to the customer can play an important role in scenario building (section 6.3.2), the focus of “System Concept” lies in the identification of Change Objects, generating Flexible Design Concepts and Flexible Design Solutions.
- “Lifecycle engineering” focuses mainly on the after sales market, in particular, the upgrades of previous system deliveries. The participants represent a subset of the experts that were already interviewed on the mini-cases (section 5.2.1). They are considered important stakeholders as they significantly profit from embedding flexible design. At the same time, they can provide valuable feedback on the FDO Methodology as they have gained extensive experience on upgrades and are able to pinpoint potentials and deficits of the FDO Methodology.
- “Research & Development” consider internally and externally driven product, system and process innovations across the organization based on the superordinate corporate strategy. As owners of the research project, they are important stakeholders also responsible for positioning the developed methodology in the organization.

The evaluation can be divided into an overall evaluation process (macro evaluation process) and a micro evaluation process which focuses on the sequence of each single evaluation session (Figure 8-10).

The macro evaluation process started by preparing the evaluation. Here the focus lay on identifying the focus of the evaluation ("What is to be evaluated?") and the manner the evaluation is performed ("How is to be evaluated?"). This defined the "Micro evaluation process" together with the contents that were presented and evaluated by the experts. The main focus was on the development of a thorough introduction of the FDO Methodology to the evaluators, building of a software demonstrator model that illustrates the practical application of the methodology and the conceptualization of an evaluation sheet that was separated into two parts to receive feedback on the design support.

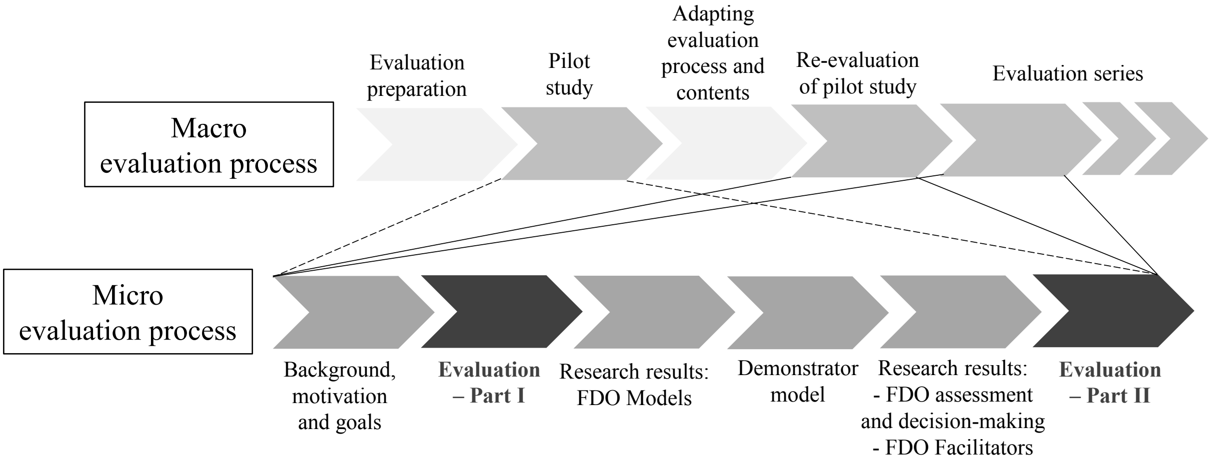


Figure 8-10 Overall and session-dependent evaluation process of FDO Methodology

The evaluation started out by performing a pilot study which aimed at applying the research method to identify potential problems that may affect the quality and validity of results [BLESSING & CHAKRABARTI 2009, p. 114]. In this step the tentative micro evaluation process was applied and feedback by the evaluators was provided to improve the evaluation process / contents and, hence, the quality of the subsequent evaluations. As Table 8-1 reflects, this extended pilot evaluation was performed within the Research & Development department whose feedback led to minor adaptations related to:

- Aloud reading of each FDO requirement (Evaluation - Part I) and FDO contribution with additional explanation to ensure a homogenous understanding by evaluators (Evaluation - Part II)
- Improvements in recalling contribution from presentation by highlighting key contributions in printouts (Evaluation - Part II)
- Single adaptations in evaluation sheet to avoid misunderstandings
- Improvements in time management regarding the entire evaluation process

The pilot study ensured that evaluation questions were realistic, appropriate and answerable in accordance with ROSSI ET AL. [1999, pp. 81–84]. Based on those insights and adaptations, both evaluation parts could be repeated with the pilot evaluator group leading to adjustments of the initial results. Based on this re-evaluation the next three sessions (evaluation series) could be performed without any changes of the evaluation process and contents.

8.3.2 Micro evaluation process and evaluation sheet structure

In line with Blessing & Chakrabarti [2009, p. 209] the evaluation feedback was attained by a combination of questionnaires that was part of an "evaluation sheet"[314] (Figure 8-11) and planned group discussions at various stages of the micro evaluation process illustrated in Figure 8-10. As the quality of the introduction of the support influences the outcome of the evaluation [Blessing & Chakrabarti 2009, p. 200], emphasis was set on a proper and clear presentation and demonstration of the FDO Methodology.

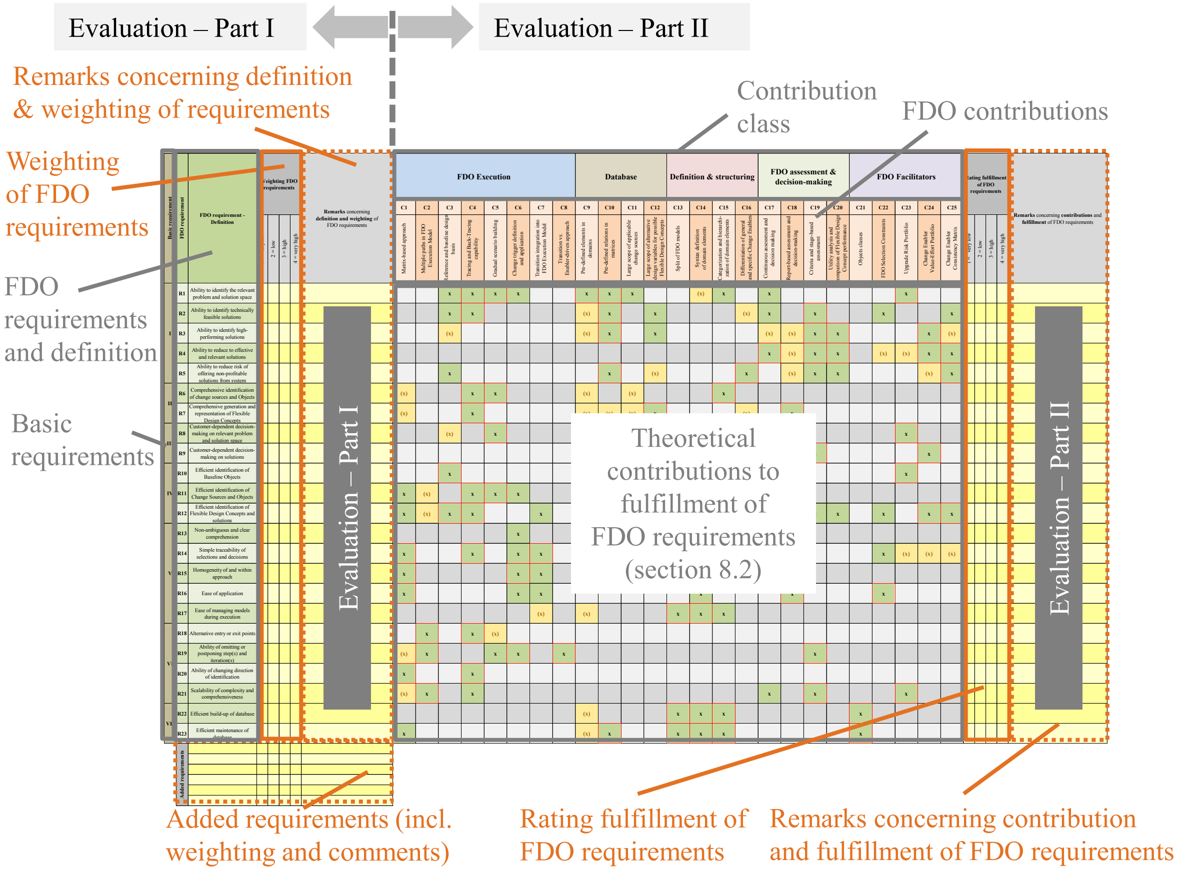


Figure 8-11 Evaluation sheet for performing first and second part of evaluation

The evaluation session was initiated by providing background information on the topic, a motivation and the goals that the FDO Methodology pursues always with respect to the industrial and corporate context. Then the first part of the evaluation was performed by each evaluator filling in the handed out evaluation sheet (Figure 8-11). It concerned identifying the subjective importance of each determined FDO requirement (section 4.3.2); in order to avoid bias the evaluation was performed after aloud reading of the researcher and by being responsive

---

[314] A detailed representation of the evaluation sheet can be found in appendix 11.8.

to the entire evaluation group (45 min) in case of lack of clarities. Four levels of weightings from very low ("1") to very high ("4") were possible. Additional remarks concerning the requirement's definition and the weighting could be added voluntarily helping the posteriori interpretation of the results. Alternative to those written remarks, or additionally, the ratings were followed by commenting or a short group discussion where important aspects of this first evaluation part were addressed[315]. At last the evaluation sheet allowed adding new FDO requirements together with additional weightings and comments[316].

The main research results, in particular the FDO models and its constituents (section 1, 5 and 6) were then presented supported by a poster of the original FDO Data Model which was then discussed. After a general introduction to the FDO Execution Model, the Excel® based software demonstrator model was applied by the researcher with the audience observing the application that based on the use case presented in section 8.1. Equally to the presented use case in section 8.1, its scope and, hence, the addressed matrices were reduced to a set that could be mastered without overwhelming the audience. It was emphasized to the evaluators that the Excel® based tool was not subject to evaluation but only provided a means to demonstrate how the FDO Execution Model worked.

Based on the demonstrator model, the third part of the presentation focused on the assessment and decision-making on high-performing Flexible Design Concepts[317] to generate Flexible Design Solutions. Then the FDO Facilitators were introduced. By presenting those contents, the additional use of posters which included the original data and by referring to the already presented demonstrator model, the purpose and value of the FDO Facilitators were conveyed. Based on the theoretical contributions to the fulfillment of FDO requirements (section 8.2), the overall fulfillment of FDO requirements was assessed by the evaluators. The rating was performed row by row by aloud reading of the researcher and by pinpointing to specific contributions in printouts to make the evaluator recall the presented contents. In order to ensure an efficient execution in the pre-defined timeframe of the evaluation, only the main contributions for fulfilling FDO requirements were highlighted and emphasized[318]. As illustrated in Figure 8-11, after each row the overall fulfillment of FDO requirements was rated individually by the evaluators from very low ("1") to very high ("4"). Similar to the first part of the evaluation, additional remarks concerning contributions and fulfillment of those requirements could be added which, again, were intended to support the subsequent interpretation of those ratings. As before a group discussion was performed to generate feedback on inquired contents, closing with a general feedback on the entire FDO Methodology.

The results of the entire evaluation are presented in section 8.3.3.

---

[315] Group discussions that reflected opinions to the rated FDO requirements (not clarifications) were often performed after each rating to elaborate on currently thought of aspects while avoiding influences across the group.

[316] However, no evaluator used this possibility in the evaluation sheet.

[317] The demonstration of the assessment and decision-making was not necessarily related to the previously identified Flexible Design Concepts in the FDO Execution Model.

[318] Those have been previously identified and highlighted as bold red boxes in appendix 11.8.

8.3.3 Expert evaluation results

The evaluation results can be divided into results from the ratings of the first and second part of the evaluation. Additionally, each of those evaluations also include the explanatory written remarks that were often also commented and meant as additional information; new insights were also provided from group discussions amongst the evaluators. In the following the quantifiable results from the ratings are presented first followed by the qualitative information generated from the additional written remarks, comments and group discussions made during the evaluation.

In the following the focus lies upon the quantifiable ratings.

Quantitative results from expert evaluation

The results from ratings contain both the weighting of the FDO requirements (Evaluation – Part I) and the degree of fulfilling those requirements by contributions of the FDO Methodology (Evaluation – Part II). Both ratings have the same scale (1-4) and the same subjects of assessment, namely the "FDO requirements". They are represented in a radar chart which represents an aid for a graphical representation of multi-dimensional target systems and the demanded, or respectively, actual target characteristics of objects of observation [Ponn & Lindemann 2011, p. 446]. In this context of application, it is a two-dimensional chart of three or more quantitative variables represented by FDO requirements which lie on axes that root in the same point. This allows the identification of points of strongest similarity (e.g. variables with similar max. ratings) and highlights outliers.

Figure 8-12 displays the resulting radar chart for the weightings of the FDO requirements based on the 12 performed evaluations. For each of the 23 variables the minimum and maximum values are highlighted as well as the average across all ratings. Note that the full list of FDO requirements can be found in the appendix 11.4.

Based on this visualization, the following can be observed:

- Max. weighting is always at its maximum, i.e. at least one evaluator finds the FDO requirement extremely important
- Min. weightings strongly vary across requirements. Highest minimum weightings of representatives (>=3) can be attributed to the basic requirements IV: "Efficient identification of FDOs" (R11, R12), V: "Appropriate usability for engineers" (R13, R14, R15, R16, R17), VI: "Flexible application of FDO Methodology" (R19) and VII: "Efficient build-up and maintenance of database" (R22, R23)
- Peaks of average weightings (here: >=3,9) reflect most important FDO requirements which are represented by R14: "Simple traceability of selections and decisions", R19: "Ability of omitting or postponing step(s) and iteration(s)" and R23: "Efficient maintenance of database"

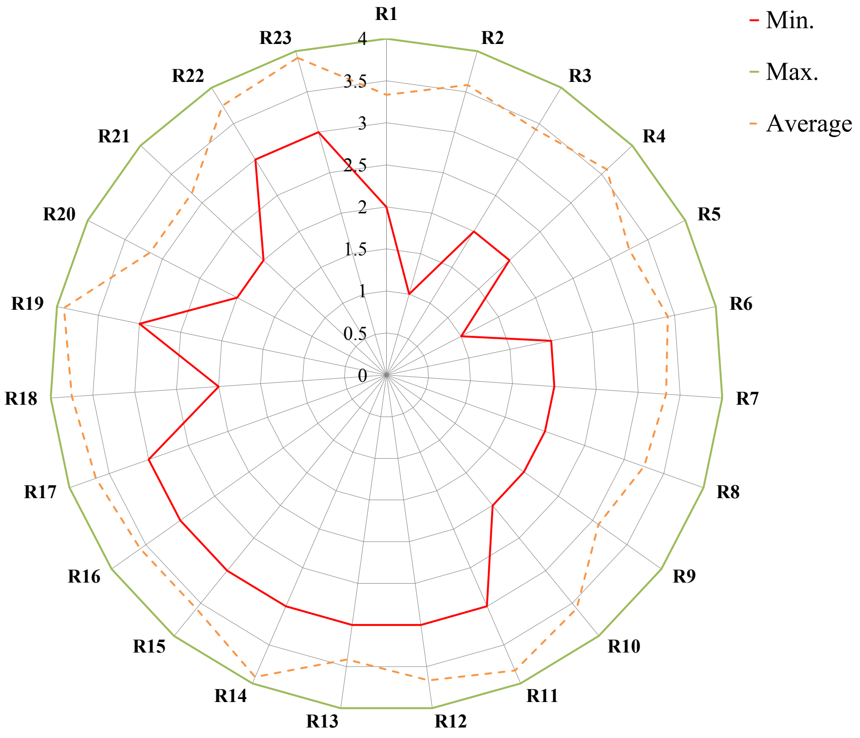


Figure 8-12 Weighting of FDO requirements (Evaluation - Part I)

As can be seen based on the evaluation data, there is partly a very heterogeneous perception (1-4) on the importance of FDO requirements. However, there are some FDO requirements whose importance is shared amongst all evaluators usually leading to high average weightings.

The relatively high average weightings (above 3) also indicate that all basic and FDO requirements are relevant for the FDO Methodology. As no new FDO requirements were explicitly[319] added by the evaluators in the evaluation sheet, most important requirements seem to be covered[320] by the FDO Methodology.

Figure 8-13 displays the chart for the fulfillment of FDO requirements by the various contributions introduced in section 8.2.

- Max. fulfillment is always at its maximum, i.e. at least one evaluator finds the FDO requirement fully fulfilled
- Min. fulfillments partially vary across requirements. Highest minimum fulfillments of representatives (>=3) can be attributed to the basic requirements I: “Identification of effective FDOs” (R2), III: “Customer-oriented identification of FDOs” (R8), IV: “Efficient identification of FDOs” (R11), VI: “Flexible application of FDO Methodology” (R18, R19, R20, R21)

---

[319] Suggestions on improvements and extension of the FDO Methodology based on group discussions are not considered as main FDO requirements of the methodology.

[320] Always with respect to the limited number of evaluators.

- Highest average ratings (here: >=3,6) mirror the most fulfilled single FDO requirements assessed by the group of evaluators: R2: "Ability to identify technically feasible solutions", R6: "Comprehensive identification of change sources and Objects", R14: "Simple traceability of selections and decisions", R20: "Ability of changing direction of identification", R21: "Scalability of complexity and comprehensiveness"

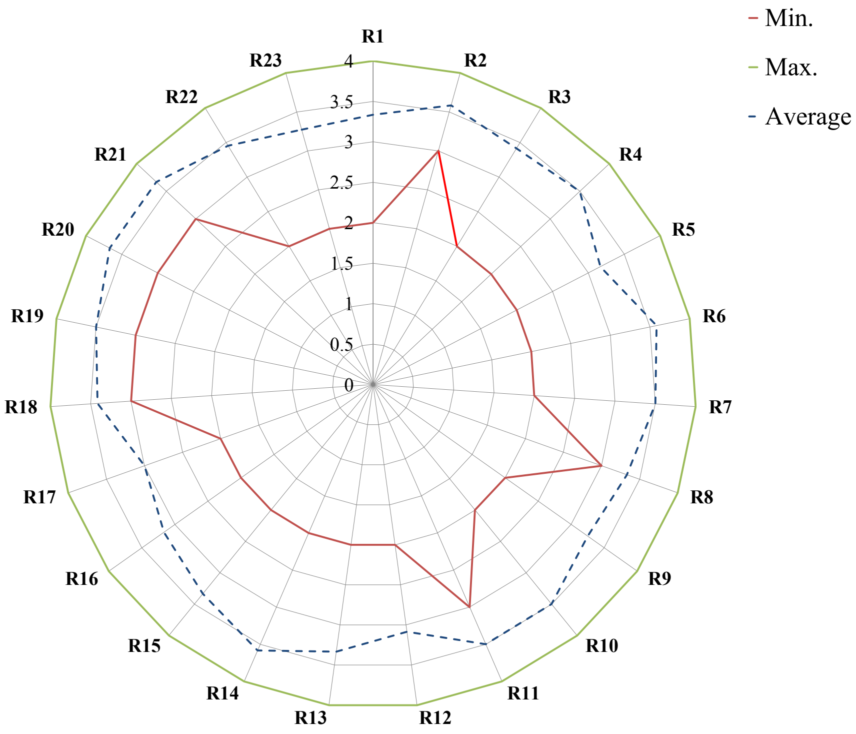


Figure 8-13 Fulfillment of FDO requirements (Evaluation - Part II)

As can be seen based on the evaluation data, there is less of a very heterogeneous perception (rating between "2" and "4") on the fulfillment of FDO requirements as on the weighting of it. Similar to "Evaluation – Part I" there are some FDO requirements whose fulfillment is rated homogenously high by all evaluators leading to high average fulfillment ratings.

As the same variables (FDO requirements) and scale (1-4) are used for both evaluation parts, they can be considered as two separate series in the radar chart. The overlap of the average ratings of weighting and fulfillment of FDO requirements (Figure 8-14) provides an indication of the degree of fulfillment (or over fulfillment) of FDO requirements. It can be observed that the "effectiveness related" requirements (R1-R9), which belong to aspect 1 (section 1.3.1 and 1.3.3.) have a strong correspondence in weighting and rating.

Slightly larger deviations exist for the other two aspects that may be carefully interpreted as indications for shifting the future development focus of the FDO Methodology both in case of over fulfillment or for closing gaps when requirements are considered to be under-fulfilled. Aspect 2, namely the efficiency-related requirements R10-R21, depict, besides some exceptions, still room for improvement. The efficient build-up and maintenance of the database (aspect 3 or R22, R23) depict largest potentials for improvement or extension, which could be confirmed by remarks, comments and discussions.

Naturally, the interpretations from the radar chart must be performed very cautiously and are considered to be only an indication due to the limited numbers of evaluators and the high impact of single deviations from the displayed average ratings.

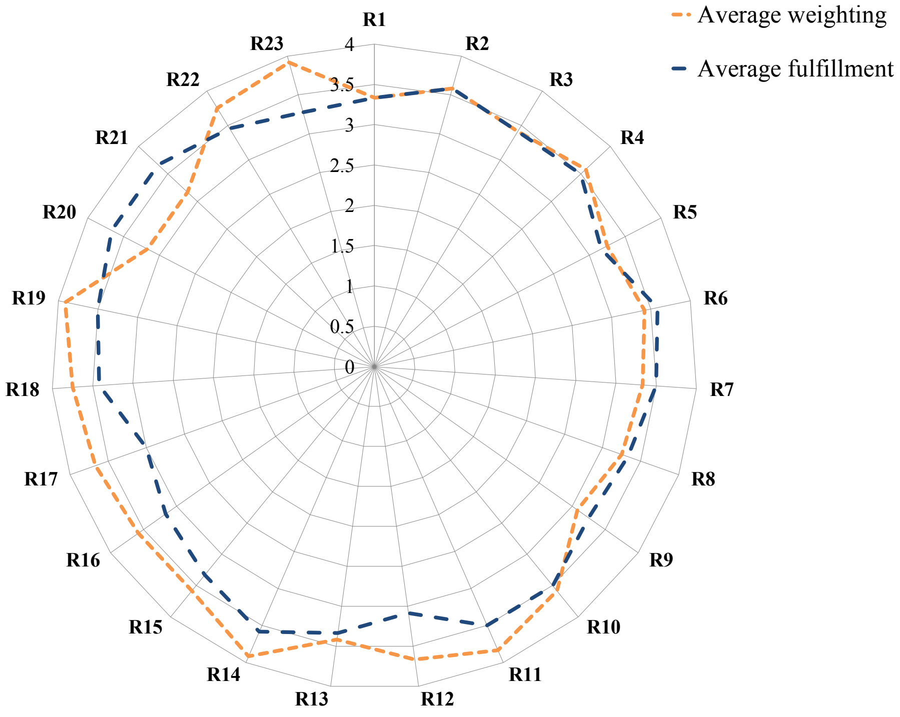


Figure 8-14 Average weighting and fulfillment of FDO requirements

Consequently, it is also especially important to account for the complementary qualitative statements from the written remarks, oral comments and group discussions which are presented in the following.

Qualitative results from expert evaluation

Based on the written remarks, oral comments and group discussions for both parts of the evaluation, the generated information was processed iteratively by a central representation and systematization of data followed by homogenizing information and terminology, removal of redundancies and grouping to various main- and subcategories. The feedbacks and observations from evaluators could be assigned to the following four main categories:

- Emphasis: feedback on priorities and confirmations on already set foci of the FDO Methodology
- Improvement & extension: feedback on potential improvements and extensions of FDO Methodology to provide even more utility to future users
- Limits & constraints: observations on natural limits and constraints of the FDO Methodology

- Contribution: interpretation of the purpose of the FDO Methodology

Table 8-2 depicts the consolidated and systematized evaluation feedback on both “emphasis” and “improvement & extension” of the FDO Methodology. Both main categories could be assigned to six different content-related categories. It can be seen that both many affirmations and further improvements and extensions of the FDO Methodology exist. For instance, the continuous improvement of the model by maintenance and learning had already been envisioned by the need of supporting the maintenance of the FDO Data Model after initial build-up and use (Figure 7-1). Accounting for software changes beyond the physical changes that are addressed by the methodology, however, entails the new consideration of software Objects[321] as potential Change Objects for the future.

Table 8-2 Systematized feedback of evaluators on emphasis and improvements & extension of FDO Methodology

	(1) Working efficiency and effectiveness	(2) Scope	(3) User orientation	(4) Customer orientation	(5) Corporate focus	(6) Model implementation
Emphasis of FDO Methodology	Continuous improvement of model by maintenance and learning	Flexible scope of applying methodology	Integration of experience of user	Integration of customer in selection and decision-making	Focus on profitable solutions	
	Efficient reduction to effective solutions		Limit range of interpretations	Transparency of decisions across lifecycle		
	Account for overlapping assessment criteria		Limit complexity of application	Intuitive understanding of application by customer		
			User-friendly maintenance of model	Cost orientation on specification		
				Quantifying cost-benefit of solutions		
Improvement & extension of FDO Methodology	Targeted querying of database for specific domain constituents	Account for software changes beyond physical changes	Account for heterogeneous users and profiteers	Accounting for unique customer preferences	Product Service Systems as new type of offers	Easily understandable and applicable software tool
	Reuse of proven paths and solutions	Outsourcing performance assessment from model to experienced users	Further simplification of application	Advanced quantification of cost-benefit of solutions	Alignment of FDO requirements and corporate strategy	Object-oriented programming for ease of maintenance and handling
		Outsourcing baseline design identification from model to experienced users	Increased precision of specifications with additional attributive information of domain constituents			

Observations on “Limits & constraints” of the FDO Methodology could be divided into four groups:

- High complexity: The high number of the considered constituents, relations and the need for comprehensiveness will always lead to significant complexity of the methodology. Hence, those limits are considered to negatively affect the traceability of decisions (R14) and the ease of applications (R16).
- Context dependency: With changing boundary conditions the drilling system is to be operating in, the feasibility (R2) and, especially, the performance of solutions (R3) will strongly vary. Although accounting for unique circumstances by only semi-automating the exercise in the FDO Execution Model through confirmation or rejection of potential relations by domain experts, it represents a prevalent challenge of the FDO Methodology.

---

[321] Although, in general the applicability of the FDO Methodology is equally valid for software, the identified constituents, in particular Change Enablers and Transitions, will have to be re-considered.

- Data(base) bias: The FDO Data Model is built upon System Supplier's internal (e.g. interviewees) or internally used sources only (e.g. tender specifications). This might constrain the comprehensiveness of FDO elements (R6, R7) in contrast to basing data on various sources and stakeholders.
- Build-up effort: The effort of building the first data model is high which usually ties up the most asked for resources in organizations. Constraining the effort further by addressing R22 even more is highly important for successfully implementing the methodology.

The FDO Methodology contains various facets to meet the initially defined goals. Depending on the background of the evaluator, the perception of the methodology's purpose differs. The following interpretations of the FDO Methodology exist that were noted by the evaluators during or after the evaluation sessions:

- "Decision-support tool" as it assists the user to make the right decisions by integrating the user's experience and knowledge while making customers aware of the implications of their desires and decision-making.
- "Communication tool" as it allows the collaboration of engineers at various experience levels and coming from different disciplines (e.g. sales, product development). Departments and responsible engineers can contribute either when running the FDO Methodology with the sales team or, afterwards, by commenting on previously performed decisions which can then be retraced.
- "Multi-purpose tool" as it may not only support the identification of FDOs during tenders but pinpoints to gaps and deficits in the product portfolio by yet unrealized Change Enablers which can be addressed by product development.
- "Scope of delivery tool" as it documents the scope of selected deliverables to the customer.
- "Risk and opportunity management tool" as it prevents missing out on important change sources, affected Objects and high-performing Flexible Design Concepts and, especially, Flexible Design Solutions.
- "Marketing tool" for System Supplier as it makes the customers aware of the "added value" and "opportunities" when considering FDOs.
- "Proven concepts database" as with the evolution of the FDO Methodology, proven FDO combinations can be stored allowing for continuous improvement of choices and guidance.

The following section closes by providing an overall conclusion based on the expert evaluation.

8.4 Conclusion of evaluation

The developed FDO Methodology was evaluated to confirm the intentions of the design support ("Was the right design support developed?") and the achievement of those intentions ("Can the design support successfully fulfill what it aims for?"). The results in section 8.3.3 illustrate that the design support is built upon the right System Requirements. Although local deviations in weightings exist, the average weightings imply their relevancy. As no new FDO requirements were explicitly added to the existing set, it suggests that the most important requirements are covered. However, contributions on “improvement & extension of the FDO Methodology” suggest that there are further potentials in enhancing the FDO Methodology (Table 8-2).

Regarding the fulfillment of FDO requirements it could be demonstrated that the FDO requirements highly fulfill the approved FDO requirements, especially regarding aspect 1. Aspect 2 and, especially, aspect 3 still indicate potentials in improvement and extensions in the future.

The general feedback on the developed methodology was positive. Depending on the individual needs, experience, role in the organization, however, the interpretation of the methodology varied across evaluators. Nevertheless, all attendees of the evaluation agreed on the design support as a valuable “decision-support tool” for early phases of design which mirrors the intention of the developed FDO Methodology.

Due to the challenging market situation at the time of the study and the significant effort of building an exercisable model and software tool, however, the introduction of the suggested methodology is only considered in the long run by the System Supplier. The immediate main value of the FDO Methodology was repetitively highlighted by evaluators as providing transparency to the complexity and on the required considerations when the identification of FDOs is addressed. In the short and mid-term, partial results (e.g. lists of design guidelines, portfolios) may be used independently of the overall methodology.

As often is the case, the realization of the design support is usually incomplete and the scope of evaluation limited due to various boundary conditions [BLESSING & CHAKRABARTI 2009, p. 204]. Hence, despite the positive results, limits of the evaluation also exist in this application context that one must be aware of such as:

- Partially sparsely populated matrices in FDO Data and FDO Execution Model
- Restricted stakeholder perspective on design support
- Evaluators only observers and not users of the FDO Methodology
- Restrictions in number of evaluators and available time-frame for expert evaluation
- Smaller scope and different representation of functionality in demonstrator model compared to intended full-scope model in future (e.g. omitting import of Baseline Objects, export into FDO EM Report)
- Reduced scope of use case

It must also be acknowledged that some of the results may not only be attributed to the design support but also to other influences [BLESSING & CHAKRABARTI 2009, p. 210]. For instance, personal experience, role in the organization and skepticism or enthusiasm towards changes might differ across the evaluators. Consequently, based on those limits and influences, the findings can only be treated as results of an initial evaluation and not as a proof [BLESSING & CHAKRABARTI 2009, p. 209].

9. Conclusion and outlook

This chapter closes this research work. Section 9.1 provides a short summary of the steps leading to the development of the FDO Methodology, the results and, finally, the application and expert evaluation. In section 9.2 both the results and the implications for academia and industry are discussed. Section 9.3 elaborates on potentials when extending the FDO Methodology that must be addressed in the future as they could not all be dealt with in this research context.

9.1 Summary of results

This thesis is based on research addressing the development of a methodology for System Suppliers of large-scale systems facing significant uncertainty in utilization phases to account for that uncertainty in early phases of design by systematic identification of affected objects, flexible design concepts and, based on an assessment, final solutions. The industrial boundary conditions of the offshore drilling industry form the basis for the higher level basic requirements and, later on, the more specific requirements (Flexible Design Opportunity or "FDO" requirements) of the methodology. Nevertheless, although this research bases upon the situation in the offshore drilling industry, relevancy and applicability of the developed methodology is also valid for other, especially similar industrial fields.

Based on an in-depth analysis of the situation in the offshore drilling industry and the identification of the research gap of end-to-end procedural models that enable the identification of FDOs, the need for this research was deduced. Next to that, as further literature reviews had shown, matrix-based methodologies that strongly support the basic requirements of the targeted methodology, and, hence, are highly relevant to this research, also require additional research. Lastly, next to the procedural aspects of the methodology, another main contribution lies in the so far neglected phase of concept generation in literature and the definition of certain operators and heuristics.

The developed methodology is divided into three parts that are strongly interdependent: a procedural model that illustrates the process of FDO identification, a data model where relevant data is stored and an execution model that bases upon the procedural and data model enabling the application of the methodology by their users. Based on the generated flexible design concept alternatives that result from the execution model, an assessment allows the identification of only the most relevant and high-performing solutions.

In order to meet the basic and FDO requirements, complementary methods, namely FDO Facilitators, represent an integrated part of the methodology. They support both the phases of application, but also the initial build-up and subsequent maintenance of the data model.

The methodology is then applied on an industrially relevant case that exhibits large usage uncertainty and potentials for embedding flexibility. Besides continuous support evaluation to account for possible errors, deviations and guiding the process of support development, a concluding expert evaluation of the FDO Methodology is performed. First, the individual theoretical contributions to fulfilling the defined FDO requirements are determined and highlighted. Finally, an expert evaluation is run in the industry that bases both on the theoretical contributions to requirements fulfillment and the use case.

On the one hand, the results of the expert evaluation illustrate that the methodology was built on the right requirements. On the other hand, the evaluation highlights that the methodology mostly fulfills those requirements. Hence, although improvement and extension potentials exist, the expert evaluation affirmed the attainment of the initially defined objectives.

9.2 Discussion on research results and implications

The next two sections address the results and implications of the FDO Methodology. Section 9.2.1 discusses the strengths and weaknesses of the FDO Methodology by regarding procedural and data related aspects separately relating to the initially defined research question and sub-questions. Section 9.2.2 argues how the FDO Methodology contributes to research by referring to the initially defined main research contributions. In this section the emphasis also lies on the contribution to the industry, which is especially important as this research builds upon an industrially motivated problem.

9.2.1 Strengths and weaknesses

The research was guided by the following research question introduced in section 1.3.4:

Which methods and tools enable designers in early stages of system design to successfully identify and offer flexible design solutions to their customers to allow system users better deal with uncertainty in utilization phases?

As summarized in Figure 9-1, the research question was derived from the research goal formulated in section 1.3.1 and based on the identified research gap of section 3.2.2. It accounts both for the unique boundary conditions in the industry and the related basic requirements which were clustered to “aspects” when having strong interdependencies (section 1.3.3). Section 4.3 further detailed those requirements (FDO requirements) which guided the methodology development and represented the evaluation criteria to validate the importance of those requirements and assess its fulfillment by the methodology. Those FDO requirements coined the characteristics of the developed methodology and, hence, also the way of how the research sub-questions were answered.

Hence, the strengths and weaknesses of the methodology can be discussed by referring to the research sub-questions (section 1.3.4) and the performed evaluation (section 8), hereby, integrating also own observations when building and applying the methodology.

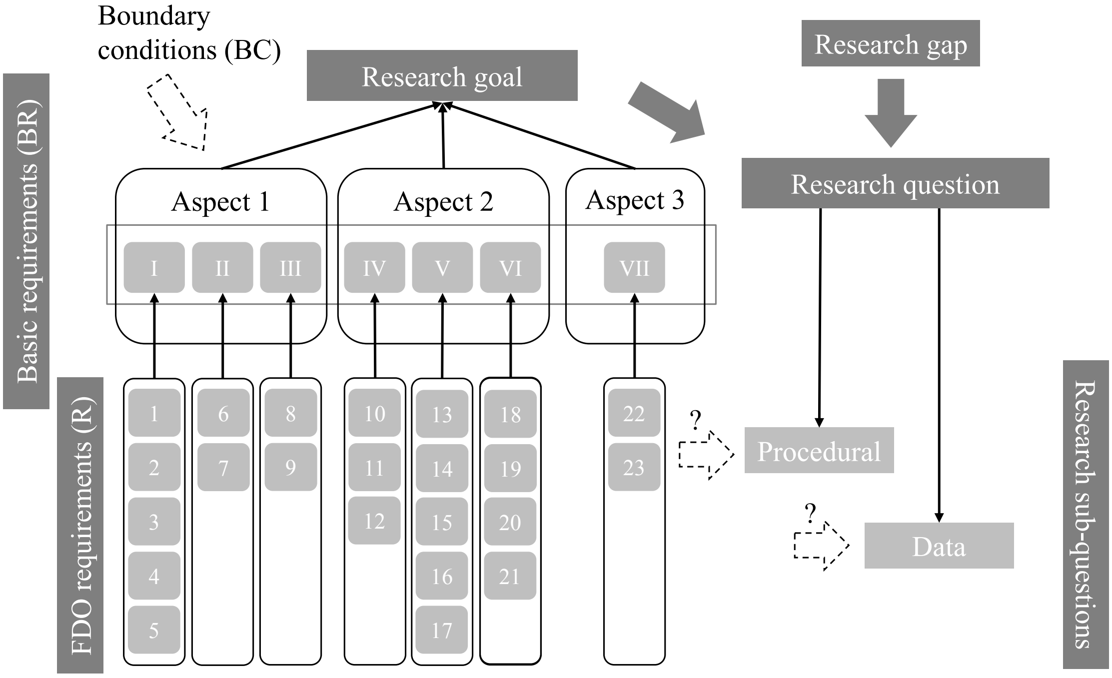


Figure 9-1 Basis for determining strengths and weaknesses of FDO Methodology

The procedural aspects of the research question are to be discussed first.

Procedural aspects

The research sub-questions related to the procedural aspects of the methodology target the main process of identifying Change Objects, enabling them and the assessment of those design concepts to generate decisions on suitable solutions. It includes both aspects of the FDO Procedural Model and the FDO Execution Model which are considered application-context independent.

The identification of Change Objects describes the first stage of the FDO Methodology. The methodology bases upon already known and physically existing Objects which facilitates the process of FDO identification[322]. Those baseline designs include only the most relevant Objects of the system due to a prior risk assessment in an Upgrade Risk Portfolio and by filtering out less relevant Objects which makes the subsequent screening process more efficient and leads to more effective results.

In the stage of Change Object identification, the gradual building of scenarios which is facilitated by tracing techniques in the model, ensures accounting for also unarticulated needs. This implies the disclosure of relevant Change Objects that usually remain undiscovered, hence, avoiding risks or missed opportunities during system design and across the lifecycle.

In stage II, the generation of Flexible Design Concepts, Transitions can either be treated as predetermined boundary conditions (Transition-driven) or as design variables for concept

---

[322] Besides the identification of Change Objects, it also eases the embedment of flexibility due to a more concrete level of specification.

generation where they are considered concurrently with Change Enablers for a given Change Object (Enabler–driven). This usage flexibility is further enhanced by offering a scalable execution model which ensures different levels of comprehensiveness depending on the project boundary conditions for both stages of the FDO Methodology. During concept generation Change Enablers also account for Prerequisite Change Enablers as integration and exercise might be hindered if considered isolated which, in turn, prevents misinvestments.

In general, the matrix-based approach embedded in an Excel® based tool as a demonstrator enables a very systematic and user-friendly identification of FDOs. It enables retracing decisions which is advantageous for various reasons such as internal documentation, communication across internal and external stakeholders, etc. By integrating pre-defined constraints (FDO Selection Constraints) amongst selections into the execution model, the cognitive limits of users are accounted for ending up in more consistent and higher quality results. A unique set of constraints embodied by the Change Enabler Consistency Matrix, ensures that only consistent Change Enablers are selected during exercise of the model but also during posterior assessment (stage III). The continuous consideration of change risk factors, i.e. the probability and transition costs, in stage I and the project context when exercising stage I and II of the model, reduces irrelevant selections, and, hence, limits the efforts especially for stage III when generating Flexible Design Solutions. Additionally, the pre-defined "Change Enabler Value – Effort Portfolio" ensures that the value-effort ratios of Change Enablers are already accounted for with the selection of Flexible Design Concepts and, later, during performance assessment. The intermediate or final assessment (stage III) integrates accelerators by e.g. accounting for expert knowledge or highly important criteria and, hence, improves the efficiency of the assessment process. The assessment is performed by a comparison amongst alternative concepts with regards to the initially defined Baseline Object ensuring that the flexible design must be of higher value than its peers and, naturally, the Baseline Object itself to be considered further. By the use of weighted criteria for the assessment heterogeneous preferences of evaluators are accounted for. As the assessment is performed in a separate report (FDO EM Report) imported from the FDO Execution Model, it represents not only an effective tool for the assessment but also an effective means of documentation and, especially, communication of results. In case of unsatisfactory Flexible Design Concepts and Flexible Design Solutions, the methodology allows a situation-dependent reconsideration of the initially defined Baseline Objects by lowering acceptability thresholds within the Upgrade Risk Portfolio. This allows taking advantage of further opportunities if boundary conditions in the project are still favorable.

On the downside, however, the Upgrade Risk Portfolio does not differentiate amongst customer preferences; hence, less critical Objects that remain unconsidered might be relevant due to a specific stakeholder interest (e.g. system responsibility). Also, the consideration of each selected Baseline Object during the screening for Change Objects in stage I still requires significant effort. The methodology only accounts for one possible future of articulated and unarticulated attributes and characteristics, i.e. without accounting for possible alternative future developments of the same attributes (e.g. two scenarios for "increased" and "reduced" water depth in the future compared to the initial design specifications). Hence, if future developments deviate from the anticipated development, certain Objects might not be prepared for or only in a suboptimal way as other Transitions or Change Enablers may represent better fits.

Additionally, although change propagation is explicitly accounted for, the process may become more difficult to manage if higher degree change propagations are considered which, however, can be relativized especially as technical systems have a limited change propagation extent[323] [KOH ET AL. 2013; PASQUAL & WECK 2012]. Especially as indirectly affected Change Objects can only be determined once the Transitions for the upstream Change Objects are known, the Enabler-driven approach results in a larger iteration as Transitions are determined after an intermediate assessment of the concept and a subsequent homogenization of Transitions for the identified Change Objects. This effort is even amplified if the Enabler-driven approach is also preferred for the downstream indirectly affected Change Objects resulting in possibly multiple such iterations.

Although only feasible options are highlighted during Change Object identification and Flexible Design Concept generation, the high number of options may still be overwhelming and time-consuming. Although the use of matrices outbalances the disadvantages, it must be noted that the matrix-based approach may become difficult to handle (data storage, process execution) if a critical size is exceeded. Hence, although the Excel® demonstrator model fulfilled its purpose for the evaluation, it certainly requires a reconsideration for a full-scale application in a corporate context (e.g. workflow, visualization of active steps only). Finally, the intermediate and final assessment based on the FDO EM Report is time-consuming, however, compared to the quantitative design space explorations still acceptable, especially as it can account for a much wider range of design variables, hence, is more comprehensive.

Data aspects

The research sub-questions related to data aspects of the methodology target the main domains, their dependencies and definition of constituents. It also addresses how and to which extent context-dependent knowledge is embedded. Finally, it concerns how the model build up and maintenance can be supported. For the data aspects, the FDO Data Model is of relevancy.

Five domains are defined for the FDO Data Model to support the identification of FDOs. The expert evaluation has neither shown the need for differentiating further domains nor was the level of abstraction challenged. The Transition domain is the only domain that is considered integrated by a dropdown option in the execution model of the Excel® tool. It is also the domain with the least number of elements which shall remain constant in the future and, in contrast to the other domains, is not further categorized. Despite the systematization of domain elements, the categorization and subcategorization of Change Drivers is essential part of the methodology by supporting the prompting of yet unarticulated Change Drivers. Nine dependency types interrelating those domains were confirmed to exist to sufficiently facilitate the identification of FDOs. As Figure 5-1 depicts, they belong either to the stage of “Identification of Change Objects” (stage I) or the “Generation of Flexible Design Concepts”.

The methodology bases upon a large pre-stored set of data on domain elements and their relations within and across domains to support the identification of FDOs. Hence, as the information is elicited, systematized and verified outside of projects, it facilitates an efficient

---

[323] Number of generations of descendants triggered by an initiating change.

identification of FDOs and ensures the effectiveness of those results. The FDO Data Model and its domains are application-context independent which makes the methodology universally applicable but especially relevant for certain fields of application where large-scale systems undergo long lifecycles, exogenous uncertainty and are subject to large irreversible investments. The model constituents and its relations, in contrast, represented in the FDO Data Model are mainly application-context specific although, especially Change Enablers and Transitions, are also considered to be universally applicable and a contribution on its own. Constituents in each domain follow a standardized terminology to avoid misinterpretations which in turn increases the quality of results.

In order to support the initial build-up and maintenance of the FDO Data Model, Object classes are defined that build upon common properties and address stage II of the FDO Procedural Model. Objects of those classes require the same Change Enablers and, as has been confirmed, also facilitate the same Transitions. This fosters the build-up and maintenance of stage II relevant matrices as not every Object is handled individually but instead as an Object class. Hereby the process of building and maintaining becomes more efficient ending up in consistent and densely populated matrices. The Upgrade Risk Portfolio can serve as means of prioritizing the building process by determining which Objects are relevant or have to be addressed first.

The downside of building and maintaining a FDO Data Model as part of the methodology is the large effort of eliciting data regarding individual elements and relations within and across domains. Especially, the thinly populated matrices in the stage of "Identification of Change Objects", illustrate the high effort of completing such matrices if FDO Facilitators such as classes are not applicable. Generally, the maintenance of data, i.e. elements and relations, must also be accounted for as all of the domains with the exception of elements in the domain "Transition" are likely to be subject to change. The generation of Objects classes for the "Generation of Flexible Design Concepts" is considered as an essential part of the methodology to reduce the effort and threshold of incorporating the methodology in the first place. Nevertheless, Object classes always represent a simplification, hence, Objects may be assigned to alternative classes and allow possibly for other Change Enablers and Transitions. As could be shown, there may also exist exceptions where Objects with common properties still slightly vary in their suitable Change Enablers and Transitions. Hence, checking individual Objects for the suitability in classes is important and efforts must also be accounted for. Lastly, although the existence of Object classes could be validated, certain Change Enablers may not be related to Object properties but have general applicability[324] which could partly ease the process of building denser matrices compared to the use of Object classes.

9.2.2 Contribution to research and industry

As emphasized in BLESSING & CHAKRABARTI [2009, p. 46], the research on the methodology and the resulting contributions should be both academically and practically worthwhile. Based on an extensive problem statement (section 1.2) and the industrially and scientifically relevant research goal (section 1.3.1), the contribution is considered both from an academic and

---

[324] Hence, theoretically those Change Enablers could be related to all Objects independently of their class.

industrial perspective. In particular, the contribution to the industry is presented from a wider viewpoint as the generated research results must be complementary to other measures to have the desired positive impact when being integrated.

Contribution to research

The two main contributions of this research were discussed in section 1.3.3 and 3.2.2. The first contribution addresses generating a comprehensive methodology with the ability of embedding systematized empirical data and heuristics which guide[325] the user interactively in identifying affected Objects and short-listing relevant concepts to generate flexible solutions. Hereby, the focus lies especially on the stage of "concept generation" where according to CARDIN [2013] "more research is needed to develop new procedures or adapt existing ones". Consequently, and based on section 3.3, the second main contribution lies upon the empirically-based and generally applicable Transitions and Changes Enablers. For each of those two main contributions, other subordinate contributions exist (section 8.2) of which the most important ones are referred to in the following. First, the contribution of a comprehensive methodology is highlighted.

The split-up of the FDO Methodology into three different but interdependent models (section 4.1 and contribution "C13") is an important contribution as it allows reuse across application contexts by separating the generically applicable FDO Procedural Model from the FDO Execution Model that builds upon the application-specific FDO Data Model. Across all stages clear guidance is provided by unambiguous definitions of domains, constituents and paths and, in contrast to other methodologies, domain experts and their tacit knowledge play an important complementary role when running the methodology. Especially the so far neglected phase of generating Flexible Design Concepts (section 3.2.2) is highly emphasized in the FDO Methodology and part of the matrix-based approach. The data-based execution of the FDO Methodology with the large scope of predefined elements and relations (C9 – C12) stands in strong contrast to the prevalent "ad hoc" identification of especially Flexible Design Concepts as discussed in section 3.2.2.

Hereby, the executive part ("FDO Execution") includes the core contributions of the FDO Methodology. In contrast to most other general or matrix-based methodologies (section 3.1 and 3.2), the explicit selection of suitable baseline designs (C3) is an important part of the methodology, especially as the quality of subsequent solutions highly depends on that initial design basis. The core contribution is the matrix-based approach of aligned original and transposed DSMs and DMMs (C1) enabling the systematic identification of FDOs. Based on that representation the subsequent contributions are especially the tracing capabilities (C4). Next to the identification of change instigating components and direct change propagation, the focus is also on indirect change propagation which oftentimes remains unconsidered in prevalent FDO methodologies (section 3.1.3). Especially the gradual scenario building (C5) is an important contribution as it ensures a comprehensive consideration of the basis for flexible design that so

---

[325] NEUFVILLE & SCHOLTES [2011, pp. 122–123] refer to a "patterned search" for short-listing flexible designs, which, in contrast to this methodology, bases upon simulation to explore many alternatives systematically and only targets "concept generation".

far has not had enough focus in prevalent methodologies. Within that matrix-based methodology, the concurrent and integrated consideration of “Transitions” when generating Flexible Design Concepts (C7) is especially important as a detached decision-making of “Objects” and “Change Enablers” would lead to suboptimal Flexible Design Solutions. In this regard, the differentiation between pre-defined Transitions as boundary conditions (Transition-driven approach) or design variables when generating Flexible Design Concepts (Enabler-driven approach) is a significant contribution (C8) as it considers the heterogeneous circumstances in projects (e.g. time constraints) to account for flexible design.

Opposed to the rather high-effort valuations of existing approaches that usually focus on a very limited set of design variables, the two complementary ways of assessment & decision-making in the FDO Methodology allows both the efficient identification of FDOs and the consideration of a larger problem and solution space ensuring effective solutions in the end. Thereby, the continuous assessment & decision-making (C17) acts as a gradually applied filter whereas the assessment & decision-making in the separate FDO EM Report (C18) ensures getting from the relevant Flexible Design Concepts to high-performing Flexible Design Solutions. FDO Facilitators only play a supportive role to make the FDO Methodology practically applicable in the first place.

The second and other main research contribution of the developed FDO Methodology is both the identified and more generic Transition operators and the Change Enablers for concept generation (C12) that base upon data from case-based interviews discussed in section 5.2:

As shown in section 3.3.1 various definitions of Transitions, i.e. change strategies, already exist. However, partially they have a project managerial perspective (e.g. TRIGEORGIS [1996, pp. 2–3]) and are not applicable for the Transitions that concern engineering changes of physically fielded systems that require specific operators. BALDWIN & CLARK [2000, pp. 123–146] and PONN & LINDEMANN [2011, p. 337] suggest such operators but they concern operations that are suitable for certain type of changes (e.g. module design, functions) but not for the physical changes of already fielded systems that are addressed by this research. HILDEBRAND ET AL. [2005, p. 25] address operators for fielded modular systems that, however, are not sufficiently comprehensive and applicable in the context of the FDO Methodology. Hence, although there are communalities and overlaps between those operators and the ones presented in the FDO Methodology, the case-based interviews illustrate that new operators are required (e.g. differentiation between “Adding” and “Extending”) while certain operators are not applicable such as “inversion” by BALDWIN & CLARK [2000, pp. 138–140] which targets changes in the design hierarchy of modules. Additionally, the consideration of Transitions as variables that contribute to the generation of Flexible Design Concepts has a strong impact on the definition of those operators. For instance, the possibility of “no changes”, embodied by the Transition “Passive” for robust Flexible Design Concepts, cannot be ignored as an operator if considered together with Change Objects and Change Enablers to attain high-performing solutions. Consequently, the generated Transition operators represent a set of relevant operations that are applicable for fielded systems and are suitable to be used within the suggested FDO Methodology.

The other aspect of the second main contribution relates to the Change Enablers derived from case-based interviews. Those identified Change Enablers contribute to the empirical design guidelines in literature (section 3.3.2) and base upon the existing Change Enabler principles that were used as a means of systematization. As illustrated by SCHLATHER [2015, pp. 135–136] those heuristics partially overlap with existing ones but also extend the design guideline basis. Next to the application field of offshore drilling, they are especially applicable for the field of plant engineering. Beyond contributing with new heuristics and inspired by BISCHOF [2010, pp. 91–92], further descriptions make those guidelines more practical and clearer for the user. Especially the definition of Change Enablers as a combination of design guidelines and Enabler Reference Objects (part of C14), that must not always correspond to the Change Object, is an important contribution to avoid ambiguousness when applying Change Enablers. Hence, although Change Enablers are defined to fit into the overall FDO Methodology, the generated heuristics (design guidelines), their representation and configuration go beyond the use within the FDO Methodology and, hence, represent a contribution to research on their own.

Contribution to industry

This methodology was intentionally and carefully built based on the boundary conditions of the application field, the offshore drilling industry, to generate a research contribution that can be incorporated realistically in this real-world setting. As discussed in section 1.3.1, nevertheless, the results are still relevant and applicable for industries with similar characteristics. From an industrial perspective and based on the feedback of the expert evaluation, this methodology is able to attain the defined goal of section 1.3.1 as it builds upon and fulfills the basic and FDO requirements. Especially with the remarks and comments made by experts on future “improvement & extension of the methodology” (section 8.3.3), however, important measures are addressed that can further increase the chances of incorporation and success in the industrial context.

Despite the challenging boundary conditions in the addressed offshore industry (section 1.3.2), the FDO Methodology offers the opportunity to account for lifecycle value in early phases of design. Naturally, the incorporation of such a methodology must go beyond the consideration of technical aspects to close the value gap as addressed in section 1.2.2. As section 1.2.3 highlighted beyond the consideration of flexible design, other aspects must be overcome to make it a success in the offshore drilling industry and beyond such as: sufficient training on embedding and properly exercising flexibility, suitable design documentation for properly exercising flexibility, overcoming agency problems and information asymmetries of the various stakeholders involved and possibly even changes of the business model. This involves discussions and agreements across various stakeholders not being bound to specific projects.

In the meantime, a gradual integration of parts of the FDO Methodology can be an option to get users acquainted with the new mindset and ensure a sustainable integration into the organization and industry. This, however, must be done with caution and professional surveillance.

9.3 Outlook

Beyond the efforts invested in this research, there still remain aspects that are not yet resolved and, hence, represent opportunities for further research. They can be divided into contributions to the data models, execution models, assessment and decision-making or represent a general extension of the methodology.

Especially the building and maintenance of the FDO Data Model should be further facilitated by complementary conceptual measures to the use of Object classes. This may also involve alternative means of implementation (e.g. object-oriented programming). Alternatives to more efficiently populate and organize data in MDMs such as the elicitation by deducing indirect dependencies from directly elicited ones as shown in LINDEMANN ET AL. [2009, pp. 99–117], or software application support (e.g. SMaRT[326] by BARTOLOMEI [2007, pp. 148–153]) may be further explored for this context of application. Especially matrices related to stage I, the “Identification of Change Objects”, still miss facilitators for building and maintaining FDO Data Models representing a large potential. Concerning Object classes, further research is needed to better understand and allow differentiating general and Object class specific Change Enablers. Naturally, the extension of the already gathered design guidelines of Change Enablers is considered to be a relevant continuous process which is highly valuable as better Flexible Design Solutions could be created.

Generally, future research should target the systematization of data in the FDO Data Model to ease the exercise in the FDO Execution model. The FDO Data Model could benefit from further structuring of elements within domains to groups which are then interrelated across domains and facilitate targeting specific type of elements during execution. For instance, System Requirements might only affect Objects at certain hierarchical levels (e.g. factory level, machine level) and this information may allow hiding elements of irrelevant groups which then enhances the usability when running the FDO Execution Model. Furthermore, the integration of further features discussed in literature such as “compound options”, i.e. the “option on an option” (section 5.1) which had no applicable use case in this research, could be subject to future work.

In the FDO Execution Model the identification of FDOs can be further formalized by explicit-making of element characteristics which supports the continuous assessment when running the model. In particular, the assessment of change risk can also be made more formal and explicit, which as for now, only serves as an indication if potential relations are at all applicable in stage I of the methodology. This may also become important as a means of documentation where performed decisions are made transparent during design but also during utilization phases of the system. Although tracing change propagations of higher orders are supported by the model, research could focus on further increasing the usability of the model in this regard. Concerning the implementation in a software tool, the FDO Execution Model would profit from a step-wise implementation of FDO steps within a workflow to enable a successful application in an industrial context. Research would then address matching the user-specific boundary conditions and preferences to existing workflow alternatives.

Research could also target stage III of the FDO Methodology. After short-listing Flexible Design Concepts and before Flexible Design Solutions are generated, further research on valuing concepts within the FDO Methodology could be worthwhile as they can increase the

---

[326] System Modeling and Representation Tool (SMaRT) to speed up the data acquisition and simplifying the visualization of Engineering Systems knowledge in the ES-MDM framework.

effectiveness of results and reinsure decision-makers on the correctness of their decisions. Research would have to address the integration of valuation methods into the FDO Methodology while accounting for the challenges of defining clear payback functions (section 3.2.2). In this regard, a further detailing on identified FDOs such as the suitable degree of flexibility (e.g. degree of modularity as emphasized in ENGEL ET AL. [2016] and introduced exemplarily in section 3.2.1) would be reasonable to further concretize Flexible Design Concepts. This will require an Object or Object class specific architectural analysis.

Despite the extension of already embedded aspects in the methodology, the focus could also be on "process management" (section 3.1.1) especially as next to "concept generation" it also provides "a rich environment for novel research contributions" [CARDIN 2013]. One potential for a successful introduction of flexibility lies in a market segmentation of customers while accounting for the stakeholder network which was already addressed and discussed in ALLAVERDI ET AL. [2014]. By targeting market segments with different preferences and acceptability thresholds of companies, company divisions or even individuals, the efficiency of identifying FDOs could be significantly supported. The previously gained knowledge on market segments across the five domains and their matrices[327], can support omitting irrelevant choices from the beginning or highlight favorable choices during process execution.

Despite the improved introduction of flexibility into the market, another aspect of process management could be considered by closing the gap between envisioned changes during design and the exercise of changes during system utilization. A shift from the rather "focused strategy" with one possible future in the FDO Methodology could be extended to a more "future robust" one (section 2.2.2) where various characteristics of Change Drivers are accounted for (e.g. water depth increases from envisioned 5000 ft to 7000 ft or 10000 ft). Additionally, the selection of multiple alternative Transitions for a Flexible Design Solution may be advantageous to consider as preferences on those future Transitions may change or new stakeholders are involved that favor other Transitions. Hence, initially ideal Flexible Design Solutions may turn out to be suboptimal due to a shift of preferences across the lifecycle. Thus, by further research on closing the gap between envisioned and actually occurring futures and changes, the effectiveness of Flexible Design Solutions could be further increased. A general extension of the FDO Methodology which would be subject to relevant research is:

- Extending the field of application to also include software changes and according Change Enablers
- Extending the addressed application field of the FDO Methodology which includes adaptations of the methodology and evaluations across industries
- Extending the field of application to design phases, i.e. not only targeting flexibility of fielded systems but also "design flexibility" which differs especially in the targeted Change Enablers

If future research can successfully address those aspects, the value of the methodology can be further increased.

---

[327] For instance, some customers do not operate floaters but only fixed platforms / jack-ups which makes Change Drivers such as "Change of Rig Motion" or System Requirements such as "Heave Compensation" irrelevant.

10. References

AARLE 2013
Aarle, R.: A Real-Options approach to company valuation. Master Thesis. University of Twente. Department Finance & Accounting. Enschede [Netherlands]: 2013.

ALLAVERDI 2012
Allaverdi, D.: Systematization of context and external influences for more efficient drilling processes of floaters. In: Proceedings of Systems Engineering in Ship & Offshore Design Conference. Systems Engineering in Ship & Offshore Design. London [UK], 28.03.-29.03.2012. The Royal Institution of Naval Architects (RINA) 2012.

ALLAVERDI ET AL. 2013
Allaverdi, D.; Herberg, A.; Lindemann, U.: Lifecycle perspective on uncertainty and value robustness in the offshore drilling industry. In: Proceedings of 7th Annual IEEE Systems Conference (SysCon 2013). Orlando [FL, USA], 15.04.-18.04.2013. Piscataway [NJ, USA]: IEEE 2013, pp. 886–893. ISBN 9781467331074.

ALLAVERDI ET AL. 2014
Allaverdi, D.; Herberg, A.; Lindemann, U.: Identification of Flexible Design Opportunities (FDO) in offshore drilling systems by market segmentation. In: D. Marjanović, M. Štorga, N. Pavković and N. Bojčetić (Eds.): Proceedings of the 13th International Design Conference (DESIGN 2014). Dubrovnik [Croatia], 19.05.-22.05.2014. Glasgow [UK]: The Design Society 2014, pp. 1451–1462.

ALLAVERDI ET AL. 2015
Allaverdi, D.; Herberg, A.; Lindemann, U.: Identifying Flexible Design Opportunities: Getting from a Procedural to an Execution Model. In: C. Weber, S. Husung, M. Cantamessa, G. Cascini, D. Marjanović and S. Venkataraman (Eds.): Proceedings of the 20th International Conference on Engineering Design (ICED '15). Milan [IT], 27.07.-30.07.2015. Glasgow [UK]: The Design Society 2015. ISBN 978-1-904670-73-5.

AMRAM & KULATILAKA 2000
Amram, M.; Kulatilaka, N.: Real options – Managing strategic investment in an uncertain world. Boston [MA, USA]: Harvard Business School Press 2000. ISBN 9780875848457.

ANDERSON & NARUS 1998
Anderson, J. C.; Narus, J. A.: Business marketing: understand what customers value. In: Harvard Business Review 76 (1998) 98601, pp. 53–67.

Archer 2013
Archer: Modular Rig. 2013
URL:
http://archerwell.com/content/uploads/2014/10/BR_US_MR_05052015_letter_screen.pdf
Access date: 02.09.2015.

BABAJIDE ET AL. 2009
Babajide, A.; Neufville, R. de; Cardin, M.-A.: Integrated Method for Designing Valuable Flexibility In Oil Development Projects. In: SPE Projects, Facilities & Construction 4 (2009) 2, pp. 3–12.

BALDWIN & CLARK 2000
Baldwin, C. Y.; Clark, K. B.: Design rules. Cambridge [MA, USA]: MIT Press 2000. ISBN 9780262024662.

BARTOLOMEI ET AL. 2007
Bartolomei, J. E.; Cokus, M.; Dahlgren, J.; Neufville, R. de; Maldonado, D.; Wilds, J. M.: Analysis and Applications of Design Structure Matrix, Domain Mapping Matrix, and Engineering System Matrix Frameworks. Working paper. Massachusetts Institute of Technology. Cambridge [MA, USA]: 2007.

BARTOLOMEI 2007
Bartolomei, J. E.: Qualitative knowledge construction for engineering systems: Extending the design structure matrix methodology in scope and procedure. Doctoral Thesis. Massachusetts Institute of Technology. Engineering Systems Division. Cambridge [MA, USA]: 2007.

BARTOLOMEI ET AL. 2012
Bartolomei, J. E.; Hastings, D. E.; Neufville, R. de; Rhodes, D. H.: Engineering Systems Multiple-Domain Matrix – An organizing framework for modeling large-scale complex systems. In: Systems Engineering 15 (2012) 1, pp. 41–61.

BAUDZUS ET AL. 2013
Baudzus, B. H.; Krebs, M.; Deuse, J.: Design of Manual Assembly Systems Focusing on Required Changeability. In: C. Schutte, D. Dimitrov and P. Conradie (Eds.): Proceedings of the International Conference on Competitive Manufacturing (COMA '13). Stellenbosch (ZA), 30.01.- 01.02.2013. The International Academy for Production Engineering (CIRP) 2013.

BAUMBERGER 2007
Baumberger, G. C.: Methoden zur kundenspezifischen Produktdefinition bei individualisierten Produkten. Doctoral Thesis. Technische Universität München. Lehrstuhl für Produktentwicklung. Munich: 2007.

BEIL 2010
Beil, D. R.: Supplier selection. In: Wiley Encyclopedia of Operations Research and Management Science (2010).

BEREKOVEN ET AL. 2009
Berekoven, L.; Eckert, W.; Ellenrieder, P.: Marktforschung: methodische Grundlagen und praktische Anwendung. Berlin, Heidelberg: Springer 2009. ISBN 3834982679.

BERTALANFFY 1970
Bertalanffy, L. von: Gesetz oder Zufall: Systemtheorie und Selektion. In: Das neue Menschenbild—Die Revolutionierung der Wissenschaften vom Leben, Molden (1970, pp. 71–95.

BIRKHOFER & WAELDELE 2008
Birkhofer, H.; Waeldele, M.: Properties and characteristics and attributes and … - An approach on structuring the description of technical systems. In: V. Vanek, S. Hosnedl and J. Bartak (Eds.): Proceedings of Applied Engineering Design Science Workshop (AEDS 2008). Pilsen [Czech Republic], 31.10.-1.11.2008. The Design Society 2008, pp. 19–34. ISBN 978-80-7043-685-1.

BISCHOF 2010
Bischof, A.: Developing Flexible Products for Changing Environments. Doctoral Thesis. Technischen Universität Berlin. Fakultät V – Verkehrs- und Maschinensysteme. Berlin: 2010.

BLESSING & CHAKRABARTI 2009
Blessing, L.; Chakrabarti, A.: DRM, a Design Research Methodology. London: Springer 2009. ISBN 978-1-84882-586-4.

BOURANI ET AL. 2013
Bourani, M. R.; Cardin, M.-A.; Chong, W. S.; Atapattu, R.; Foo, K. S.: An integrated screening framework to analyze flexibility in engineering systems design. In: U. Lindemann, S. Venkataraman, YS. Kim, SW. Lee, A. Dong and Y. Lin (Eds.): Proceedings of 19th International Conference on Engineering Design (ICED '13). Seoul [South Korea], 19.08.-22.08.2013. Glasgow [UK]: The Design Society 2013. ISBN 978-1-904670-52-0.

BROWNE ET AL. 1984
Browne, J.; Dubois, D.; Rathmill, K.; Sethi, S. P.; Stecke, K. E.: Classification of flexible manufacturing systems. In: The FMS magazine 2 (1984) 2, pp. 114–117.

BROWNING & HONOUR 2008
Browning, T. R.; Honour, E. C.: Measuring the life-cycle value of enduring systems. In: Systems Engineering 11 (2008) 3, pp. 187–202.

BROWNING & RAMASESH 2015
Browning, T. R.; Ramasesh, R. V.: Reducing unwelcome surprises in project management. In: MIT Sloan Management Review 56 (2015) 3, pp. 23–32.

BStMUGV 2009
BStMUGV (Ed.): Verordnung über Anlagen zum Umgang mit wassergefährdenden Stoffen und über Fachbetriebe. Anlagenverordnung - VAwS. Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz. Munich: 2009.

BURROWES & SQUAIR 1999
Burrowes, D.; Squair, M.: Managing the Emergent Properties of the Design. In: Proceedings of the INCOSE International Symposium. Brighton [UK], 6.06.-11.06.1999. INCOSE 1999, pp. 190–194.

CARATHANASSIS 2015
Carathanassis, D.: Identifying Flexible Design Opportunities: Systematization of change sources for offshore drilling systems and application in execution model. Semestral Thesis. Technische Universität München. Lehrstuhl für Produktentwicklung. Munich: 2015.

CARDIN ET AL. 2012
Cardin, M.-A.; Kolfschoten, G. L.; Frey, D. D.; Neufville, R.; Weck, O. L.; Geltner, D. M.: Empirical evaluation of procedures to generate flexibility in engineering systems and improve lifecycle performance. In: Research in Engineering Design 24 (2012) 3, pp. 277–295.

CARDIN 2013
Cardin, M.-A.: An Organizing Taxonomy of Procedures to Design and Manage Complex Systems for Uncertainty and Flexibility. In: M. Aiguier, Y. Caseau, D. Krob and A. Rauzy (Eds.): Complex Systems Design & Management. Berlin, Heidelberg: Springer 2013. ISBN 978-3-642-34403-9.

CARDIN 2014
Cardin, M.-A.: Enabling Flexibility in Engineering Systems – A Taxonomy of Procedures and a Design Framework. In: Journal of Mechanical Design 136 (2014) 11005, pp. 1–14.

CARDIN & NEUFVILLE 2008
Cardin, M.-A.; Neufville, R. de: A survey of state-of-the-art methodologies and a framework for identifying and valuing flexible design opportunities in engineering systems. Working paper. Massachusetts Institute of Technology. Cambridge [MA, USA]: 2008.

CHAFCOULOFF ET AL. 1995
Chafcouloff, S.; Michel, G.; Trice, M.; Clark, G.; Cosad, C.; Forbes, K.: Integrated services. In: Oilfield Review 7 (1995) 2, pp. 11–25.

CHMARRA ET AL. 2008
Chmarra, M. K.; Arts, L.; Tomiyama, T.: Towards Adaptable Architecture. In: Proceedings of the 34th Design Automation Conference (DAC). Brooklyn [NY: USA], 03.08.-06.08.2008. American Society of Mechanical Engineers (ASME) 2008, pp. 367–376. ISBN 978-0-7918-4325-3.

CHUCHOLOWSKI ET AL. 2013
Chucholowski, N.; Langer, S.; Behncke, F.; Lindemann, U.: Comparison of engineering change cause analysis in literature and industrial practice. In: U. Lindemann, S. Venkataraman, YS. Kim, SW. Lee, A. Dong and Y. Lin (Eds.): Proceedings of 19th International Conference on Engineering Design (ICED '13). Seoul [South Korea], 19.08.-22.08.2013. Glasgow [UK]: The Design Society 2013. ISBN 978-1-904670-52-0.

CLARKSON ET AL. 2004
Clarkson, P. J.; Simons, C.; Eckert, C.: Predicting Change Propagation in Complex Design. In: Journal of Mechanical Design 126 (2004) 5, pp. 788–797.

CLARKSON & ECKERT 2005
Clarkson, P. J.; Eckert, C. M. (Eds.): Design process improvement – A review of current practice. London: Springer 2005. ISBN 9781852337018.

CLOUTIER 2006
Cloutier, R. J.: Applicability of patterns to architecting complex systems. Doctoral Thesis. Stevens Institute of Technology. Hoboken [NJ, USA]: 2006.

CONRAT 1997
Conrat, J.-I.: Änderungskosten in der Produktentwicklung. Doctoral Thesis. Technische Universität München. Lehrstuhl für Allgemeine und Industrielle Betriebswirtschaftslehre. Munich: 1997.

COPELAND & ANTIKAROV 2001
Copeland, T. E.; Antikarov, V.: Real options: a practitioner's guide. New York [NY, USA]: Texere 2001. ISBN 1587990288.

COX ET AL. 1979
Cox, J. C.; Ross, S. A.; Rubinstein, M.: Option pricing: A simplified approach. In: Journal of Financial Economics 7 (1979) 3, pp. 229–263.

CRAWLEY 2004
Crawley, E.: The influence of architecture in engineering systems. In: D. Hastings, E. Crawley, Joel Moses and Richard de Neufville (Eds.): Engineering Systems Monograph. Engineering Systems Symposium. Cambridge [MA, USA], 29.03.-31.03.2004. MIT Engineering Systems Division 2004.

DE NEUFVILLE 2004
de Neufville, R.: Uncertainty management for systems planning and design. In: D. Hastings, E. Crawley, Joel Moses and Richard de Neufville (Eds.): Engineering Systems Monograph. Engineering Systems Symposium. Cambridge [MA, USA], 29.03.-31.03.2004. MIT Engineering Systems Division 2004.

DE WECK ET AL. 2007
de Weck, O. L.; Eckert, C.; Clarkson, J.: A classification of uncertainty for early product and system design. In: J.-C. Bocquet (Ed.): Proceedings of 16th International Conference on Engineering Design (ICED '07). Paris [France], 28.07.-31.07.2007. Glasgow [UK]: The Design Society 2007. ISBN 1-904670-02-4.

DE WECK 2007
de Weck, O. L.: On the role of DSM in designing systems and products for changeability. In: U. Lindemann, M. Danilovic, F. Deubzer, M. Maurer and M. Kreimeyer (Eds.): Proceedings of 9th International DSM Conference. Munich, 16.10.-18.10.2007. The Design Society. Aachen: Shaker Verlag 2007. ISBN 3-8322-6641-7.

DE WECK 2008
de Weck, O. L.: Systems Engineering for Changeability: Designing Systems for an Uncertain Future – Research Overview. INCOSE New England Chapter Meeting. 2008.

DE WECK ET AL. 2011
de Weck, O. L. de; Roos, D.; Magee, C. L.: Engineering systems – Meeting human needs in a complex technological world. Cambridge [MA, USA]: MIT Press 2011. ISBN 0262016702.

DE WECK ET AL. 2012
de Weck, O. L. de; Ross, A. M.; Rhodes, D. H.: Investigating relationships and semantic sets amongst system lifecycle properties (Ilities). In: Proceedings of 3rd International Engineering Systems Symposium (CESUN 2012). Delft [Netherlands], 18.06.-20.06.2012. Council of Engineering Systems Universities (CESUN) 2012.

De Weck, Olivier L et al. 2004
De Weck, Olivier L; Neufville, R. de; Chaize, M.: Staged deployment of communications satellite constellations in low earth orbit. In: Journal of Aerospace Computing, Information, and Communication 1 (2004) 3, pp. 119–136.

DEMPSTER 1967
Dempster, A. P.: Upper and Lower Probabilities Induced by a Multivalued Mapping. In: The Annals of Mathematical Statistics 38 (1967) 2, pp. 325–339.

EARL ET AL. 2005
Earl, C.; Johnson, J.; Eckert, C.: Complexity. In: P. J. Clarkson and C. M. Eckert (Eds.): Design process improvement – A review of current practice. London: Springer 2005. ISBN 9781852337018.

ECKERT ET AL. 2004
Eckert, C.; Clarkson, P. J.; Zanker, W.: Change and customisation in complex engineering domains. In: Research in Engineering Design 15 (2004) 1, pp. 1–21.

ECKERT ET AL. 2009
Eckert, C.; Clarkson, J.; Weck, O. d.; Keller, R.: Engineering change: Drivers, sources, and approaches in industry. In: M. Norell Bergendahl, M. Grimheden, L. Leifer, P. Skogstad and U. Lindemann (Eds.): Proceedings of the 17th International Conference on Engineering Design (ICED '09). Palo Alto [CA, USA], 24.08.-27.08.2009. Glasgow [UK]: The Design Society 2009, pp. 47–58. ISBN 978-1-904670-08-7.

ECKERT ET AL. 2012
Eckert, C.; Isaksson, O.; Earl, C.: Product Property Margins: An underlying critical problem of engineering design. In: Proceedings of Tools and Methods of Competitive Engineering (TMCE 2012). Karlsruhe [Germany], 07.05.-11.05.2012. Karlsruhe Institute of Technology, Delft University of Technology 2012, pp. 1027–1040.

EIKILL & ATTRAMADAL 2013
Eikill, G. O.; Attramadal, A.: Driving Innovation Through Collaboration in the Rig Market. In: Proceedings of Offshore Technology Conference 2013 (OTC 2013). Houston [TX, USA], 6.05.-9.05.2013. Society of Petroleum Engineers (SPE) 2013.

ELMARAGHY 2005
ElMaraghy, H. A.: Flexible and reconfigurable manufacturing systems paradigms. In: International Journal of Flexible Manufacturing Systems 17 (2005) 4, pp. 261–276.

ELMARAGHY & WIENDAHL 2009
ElMaraghy, H. A.; Wiendahl, H.-P.: Changeability – An Introduction. In: H. A. ElMaraghy (Ed.): Changeable and Reconfigurable Manufacturing Systems. London: Springer 2009. ISBN 978-1-84882-066-1.

ENGEL ET AL. 2016
Engel, A.; Browning, T. R.; Reich, Y.: Designing Products for Adaptability: Insights from Four Industrial Cases. Working Paper. Tel Aviv University. 2016.

ENGEL & BROWNING 2008
Engel, A.; Browning, T. R.: Designing systems for adaptability by means of architecture options. In: Systems Engineering 11 (2008) 2, pp. 125–146.

EPPINGER & BROWNING 2012
Eppinger, S. D.; Browning, T. R.: Design structure matrix methods and applications. Cambridge [MA, USA]: MIT Press 2012. ISBN 1628709111.

FÖRSTER 2003
Förster, M.: Variantenmanagement nach Fusionen in Unternehmen des Anlagen- und Maschinenbaus. Doctoral Thesis. Technische Universität München. Lehrstuhl für Produktentwicklung. Munich: 2003.

FRANCALANZA ET AL. 2014
Francalanza, E.; Borg, J.; Constantinescu, C.: Deriving a Systematic Approach to Changeable Manufacturing System Design. In: Proceedings of the 47th CIRP Conference on Manufacturing Systems (CIRP 2014). Windsor [ON, Canada], 28.04.-30.04.2014. The International Academy for Production Engineering (CIRP) 2014, pp. 166–171.

FREDERICKS & REITSMA 2006
Fredericks, P. D.; Reitsma, D.: MPD automation addresses drilling challenges in conventional, unconventional resources. In: Journal of Drilling Contractor 62 (2006) 6, pp. 46–49.

FRICKE & SCHULZ 2005
Fricke, E.; Schulz, A. P.: Design for changeability (DfC) – Principles to enable changes in systems throughout their entire lifecycle. In: Systems Engineering 8 (2005) 4, pp. 342–359.

FULKS & COOK 2002
Fulks, R. W.; Cook, A.: Managing the Operator/Supplier Relationship on The Mad Dog Project – The Supplier's Perspective. In: Proceedings of 2002 IADC/SPE Drilling Conference. Dallas [TX, USA], 26.02.-28.02.2002. Society of Petroleum Engineers (SPE) 2002.

GAUSEMEIER ET AL. 2000
Gausemeier, J.; Lindemann, U.; Reinhart, G.; Wiendahl, H.-P.: Kooperatives Produktengineering – Ein neues Selbstverständnis des ingenieurmäßigen Wirkens. Paderborn: Heinz-Nixdorf-Institut 2000. ISBN 9783931466787.

GAUSEMEIER ET AL. 2001
Gausemeier, J.; Ebbesmeyer, P.; Kallmeyer, F.: Produktinnovation: strategische Planung und Entwicklung der Produkte von morgen. Munich: Hanser 2001. ISBN 3446216316.

GIFFIN ET AL. 2009
Giffin, M.; Weck, O. d.; Bounova, G.; Keller, R.; Eckert, C.; Clarkson, P. J.: Change propagation analysis in complex technical systems. In: Journal of Mechanical Design 131 (2009) 81001, pp. 1–12.

GIL 2007
Gil, N.: On the value of project safeguards – Embedding real options in complex products and systems. In: Research Policy 36 (2007) 7, pp. 980–999.

GÖPFERT 1998
Göpfert, J.: Modulare Produktentwicklung – Zur gemeinsamen Gestaltung von Technik und Organisation. Wiesbaden: Deutscher Universitätsverlag 1998. ISBN 9783824468270.

GREDEN 2005
Greden, L. V.: Flexibility in building design: a real options approach and valuation methodology to address risk. Doctoral Thesis. Massachusetts Institute of Technology. Department of Architecture. Cambridge [MA, USA]: 2005.

GU ET AL. 2009
Gu, P.; Xue, D.; Nee, A Y C: Adaptable design: concepts, methods, and applications. In: Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 223 (2009) 11, pp. 1367–1387.

GÜNTHNER ET AL. 2006
Günthner, W. A.; Wilke, M.; Heinecker, M.: Modulare Materialflusssysteme für wandelbare Fabrikstrukturen. Final report. Ed. by W. A. Günthner, Lehrstuhl für Fördertechnik Materialfluss Logistik (FML). Munich: 2006.

HALPERN 2003
Halpern, J. Y.: Reasoning about uncertainty. Cambridge [MA, USA]: MIT Press 2003. ISBN 9780262083201.

HANSEN 2002
Hansen, R. C.: Overall equipment effectiveness – A powerful production/maintenance tool for increased profits. New York, NY: Industrial Press 2002. ISBN 0-8311-3138-1.

HARRIS 1989
Harris, J.: Selecting an offshore drilling rig - the competitive tendering process. In: Proceedings of Offshore Europe 89. Aberdeen [UK], 5.09.-8.09.1989. Society of Petroleum Engineers (SPE) 1989.

HARTUNG ET AL. 2012
Hartung, J.; Baudzus, B.; Deuse, J.: A Life Cycle Oriented Evaluation of Changeable Manufacturing and Assembly Systems. In: David A. Dornfeld and Barbara S. Linke (Eds.): Leveraging Technology for a Sustainable World. Berlin, Heidelberg: Springer 2012. ISBN 978-3-642-29068-8.

HASHEMIAN 2005
Hashemian, M.: Design for adaptability. Doctoral Thesis. University of Saskatchewan. Department of Mechanical Engineering. Saskatoon [Saskatchewan, Canada]: 2005.

HAUSER & CLAUSING 1988
Hauser, J. R.; Clausing, D.: The house of quality. In: Harvard Business Review 66 (1988) 3, pp. 63–73.

HEGER 2007
Heger, C. L.: Bewertung der Wandlungsfähigkeit von Fabrikobjekten. Doctoral Thesis. Universität Hannover. Institut für Fabrikanlagen und Logistik. Hannover: 2007.

HELMER-HIRSCHBERG 1967
Helmer-Hirschberg, O.: Analysis of the future: The Delphi Method. In: Rand Corporation P-3558 (1967).

HERBERG 2016
Herberg, A.: Planung und Entwicklung multifunktionaler Kernmodule in komplexen Systemarchitekturen und -portfolios – Methodik zur Einnahme einer konsequent modulzentrierten Perspektive. Doctoral Thesis (Submitted version). Technische Universität München. Lehrstuhl für Produktentwicklung. Munich: 2016.

HERNÁNDEZ 2003
Hernández, R.: Systematik und Wandlungsfähigkeit in der Fabrikplanung. Doctoral Thesis. Universität Hannover. Institut für Fabrikanlagen und Logistik. Hannover: 2003.

HIGHAM 2004
Higham, D. J.: An introduction to financial option valuation – Mathematics, stochastics and computation. Cambridge [UK]: Cambridge University Press 2004. ISBN 978-0-521-54757-4.

HILDEBRAND ET AL. 2005
Hildebrand, T.; Mäding, K.; Günther, U.: PLUG+ PRODUCE: Gestaltungsstrategien für die wandlungsfähige Fabrik. Chemnitz: Institut für Betriebswissenschaft und Fabriksysteme (IBF), Technische Universität Chemnitz 2005. ISBN 3000160760.

HOPE ET AL. 2012
Hope, I.; Livingston, S.; Ogg, J. L.: Newbuild Construction Cycles - An Evolving Paradigm. In: Proceedings of 2012 IADC/SPE Drilling Conference and Exhibition. San Diego [CA, USA], 06.03.-08.03.2012. Society of Petroleum Engineers (SPE) 2012.

HSE 2001
HSE (Ed.): Offshore Technology Report – Environmental considerations. Sudbury [UK]: HSE Books 2001. ISBN 0717623793.

HU 2012
Hu, J.: Flexible Engineering System Design with Multiple Exogenous Uncertainties and Change Propagation. Doctoral Thesis. National University of Singapore. Department of Industrial and Systems Engineering. Singapore: 2012.

HU ET AL. 2013
Hu, J.; Cardin, M.-A.; Poh, K.-L.; Chia, E. S.: An approach to generate flexibility in engineering design of sustainable waste-to-energy systems. In: U. Lindemann, S. Venkataraman, YS. Kim, SW. Lee, A. Dong and Y. Lin (Eds.): Proceedings of 19th International Conference on Engineering Design (ICED '13). Seoul [South Korea], 19.08.-22.08.2013. Glasgow [UK]: The Design Society 2013. ISBN 978-1-904670-52-0.

HU & CARDIN 2015
Hu, J.; Cardin, M.-A.: Generating flexibility in the design of engineering systems to enable better sustainability and lifecycle performance. In: Research in Engineering Design 26 (2015) 2, pp. 121–143.

HUBKA 1984
Hubka, V.: Theorie technischer Systeme – Grundlagen einer wissenschaftlichen Konstruktionslehre. 2. edition. Berlin, Heidelberg: Springer 1984. ISBN 978-3-540-12953-0.

HUTCHINSON & PFLUGHOEFT 1994
Hutchinson, G. K.; Pflughoeft, K. A.: Flexible process plans – Their value in flexible automation systems. In: International Journal of Production Research 32 (1994) 3, pp. 707–719.

INCOSE 2010
INCOSE (Ed.): INCOSE Systems Engineering Handbook – Improving the Process for SE Practitioners. 3.2. edition. Hoboken [NJ, USA]: Wiley 2010. ISBN 1118999401.

Infield Systems Ltd 2016
Infield Systems Ltd: Infield System Rig Glossary – MODU definitions. 2016
URL: http://www.infield.com/rigs/rig-glossary
Access date: 22.07.2016.

IEEE 610:1990
Institute of Electrical and Electronics Engineers. IEEE 610: IEEE Standard Glossary of Software Engineering Terminology. IEEE Std 610-1990. New York [NY, USA]: IEEE 1990.

IEEE 1233:1996
Institute of Electrical and Electronics Engineers. IEEE 1233: IEEE Guide for Developing System Requirements Specifications. IEEE Std 1233-1996. New York [NY, USA]: IEEE 1996.

IEEE 1471:2000
Institute of Electrical and Electronics Engineers. IEEE 1471: Recommended Practice for Architectural Description of Software-Intensive Systems. IEEE Std 1471-2000. New York [NY, USA]: IEEE 2000.

JACOBS & DONNELLY 2011
Jacobs, S.; Donnelly, J.: Crossing the Technology Chasm – Managed Pressure Drilling. In: Journal of Petroleum Technology 63 (2011) 2, pp. 30–35.

JARRATT ET AL. 2011
Jarratt, T. A. W.; Eckert, C. M.; Caldwell, N. H. M.; Clarkson, P. J.: Engineering change: an overview and perspective on the literature. In: Research in Engineering Design 22 (2011) 2, pp. 103–124.

JOHNSON & CHRISTENSEN 2008
Johnson, B.; Christensen, L.: Educational research – Quantitative, qualitative, and mixed approaches. 3. edition. Thousand Oaks [CA, USA]: Sage Publications 2008. ISBN 978-1-4129-5456-3.

JUNG 2006
Jung, C.: Anforderungsklärung in interdisziplinärer Entwicklungsumgebung. Doctoral Thesis. Lehrstuhl für Produktentwicklung. Technische Universität München. Munich: 2006.

KADIYALA & WHOOLEY 2011
Kadiyala, R.; Whooley, A.: Deepwater DP Drilling Rigs on Shallow Water Wells, Can it Work? In: Proceedings of SPE/IADC Drilling Conference and Exhibition 2011. Amsterdam [Netherlands], 01.03.-03.03.2011. Society of Petroleum Engineers (SPE) 2011.

KAISER & SNYDER 2013
Kaiser, M. J.; Snyder, B.: The five offshore drilling rig markets. In: Marine Policy 39 (2013) 5, pp. 201–214.

KALLIGEROS 2006
Kalligeros, K. C.: Platforms and real options in large-scale engineering systems. Doctoral Thesis. Massachusetts Institute of Technology. Engineering Systems Division. Cambridge [MA, USA]: 2006.

KEESE ET AL. 2007
Keese, D. A.; Tilstra, A. H.; Seepersad, C. C.; Wood, K. L.: Empirically-derived principles for designing products with flexibility for future evolution. In: Proceedings of ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference 2007 (IDETC/CIE 2007). Las Vegas [NV, USA], 4.09.-7.09.2007. American Society of Mechanical Engineers (ASME) 2007, pp. 483–498. ISBN 0-7918-4804-3.

KISSEL ET AL. 2012
Kissel, M.; Schrieverhoff, P.; Lindemann, U.: Design for Adaptability – Identifying Potential for Improvement on an Architecture Basis. In: Proceedings of NordDesign 2012. Aalburg [Denmark], 22.08.-24.08.2012. The Design Society 2012. ISBN 978-87-91831-51-5.

KLEMKE 2014
Klemke, T.: Planung der systemischen Wandlungsfähigkeit von Fabriken. Doctoral Thesis. Universität Hannover. Institut für Fabrikanlagen und Logistik. Hannover: 2014.

KOH 2010
Koh, E. C. Y.: Managing Change Propagation in the Development of Complex Products. Doctoral Thesis. University of Cambridge. Cambridge [UK]: 2010.

KOH ET AL. 2012
Koh, E. C. Y.; Caldwell, Nicholas H. M.; Clarkson, P. J.: A method to assess the effects of engineering change propagation. In: Research in Engineering Design 23 (2012) 4, pp. 329–351.

KOH ET AL. 2013
Koh, E. C.Y.; Caldwell, N. H.M.; Clarkson, P. J.: A technique to assess the changeability of complex engineering systems. In: Journal of Engineering Design 24 (2013) 7, pp. 477–498.

KOREN & SHPITALNI 2011
Koren, Y.; Shpitalni, M.: Design of reconfigurable manufacturing systems. In: Journal of Manufacturing Systems 29 (2011) 4, pp. 130–141.

KOREN & ULSOY 2002
Koren, Y.; Ulsoy, A. G.: Vision, principles and impact of reconfigurable manufacturing systems. In: Powertrain International 5 (2002) 3, pp. 14–21.

KREBS 2011
Krebs, P.: Bewertung vernetzter Produktionsstandorte unter Berücksichtigung multidimensionaler Unsicherheiten. Doctoral Thesis. Technische Universität München. Lehrstuhl für Betriebswissenschaften und Montagetechnik. Munich: 2011.

KREIMEYER 2010
Kreimeyer, M. F.: A Structural Measurement System for Engineering Design Processes. Doctoral Thesis. Technische Universität München. Lehrstuhl für Produktentwicklung. Munich: 2010.

KVALØY & SØRENES 2009
Kvaløy, M.; Sørenes, T.: Discovering a less expensive way. In: Norwegian Continental Shelf (2009) 3, pp. 42–43.

LAFLEUR & SALEH 2010
Lafleur, J. M.; Saleh, J. H.: Survey of intra- and inter-mission flexibility in space exploration systems. In: Acta Astronautica 67 (2010) 1-2, pp. 97–107.

LINDEMANN 2005
Lindemann, U.: Methodische Entwicklung technischer Produkte – Methoden flexibel und situationsgerecht anwenden. 3. edition. Berlin, Heidelberg: Springer 2005. ISBN 978-3-540-14041-2.

LINDEMANN ET AL. 2009
Lindemann, U.; Maurer, M.; Braun, T.: Structural complexity management – An approach for the field of product design. Berlin, Heidelberg: Springer 2009. ISBN 9783540878896.

LINDEMANN & LORENZ 2008
Lindemann, U.; Lorenz, M.: Uncertainty handling in integrated product development. In: D. Marjanović, M. Štorga, N. Pavković and N. Bojčetić (Eds.): Proceedings of the 10th International Design Conference (DESIGN 2008). Dubrovnik [Croatia], 19.05.-22.05.2008. Glasgow [UK]: The Design Society 2008, pp. 175–182. ISBN 978-953-6313-89-1.

LINDEMANN & REICHWALD 1998
Lindemann, U.; Reichwald, R. (Eds.): Integriertes Änderungsmanagement. Berlin, Heidelberg: Springer 1998. ISBN 3642719589.

MAIER & RECHTIN 2009
Maier, M. W.; Rechtin, E.: The art of systems architecting. 3. edition. Boca Raton [FL, USA]: CRC Press 2009. ISBN 1420079131.

MALLOY 2007
Malloy, K. P.: Managed pressure drilling: What is it anyway? In: World oil 228 (2007) 3, pp. 27–34.

MANDELBAUM & BUZACOTT 1990
Mandelbaum, M.; Buzacott, J.: Flexibility and decision making. In: European Journal of Operational Research 44 (1990) 1, pp. 17–27.

MATEIKA 2005
Mateika, M.: Unterstützung der lebenszyklusorientierten Produktplanung am Beispiel des Maschinen- und Anlagenbaus. Doctoral Thesis. Technische Universität Braunschweig. Institut für Werkzeugmaschinen und Fertigungstechnik. Braunschweig: 2005.

MATHER 2000
Mather, A.: Offshore engineering – An introduction. 2. edition. London: Witherby & Co Ltd 2000. ISBN 1856091864.

MAURER 2007
Maurer, M. S.: Structural awareness in complex product design. Doctoral Thesis. Technische Universität München. Lehrstuhl für Produktentwicklung. Munich: 2007.

MCMANUS & HASTINGS 2004
McManus, H.; Hastings, D.: A Framework for Understanding Uncertainty and its Mitigation and Exploitation in Complex Systems. In: Proceedings of the Engineering Systems Symposium 2004. Cambridge [MA, USA], 29.03.-31.03.2004. MIT Engineering Systems Division 2004.

MEKDECI ET AL. 2012
Mekdeci, B.; Ross, A. M.; Rhodes, D. H.; Hastings, D. E.: A taxonomy of perturbations: Determining the ways that systems lose value. In: Proceedings of 6th Annual IEEE Systems Conference 2012 (SysCon 2012). Vancouver [BC, Canada], 19.03.-22.03.2012. Piscataway [NJ, USA]: IEEE 2012. ISBN 978-1-4673-0750-5.

MEKDECI 2013
Mekdeci, B.: Managing the Impact of Change Through Survivability and Pliability to Achieve Viable Systems of Systems. Doctoral Thesis. Massachusetts Institute of Technology. Engineering Systems Division. Cambridge [MA, USA]: 2013.

MHWirth AS 2014
MHWirth AS: BP MPD Technical Session. Unpublished. MHWirth AS. Kristiansand [Norway]: 2014.

MIKAELIAN ET AL. 2011
Mikaelian, T.; Nightingale, D. J.; Rhodes, D. H.; Hastings, D. E.: Real Options in Enterprise Architecture: A Holistic Mapping of Mechanisms and Types for Uncertainty Management. In: IEEE Transactions on Engineering Management 58 (2011) 3, pp. 457–470.

MIKAELIAN ET AL. 2012
Mikaelian, T.; Rhodes, D. H.; Nightingale, D. J.; Hastings, D. E.: A Logical Approach to Real Options Identification With Application to UAV Systems. In: IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans 42 (2012) 1, pp. 32–47.

MIT Engineering Systems Division 2008
MIT Engineering Systems Division (Ed.): Engineering Systems – Strategic Report. Massachusetts Institute of Technology. Cambridge [MA, USA]: 2008
URL: https://esd.mit.edu/Headline/ESD_StrategicPlan2011.pdf
Access date: 22.04.2016.

MÖRTL 2002
Mörtl, M. A.: Entwicklungsmanagement für langlebige, upgradinggerechte Produkte. Doctoral Thesis. Technische Universität München. Lehrstuhl für Produktentwicklung. Munich: 2002.

MOSES 2010
Moses, J.: Flexibility and Its Relation to Complexity and Architecture. In: M. Aiguier, F. Bretaudeau and D. Krob (Eds.): Complex Systems Design & Management. Berlin, Heidelberg: Springer 2010. ISBN 978-3-642-15654-0.

MÜNCH 2013
Münch, T. J.: Stakeholderkonstellationen und Vertragsbeziehungen der Ölbohrindustrie – Systematisierung and methodische Ableitung von Stakeholderinteressen aus Systemanbieter-Perspektive. Master Thesis. Technische Universität München. Lehrstuhl für Produktentwicklung. Munich: 2013.

MURMAN 2002
Murman, E. M.: Lean enterprise value – Insights from MIT's Lean Aerospace Initiative. New York [NY, USA]: Palgrave 2002. ISBN 9781280223563.

NASA 2007
NASA (Ed.): NASA Systems Engineering Handbook. 2. edition. Washington, D.C. [USA]: U.S. Government Printing Office 2007. ISBN 978-0-16-079747-7.

NEUFVILLE & SCHOLTES 2011
Neufville, R. de; Scholtes, S.: Flexibility in Engineering Design. Cambridge [MA, USA]: MIT Press 2011. ISBN 978-0262016230.

NILCHIANI & HASTINGS 2007
Nilchiani, R.; Hastings, D. E.: Measuring the Value of Flexibility in Space Systems: A Six-Element Framework. In: Systems Engineering 10 (2007) 1, pp. 26–44.

NOWACK 1997
Nowack, M. L.: Design guideline support for manufacturability. Doctoral Thesis. University of Cambridge. Cambridge University Engineering Department. Cambridge [UK]: 1997.

NYHUIS ET AL. 2005
Nyhuis, P.; Kolakowski, M.; Heger, C. L.: Evaluation of Factory Transformability. In: Proceedings of the 3rd International CIRP Conference on Reconfigurable Manufacturing. Ann Arbor [MI, USA], 10.05.-12.05.2005. The International Academy for Production Engineering (CIRP) 2005, pp. 147–152.

NYHUIS ET AL. 2007
Nyhuis, P.; Heinen, T.; Brieke, M.: Adequate and economic factory transformability and the effects on logistical performance. In: International Journal of Flexible Manufacturing Systems 19 (2007) 3, pp. 286–307.

NYHUIS ET AL. 2008
Nyhuis, P.; Reinhart, G.; Abele, E.: Wandlungsfähige Produktionssysteme – Heute die Industrie von morgen gestalten. Garbsen: PZH (Produktionstechnisches Zentrum Hannover) 2008. ISBN 978-3-939026-96-9.

ODELL 2014
Odell, C.: Offshore drilling rig building boom continues. IHS Petrodata. 2014
URL: http://www.offshore-mag.com/articles/print/volume-74/issue-7/rig-report/offshore-rig-building-boom-continues.html
Access date: 17.02.2016.

OLEWNIK ET AL. 2004
Olewnik, A.; Brauen, T.; Ferguson, S.; Lewis, K.: A Framework for Flexible Systems and Its Implementation in Multiattribute Decision Making. In: Journal of Mechanical Design 126 (2004) 3, pp. 412.

PAHL ET AL. 2007
Pahl, G.; Beitz, W.; Feldhusen, J.; Grote, K.-H.: Engineering Design – A Systematic Approach. 3. edition. London: Springer 2007. ISBN 1846283183.

PALANI RAJAN ET AL. 2005
Palani Rajan, P. K.; van Wie, M.; Campbell, M. I.; Wood, K. L.; Otto, K. N.: An empirical foundation for product flexibility. In: Design Studies 26 (2005) 4, pp. 405–438.

PASQUAL & WECK 2012
Pasqual, M. C.; Weck, O. L. de: Multilayer network model for analysis and management of change propagation. In: Research in Engineering Design 23 (2012) 4, pp. 305–328.

PAVEL & HUMPHREYS 2012
Pavel, D.; Humphreys, G.: Rig design shift would put MPD at the ready. Drilling Contractor. 2012
URL: http://www.drillingcontractor.org/rig-design-shift-would-put-mpd-at-the-ready-14792
Access date: 04.02.2015.

PINDYCK 2007
Pindyck, R. S.: Mandatory unbundling and irreversible investment in telecom networks. In: Review of Network Economics 6 (2007) 3, pp. 274–298.

PONN & LINDEMANN 2011
Ponn, J.; Lindemann, U.: Konzeptentwicklung und Gestaltung technischer Produkte – Systematisch von Anforderungen zu Konzepten und Gestaltlösungen. 2. edition. Berlin, Heidelberg: Springer 2011. ISBN 978-3-642-20579-8.

PSAC 2016
PSAC: Industry Overview – What is the upstream oil & gas industry? Petroleum Services Association of Canada. 2016
URL: http://www.psac.ca/business/industry-overview/
Access date: 10.03.2016.

QURESHI ET AL. 2006
Qureshi, A.; Murphy, J. T.; Kuchinsky, B.; Seepersad, C. C.; Wood, K. L.; Jensen, D. D.: Principles of product flexibility. In: Proceedings of the International Design Engineering Technical Conferences & Computers and Information in Engineering Conference 2006 (IDETC/CIE 2006). Philadelphia [PA, USA], 10.09.-13.09.2006. American Society of Mechanical Engineers (ASME) 2006, pp. 295–325. ISBN 0-7918-4258-4.

RASSENFOSS 2015
Rassenfoss, S.: Drilling Automation – A Catalyst for Change. In: Journal of Petroleum Technology 63 (2015) 9, pp. 28–34.

REINHART ET AL. 1996
Reinhart, G.; Lindemann, U.; Heinzl, J.: Qualitätsmanagement – Ein Kurs für Studium und Praxis. Berlin, Heidelberg: Springer 1996. ISBN 978-3-540-61078-6.

REINHART ET AL. 2008
Reinhart, G.; Kerbs, P.; Schellmann, H.: Flexibilität und Wandlungsfähigkeit–das richtige Maß finden. In: M. Zäh, H. Hoffmann and G. Reinhart (Eds.): Münchener Kolloquium - Innovationen für die Produktion. Produktionskongress 2008. Munich, 09.10.2008. IWB (IWB Seminarberichte). Munich: Utz Herbert 2008, pp. 45–55. ISBN 978-383-1608447.

REINHART & GRUNWALD 2001
Reinhart, G.; Grunwald, S.: Changeability through flexible and integrated product design and assembly planning. In: Proceedings of the International Symposium on Assembly and Task Planning 2001 (ISATP 2001). Fukuoka [Japan], 28.05.-29.05.2001. Institute of Electrical and Electronics Engineers (IEEE) 2001, pp. 318–323. ISBN 0-7803-7004-X.

RHODES & ROSS 2009
Rhodes, D. H.; Ross, A. M.: Anticipatory capacity: Leveraging model-based approaches to design systems for dynamic futures. In: Proceedings of International Conference on Model-Based Systems Engineering 2009 (MBSE '09). Herzeliya and Haifa [Israel], 02.03.-05.03.2009. Institute of Electrical and Electronics Engineers (IEEE) 2009, pp. 46–51. ISBN 9781424429677.

ROGERS 2011
Rogers, J.: “How Other Industries Got It Right”. In: Proceedings of IADC World Drilling Conference & Exhibition 2011. Copenhagen [Denmark], 15.06.-16.06.2011. International Association of Drilling Contractors (IADC) 2011.

RÖSIÖ 2012
Rösiö, C.: Supporting the Design of Reconfigurable Production Systems. Doctoral Thesis. Mälardalen University. Department of Industrial Engineering and Management. Västerås [Sweden]: 2012.

ROSS ET AL. 2008
Ross, A. M.; Rhodes, D. H.; Hastings, D. E.: Defining changeability – Reconciling flexibility, adaptability, scalability, modifiability, and robustness for maintaining system lifecycle value. In: Systems Engineering 11 (2008) 3, pp. 246–262.

ROSS & RHODES 2007
Ross, A. M.; Rhodes, D. H.: Mitigating Value Mismatch at the Dynamic Interface of Stakeholder Preferences and Systems Options. Working paper WP-2007-6-1 (SEAri Working Paper Series). Massachusetts Institute of Technology. Cambridge [MA, USA]: 2007.

ROSS & RHODES 2008
Ross, A. M.; Rhodes, D. H.: Architecting Systems for Value Robustness: Research Motivations and Progress. In: Proceedings of 2nd Annual IEEE Systems Conference (SysCon 2008). Montreal [QC, Canada], 07.04.-10.04.2008. Piscataway [NJ, USA]: IEEE 2008, pp. 110–117.

ROSS & RHODES 2015
Ross, A. M.; Rhodes, D. H.: Towards a Prescriptive Semantic Basis for Change-type Ilities. In: Procedia Computer Science 44 (2015, pp. 443–453.

ROSSI ET AL. 1999
Rossi, P. H.; Freeman, H. E.; Lipsey, M. W.: Evaluation, a systematic approach. 6. edition. Thousand Oaks [CA, USA]: Sage 1999. ISBN 0-7619-0893-5.

SALEH ET AL. 2003
Saleh, J. H.; Hastings, D. E.; Newman, D. J.: Flexibility in system design and implications for aerospace systems. In: Acta Astronautica 53 (2003) 12, pp. 927–944.

SALEH ET AL. 2009
Saleh, J. H.; Mark, G.; Jordan, N. C.: Flexibility: a multi-disciplinary literature review and a research agenda for designing flexible engineering systems. In: Journal of Engineering Design 20 (2009) 3, pp. 307–323.

SCHLATHER 2015
Schlather, F.: Identification of Flexible Design Opportunities: Systematization and classification of drilling systems regarding common change enablers. Master Thesis. Technische Universität München. Lehrstuhl für Produktentwicklung. Munich: 2015.

Schlumberger 2015
Schlumberger: Schlumberger Oilfield Glossary – Marine drilling riser. 2015
URL: http://glossary.oilfield.slb.com/Terms/m/marine_drilling_riser.aspx
Access date: 20.12.2015.

Schlumberger 2016
Schlumberger: Schlumberger Oilfield Glossary – Christmas tree. 2016
URL: http://glossary.oilfield.slb.com/Terms/c/christmas_tree.aspx
Access date: 09.03.2016.

SCHRIEVERHOFF ET AL. 2012
Schrieverhoff, P.; Bender, T.; Kissel, M.; Lindemann, U.: Evaluation of Architecture Options in Systems Engineering. In: D. Marjanović, M. Štorga, N. Pavković and N. Bojčetić (Eds.): Proceedings of the 12th International Design Conference 2012 (DESIGN 2012). Dubrovnik [Croatia], 21.05. - 24.05.2012. The Design Society 2012, pp. 1791–1802. ISBN 978-953-7738-17-4.

SCHRIEVERHOFF 2014
Schrieverhoff, P.: Valuation of Adaptability in System Architecture. Doctoral Thesis. Technische Universität München. Lehrstuhl für Produktentwicklung. Munich: 2014.

SCHUH ET AL. 2007
Schuh, G.; Arnoscht, J.; Nussbaum, C.: Produktarchitekturen richtig gestalten. In: Industrie Management 23 (2007) 6, pp. 29–32.

SCHUH ET AL. 2009
Schuh, G.; Lenders, M.; Nussbaum, C.; Kupke, D.: Design for Changeability. In: H. A. ElMaraghy (Ed.): Changeable and Reconfigurable Manufacturing Systems. London: Springer 2009. ISBN 978-1-84882-066-1.

SCHULZ & FRICKE 1999
Schulz, A. P.; Fricke, E.: Incorporating flexibility, agility, robustness, and adaptability within the design of integrated systems - key to success? In: Proceedings of the 18th Digital Avionics Systems Conference 1999 (DASC 1999). St. Louis [Missouri, USA], 24.10.-29.10.1999. Piscataway, N.J.: IEEE 1999, 1.A.2-1-1.A.2-8. ISBN 0-7803-5749-3.

SETHI & SETHI 1990
Sethi, A. K.; Sethi, S. P.: Flexibility in Manufacturing: A Survey. In: The International Journal of Flexible Manufacturing Systems 2 (1990) 4, pp. 289–328.

SHAFER 1976
Shafer, G.: A mathematical theory of evidence. Princeton [NJ, USA]: Princeton University Press 1976. ISBN 069110042X.

SHARIFI & ZHANG 1999
Sharifi, H.; Zhang, Z.: A methodology for achieving agility in manufacturing organisations: An introduction. In: International Journal of Production Economics 62 (1999) 1, pp. 7–22.

SILVER & DE WECK 2007
Silver, M. R.; de Weck, O. L.: Time-expanded decision networks: A framework for designing evolvable complex systems. In: Systems Engineering 10 (2007) 2, pp. 167–188.

STEWARD 1981
Steward, D. V.: The design structure system – A method for managing the design of complex systems. In: IEEE Transactions on Engineering Management EM-28 (1981) 3, pp. 71–74.

SUH 1990
Suh, N. P.: The principles of design. New York [NY, USA]: Oxford University Press 1990. ISBN 0195043456.

SUH ET AL. 2007
Suh, E. S.; de Weck, O. L.; Chang, D.: Flexible product platforms – framework and case study. In: Research in Engineering Design 18 (2007) 2, pp. 67–89.

SUMMERS & ECKERT 2013
Summers, J. D.; Eckert, C.: Interviewing as a method for data gathering in engineering design research. Working paper. 2013.

SURBHI 2016
Surbhi, S.: Differences Between Rules and Regulations. KeyDifferences. 2016
URL: http://keydifferences.com/difference-between-rules-and-regulations.html
Access date: 12.08.2016.

TERKAJ ET AL. 2009
Terkaj, W.; Tolio, T.; Valente, A.: Focused Flexibility in Production Systems. In: H. A. ElMaraghy (Ed.): Changeable and Reconfigurable Manufacturing Systems. London: Springer 2009. ISBN 978-1-84882-066-1.

THOMMEN & ACHLEITNER 1998
Thommen, J.-P.; Achleitner, A.-K.: Allgemeine Betriebswirtschaftslehre: Umfassende Einführung aus managementorientierter Sicht. 2. edition. Wiesbaden: Gabler 1998. ISBN 3834913251.

TONI & TONCHIA 1998
Toni, A. de; Tonchia, S.: Manufacturing flexibility – A literature review. In: International Journal of Production Research 36 (1998) 6, pp. 1587–1617.

TRIGEORGIS 1993
Trigeorgis, L.: Real options and interactions with financial flexibility. In: Financial management 22 (1993) 3, pp. 202–224.

TRIGEORGIS 1996
Trigeorgis, L.: Real options – Managerial flexibility and strategy in resource allocation. Cambridge [MA, USA]: MIT Press 1996. ISBN 026220102X.

TROPSCHUH 1988
Tropschuh, P. F.: Rechnerunterstützung für das Projektieren mit Hilfe eines wissensbasierten Systems. Doctoral Thesis. Technische Universität München. Lehrstuhl für Konstruktion. Munich: 1988.

TUKKER 2004
Tukker, A.: Eight types of product–service system: eight ways to sustainability? Experiences from SusProNet. In: Business Strategy and the Environment 13 (2004) 4, pp. 246–260.

ULLMAN 2010
Ullman, D. G.: The mechanical design process. 4. edition. New York [NY, USA]: McGraw-Hill 2010. ISBN 978-0-07-297574-1.

ULRICH 1995
Ulrich, K.: The role of product architecture in the manufacturing firm. In: Research Policy 24 (1995) 3, pp. 419–440.

VAN WIE 2002
van Wie, M. J.: Designing product architecture: a systematic method. Doctoral Thesis. The University of Texas. Austin [TX, USA]: 2002.

VDMA 1976
VDMA (Ed.): Statistisches Erfassungsmaterial des VDMA. Lagebericht 1976 – Arbeitsgemeinschaft Großanlagenbau. Verband Deutscher Maschinen- und Anlagenbau (VDMA). Frankfurt am Main: 1976.

VDMA 2011
VDMA (Ed.): Was macht den Großanlagenbau robust für die Zukunft? – Erfolgsfaktor Wettbewerbsfähigkeit. Ergebnisse einer Gemeinschaftsstudie von Management Engineers und der VDMA Arbeitsgemeinschaft Großanlagenbau. Verband Deutscher Maschinen- und Anlagenbau. Stuttgart: 2011.

WANG & NEUFVILLE 2005
Wang, T.; Neufville, R. de: Real Options "in" Projects. In: Proceedings of the 9th Real Options Annual International Conference 2005. Paris [France], 22.06.-25.06.2012. Real Options Group 2005.

WARDT 2014
Wardt, J. P. de: The Drilling Business Model: Driver or Inhibitor of Performance and Innovation. In: IADC/SPE Drilling Conference and Exhibition 2014. Fort Worth [TX, USA], 04.03.-06.03.2014. Society of Petroleum Engineers (SPE) 2014.

WESTKÄMPER ET AL. 2000
Westkämper, E.; Zahn, E.; Balve, P.; Tilebein, M.: Ansätze zur Wandlungsfähigkeit von Produktionsunternehmen – Ein Bezugsrahmen für die Unternehmensentwicklung im turbulenten Umfeld. In: Werkstattstechnik-Forschung und Entwicklung für die Produktion 90 (2000) 1-2, pp. 22–25.

WESTKÄMPER & ZAHN 2009
Westkämper, E.; Zahn, E.: Wandlungsfähige Produktionsunternehmen: Das Stuttgarter Unternehmensmodell. Berlin, Heidelberg: Springer 2009. ISBN 978-3-540-21889-0.

WHITESIDE 2001
Whiteside, M. W.: The Key to Enhanced Shareholder Value. In: Proceedings of SPE Annual Technical Conference and Exhibition 2001. New Orleans [LA, USA], 30.09.-03.10.2001. Society of Petroleum Engineers (SPE) 2001.

WIENDAHL ET AL. 2007
Wiendahl, H.-P.; ElMaraghy, H. A.; Nyhuis, P.; Zäh, M. F.; Wiendahl, H.-H.; Duffie, N.; Brieke, M.: Changeable manufacturing - Classification, Design and Operation. In: CIRP Annals-Manufacturing Technology 56 (2007) 2, pp. 783–809.

WIENDAHL ET AL. 2015
Wiendahl, H.-P.; Reichardt, J.; Nyhuis, P.: Handbook Factory Planning and Design. Berlin, Heidelberg: Springer 2015. ISBN 3662463911.

WIENDAHL & HERNÁNDEZ 2006
Wiendahl, H.-P.; Hernández, R.: The Transformable Factory – Strategies, Methods and Examples. In: A. I. Dashchenko (Ed.): Reconfigurable Manufacturing Systems and Transformable Factories. Berlin, Heidelberg: Springer 2006. ISBN 978-3-540-29397-2.

WILBURN ET AL. 1998
Wilburn, M. D.; Steddum, R. E.; Shaughnessy, J. M.: Deepwater Rig Design for 10,000 Feet of Water. In: Proceedings of Offshore Technology Conference 1998 (OTC 1998). Houston [TX, USA], 04.05.-07.05.1998. Offshore Technology Conference (OTC) 1998, pp. 327–334.

WILDS 2008
Wilds, J. M.: A Methodology For Identifying Flexible Design Opportunities. Master Thesis. Massachusetts Institute of Technology. Engineering Systems Division. Cambridge [MA, USA]: 2008.

YOUNG 2004
Young, R. R.: The requirements engineering handbook. Norwood [MA, USA]: Artech House 2004. ISBN 1580532667.

ZADEH 1978
Zadeh, L.A.: Fuzzy sets as a basis for a theory of possibility. In: Fuzzy sets and systems 1 (1978) 1, pp. 3–28.

11. Appendix

11.1 Descriptions and traceability for homogenized sub-steps of procedural models for identifying FDOs

11.1.1 Homogenized sub-steps

As presented in section 3.1.2, the following sub-steps in Table 11-1 were derived based on various references in the field of “engineering design” and “manufacturing and factory planning”. In order to allow a comparison amongst the procedural models, those homogenized sub-steps are usually expressed more generally than in each of the corresponding references. Based on the work of CARDIN [2014] and as introduced in section 3.1.1, they are assigned to the five different phases representing a sorting framework for the procedural models: Baseline Design (I), Uncertainty Recognition (II), Concept Generation (III), Design Space Exploration (IV) and Process Management (V). Here, especially phase IV has a wider meaning than discussed by CARDIN [2014] as it includes all activities that can be related to the evaluation of FDOs.

Table 11-1 Homogenized sub-steps of procedural models for the identification of FDOs

I	**Baseline Design**	(a) Determining and characterizing system scope
		(b) Decomposition of system into multiple subsystems and elements
		(c) Identifying suitable rigid baseline of Object from which flexible designs are developed and compared against
II	**Uncertainty Recognition**	(a) Defining relevant sources of uncertainties / Change Drivers
		(b) Consideration of uncertainty profile over time / scenario building
		(c) Classifying uncertainties according to attributes (e.g. entry frequency, cause)
III	**Concept Generation**	(a) Determining changeability type depending on factory level (reconfigurability, transformability, etc.)
		(b) Determining time window of addressed flexibility (frequent runtime changes vs. larger scale lifetime changes)
		(c) Identifying suitable change measures / flexible design strategies for Change Objects (e.g. extend, switch, replace machine)
		(d) Determining and classifying change profiles of Change Objects (frequency, amplitude)
		(e) Characterizing interdependencies between Change Objects (type, number, frequency of interaction)
		(f) Identifying already existing flexibility in Objects to deal with uncertainty
		(g) Determining action alternatives (e.g. increase automation) and modifications of Change Objects (e.g. equip with sensors)
		(h) Identifying new Object requirements as a result of unfolding uncertainty
		(i) Determining change requirements on allowable time and costs to perform change
		(j) Identifying required flexibility / suitable Change Enablers for Change Objects (e.g. modular machine, space for extension)
		(k) Separation of complex and complicated system elements
		(l) Specifying flexible design concepts for Change Objects
		(m) Modifying rigid baseline of Object to flexible design concept
		(n) Selecting best performing flexible design concepts and initiate embodiment / integration
		(o) Short listing / delimiting affected or uncertainty sensitive Objects
		(p) Short-listing / delimiting Objects not fulfilling future requirements
		(q) Selecting Objects affected by other Objects (change propagation)
		(r) Selecting Objects not fulfilling changeability requirements (e.g. time for change)
		(s) Short-listing flexible candidate designs of Change Objects
IV	**Design Space Exploration (Evaluation)**	(a) Assessing change sensitivity of Objects with regards to unfolding uncertainties
		(b) Assessing Objects' fulfillment of future requirements
		(c) Assessing impact on indirectly affected Objects (systemic consideration)
		(d) Assessing Objects' fulfillment of change requirements (e.g. time for change)
		(e) Screening flexible candidate designs of Change Objects
		(f) Estimating cost-benefit of measures / flexible design concepts
		(g) Risk assessment of sufficient extent of Change Enablers in case of simultanously unfolding uncertainties
		(h) Determining criteria for measurable value delivery (e.g. operational costs) related to monetary and non-monetary benefits
		(i) Selecting suitable evaluation methodology (e.g. Monte Carlo simulation, decision analysis)
		(j) Valuating flexible design alternatives and baseline design
		(k) Confronting actual and target flexibility of Objects
		(l) Comparing performance amongst flexibly designed Change Objects
		(m) Sensitivity analysis of Change Objects concerning flexible design performance
V	**Process Management**	(a) General initial preventive actions (e.g. integrating stakeholders during system development)
		(b) General ongoing operational actions (e.g. maintaining the legal permission and knowledge to exercise flexiblity)
		(c) Specific initial preventive actions: Record proper exercise of flexibility and relevant data
		(d) Specific initial preventive actions: Selection of flexibility that is accessible / can be exercised across lifecycle
		(e) Specific ongoing operational actions: Transfer knowledge to responsible for proper management of flexibility
		(f) Specific ongoing operational actions: Monitoring of uncertain events to occur and feedback

11.1.2 Original steps and homogenized sub-steps of relevant procedural models

Table 11-2 confronts the original steps of relevant procedural models with the deduced homogenized sub-steps of Table 11-1 to allow a comparison amongst them. Although in most cases those steps were provided explicitly by those authors, in some cases such as in MIKAELIAN ET AL. [2011], HERNÁNDEZ [2003] and FRANCALANZA ET AL. [2014] they did not follow an explicit enumeration. Hence, in those cases the enumeration is deduced from the logical order of those steps.

Table 11-2 Confrontation of original steps and homogenized sub-steps in procedural models

Nomenclature of homogenized sub-steps in table	
#	Order of derived sub-steps from procedural models of reference
# (!)	Sub-step referred to as "input" in procedural models of reference
(#)	Optional sub-step mentioned for procedural models of reference

		Homogenized sub-steps of relevant procedural models																																											
		I. Baseline Design			II. Uncertainty Recognition			III. Concept Generation																			IV. Design Space Exploration (Evaluation)													V. Process Management							
Original steps of relevant procedural models		(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)	(q)	(r)	(s)	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(a)	(b)	(c)	(d)	(e)	(f)	Reference	Title
Identify uncertainties	1				1	2																																								GREDEN [2005, pp. 55-76]	Approach to flexible design
Define flexibility	2								3	4																																					
Design (for flexibility)	3																		5													6															
Evaluate with real options	3																																			7											
Make decisions	4																				9																	8									
Transfer & manage	5																																									10		11	12		
Defining system's aspects of interest	1									1																																				NILCHIANI & HASTINGS [2007]	6E flexibility framework
Defining system boundary	2	2																																													
Defining time window	3								3																																						
Identifying uncertainty sources and profiles within time window	4				4	5																																									
Determining types of benefit	5																																	6													
Creating a baseline case and possible alternatives based on the degree of access	6			7															8																								9				
Modification or change of the baseline technical design and architecture	7																			(10)																											
Choice of evaluation methodology	8																																		11												
Calculations of expected benefits/revenues and costs for baseline and alternatives	9																																			12											
Calculation of ΔECs (expected costs) and ΔEBs (expected benefits) of alternatives compared to baseline	10																																			12											
Valuing nonmonetary benefits and prospect theory (optional)	11																																			(12)											
Flexibility Tradespace Exploration	12																				14																	13									
Estimating the distribution of future possibilities	1				1	2																																								NEUFVILLE & SCHOLTES [2011]	Flexibility in engineering design
Identifying candidate flexibilities	2																									4					3																
Evaluating and choosing flexible designs	3																				8															5		6	7								
Implementing flexibility	4																																							9	10						
Determine uncertainty factors	1				1 (!)																																									MIKAELIAN ET AL. [2011]	Integrated real-option framework (IRF)
Identify existing real options (Analysis)	2												2																																		
Generate new mechanism and types (Synthesis)	3																		3																												
Building uncertainty model*	4																																														
Real options valuation	5																																			4											
Comparison of alternative real options	6																				6																	5									
Scenario management in factory planning	1				1	2																																								HERNÁNDEZ [2003, pp. 92-153]	Scenario-supported examination of potential transformability requirements
Analysis of changeability width	2																										3																				
Analysis of changeability depth and determination of requirements profile	3									6					4		7											5																			
Classification (based on changeability width and depth) and selection of change objects	4																					8	8																								
Deduction of future robust measures for selected (groups of) change objects	5																		9																												
Factory analysis	1	1																																												NYHUIS ET AL. [2005]	Evaluation of factory transformability
Quantification of actual transformability	2												2																																		
Development of scenarios	3				3	4																																									
Derivation of requirement profiles	4																5																														
Quantification of target transformability	5																																				6										
Deriving measures for action	6																		7																	8 (!)											
Identify and classify the change drivers	1				1	2	3																																							SCHUH ET AL. [2009]	Object-oriented design of production systems
Description of the production system: Detailing of the production system	2		4																																												
Description of the production system: Evaluation of change profiles	2										5																																				
Description of the production system: Define interdependencies and interfaces of the production system	3											6																																			
Object-oriented design: Separation of merely complicated and really complex elements	4																	7	9			8																									
Determining developments in change dimensions	1				1 (!)	2 (!)																																								BAUDZUS ET AL. [2013]	Design of manual assembly systems focusing on required changeability
Determination of the required changeability	2																3																														
Compare required changeability with actual changeability (of existing system)	3												(4)																								(5)										
Identification of change enabling solutions	4																		6		7																										
Analysis of requirements	1														1																															FRANCALANZA ET AL. [2014]	A changeable manufacturing system design approach
Developing solutions for the manufacturing system problems	2							4									5		6				3					2																			
Simulation of the provisional design solution	3																																			7											
Evaluation of the provisional design solution	4																																					8									
Decision on provisional design solution	5																				9																										
Analysis of product spectrum	1	1*																																												KLEMKE [2014, pp. 83-107]	Approach to evaluate and design changeability
Mapping of primary process layer in changeability graph	2																																														
Identification of change drivers	3				2																																										
Capturing future change driver developments	4					3																																									
Determining focus of consideration	5																					4																									
Extension of changeability graph (by including focus of consideration secondary process layer and views)	6																																														
Determination of action alternatives and modifications	7													7									6	9				5	8																		
Deduction of measures for realization of action alternatives	8									10																																					
Analysis of changeability	9															11									13					12																	
Deduction of potentials for increase of changeability	10																14		17													15/18	16														

* "System" usually includes potential Change Objects to be enabled (e.g. manufacturing system). However, here the identification of to-be manufactured product families is meant that are subject to variation. Changes of product variants (e.g. in their shape, number) are subject to uncertainty and lead to changes of relevant Objects in the manufacturing system (e.g. workholding device of manufacturing machine).

11.2 Description of matrix-based methodologies on identification of FDOs

The following provides a detailed description on the relevant matrix-based methodologies that are introduced and discussed in section 3.2.1. Note that in contrast to Figure 3-2 and the developed FDO Methodology of this work, all the references in this section use the convention where column headings represent instigating elements and row headings are elements that receive change.

11.2.1 Change prediction method by CLARKSON ET AL. [2004]

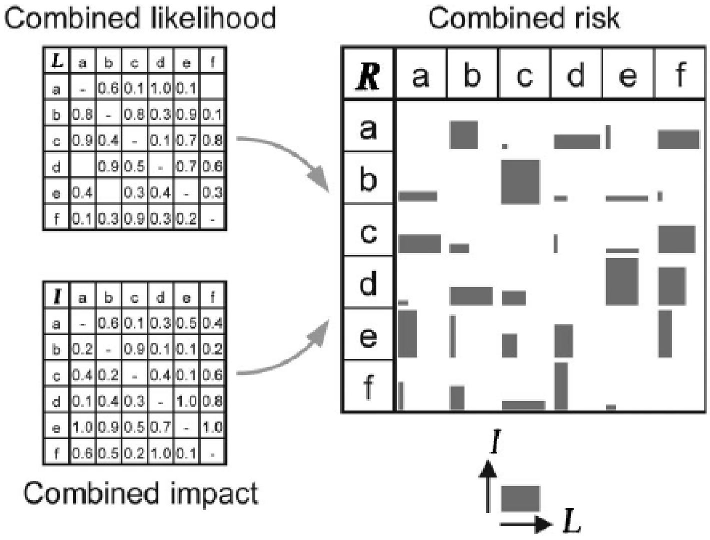
Initially, the product model must be built where the product is broken down into a suitable number of subsystems. That breakdown allows capturing the change relationships[328] between adjacent sub-systems of the product. Those change relationships can be divided into determining average likelihood of change “l” (probability of change influence) and the average impact of change “i” (proportion of redesign work) between adjacent sub-systems. The direct risk of change (r) is then the product of “likelihood” and “impact” of change.

However, in addition to direct dependencies between adjacent systems, a predictive model must also allow accounting for indirect change propagation effects. Hence, based on the initial likelihood (l) and an algorithm which views propagation trees as logic trees, the combined likelihood (L) can be determined. It represents the probability that the end effect will arise which is independent of the path taken. By using a separate algorithm that is based on the initial likelihood (l) and impact (i), the combined risk of propagation (R) is determined. The combined impact (I), which represents the total impact on the affected subsystem, can be then determined from the combined likelihood (L) and risk (R).

The resultant risk data is represented in a product risk matrix (Figure 11-1) where the relationships are indicated by rectangles showing the combined likelihood (width of rectangle) and impact (height of rectangle). The risk matrix may be reordered to indicate the relative influence (column headings) and susceptibility of sub-systems (row headings). After reordering, the sub-systems to the right in the column heading have the highest influence on other components. In contrast, the top row headings indicate components with highest susceptibility.

---

[328] Those change relationships may be derived from history of previous design changes and from views of experienced product engineers.



L	a	b	c	d	e	f
a	-	0.6	0.1	1.0	0.1	
b	0.8	-	0.8	0.3	0.9	0.1
c	0.9	0.4	-	0.1	0.7	0.8
d		0.9	0.5	-	0.7	0.6
e	0.4		0.3	0.4	-	0.3
f	0.1	0.3	0.9	0.3	0.2	-

I	a	b	c	d	e	f
a	-	0.6	0.1	0.3	0.5	0.4
b	0.2	-	0.9	0.1	0.1	0.2
c	0.4	0.2	-	0.4	0.1	0.6
d	0.1	0.4	0.3	-	1.0	0.8
e	1.0	0.9	0.5	0.7	-	1.0
f	0.6	0.5	0.2	1.0	0.1	-

Figure 11-1 A graphical product risk matrix (not yet reordered) [CLARKSON ET AL. 2004]

The "case-by-case" analysis initiates the process for a specific case by identifying the instigating requirement change(s) of subsystem(s) and their propagation paths. Based on results of the initial analysis, the combined likelihood (L), impact (I) and risk (R) of changes for the downstream sub-systems can be determined. The L and I values of the affected sub-systems can then be mapped on the risk scatter graph which allows a comparison of data. Relying on the "case-by-case analysis" the designer and managers should now be able to identify the critical sub-systems in a better way. Naturally, design changes must be updated in the product model and direct dependency matrices for use in later projects.

11.2.2 HoQ-CPM approach to assess the changeability in complex engineering systems by KOH ET AL. [2012]

The assessment of engineering change propagation effects is conducted through four steps that follow a certain path within the MDM of Figure 11-2.

The following steps have to be performed:

1. Rate change options and their interactions: In Field A performance ratings are assigned to change options in order to highlight how well they will perform when addressing product requirements (e.g. change option "reduce fan blade height" with respect to product requirements "low weight"). The relationship is provided by a bipolar rating from "-5" to "5". Field B addresses the interaction between change options, i.e. captures the implicit design constraints and how change options affect each other. Here the ratings are bipolar lying between "-1", i.e. totally conflict each other and "+1", i.e. totally complement each other.

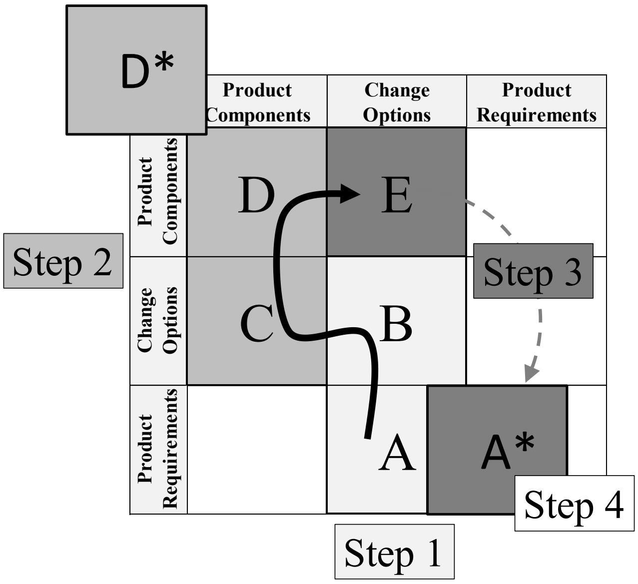


Figure 11-2 Modeling method illustrated in a MDM [Koh et al. 2012]

2. Change propagation analysis: Here the change options are related to the relevant product components for change propagation analysis (e.g. “reducing the fan blade height” leads to changing the “fan blade”). The entries in Field C are binary (0,1) with “1” if a change option is related to a given product component. The intention is to map the change options to the appropriate product components which represent the change instigating components for the change propagation analysis in Field D[329]. For that field the CPM analysis technique is described by Clarkson et al. [2004] where inputs of likelihood (l) range from “0” to “1”. By use of the CPM algorithm the combined change propagation likelihood (L) is calculated with the new matrix values D*.

3. Revise ratings for change options: In this step the combined change propagation likelihood “L” of affected product components is linked back to the relevant change options in Field E. Hence, based on the affected product components by change propagation, the performance of initial change options may change. As a result, the performance ratings for all change options (Field A) should be revised to better reflect the propagation effects by a calculated revised performance rating of Field A*. According to Koh et al. [2012], the revised performance rating of change option “j” when addressing product requirement “x” is:

   $$A^*_{x,j} = A_{x,j} + \sum_{k=1}^{n}[L_{k,j} \times B_{k,j} \times A_{x,k}] \qquad (11\text{-}1)$$

   $A_{x,j}$ and $A_{x,k}$ reflect the initial performance ratings of change options “j” and “k” when addressing product requirement “x”. $B_{k,j}$ represents the potential interaction between the relevant parameters brought about by change option “j” on change option “k”. $L_{k,j}$ represents the combined likelihood of component change propagation initiated by change

---

[329] As the change instigating components are represented in the column headings of Field D, this mapping process is carried out in field C (and not field E).

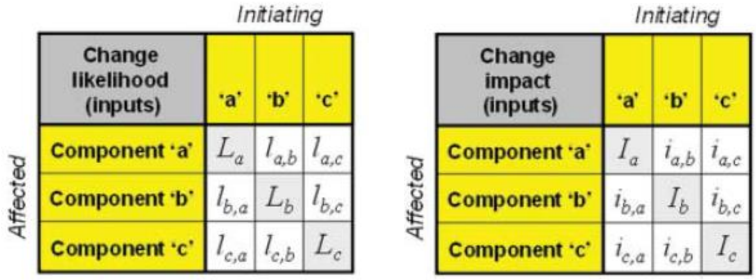
option “j” towards change option “k” and “n” represents the total number of change options analyzed.

4. Select the best change option: Based on the revised performance ratings in Field A*, engineers can evaluate different change options. Suitable change options can be selected that have the highest rating against the most important product requirement. Alternatively, those change options may be selected that have the best overall rating either with or without accounting for individual weightings of product requirements.

11.2.3 Step-based CPM by Koh et al. [2013]

First, the change data is captured which usually comes from domain experts or by referring to change documents within the organization of concern. Here the change data is elicited where both the change likelihood and the change impact are mapped into two separate matrices (Figure 11-3). According to Koh et al. [2013] each component can either be affected by planned changes, which is not accounted for in the methodology by Clarkson et al. [2004], representing exogenous factors such as customer requirements, or through change propagation between components. Planned changes are represented on the diagonal of those matrices which depending on the type of matrix address the following:

- Change likelihood matrix (Figure 11-3, left): likelihood of planned component changes in the future due to exogenous factors
- Change impact matrix (Figure 11-3, right): impact of planned component changes describing the average redesign cost[330] of carrying out change work



Change likelihood (inputs)	‘a’	‘b’	‘c’
Component ‘a’	L_a	$l_{a,b}$	$l_{a,c}$
Component ‘b’	$l_{b,a}$	L_b	$l_{b,c}$
Component ‘c’	$l_{c,a}$	$l_{c,b}$	L_c

Change impact (inputs)	‘a’	‘b’	‘c’
Component ‘a’	I_a	$i_{a,b}$	$i_{a,c}$
Component ‘b’	$i_{b,a}$	I_b	$i_{b,c}$
Component ‘c’	$i_{c,a}$	$i_{c,b}$	I_c

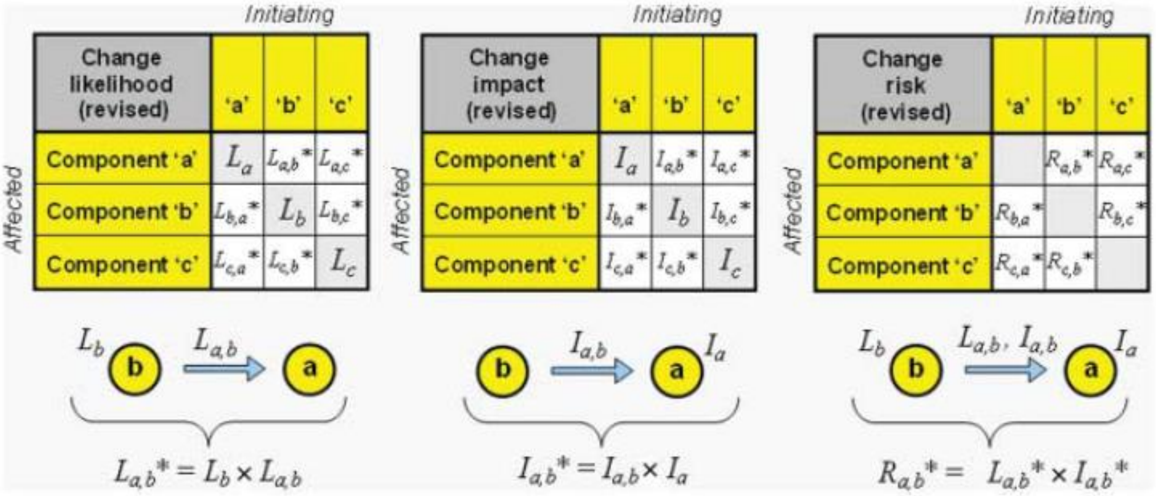
Figure 11-3 Capturing and tabulating change data in DSMs [Koh et al. 2013]

Direct change propagation between components, in contrast, is mapped off-diagonal in those two matrices. For change likelihoods (Figure 11-3, left), it describes how likely a change in an initiating component leads to a design change in the affected component across their common interface. For change impacts (Figure 11-3, right), it describes the average proportion of design work required if the change propagates. Entries for the matrices are assigned values between “0” and “1” to indicate “low” or “high”.

---

[330] Hence, in contrast to Clarkson et al. [2004], here the impact on components does not only consider the proportion of redesign work (off-diagonal) but also the absolute scope of redesign work when a change occurs which is relevant when calculating the revised change impacts in step 2.

Step 2 concerns the computation of change indices. First by using a step-based CPM, the combined change propagation is calculated that accounts for both direct and indirect change propagation of each component. In contrast to CLARKSON ET AL. [2004], the algorithm also considers a reachability factor α[331] limiting the number of change propagation steps to be examined. The direct change propagation entries in Figure 11-3 are now modified to entries addressing combined change propagation likelihoods and impacts which are now represented by $L_{k,j}$ and $I_{k,j}$ respectively (capital letters!). The prediction of change propagation is refined further by accounting additionally for the planned changes that are to occur (entries on diagonal in Figure 11-3). Hereby the new off-diagonal values for the revised change likelihood and impact matrices are determined as illustrated in Figure 11-4. Subsequently, the revised risk of change propagation between system components can be determined (Figure 11-4, right).



Change likelihood (revised)	'a'	'b'	'c'
Component 'a'	L_a	$L_{a,b}^*$	$L_{a,c}^*$
Component 'b'	$L_{b,a}^*$	L_b	$L_{b,c}^*$
Component 'c'	$L_{c,a}^*$	$L_{c,b}^*$	L_c

Change impact (revised)	'a'	'b'	'c'
Component 'a'	I_a	$I_{a,b}^*$	$I_{a,c}^*$
Component 'b'	$I_{b,a}^*$	I_b	$I_{b,c}^*$
Component 'c'	$I_{c,a}^*$	$I_{c,b}^*$	I_c

Change risk (revised)	'a'	'b'	'c'
Component 'a'		$R_{a,b}^*$	$R_{a,c}^*$
Component 'b'	$R_{b,a}^*$		$R_{b,c}^*$
Component 'c'	$R_{c,a}^*$	$R_{c,b}^*$	

$$L_{a,b}^* = L_b \times L_{a,b} \qquad I_{a,b}^* = I_{a,b} \times I_a \qquad R_{a,b}^* = L_{a,b}^* \times I_{a,b}^*$$

Figure 11-4 Revised change matrices with indices based on calculated combined changes and initially defined planned changes [KOH ET AL. 2013]

Finally, based on the revised data of the change matrices, three change indices are generated for each system component. The ICL (incoming change likelihood), the ICI (incoming change impact) and the OCR (outgoing change risk) are determined by a summation of entries in rows (ICL, ICI) and columns (OCR), respectively, divided by the total number of components[332] which are then normalized. The ICL and ICI indicate how likely and hard it is to change a system component. The OCR, instead, indicates how changes to a system component will affect other components.

Plotting those components to an ICI versus ICL chart supports the assessment and helps deriving recommendations (step 3). The OCR provides further insights if decisions in the ICI versus ICL chart remain unclear. In general, the recommendations follow strategies to either

---

[331] The reachability of change propagation is the ability to propagate changes from an initiating component (source) to a specific component (sink) given a set of constraints [KOH 2010, p. 123]. Based on empirical analyses both CLARKSON ET AL. [2004] and PASQUAL & WECK [2012] also indicate that there is a limit in change propagation steps.

[332] For OCR: Total number of components – 1.

reduce likelihood or impact by means of changeability (by e.g. standardization, redundancy, flexibility). The indices can only be used as indicators and further reviewing processes might be required to identify the most feasible options with the available resources.

11.2.4 Sensitivity DSM by KALLIGEROS [2006]

KALLIGEROS [2006, pp. 60–66] explores elements of a system's design that are kept unchanged from one design variant to another, i.e. identifies which components / systems may or may not be standardized as a part of a platform between e.g. two variants (α, β) with varying functional requirements (FR^{α}, FR^{β}). He argues that the variables "x_p" of the sDSM[333] that are insensitive to exogenous changes, directly or indirectly and within a certain tolerance, represent potential platform components[334] and can be aggregated together to form a platform (Figure 11-5). The goal is to maximize the number of those platform components while minimizing the customized components ($x_c^{\alpha}, x_c^{\beta}$) for the functional requirements of each variant (FR^{α}, FR^{β}).

The functional requirements (FR) and design variables (x) are listed in the left column and top row[335] of the normalized sDSM (Figure 11-5, left). According to KALLIGEROS [2006, p. 60] each entry i, j in the matrix represents a percent change in variable i (row headings) caused by a percent change in variable j (column headings). Whereas each row in the southwestern quadrant depicts the sensitivity of design variables x_i to changes in functional requirement j (FR_j), the southeastern quadrant addresses the sensitivity of design variables x_i to changes in design variables that are affected by changes in functional requirements (Fr_j) of the southwestern quadrant [KALLIGEROS 2006, p. 62].

Based on a seven-step algorithm (IDR algorithm) the sDSM is partitioned (Figure 11-5, right). The steps 1- 4 (first loop) generate a list Π_k (with "k" being the number of iterations) of variables that are insensitive to functional requirement changes resulting in the maximum number of platform components x_p. Steps 5 to 7 (second loop) then reduce those platform components x_p from this list that are sensitive to the previously identified customized variables (x_c). The iterations stop when the list of x_p's remains unchanged or is empty resulting in a final set of platform components x_p.

---

[333] Whereas the DSM representation is identical for all designs, the sDSM refers to a particular design representing only the sensitivity between design variables. Hence, the sDSM is more sparsely populated than the corresponding variable-based DSMs. Variables may depend on each other but still be insensitive to changes [KALLIGEROS 2006, p. 60].

[334] According to BALDWIN & CLARK [2000] design rules refer to system components or variables that are established first in the design process and dictate the design of other components of variables. Hence, according to KALLIGEROS [2006, p. 64] platform components represent "design rules".

[335] Top row not visualized in Figure 11-5.

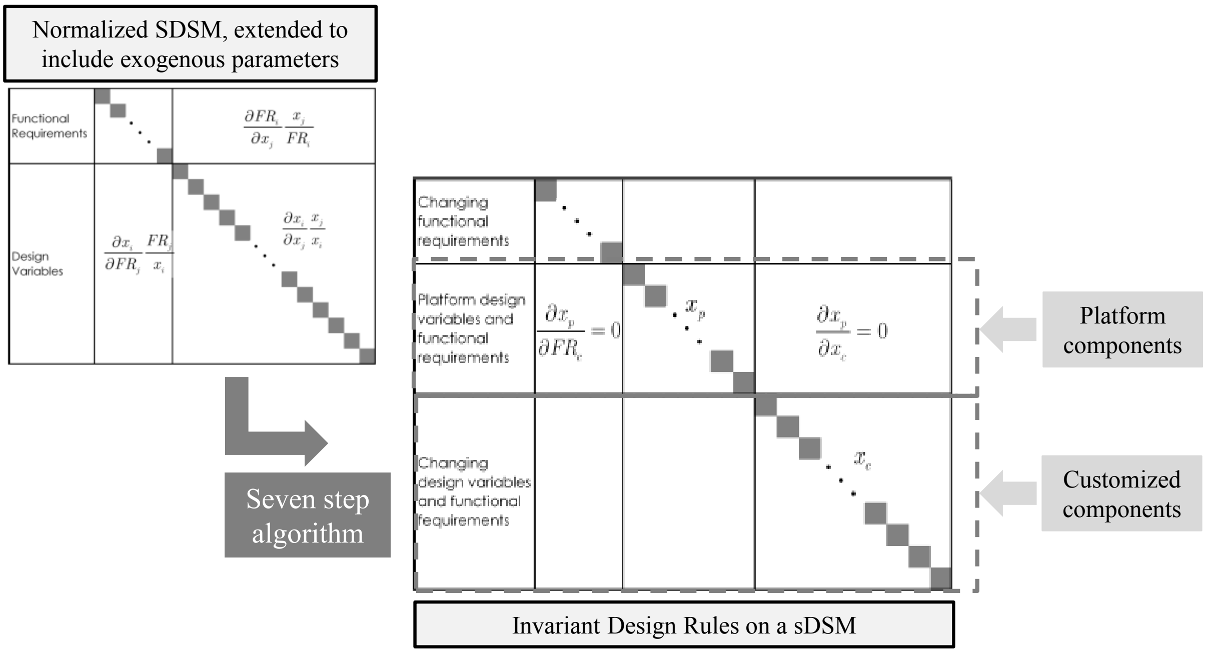


Figure 11-5 Normalized sDSM and Invariant Design Rules on an sDSM [KALLIGEROS 2006]

Further platform components can be defined by using the IDR algorithm and removing certain entries in the sDSM. This requires introducing a "slack" between variables which is to be kept at a minimum by not exactly meeting specification requirements (e.g. due to over-sizing). In this regard pareto optimal strategies consider maximizing the number of standardized components for a given number of entries removed [KALLIGEROS 2006, pp. 126–129]. KALLIGEROS [2006, pp. 74–76] suggests to perform this procedure step-wise where platform components are determined on a high-level first being followed by breaking down customized components to lower-level system components which, in turn, may also contain platform components.

The normalized sDSM is partitioned according to the IDR. The partition on the top of Figure 11-5 (right) represents externally imposed "changing functional requirements" that change between variant α and β. The partition in the middle represents platform design variables and functional requirements x_p which do not change and, hence, represent platform components. The partition on the bottom shows customized design variables and functional requirements x_c.

11.2.5 Flexible platform design process by SUH ET AL. [2007]

Figure 11-6 illustrates the seven-step flexible platform design process (FPDP). In step I market segments, product variants and critical uncertainties are identified that the product platform must be able to account for. Functional attributes are then determined that are affected by the uncertainty and are then related to system level design variables of the system (step II). The identified set of design variables for each product in the product family is then optimized in order to maximize product family revenue (step III). Hence, the product family bandwidth[336] of key product design variables is determined.

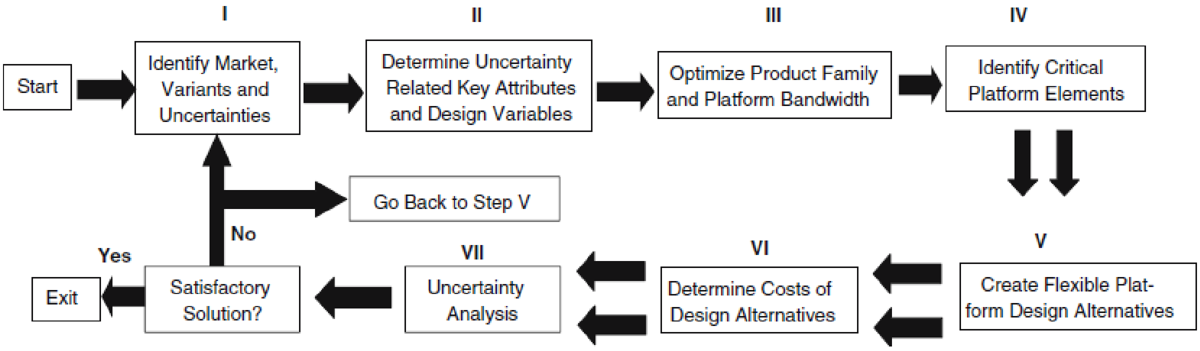


Figure 11-6 FPDP, a Flexible platform design process[337] [SUH ET AL. 2007]

A set of critical physical elements affected by the design variable changes within the determined bandwidth is identified by performing a change propagation analysis (step IV). It bases upon ECKERT ET AL. [2004] and introduces a new measure, the Change Propagation Index[338] (CPI), which helps classify elements and measures the degree of physical change propagation caused by an element when an external change is imposed on the system with

$$CPI_i = \sum_{j=1}^{n} \Delta E_{j,i} - \sum_{k=1}^{n} \Delta E_{i,k} = \Delta E_{out,i} - \Delta E_{in,i} \tag{11-2}$$

where ΔE is a binary change propagation matrix, n is the number of elements in the system and $\Delta E_{j,i}$ is a binary number showing the *i*th element is changed because of element *j*. Figure 11-7 depicts a graph-based (left) and DSM-based (right) exemplary representation of change propagation visualizing the resulting CPIs. SUH ET AL. [2007] argue that change multipliers with CPI>0 are prime candidates for incorporating flexibility. This also applies to components that are affected by change multipliers. The more of these change multiplier components are changed, the more changes are propagated which makes it harder to change the system as a whole. In this application context of platform design, flexible components can be incorporated as buffers to limit the number of affected components, i.e. the degree of physical change propagation, and the economic consequence indicated by the switching costs (K_{switch}) for those affected components. SUH ET AL. [2007] highlight that "carriers" may also be relevant to consider, especially when a large number of incoming and outgoing changes exist. In addition to the number and degree of change propagation a high K_{switch} alone (K_{switch}>>0) also indicates prime candidates for embedding flexibility as it can lower the cost of changing that component.

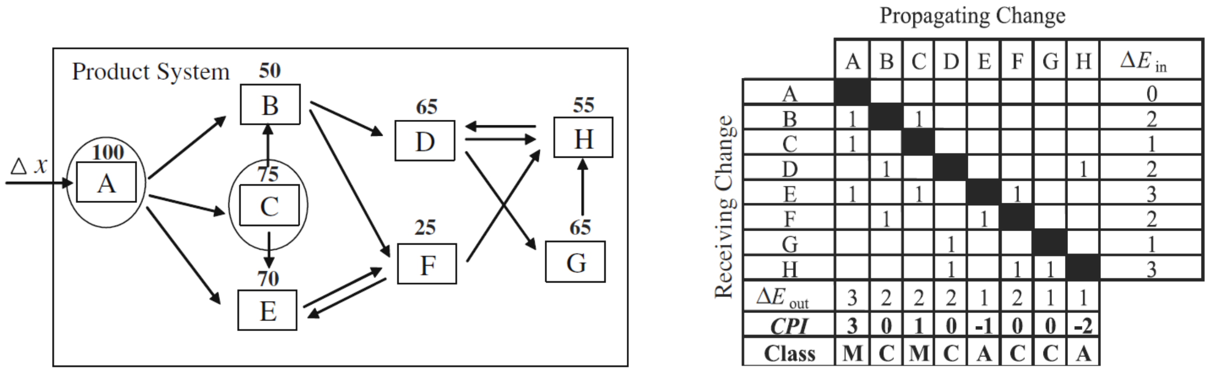
Based on the derived critical elements in step IV and the given bandwidth requirements from step III, step V generates flexible platform design alternatives.

---

[336] Bandwidth of the product platform in both the system–level design variable space and customer-preferred attribute space.

[337] Multiple arrows indicate that several alternatives could be carried along.

[338] It is noted that GIFFIN ET AL. [2009] extend the CPI definition of SUH ET AL. [2007] by suggesting a normalization of CPIs which eases the comparison between elements when analyzing design changes.



	A	B	C	D	E	F	G	H	ΔE_{in}
A	■								0
B	1	■	1						2
C	1		■						1
D		1		■				1	2
E	1		1		■	1			3
F		1			1	■			2
G				1			■		1
H				1		1	1	■	3
ΔE_{out}	3	2	2	2	1	2	1	1	
CPI	**3**	**0**	**1**	**0**	**-1**	**0**	**0**	**-2**	
Class	**M**	**C**	**M**	**C**	**A**	**C**	**C**	**A**	

Figure 11-7 Change propagation in a system and K_{switch} for each component [SUH ET AL. 2007]

In order to compare the flexible design alternatives against the rigid design and, if desired, amongst each other, their costs are determined in step VI. The lower switching cost[339] (K_{switch}) of those alternatives when making changes must be considered and traded off against the usually higher initial investment cost[340] (K_{init}) and variable cost C_{total}[341]. For verification that the generated design alternatives are more flexible than the original rigid design and to determine the performance amongst them, the new CPIs and K_{switch} for those flexible design alternatives are determined. However, the benefit of the flexibility (real option) must be identified by also considering the amortization over the course of the product platform lifecycle.

Consequently, the designs are evaluated (step VII) by calculating the expected net present value of each flexible design alternative under variation of several scenarios. In the end, either the best platform design alternative is selected or, if unsatisfactory, the process is restarted in step I or step V respectively.

11.2.6 Engineering Systems MDM framework by BARTOLOMEI [2007]

The ES-MDM methodology contains six domains that are embedded in the ES-MDM framework shown in Figure 11-8. According to BARTOLOMEI [2007, pp. 73–86], those domains are defined as:

- The "system drivers" domain represents the environmental domain that captures the exogenous variables that influence or are influenced by the system. This includes economic, political, social and technical influences that constrain, enable or alter the characteristic of components in the system.
- The "stakeholders" domain represents the social domain that includes individuals, groups and/or organizations that affect or are affected by the system. They include both internal and external stakeholders depending on if they have or have not control of the entities (defined by the system boundary in Figure 11-8).

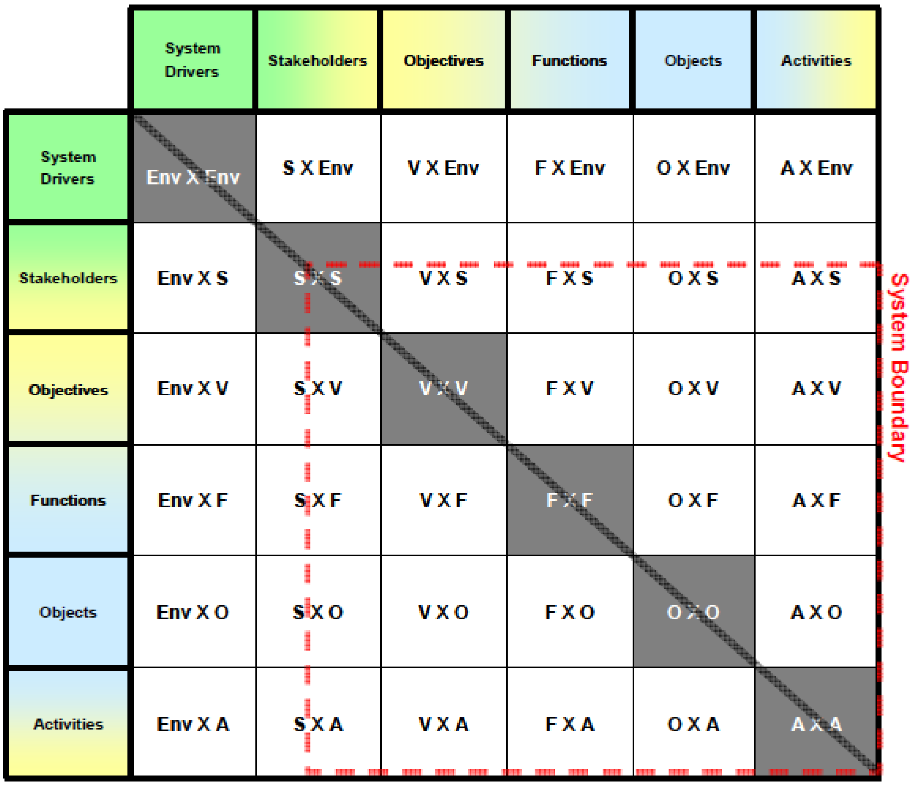
---

[339] Engineering costs of changes, additional fabrication, assembly tooling and equipment investment.

[340] Fabrication, assembly equipment and corresponding tooling.

[341] Unit costs of each product variant multiplied by the number of product variants produced.

- The “objectives” domain defines the combined purposes / goals of the system that are defined by stakeholders. It includes all articulated and unarticulated customer needs, system requirements and goals / objectives.
- The “functions” domain describes what the system must do to achieve those stakeholder objectives.
- The “objects” domain represents the technical domain with the physical components of the system that contribute to the objectives of the system. They include the architectural / physical entities required to carry out functions that can represent hardware, software, infrastructure, etc.
- The “activities” domain includes the process, sub-processes, procedures, tasks, and work units associated with an engineering system.



	System Drivers	Stakeholders	Objectives	Functions	Objects	Activities
System Drivers	Env X Env	S X Env	V X Env	F X Env	O X Env	A X Env
Stakeholders	Env X S	S X S	V X S	F X S	O X S	A X S
Objectives	Env X V	S X V	V X V	F X V	O X V	A X V
Functions	Env X F	S X F	V X F	F X F	O X F	A X F
Objects	Env X O	S X O	V X O	F X O	O X O	A X O
Activities	Env X A	S X A	V X A	F X A	O X A	A X A

Figure 11-8 ES-MDM framework [BARTOLOMEI 2007, p. 73]

The ES-MDM components and relations in the system can be characterized by certain characteristics (e.g. numeric values, mathematical equations, design parameters). Unlike conventional DSMs or DMMs, the ES-MDM allows storing multiple relations in the same matrix, i.e. the matrix is not flat. It allows describing the evolution of the system over time by allowing modeling structural changes of nodes and relations and, additionally, changes in the characteristics of the components.

Within this framework, BARTOLOMEI [2007, p. 135] suggests a nine-step process which enables the identification of flexibility by detecting “hot spots” in socio-technical systems:

1. "Construct the ES-MDM for a particular system" means the elicitation and representation of the data
2. "Identify sources of uncertainty driving change" represents the identification of relevant general change categories which may be organizational, related to technology innovation, etc.
3. "Define change scenarios" relates to the alternative future developments (e.g. change of objectives with stricter requirements on system endurance)
4. "Determine the sensitivity of each scenario" (e.g. sDSM in KALLIGEROS [2006]), i.e. identify the sensitivity of the components to change given potential contextual changes
5. "Identify change modes[342] for each scenario" (e.g. change propagation method in SUH ET AL. [2007]), i.e. account for the ability of a component to propagate change throughout the system
6. "Calculate the cost of change for each scenario" (e.g. cost analysis in SUH ET AL. [2007]) which accounts for the switching cost when changing the component

"Hot spots" in design relate to the location of the best opportunities for options in the design [BARTOLOMEI 2007, p. 134]. Hereby, the magnitude of "hotness" represents a ranking amongst flexibility candidates. Hence, the process continues by:

7. "Identifying hot / cold[343] spots for each scenario"
8. "Examine hot / cold spots across scenarios"
9. "Value flexibility using real options analysis"

According to BARTOLOMEI [2007, p. 136] and WILDS [2008, p. 35] those hot spots are subject to three metrics that are represented in a three-axis graph: "Measure of uncertainty / volatility" refers to the likelihood that the component will change due to contextual change occurring in the future by use of forecasts. Second, "benefit" is a measure to evaluate how much utility is gained or lost from changing a component. Last, "cost" refers to the switching cost (technique) introduced by SUH ET AL. [2007].

11.2.7 Methodology for identification of FDOs by WILDS [2008]

WILDS [2008, pp. 40–55] suggests a seven-step methodology for the identification of FDOs:

1. Construction of the ES-MDM: The methodology uses the same ES-MDM framework as introduced by BARTOLOMEI [2007]. The construction of the ED-MDM follows the QKC building process by BARTOLOMEI [2007, pp. 97–102].

---

[342] According to PALANI RAJAN ET AL. [2005] a "change mode" is a characterization of change (e.g. change of design variables, module, material).

[343] In contrast to hot spots, cold spots represent spots in the ES-MDM that are least suitable for embedding flexible design as they are not sensitive to future change. As discussed by BARTOLOMEI [2007, p. 134], they correspond to the platform components by KALLIGEROS [2006].

2. Identifying the change scenarios: In this step, the set of uncertainties (e.g. laptop with changes in size of battery, availability of power source) is defined to which the system should be flexible. Change scenarios[344] are defined which represent events or actions from the change of a single or multiple system drivers (e.g. new battery technology trends). Each change scenario is defined by (1) the identification of uncertainties that each system driver is exposed to and (2) the probability P_{CS} that the system driver will change in the future.
3. Identifying the change initiators and relationship types (CIRT pairings): Identification of where and how the change will enter the system where each scenario is analyzed individually. Thereby, change initiators[345] (e.g. battery) are the components that are directly related to the system drivers (e.g. battery technology). They are linked by certain relationship types which depend upon the domain of the change initiator (e.g. change initiator "battery" related to system driver "battery technology" by relationship types "power transfer", "space" or "hardware interfaces"). Depending on the change scenario of the change driver (e.g. change of internal chemistry of battery) the probabilities of being related to the change initiator "battery" are e.g. high for the influence for the relationship "power transfer" and low for "space"[346].
4. Reducing the ES-MDM to subgraphs[347]: Components in the ES-MDM that are not affected by the change scenario or unrelated to the change initiator can be faded out or removed creating a subgraph. This reduces the complexity of the ES-MDM in the following steps, especially as change propagation analysis (step 5) requires human input which is eased by addressing only the relevant scope.
5. Change Propagation Analysis (CPA): A change graph is built that only shows the possibly affected downstream components based on an incoming change "Δx" (subgraph). Based on this change graph, components which are very unlikely to change, i.e. have a low probability of change propagation (P_c), are also faded out / removed. Figure 11-9 represents a change graph for an example system.

---

[344] WILDS [2008] uses "change scenarios" as combinations of specific future system requirements.

[345] Must not only be in the physical "objects" domain, but can also appear in the "social" or "environmental" domain [WILDS 2008, p. 68]. However, the work of WILDS [2008] only considers physical objects as change initiators. They are identified by screening the first column and row of submatrices in the ES-MDM which eliminates the need to search the entire ES-MDM [BARTOLOMEI ET AL. 2007, p. 46].

[346] WILDS [2008, p. 47] suggests to build a "Change Initiator / Relationship Type" (CIRT) Matrix for each change scenario to support the decision-maker.

[347] The number of subgraphs (e.g. 12), i.e. the representations of reduced ES-MDMs, depends on the number of change scenarios (e.g. 3) and CIRT pairings between change initiator (1) and relationship type (4). The following steps 5 and 6 are repeated for each subgraph, i.e. 12 times in this example.

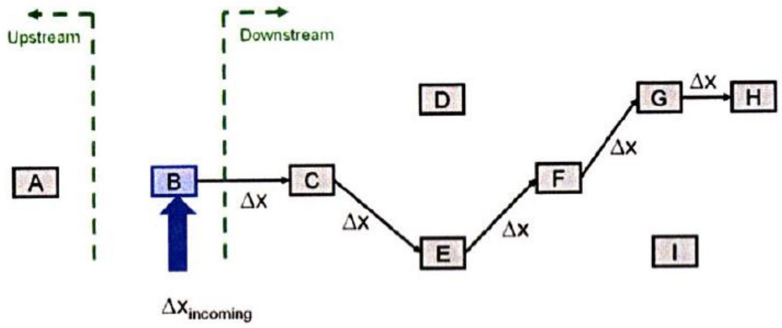


Figure 11-9 Change graph for example system [WILDS 2008, p. 49]

For the remaining change graph switching costs (SC), i.e. the cost associated with modifying or replacing the component in response to incoming change, are assigned to each component. The Component Expected Expense (CEE) is calculated for each component by determining CEE_{CIRT} of the component under investigation assuming path independency[348] with

$$CEE_{CIRT,k} = (P_{c_k} \times SC_k) + \sum_{l=k+1}^{n} (P_{c_l} \times SC_l) \qquad (11\text{-}3)$$

for component k, with n downstream components in the change graph. Figure 11-10 shows the calculation of the CEE_{CIRT} for component "F" in the example system.

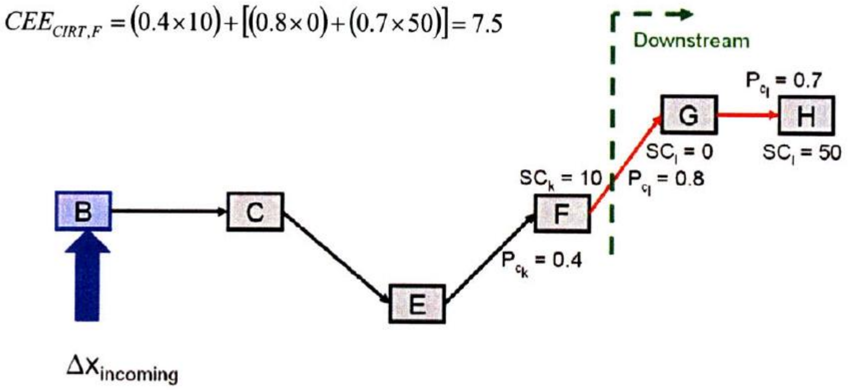


Figure 11-10 CEE_{CIRT} calculation for example system [WILDS 2008, p. 51]

Finally, the aggregate CEE, namely "CEE_{CS}", for each change scenario and component is determined by adding all CEE_{CIRT} of various subgraphs of different change initiators and relationship types:

---

[348] For instance, the change of a fuselage may be due to a change of the motor or a change in the size of power supply [WILDS 2008, p. 75]; the cost of change to accommodate the new motor may be different from accommodating the power supply which results in different switching costs. If switching costs are not path independent, i.e. depend on previous events, then CEE must be statistically solved using Monte Carlo simulation and a lookup table for the assigned switching costs [WILDS 2008, p. 51].

$$CEE_{CS,k} = \sum_{i=1}^{N} \sum_{j=1}^{M} (P_{i,j} \times CEE_{CIRT,k}) \tag{11-4}$$

where N is the number of change initiators, M is the number of relationship types, $P_{i,j}$ is the probability that the CIRT is activated in response to the change scenario under investigation.

6. Calculation of the Desired Flexibility Score (DFS): The DFS is a one-dimensional metric that facilitates the direct comparison of components regarding their potential of embedding flexibility. Thereby, it accounts for the components' impact on the system as a whole by considering the potential of propagating change and the related switching cost under all possible change scenarios. The DFS is defined as

$$DFS_k = \sum_{z=1}^{q} (P_{CS} \times CEE_{CS,k}) \tag{11-5}$$

with q being the number of considered change scenarios and P_{CS} the probability of the change scenario occurring. The DFS is calculated for each component in the system.

7. Recognizing FDOs: In the end the components with their DFS scores are plotted in a chart in descending order. Components that were not connected to the ES-MDM subgraphs or were removed in the change graph have a DFS = 0, hence, are not candidates for flexible design as they remain unaffected concerning the considered uncertainties[349]. High scoring components, in contrast, are strong candidates for embedded flexibility (FDOs). The threshold for a critical DFS score to further consider a component as a FDO can be adjusted.

11.2.8 Logical-MDM by Mikaelian et al. [2012]

The Logical-MDM builds upon a network representation highlighted in Mikaelian et al. [2012] and shown in Figure 11-11.

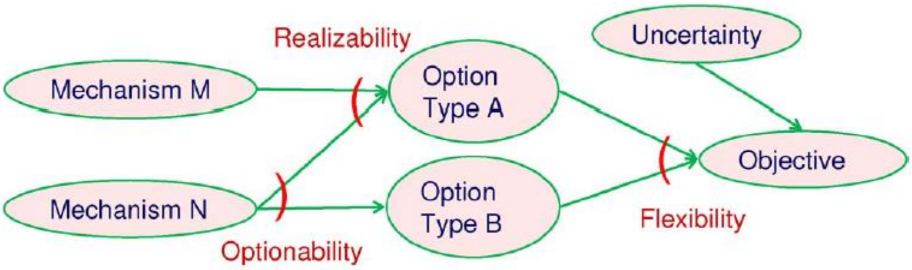


Figure 11-11 Nodes with relevant properties "flexibility", "optionability" and "realizability" in a dependency model [Mikaelian et al. 2012]

In this regard three different properties and metrics are introduced that are relevant for the identification of real options:

---

[349] On the contrary, not all Objects with a DFS ≠ 0 are also FDOs [Wilds 2008, p. 80] which requires this subsequent prioritization.

- “Flexibility”, a pre-condition of achieving a given objective under uncertainty, as the ability to exercise “real options”. The metric “Flex” indicates the existence of options for achieving an objective (“How many different “types” exist to re-fulfill a given objective?”).
- “Optionability”, a post-condition of a mechanism, as the ability of a mechanism to enable types of real options with the metric “Opt” as the number of options enabled by the implementation of a mechanism (How many “types” can be facilitated by each “mechanism”?).
- “Realizability”, a pre-condition of a real option type, as the ability of a mechanism to enable a given type of real option. The metric “Rz” represents the number of different ways that a type of option can be enabled (How many “mechanisms” are available to facilitate the specific “type”?).

The classical MDM is a structural model of dependencies and influences which specifies the topology of interactions between nodes rather than its logical behavior. Hence, the MDM dependency network semantics is interpreted as a logical “AND” relationship in such a MDM. In a state-based model the edges, representing logical “OR” relationships, display a choice amongst various transitions. According to MIKAELIAN ET AL. [2012], as the MDM misses the ability of modeling choice it is also incompatible to modeling flexibility. Consequently, a Logical-MDM is introduced that allows modeling structural dependencies but also logical behavior [MIKAELIAN ET AL. 2012]. It augments the MDM model by specifying the logical dependency structures where for each node “i” a logical dependency structure is added to specify the logical relationship among the nodes that affect *“i”*. Hereby the logical dependency structure is transformed into disjunctive normal form (DNF), a logical formula[350] consisting of disjunction of conjunctions where no conjunction contains a disjunction. Hence, the following formula is in DNF

$$F = \left(\bigvee_{i=1}^{n}\left(\bigwedge_{j=1}^{m_i} L_{i,j}\right)\right) \qquad (11\text{-}6)$$

where $L_{i,j}$ is a literal that can be a positive variable “p” or negative “¬p” with “¬” being the negation operator which allows representing exclusive *ORs*. The three already introduced metrics also shown in Figure 11-11within the DNF of the logical formula are interpreted as:

- “Flex” as number of conjunctive clauses associated with the objective node. Flex > 1 indicates the presence of options.
- “Opt” for a candidate mechanism C[351] as number of conjunctive clauses of all objective nodes that contain any positive literal (e.g. type “switch”) that is enabled by the mechanism (1) and the number of clauses in which this literal appears[352] (2)
- “Rz” for a type of option T as number of conjunctive clauses associated with node T

---

[350] The formula contains both conjunctions (“∧”, “*AND”*) and disjunctions (“∨”, “*OR”*).

[351] Priorly, for each node N in the model that appear as a positive literal (and is not an uncertainty literal) in the DNF formula of the objective node N, the dependency model is backtracked to identify the candidate mechanisms which are grouped into a set S.

[352] Except if the literal appears in all clause(s) of a single DNF which then represent “obligations” and no “options”.

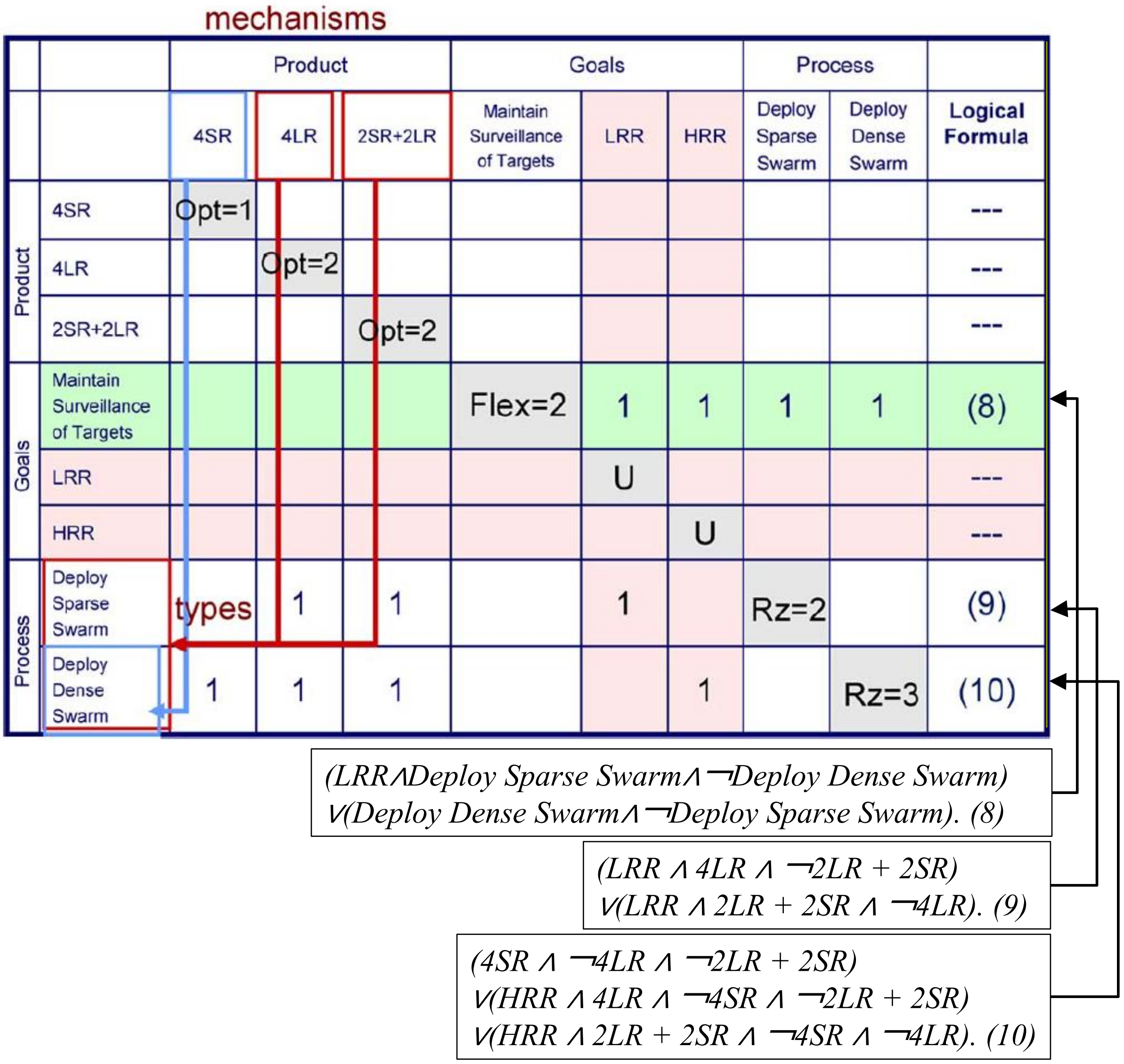
Whereas in a classical MDM certain type of real options A, B, C and the uncertainty U are shown to affect an objective node (e.g. endurance), the Logical-MDM can now specify the choices:

$(A \land B \land \neg C \land U) \lor (A \land \neg B \land C \land U) \lor (\neg A \land B \land C \land U)$

resulting in three conjunctive clauses and, hence, Flex=3 in this case.

Hereby the MDM is extended to the Logical-MDM which allows the identification of the <Mechanism, Type> tuples based on previously identified sources of uncertainty which, in turn, can be used by applying standard real options valuation to decide which tuples represent the most valuable means of managing uncertainty. In addition to representing the embedded real options, the Logical-MDM allows mapping different scenarios by accounting for multiple domains such as “system components”, “functions”, “activities”, “mission objectives” and “uncertainties”.

Figure 11-12 displays a Logical-MDM focusing on “end user operations”, i.e. operations of fielded systems such as unmanned air vehicles (UAVs). In this example, to “maintain surveillance at target” is considered as the main target while the revisit rate of the UAVs (Low revisit rate (LRR) / High revisit rate (HRR)) is subject to uncertainty. As the example shows, 4SR (four UAVs with short-range communication system) facilitate only one real option type (deploy dense swarms) while the other two configurations (four UAVs with long-range communication system (4LR), mix of 2SR and 2LR) facilitate both sparse and dense swarms, i.e. two types of real options.



		Product			Goals			Process		
		4SR	4LR	2SR+2LR	Maintain Surveillance of Targets	LRR	HRR	Deploy Sparse Swarm	Deploy Dense Swarm	**Logical Formula**
Product	4SR	Opt=1								---
	4LR		Opt=2							---
	2SR+2LR			Opt=2						---
Goals	Maintain Surveillance of Targets				Flex=2	1	1	1	1	(8)
	LRR					U				---
	HRR						U			---
Process	Deploy Sparse Swarm	types	1	1		1		Rz=2		(9)
	Deploy Dense Swarm	1	1	1			1		Rz=3	(10)

$$(LRR \wedge Deploy\ Sparse\ Swarm \wedge \neg Deploy\ Dense\ Swarm) \vee (Deploy\ Dense\ Swarm \wedge \neg Deploy\ Sparse\ Swarm). \quad (8)$$

$$(LRR \wedge 4LR \wedge \neg 2LR + 2SR) \vee (LRR \wedge 2LR + 2SR \wedge \neg 4LR). \quad (9)$$

$$(4SR \wedge \neg 4LR \wedge \neg 2LR + 2SR) \vee (HRR \wedge 4LR \wedge \neg 4SR \wedge \neg 2LR + 2SR) \vee (HRR \wedge 2LR + 2SR \wedge \neg 4SR \wedge \neg 4LR). \quad (10)$$

Figure 11-12 Identification of mechanism and types of options in Logical-MDM [Mikaelian et al. 2012]

The calculation of the suggested three metrics within the Logical-MDM reveals which mechanisms and types of options exist and where they are embedded. By knowing the <Mechanism, Type> tuples, they can now be valued under the uncertainty (here: LRR, HRR) by accounting for the flexibility to exercise available real options and the associated costs and benefits of embedding that flexibility.

11.2.9 Flexibility in the design of engineering systems by Hu & Cardin [2015]

Hu & Cardin [2015] suggest the following steps to be performed:

1. Initial design: The objective is to identify the best performing baseline design which can be determined by various techniques such as discounted cash flow (DCF) analysis, discrete event simulation and computer-aided design. The DCF model, for instance, is analyzed

based on deterministic point forecasts[353] of uncertainty factors to determine the design concept with the best net present value (NPV) from the various candidates. The selected baseline design represents the benchmark design for the generated flexible design concepts when valuation takes place in step 4.

2. Dependency and uncertainty analysis: The objective in this step is to identify dependencies and major uncertainties in the model. Relevant uncertainty sources are identified by using e.g. prompting methods [CARDIN ET AL. 2012]. The ES-MDM is built based on expert knowledge and historical data by including, in contrast to BARTOLOMEI [2007], conditional probability[354] amongst system elements; additionally, prior probability[355] and the cost of change for system elements are also accounted for. In that context, the identified uncertainty drivers are related to the other domains and elements. They often come from the "system drivers" domain as was demonstrated in the use case in HU & CARDIN [2015]. Besides building the ES-MDM the major uncertainties are modeled to consider a wide range of possible scenarios by e.g. use of lattice models, diffusion models or scenario planning (section 2.2.2). They are needed in step 3 and, especially, step 4 for identifying and valuing flexible design concepts.
3. Flexible design opportunities identification[356]: As Figure 11-13 shows, the output of step 2 is now used in this step.

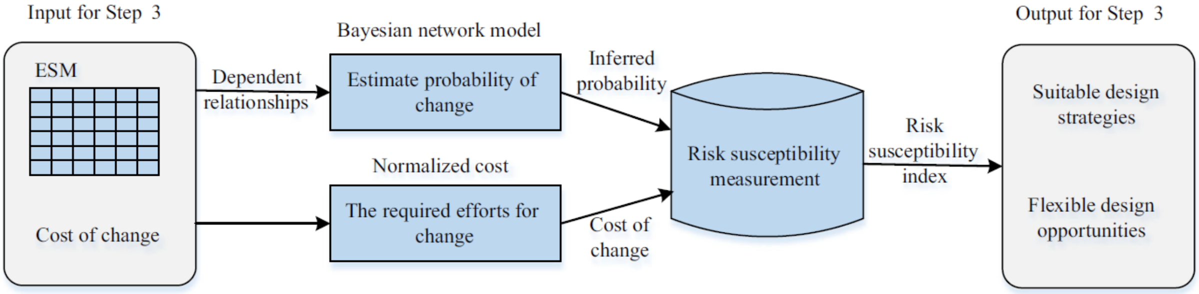


Figure 11-13 Main procedures for flexible design opportunities identification [HU & CARDIN 2015]

The Bayesian network model is required to model complex system interdependencies and system elements to derive "posterior conditional probabilities" of elements based on the previously identified conditional and prior probabilities in the ES-MDM; in contrast to

---

[353] The variables capturing uncertainty may exist already in this performance model, but variability is not yet accounted for which is part of step 2.

[354] Probability that change of one element will lead to a change in neighboring element. It coincides with P_C by WILDS [2008].

[355] Probability that uncertainty scenario occurs in the future. It coincides with P_{CS} by WILDS [2008].

[356] Although this step refers to FDOs, it considers the identification of critical system components (Change Objects) only.

conditional probabilities, they also consider indirect relationships and, hence, predict how likely one element might be affected if other upstream elements are changed.

The "risk susceptibility" is measured by the posterior conditional probability and the cost of change that has been normalized by the maximum cost of change for each system element. Hereby, $R_{s_i}^{Received}$ indicates the degree of risk received by system element s_i due to the impact of changes upstream. However, the change of that node also becomes a source of uncertainty to downstream nodes. Hence, $R_{s_i}^{Generated}$ is also needed which indicates the degree of risk[357] generated by a change in system element s_i under uncertainty U. Based on the risk susceptibility index (RSI) with

$$RSI_{s_i} = R_{s_i}^{Received} - R_{s_i}^{Generated} \tag{11-7}$$

system elements s_i with a high RSI_{s_i} indicate candidates for embedding flexibility whereas other constellations reflect either candidates for robust or fixed design (Figure 11-14).

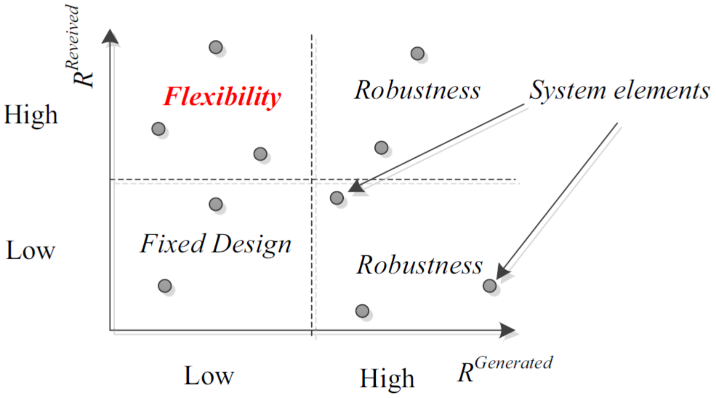


Figure 11-14 Risk susceptibility of system element [HU & CARDIN 2015]

4. Flexibility valuation: In this step, flexible strategies and change enablers, i.e. flexible design concepts, are selected for the highly-ranked system elements. The focus now lies on the evaluation of those flexible design concepts using real option analysis based on Monte Carlo simulations to generate stochastic scenarios. Hereby, the identified baseline design (step 1) and the generated flexible design concepts for the critical system components (Change Objects) are evaluated by using the uncertainty models to determine the value of flexibility (VOF), i.e. the difference between flexible and benchmark design performance of the baseline design in order to select the best performing flexible design concepts.

11.3 Change Enabler principles – Definitions

The following definitions describe the Change Enabler principles presented in section 3.3.2. They base either on one specific reference or on an additional complementary one to concretize that definition further and only if compatible.

---

[357] Probability and cost of changes of downstream system elements due to change of system element s_i.

Table 11-3 Definitions of Change Enabler principles

	Definition	Reference
Easy (Dis-) Assembly	Aims at easing the assembly and disassembly process.	BISCHOF [2010, p. 97]
Adjustability approach	Enable the device to respond to minor changes (e.g. allow tuning of design parameters, provide the capability for excess energy storage or importation).	QURESHI ET AL. [2006], KEESE ET AL. [2007]
Autarky	Independence of technical system of organisational and technical conditions. Thereby, it reduces the impact on factory operations for neighboring areas when exchanging that technical resource (e.g. machine).	HILDEBRAND [2005, pp. 52-54]
Autonomy	Characterized by objects, which are capable of providing basic functionality necessary to ensure their independence from the embedding systems.	FRICKE & SCHULZ [2005]
Automatability	The ability to upgrade or downgrade the degree of automation.	WIENDAHL ET AL. [2007]
Buffering	Allocation of reserves commonly used in the manufacturing domain handling variation of the production system (inventory, capacity, time).	MIKAELIAN ET AL. [2011]
Compatibility	Allows various interactions within and outside the factory by being networkable with regards to material, information, media and energy e.g. standard software interfaces.	WIENDAHL ET AL. [2007], WIENDAHL ET AL. [2015, p.102]
Convertibility	Ability to easily transform the functionality of existing systems, machines, and controls to suit new production requirements.	KOREN & ULSOY [2002]
Customization	Ability to adapt the customized (non-general) flexibility of production systems and machines to meet new requirements with a family of similar products (that are to be manufactured).	KOREN & ULSOY [2002]
(Interface) Decoupling (approach)	Reduce the communications between modules and enable the device to function normally regardless of the orientation, location and arrangement of its individual modules.	QURESHI ET AL. [2006]
Decentralization	Characterized by a decentralized distribution of control, information, resources, attributes, and properties within the system architecture.	FRICKE & SCHULZ [2005]
Diagnosability	Ability to automatically read the current state of a system and controls so as to detect and diagnose the root-cause of defects, and subsequently correct operational defects quickly.	KOREN & ULSOY [2002]
Exchangeability	Possibility of replacing technical resources (e.g. machine) at low effort in operational phases.	HILDEBRAND [2005, p. 37]
Expandability and reducibility	Allows spatial degrees of freedom of objects regarding expansion, growth or contraction.	HERNANDEZ [2003, p. 55]

	Definition	Reference
Extended use	Theoretical exaggeration of the initially planned product use with the ability to handle various conditions and future changes of its environment. In contrast to "over-engineering", they focus on functions instead of physical parts, modules and machine elements.	BISCHOF [2010, p. 101]
Handleability	Characterizes the property of technical resources (e.g. machine) with object-specific parameters (e.g. mass, dimensions, form/geometry) to allow relocations by changing their spatial arrangement or position.	HILDEBRAND [2005, p. 69]
Ideality / Simplicity	Aims at reducing system complexity by striving for only useful functions, which may be interpreted as establishing small, simple units / elements with a minimized number of interfaces (loose coupling among and strong cohesion within modules) within an architecture.	FRICKE & SCHULZ [2005]
Independence	Aims at minimizing the impact of changing design parameters. This principle is derived from the axiomatic approach by Suh [1990] where each system or functional requirement has to be satisfied by an independent design parameter.	FRICKE & SCHULZ [2005]
Inherent flexibility	Integrates flexible and change tolerant design features and machine elements into the design including also design solutions that can be used for the same purpose in different environment without requiring change or address self-healing and self-adjusting technologies and solutions.	BISCHOF [2010, p. 96]
Interconnectivity	Facilitates various states and relations concerning utilities for means of production, material and media within and outside the factory. It allows the machine to use required connections without any reconstruction work.	HERNANDEZ [2003, p. 55]
(Dis-)Integrability	Characterized by compatibility and interoperability applying generic, open, or common / consistent interfaces which allows the low-effort (dis-) integration of products, product groups, parts, components, production processes or means of production.	FRICKE & SCHULZ [2005], HERNANDEZ [2003, p. 56]
Mobility	Locally unrestricted movability of objects.	WIENDAHL ET AL. [2015, p.102]
Modularity (approach) / Encapsulation	Clusters the system's functions into various modules while minimizing the coupling among the modules (loose coupling) and maximizing the cohesion within the modules (strong cohesion).	FRICKE & SCHULZ [2005]
(Function- and utilization) Neutrality	Embodies properties of factory objects dimensioned and designed for multiple tasks, requirements, purposes, or functions.	HERNANDEZ [2003, p. 55]
Nonhierarchical integration	Characterized by linking units across the total system, with no respect to any type of modularity or encapsulation.	FRICKE & SCHULZ [2005]
Over-engineering	Aims at forecasting trends and developing products that are less likely to require change when requirements get higher / stricter in the future. In contrast to "extended use", they focus on physical parts, modules and machine elements instead of functions.	BISCHOF [2010, p. 103]
Parts reduction approach	Reduce the number of parts requiring manufacturing changes.	KEESE ET AL. [2007]
Pretestability	Addresses the possibility of examining and affecting a technical resource (e.g. machine) concerning its functional capability and performance prior to its integration into an existing configuration to reduce the effort in case of a system adjustment.	HILDEBRAND [2005, p. 54]
Redundancy	Enables capacity, functionality, and performance options as well as fault-tolerance.	FRICKE & SCHULZ [2005]

	Definition	**Reference**
Scalability	Provides technical, spatial and personnel extensibility and reducibility.	WIENDAHL ET AL. [2007], WIENDAHL ET AL. [2015, p.102]
Spatial approach	Facilitates the addition of a new functionality and rearrangement or scaling of parts.	QURESHI ET AL. [2006], KEESE ET AL. [2007]
Standardization	Addresses the unification of parts and the interfaces between parts and modules.	BISCHOF [2010, p. 99]
Staging	Ability to distribute investments across the lifecycle which enables other options within multiple enterprise views.	MIKAELIAN ET AL. [2011]
Universality	To be dimensioned and designed for different requirements with regards to product or technology.	WIENDAHL ET AL. [2015, p.102]

11.4 FDO requirements

Table 11-4 BR I: Identification of effective FDOs

	Definition	Description
R1	Ability to identify the relevant problem and solution space	The methodology should support the identification of only relevant change sources (Change Drivers, System Requirements) and Objects on the drilling rig.
R2	Ability to identify technically feasible solutions	The methodology should allow the identification of only those Flexible Design Concepts that are technically feasible.
R3	Ability to identify high-performing solutions	The methodology should allow the identification of the best performing Flexible Design Concepts beyond its feasibility, i.e. solutions of high value and/or high value-effort ratio.
R4	Ability to reduce to effective and relevant solutions	The methodology should allow a systematic reduction of available solutions to an effective and relevant set (relevant together with “R7”).
R5	Ability to reduce risk of offering non-profitable solutions from System Supplier's perspective	By using the methodology, the System Supplier should reduce the risk of offering Flexible Design Solutions that are non-profitable due to e.g. new and yet unproven offers, embedment of flexibility at System Supplier's cost, etc.

Table 11-5 BR II: Comprehensive identification of FDOs

	Definition	Description
R6	Comprehensive identification of change sources and Objects	The methodology should allow accounting for explicitly articulated but also non-articulated change sources (Change Drivers, System Requirements) and Objects by the customer.
R7	Comprehensive generation and representation of Flexible Design Concepts	The methodology should allow a comprehensive identification and representation of Flexible Design Concepts including suitable Transitions and Change Enablers for the identified Change Objects.

Table 11-6 BR III: Customer-oriented identification of FDOs

	Definition	Description
R8	Customer-dependent decision-making on relevant problem and solution space	The type of change sources (Change Drivers, System Requirements) and relevant Objects depend on the customer and must be accounted for during decision-making.
R9	Customer-dependent decision-making on solutions	The selection of suitable Flexible Design Concepts and Flexible Design Solutions for the selected Change Objects depend on the customer and must be accounted for during decision-making.

Table 11-7 BR IV: Efficient identification of FDOs

	Definition	Description
R10	Efficient identification of Baseline Objects	The Baseline Objects, i.e. the Objects that represent the design basis before flexibility is even considered, should be identified in a time- and resource-efficient manner.
R11	Efficient identification of change sources and Objects	The identification of change sources (Change Drivers, System Requirements) and the affected Change Objects should be performed in a time- and resource-efficient manner.
R12	Efficient identification of Flexible Design Concepts and Solutions	The identification of Flexible Design Concepts and Flexible Design Solutions for the identified Change Objects should be performed in a time- and resource-efficient manner.

Table 11-8 BR V: Appropriate usability for engineers

	Definition	Description
R13	Non-ambiguous and clear comprehension	The methodology and its constituents can be unmistakably comprehended by its users. Despite better results, it helps planners and analyst also to be more confident in them.
R14	Simple traceability of selections and decisions	The selections and decisions within the methodology are transparent and can easily be traced back.
R15	Homogeneity of and within approach	The methodology represents one integrated approach for both identifications of Change Objects and generation of Flexible Design Concepts.
R16	Ease of application	The application of the methodology is easily understood and performable.
R17	Ease of managing models during execution	The methodology should provide the means to easily adapt, integrate and remove data when being applied.

Table 11-9 BR VI: Flexible application of FDO Methodology

	Definition	Description
R18	Alternative entry or exit points	The methodology should allow the user to enter or exit the model at different stages or steps.
R19	Ability of omitting or postponing step(s) and iteration(s)	The methodology should allow the user skipping certain steps and iterations. This also includes delaying decisions such as the selection of Transitions to later phases of the methodology.
R20	Ability of changing direction of identification	The methodology should allow the user the identification of change sources and Change Objects by following different directions through the model being able to identify causally related and unarticulated prior upstream causes and downstream elements following causality.
R21	Scalability of complexity and comprehensiveness	The methodology should be able to scale both the complexity of the model and the degree of comprehensiveness.

Table 11-10 BR VII: Efficient build-up and maintenance of database

	Definition	Description
R22	Efficient build-up of database	The build-up of the initial database should be performed in a time-and resource-efficient manner.
R23	Efficient maintenance of database	The maintenance of the database, after the first build-up and in between application periods, should be performed in a time-and resource-efficient manner.

11.5 Reference questionnaire in case-based expert interviews

The following section bases upon Allaverdi et al. [2015]. It introduces the subjects of concern addressed in the case-based expert interviews to elicit relevant data as described in section 5.2.1. The questions can be divided into four different categories of which the last three address the five domains of the FDO Data Model (section 5.1). As noted, besides project-specific questions, questions regarding the generalization of statements were raised to provide details on the transferability and applicability of statements to other cases and circumstances. They are marked as grey lines in Table 11-12, Table 11-13 and Table 11-14.

Questions related to “main data” (Q I-1 - Q I-10): They relate to gaining general information on the upgrade project of concern. They are especially important for classifying this reference project, documentation, verification and follow-up on details if more information is required in the future.

Table 11-11 Main data (I.)

Q I-1	Project name
Q I-2	Project number
Q I-3	Change Object (variant)
Q I-4	Rig type
Q I-5	Derrick type
Q I-6	Upgrade initated by
Q I-7	Upgrade performed by
Q I-8	Year of delivery (rig)
Q I-9	Year of upgrade (rig)
Q I-10	Upgrade value (if known)

Questions related to "change source recognition" (Q II-1 – Q II-7): Those questions relate to the Change Drivers and affected System Requirements of the drilling system (Q II-1 – Q II-3). It is also documented if those System Requirements also affected other Objects in the project under investigation which, in turn, triggered another upgrade. Q II-5 and Q II-6 relate to the relevancy of the Change Driver(s) and the upgrade. Q II-7 asks about the applicability of Change Drivers across variants and product families.

Table 11-12 Change source recognition (II.)

Q II-1	Change Driver
Q II-2	Impact on System Requirements
Q II-3	Objective of upgrade
Q II-4	Further directly affected & upgraded Change Objects
Q II-5	Possibility of future occurrence of Change Drivers and related upgrades for rig of mini case
Q II-6	Possibility of future occurrence of Change Drivers and related upgrades for other rigs
Q II-7	Influence and impact of Change Driver and violated System Requirements applicable to other variants / variations within product family and across product families

Questions related to "Change Objects and their Transitions" (Q III-1 – Q III-8): In this phase, it was determined which Objects / Object modules of the affected product family were upgraded directly (Q III-1) and which ones due to other reasons but in the same run (Q III-2). Describing the main steps of the upgrade for the Change Objects and Objects in the outlying area (Q III-3) set the basis for addressing change propagation within (Q III-4) and amongst Objects (Q III-5) and the next category of questions (IV). Generalization questions Q III-6 and Q III-7 referred to the applicability of the addressed upgrade when facing different boundary conditions (rig, derrick type) and questioned the relevancy of the upgrade by asking about other possible reasons (change sources) for that upgrade to occur (Q III-8).

Table 11-13 Screening for Change Objects & identification of suitable Transitions (III.)

Q III-1	Physical Objects / Object modules of variant and outlying area to be upgraded (related to affected System Requirements)
Q III-2	Physical Objects / Object modules of variant and outlying area to be upgraded in same run (related to other System Requirements)
Q III-3	Brief description of upgrading process of Change Object and outlying area
Q III-4	Product internal Change Objects due to knock-on (Object modules)
Q III-5	Product external Change Objects due to knock-on (Objects, Object modules)
Q III-6	Applicability of upgrade to other rigs (e.g. jack-ups, fixed platforms)
Q III-7	Equal applicability of upgrade to other derrick types (Conventional rigs, Ramrigs)
Q III-8	Other Change Drivers / violated System Requirements in other projects responsible for identical or similar upgrade

Questions related to "Change Enablers" (Q IV-1 – Q IV-9): Q IV-1 – Q IV-3 focus on identifying embedded Change Enablers on the existing rig under investigation, suggesting any improvements or entirely new, not yet realized Change Enablers to ease the addressed upgrade.

Q IV-4 asks about further Change Enablers that are required for the already embedded or suggested ones. Both the embedded and suggested Change Enablers were then assessed qualitatively regarding their ability to reduce upgrade efforts (Q IV-5) and by rating the additional incorporation efforts that flexible designs often bring along (Q IV-6). As a means of generalization, the suitability of those Change Enablers for other product family internal variants (Q IV-7) and across product families (Q IV-8) was determined. As Change Enablers serving multiple purposes (e.g. overhaul, maintenance, etc.) usually increase the frequency of usage and are easier to be offered to potential customers (section 6.4.2), the interviewees were asked about relevant Change Enablers in this regard and the purposes they also support (Q IV-9).

Table 11-14 Identification of suitable Change Enablers (IV.)

Q IV-1	Embedded Change Enablers to reduce effort of upgrade
Q IV-2	Recommended enhancements of existing Change Enablers to reduce effort of upgrade
Q IV-3	Recommended additional Change Enablers to reduce effort of upgrade
Q IV-4	Change Enablers requiring other Change Enablers
Q IV-5	Rating reduction of upgrade effort by embedding Change Enablers
Q IV-6	Rating additional incorporation effort by embedding Change Enablers
Q IV-7	Equal applicability of Change Enablers to other variants within product family
Q IV-8	Equal applicability of Change Enablers across product family
Q IV-9	Change Enabler applicability for other purposes

Although questions are assigned to each of those four categories, some questions represent border cases that could be attributed to another category (e.g. Q II-4 which would belong to category III). As the interviews showed, however, such an order would often be disadvantageous as previously addressed subjects would have to be resumed. Hence, for practical reasons the assignments to logical superordinate categories may deviate from the actual documented and performed ones.

11.6 Change Enabler design guidelines

The following Change Enabler design guidelines base upon the synthetized and verified data by SCHLATHER [2015] that build upon the case-based interviews discussed in section 5.2.1. To ensure consistency and clarity in the larger framework of the FDO Methodology, the IDs, design guidelines and their descriptions are partially adapted from the originally synthesized design guidelines introduced by SCHLATHER [2015]. In cases of overlaps, they would be marked as "redundant" in the Change Enabler Consistency Matrix (section 7.5) to exclude that they are not be embedded simultaneously.

Design guidelines may sometimes be assigned to alternative Change Enabler principles. In this work, however, the assignment of design guidelines always follows the categorization made and described by SCHLATHER [2015, p. 58] that assigned them to the most intuitive ones already.

In the following the six categories of Change Enabler guidelines are provided in the same order as introduced in section 5.3.4.

11.6.1 Universality

Table 11-15 Universality-related Change Enabler design guidelines

ID	Design guideline	Design guideline description
UNI_1	**Design with regard to geometry and available space**	Account for future changes of geometrical requirements by exaggerating them in Objects (e.g. over-sizing beam lengths from the beginning when min. beam length is required).
UNI_2	**Oversize with regard to stress / load cases**	Account for handling higher functional or environmental loads by e.g. changing wall thickness or material.
UNI_3	**Oversize entry and exit areas spatially for easing removal / installation of Objects**	Entry and exit areas such as doors, windows, roof, caps are to be designed larger to better allow Objects of larger sizes entering or exiting especially rooms in the future.
UNI_4	**Oversize with regard to power / energy / capacity**	The maximum power, energy or capacity of an Object (e.g. Hydraulic Power Unit) should exceed the amount that is required for regular use from the beginning to be able to cope with higher requirements (e.g. by powering additional newly installed Objects) in the future.
UNI_5	**Oversize with regard to throughput capacity**	Maximum throughput capacity (e.g. of a manifold or of pipes) should exceed the amount that is required for regular use to be able to cope with new Objects that require a higher flow rate.
UNI_6	**Use material with enhanced durability**	Materials of Objects should be chosen such that they are more durable with regard to corrosion, abrasion, etc. This can be achieved e.g. by using composite materials instead of steel. The suitability strongly depends on the use context of the Object.
UNI_7	**Design higher room ceiling**	Designing higher room ceilings aims at providing more volume (above working areas) for the installation of new, larger or additional Objects in the future.
UNI_8	**Prepare for mounting alternatives**	By preparing for mounting alternatives the Object can be attached in alternative ways to the structure. For instance, tanks can be prepared for such that they are suspended from the ceiling structure or are leg-mounted on the floor.
UNI_9	**Design homogeneous load capacities across Object's modules / sub-assemblies**	Design modules / sub-assemblies of an Object (e.g. machine engine, gearbox, frame, swivel etc.) for the same maximum load capacities as any weaker modules / sub-assemblies of that chain can be a reason for an upgrade.

ID	Design guideline	Design guideline description
UNI_10	**Provide multi-purpose bores for attaching Object**	In contrast to dedicated bores (SCA_1), multi-purpose bores are able to serve as attachment points for several (types of) Objects (in particular their sub-assemblies, modules). This can be realized e.g. by slot holes or patterns of holes that fit to a multitude of Objects.
UNI_11	**Provide space above Object for subsequent adding of or access to modules**	In contrast to designing higher ceilings (UNI_7), here the aim is at providing sufficient space above an Object for adding modules / accessing the Object, regardless if this Object is located in a room or not. In this case the extent of required space needs to be considered in advance.
UNI_12	**Protect machined surfaces against corrosion**	Machined surfaces of Objects (e.g. bores) that are exposed to environmental influences (e.g. ocean water, rain, humidity) need to be protected from corrosion e.g. by applying a protective paint coating or inserting temporary plugs / covers.
UNI_13	**Provide space around Object for better accessibility**	By providing sufficient space around the Object, it should be accessed more easily. In contrast to "SCA_4", this space is much smaller as it does not concern a future expansion of that Object. However, the extent and direction of the required access space must be considered and determined carefully in advance.
UNI_14	**Internalize tubing by channels in new Objects for guiding fluid**	Integration of fluid channels within Objects is to be prefered as being less vulnerable and avoiding high installation and deinstallation efforts of common external tubings. However, the type of required channels must be considered carefully in advance and the Object must allow an integration in the first place.

11.6.2 Scalability

Table 11-16 Scalability-related Change Enabler design guidelines

ID	Design guideline	Design guideline description
SCA_1	**Provide dedicated bores for attaching Object**	In contrast to multi-purpose bores (UNI_10), dedicated bores aim at specific Objects (in particular sub-assemblies, modules) that are likely to be attached in the future (e.g. boreholes on an Object for future adding of a module / sub-assembly) by providing bores with certain geometry (diameter, shape, etc.), pre-determined pattern of bores, etc.
SCA_2	**Provide ability for integrating stronger bracings**	The integration of stronger bracings aims at reinforcing carrying structures (e.g. Derrick structure). This can be achieved e.g. by providing spare holes and reinforced attachment points on structure.
SCA_3	**Pre-install structure base for easing subsequent integration of Objects**	This can be achieved by e.g. preinstalled sockets or pads that initially interface only the structure and then the Object that is to be installed.

ID	Design guideline	Design guideline description
SCA_4	**Provide space around Object for spatial expansion**	In contrast to "UNI_13", this space is usually much larger. The direction of future Object expansion as well as its extent need to be thought of in advance.
SCA_5	**Design non-load carrying separation walls for easing their changes or removal**	Rooms can be separated by walls that are not part of the load-carrying structure. Changes or entire removals of these walls can therefore be performed without or limited structural knock-on effects in the surrounding structure.
SCA_6	**Pre-install multi-cable duct sealing systems**	Multi-cable duct sealing systems provide an effective solution for guiding cabling or piping through gastight walls and ceilings (also water, blast, smoke). Multi-cable duct sealing systems allow for different internal configurations which facilitates embedding e.g. new cabling / piping without requiring to make new openings between areas. Hereby, "hot work" and, hence, operational stops are avoided.
SCA_7	**Account for future embedment of additional systems**	Accounting for means to add new systems (i.e. Objects, modules / sub-assemblies) to an existing one by providing sufficient space, defining interfaces, provide compatibility to existing system parts, accounting for additional loads, etc.
SCA_8	**Prepare support structure for additional structural elements**	Prepare support structures of storage areas (e.g. setback for storing tubulars) for an extension of structural elements to increase storage capacity (e.g. number of tubulars) by accounting for e.g. space, sufficient structural support, interfaces.
SCA_9	**Increase number of Objects**	An increase of Objects (e.g. more identical units with lower capacity and size each) which can be allocated decentral / spread across the system facilitates especially their integrations into existing systems (e.g. if more capacity is required) as they require less space and can be integrated more flexibly without major knock-on effects. It often also allows performing decentral changes without disturbing operations.
SCA_10	**Split-up of Objects**	The design integration of numerous units into an integrated oversized one (e.g. double pump) should be avoided. By separation into single units, scaling can be performed better to meet the actual needs / allowable costs and easing their (dis-)integration as single units are more likely to be lifted without requiring a prior disassembly as lifting limits are not exceeded.
SCA_11	**Reduce number of Objects**	A reduction of Objects (e.g. less identical units with higher capacity and size each) reduces wiring, cabling and piping efforts, as wiring / cabling / piping is less spread in the system and, hence, reduces efforts if e.g. less larger units are required or removed.
SCA_12	**Provide spare cables**	By providing additional spare cables than the required ones (e.g. 6 cables to 4 Objects), additional Objects can be added in the future without requiring to lay extra cable.
SCA_13	**Pre-equip Objects with cable trays**	Cable trays can be integrated in or attached to the Object in advance to avoid extensive work on the wiring system.

ID	Design guideline	Design guideline description
SCA_14	**Design wider and less compact for easing extension or embedment of modules**	Objects that are likely to be changed (especially extended) in the future are to be designed wider and less compact at the anticipated locations of change.
SCA_15	**Prepare Object for changes by boltable assemblies**	Objects that are likely to be changed in the future (e.g. adding new grippers and forks of transporters) are prepared for adding / changing boltable assemblies.
SCA_16	**Assign dedicated areas on room ceiling for evolutionary development of piping, cabling and ducting**	The aim is to constrain changes over the lifetime to dedicated areas on the ceiling of the room that do not affect its surrounding as there are spatially separated from other Objects. This applies especially to bulk items such as piping, cabling, ducting that strongly develop across the lifecycle and due to that spatial separation would not affect other Objects.
SCA_17	**Prepare sufficient spare attachment points for boltable units**	Objects (e.g. Drillstring Compensation System) that can be connected to additional units (e.g. accumulators) should be prepared for with spare attachment points whose number must be determined in advance by anticipating future needs (e.g. future changes in compensation capacity).

11.6.3 Modularity

Table 11-17 Modularity-related Change Enabler design guidelines

ID	Design guideline	Design guideline description
MOD_1	**Encapsulate the Object**	It targets an autonomy of the Object by reducing interfaces to peripheral Objects. In contrast to "MOD_3", it does not refer to Object internal interfaces among modules.
MOD_2	**Centralize connection points for power and data supply through multi-cable connectors**	Multi-cable connectors represent "quick-connectors" that allow the integration and combination of data and power cables onto single plates. Objects can be (dis-)connected quickly without dealing with single cables.
MOD_3	**Aim for differential / modular design for (dis-)assembly and extension / reduction**	It refers to the functional separation of assemblies within an Object and the reduction of dependencies / interfaces among those (e.g. PC with graphic controller, hard drive and random access memory as separate functional units that are stacked to the mainboard). Hereby, it eases the assembly / disassembly and allows integrations through constrained areas (e.g. doors, windows) compared to integral designs.
MOD_4	**Centralize connection points for hydraulic supply through manifold**	By centralizing connection points for hydraulic supply through manifolds various hydraulic flows are bundled before entering the Object that is to be supplied. This eases changes in general and also allows splitting piping and hoses (MOD_14).

ID	Design guideline	Design guideline description
MOD_5	**Provide ability of opening up room ceiling for better accessibility**	By providing the ability of accessing a room through a large convertible opening in the ceiling, Objects of different sizes can be lifted from or into the room without major (dis-)assemblies (in contrast to when only doors or windows can be used).
MOD_6	**Design Object modules on same level for better accessibility**	By having Object modules stored next to each other instead of stacking them vertically, their accessibility can be improved.
MOD_7	**Design single centralized frame**	Objects should be, if suitable, designed with one central and possibly symmetric base frame that other modules are attached to (MOD_11). This eases the (dis-)assembly due to better accessibility and repetitive, straighforward (de-)mounting procedures. It especially eases transportation due to single lifting points on the carrying structure.
MOD_8	**Design top openings in highly elevated Objects**	For Objects and their modules (e.g. trolleys) that are located high above working areas, case openings are to be designed that are accessed from the top to allow changes on site as the danger of dropped items (e.g. bolts, tools) is reduced. Hereby, the usually very costly removal and reinstallation of the Object or its modules can be avoided.
MOD_9	**Aim for an integrated design of simultaneously added Objects**	Object modules and sub-assemblies that are usually removed or added simultaneously (e.g. due to same reasons for change) benefit from integrated design as they can be handled together (e.g. sheaves and guiderails can be handled as one assembly if integrated).
MOD_10	**Decentralize supplying Objects in system**	Objects (e.g. Local Electrical Room, Hydraulic Power Unit) supplying other Objects (e.g. with power, data) should be arranged decentralized as a single, centralized set-up (e.g. single Local Electrical Room) leads to running cables, etc. through various rooms, walls and areas across the system. A decentralized set-up of multiple supplying Objects in proximity of the to be supplied Objects, instead, leads to shorter paths with less interactions with the system. This reduces especially the changing efforts of Objects significantly.
MOD_11	**Modularize around central frame for easing (dis-)assembly**	Frames, especially central ones (MOD_7), should be combined with modularized sub-assemblies (modularized valves and chokes in e.g. manifold) that are not integrated into the frame structure and can easily be (un-)mounted due to uniform frame-module interfaces if required.
MOD_12	**Reduce distance between connected Objects**	Whenever possible, the distance between Objects that are physically connected (e.g. by pipes or cables) should be kept as short as possible to avoid major piping and cabling re-work in case of Object changes.
MOD_13	**Assign area and interfaces to specific additional piping, cabling and ducting**	Bulk items such as piping, cabling and ducting usually grow without anticipated order leading to interferences and crossings in space-restricted areas across the lifecycle. By providing dedicated areas and interfaces on room walls or ceilings for specific type of piping, cabling and ducting (e.g. specific power cables, mud pipes), new or changing bulk items can be run without newly establishing those interfaces (e.g. new bores on wall) and avoid interferences amongst those bulk items in those space-restricted areas. This reduces changing efforts, especially as disciplines with a responsibility for only certain bulk items (e.g. mud pipe) do not need to interact and agree on a solution with others.
MOD_14	**Split hoses from piping**	Hoses should be separated from piping by an adaptor part (manifold). Hereby changing efforts are significantly reduced by isolating changes to the hose that is attached to the Object (e.g. to supply it with hydraulic power) without requiring changes across the entire chain if only hoses were used. Hence, the flexible hoses should be kept as short as required for facilitating operations.

ID	Design guideline	Design guideline description
MOD_15	**Limit integration of Objects into surrounding structure**	A too strong integration of Objects, especially rooms and cabins, into the existing structure (e.g. Derrick) should be avoided as their changes may lead to significant change efforts due to knock-on effects which may exceed the isolated efforts for the Object itself.
MOD_16	**Integrate Objects into compatible other Objects**	Instead of distributing similar and compatible Objects independently across the rig (e.g. a Drilling Control Cabin (DCC) and Local Instrument Room (LIR)), they should be integrated (e.g. LIR into DCC) to reduce changing efforts for larger scale changes (e.g. entire replacement). Hereby, knock-on effects on the system are reduced as interfaces are internalized.

11.6.4 Mobility

Table 11-18 Mobility-related Change Enabler design guidelines

ID	Design guideline	Design guideline description
MOB_1	**Equip with lifting lugs / pad-eyes for Object handling**	Objects are to be designed with pad-eyes or equipped with bolted or welded lifting lugs to ease lifting (lifting lug / pad-eye on top of Object) or repositioning (additional lifting lug / pad-eye on the Object's body) of Object.
MOB_2	**Provide lifting cradle with lug for Object handling and transport**	In contrast to "MOB_1", a lifting cradle is a tailored frame for an Object variant that can be fastened to the Object. Wires are then fixed to attachment points (lifting lugs) on the frame and the Object is then lifted by a crane. The cradle facilitates handling and transport operations of Objects.
MOB_3	**Design tailored support frames for Object module / sub-assembly handling and transport**	In contrast to "MOB_2", support frames are meant for transporting and handling of Object modules / Object sub-assemblies as single Objects may often be too heavy or have restricted space to be handled or transported as a whole (e.g. handling of single cylinders, gearbox).
MOB_4	**Provide personnel mobility devices for access to Objects**	Objects, especially those that are high-mounted, are usually difficult to be accessed by personnel. By providing mobility devices (e.g. access baskets, manrider winches, telescopic runways, service platforms) the access to those Objects can be facilitated which also eases Object changes.
MOB_5	**Provide intermediate spreader bar for Object handling**	An intermediate spreader bar is a handling device that is attached to suitable attachment points on the lifting cradle / frame to ensure a balanced lifting of the Object at predefined lifting angles. This is especially important for Objects with odd / unsymmetric weight distributions where central lifting is hardly possible.
MOB_6	**Embed sliding doors for better accessibility**	Instead of conventional doors that are opened into the room and take away precious space, sliding doors can especially improve the accessibility to the room but can also free space for utilization.

ID	Design guideline	Design guideline description
MOB_7	**Reduce weight of Object**	Reduction of weight can be achieved by different means, e.g. by reduction of parts, use of lighter material. The best solution depends on the boundary conditions that must be considered (e.g. certification requirements, load cases).
MOB_8	**Equip with single lifting lug on centralized frame for ease of handling**	A lifting lug is to be designed on a centralized frame that enables handling of the Object at one single point. This limits the amount of lifting gear (pulleys) which reduces handling and preparatory efforts. It also reduces recertification efforts (recertification of only one lifting lug). However, the weight distribution of the Object needs to be accounted for.
MOB_9	**Aim for compact design for enhancing mobility**	The Object should be designed as compact as possible to avoid constraints of mobility, especially if placed in space-restricted areas of system.
MOB_10	**Provide pre-installed lifting gear on top of ceiling**	Lifting gear refers to auxiliary lifting equipment (pulleys) that are mounted on the ceiling and enable handling of Objects / their modules, sub-assemblies by e.g. use of winches on the ground. The pulley does not provide the lifting force such as a crane (MOB_11).
MOB_11	**Equip with strong crane on top of ceiling for lifting of heavy Objects**	A crane should be installed on the ceiling that is strong enough to handle the Objects (incl. modules, sub-assemblies) that are located and must be handled in the room. Hereby, late and temporary installations of lifting equipment (e.g. winches) or other means of transportation (e.g. skids) can be avoided.
MOB_12	**Design Object within reach of heavy-lift crane**	The position of the Object must be within reach of one of the heavy-lift cranes that is capable of lifting it.
MOB_13	**Provide lifting cradle and sling combination for Object handling**	For Objects and lifting cradles that do not have lifting lugs (MOB_1, MOB_2), a lifting cradle should be combined with slings that are put below and around the Object / lifting cradle to facilitate a removal or installation of the Object.
MOB_14	**Equip with dedicated lifting points for Object handling**	Dedicated points for lifting are to be designed on the Object that allow a connection of lifting aids when required (e.g. detachable lifting lugs). Hereby suitable points of balance are accounted for during design and prevent major work if attachment points were integrated on site.
MOB_15	**Use lighter material for certain modules / sub-assemblies of Objects for better handling**	Objects or specific subassemblies / modules should be reduced in weight by using lighter materials (e.g. aluminium instead of steel). Hereby the center of gravity (COG) and also total weight can be lowered which eases Object handling and (dis-)assembly efforts as there are lifting limits for handling.
MOB_16	**Design Object at position below lifting limit of heavy-lift crane**	The Object must be fitted into the system in such a way that the Object can always be lifted by a heavy-lift crane. Thereby the distance between the Object and heavy-lift crane reduces the lifting limit. If this limit is exceeded, changes require much higher efforts (e.g. (dis-)assembly of Object, use of other handling devices).

11.6.5 Connectivity

Table 11-19 Connectivity-related Change Enabler design guidelines

ID	Design guideline	Design guideline description
CON_1	**Provide plugging ability of Object on rail**	By providing plugging capabilities for power- and/or data transfer on rails, Objects (e.g. server stacks) can easily be scaled.
CON_2	**Use detachable plug-type connections to periphery**	By using a detachable plug connection, (dis-)connections of Objects (e.g. by ethernet cable) can be established easily.
CON_3	**Design detachable bolted hatch in (room) structure for removal / integration of Object**	The hatch that is detachable by being fixed with bolts covers a large opening in the wall of a (room) structure enabling the removal or integration of large Objects without requiring (dis-)assemblies and/or cutting walls. The size and location of the hatch are to be determined during design so that the Objects easily fit through.
CON_4	**Use bolts instead of welding for Object fixation**	Non-permanent, detachable bolts ease (dis-)connections between Objects and especially to (support) structures meant especially for Objects that are likely to be (re-)moved. In contrast to welding, which is meant for more permanent installations, bolting does not require "hot work" which can lead to a stop operations, especially in explosive areas.
CON_5	**Combine bolts with slot holes for Object internal fixations**	In addition to the use of bolts, slot holes provide flexibility to adjust configurations and thereby ease the making and undoing of connections between Object sub-assemblies / modules.
CON_6	**Design quick connectors for Object modules**	Quick connectors should be designed for fast wearing modules of an Object (e.g. joystick(s) of Operator Chair being frequently used). This allows easy (dis-)assembly while extending the lifetime of that Object, hence, prevents large-scale changes in the first place (e.g. replacing entire Operator Chair).
CON_7	**Embed Remote I/O Modules on Object for avoiding recabling**	Objects and their modules should be controlled wirelessly by installing RIO (Remote Input / Output) Modules on the Objects in the field instead of I/O Modules that are located centrally (e.g. inside Local Instrument Room). When Objects or Object modules in the field are changed, change efforts are significantly reduced as signal cables that are also to be replaced run much shorter distances.
CON_8	**Use bolts instead of welding for Object internal connections**	By using bolts instead of welding, internal connections of the Objects (especially across modules) can be changed more easily (e.g. Derrick bracings, removable room walls).
CON_9	**Put supply interfaces directly on Object**	Interfaces for supply lines (e.g. manifold for hydraulic power supply) should be attached directly to the Object. Thereby, a change of those Objects does not require (dis-)integration efforts of manifolds and structures they are connected to (e.g. deck or Derrick structure). This applies only to Objects that are at a fixed position, i.e. do not move, to enable safety shutoff valve of Object.

ID	Design guideline	Design guideline description
CON_10	**Use shackles and bolts for Object connection**	Shackles are to be used for ensuring quick and strong fixations between e.g. wires and tension ring of Riser. The specific type of shackle depends on boundary conditions such as use context and maximum loads.
CON_11	**Use shackles and bondura® bolts for Object connection**	Bondura® bolts are specific types of bolts that are tapered at both ends. The cone sleeves with the corresponding tapering are assembled and expand on the bolt upon tightening. Thereby, in contrast to conventional press fit bolts that can also deal with high forces, bondura® bolts can easily be disassembled by removing the cone sleeves. They allow quick connections that work safely with shackles and represent a special enhancement of "CON_10".
CON_12	**Use pad-eye and pin bolt for Object fixation**	A pad-eye that is designed into the Object is combined with a pin-bolt connection which allows simple fixations on structures and other Objects enabling easy (dis-)assembly.
CON_13	**Use sliding fit of bolts between connected Objects**	Whenever minor forces of Objects apply, sliding-fit of bolts connecting Objects are preferable as extreme press-fit connections strongly increase the effort of disassembly and may not be even necessary.
CON_14	**Design detachable bolted hatch in (room) structure for better accessibility**	The hatch that is detachable by being fixed with bolts covers an opening in the wall of a (room) structure enabling access to Objects without any cutting of walls or high-effort removal of other Objects. The size and location of the hatch are to be determined during design so that the Objects can be accessed easily.

11.6.6 Compatibility

Table 11-20 Compatibility-related Change Enabler design guidelines

ID	Design guideline	Design guideline description
COM_1	**Use standardized chassis for easing integration**	Chassis for hardware modules (e.g. server cabinet, remote I/O cabinet) should be standardized by, on the one hand, easing the integration of those modules into the chassis through standard interfaces / dimensions while, on the other hand, allowing the chassis to be integrated flexibly into the system using standardized external dimensions. This, in turn, also applies to the design of cabinet chassis..
COM_2	**Use standardized power plugs for easing connection to system**	Standardized power plugs exist for various countries. By using common standardized power plugs, Objects / their plugging interfaces must not be changed but can be used at any location in the system without changes.
COM_3	**Design for standardized replacement parts / sub-assemblies**	Parts or sub-assemblies of Objects that belong to the same product family (or beyond) that are to be exchanged across the lifecycle should either follow industry standards or company internal standards (e.g. standard window in Drillers Control Cabin). This allows changes to be performed without any impact on Objects and the integrated part / sub-assemblies.

ID	Design guideline	Design guideline description
COM_4	**Use standardized ports for data exchange and power supply**	In general, ports should be standardized for both data exchange (e.g. USB, Ethernet, HDMI) and power supply (also "COM_2") following industry standards to avoid significant change effort within the system. This ensures that Objects / their ports must not be changed but can be used at any location in the system without changes.
COM_5	**Standardize footprint of Object towards deck support structure**	The footprint of the Object with sockets / pads on the bottom is to be standardized with regard to the welded pads on deck support structure (company internal) by having equal dimensions, distances between sockets, etc. Thereby, large-effort changes are avoided as Objects may change without affecting the interface between the Object and the deck support structure.
COM_6	**Use standardized interfaces between Objects and their modules**	Here the focus is not on specific interfaces (e.g. only data ports such as in "COM_5") but aims for a general standardization (industry, company-internal) of physical interfaces between Objects and Object modules. Those may represent standard flanges for hoses, standard interfaces to rails, data and power supply, etc. Thereby, adaptator parts are avoided and existing interfaces can be reutilized when Objects / Object modules are exchanged which significantly reduces change efforts.
COM_7	**Provide adaptor parts between Objects for easing integration**	As standardization cannot always be realized, removable physical adaptor parts between Objects can significantly ease changes of Objects limiting knock-on effects in the system (e.g. adaptors for attaching different types of piping).
COM_8	**Use standardized HEB beams and distances for easing Object attachment to structure**	Deck support structures are to be equipped with standardized HEB beams that are spread at standard distances between them. This eases the exchange and integration of new Objects on the deck support structure where, in contrast to fixed footprints, there is a flexibility of where the Object can be located in the future.
COM_9	**Prepare for subsequent integration of RIO Modules**	Objects that are out in the field should be equipped with interfaces for subsequent integration of RIO Modules for allowing a wireless communication (CON_7). A subsequent integration of RIO Modules without such a preparation is difficult / takes a very high effort.
COM_10	**Equip with foundation frame for easing Object-to-deck support structure fixation**	Instead of fixing the Object directly to the (pre-welded pads of the) deck support structure, an intermediate foundation frame is installed that acts as an adaptor between the to-be installed Object and the deck support structure. Hereby, high-effort changes of the deck structure are avoided when Objects are installed / replaced that are not in line with the previous footprint.
COM_11	**Aim for standardized interfaces towards deck support structure**	The focus of standardized interfaces towards the deck support structure refers to any standardization between the Object and the deck support structure to ease an installation. This may refer to the Object's footprint (COM_5) but also other interfaces between the Object and the deck support structure such as e.g. ensuring compatible entry slots for supply pipes.

11.7 Use case: FDO Execution Model

11.7.1 Descriptions of imported elements into FDO Execution Model

The following tables contain the descriptions of all elements that were imported into the FDO Execution Model for the use case (section 8.1) belonging to the five domains: Change Driver, System Requirement, Object, Change Enabler and Transition.

Table 11-21 Considered Change Drivers in FDO Execution Model

ID	Change Driver	Description
a	Change Of Water Depth	The sea water depth changes.
b	Change Of Formation Properties	The general characteristics of the (geological) formation changes (e.g. rock hardness).
c	Change Of Well Pressure & Temperature (e.g. HPHT)	The pressure and temperature within the well changes, e.g. to high pressure / high temperature drilling sections (HPHT).
d	Depletion Of Formation	Emptying formation by extracting finite oil and gas reserves.
e	Change Of Formation Pressure Window	Increasingly less difference between formation pore pressure and formation fracture pressure leading to narrow pressure margins which makes drilling operations extremely difficult due to frequent "kick-loss" scenarios.
f	Change Of Operations From Normal To HPHT Operations	The operations change from normal to HPHT drilling mode requiring different settings, equipment and procedures on the rig.
g	Change Of Rate Of Penetration	The rate of penetration (ROP) in "ft/min" or "m/hr" marks the speed by which the drill bit breaks the rock to deepen the borehole.
h	Demand For Dynamic Well Pressure Control	The need for Managed Pressure Drilling (MPD) in contrast to conventional drilling under atmospheric pressure which is disadvantageous in complex formations.
i	Change Of True Vertical Depth (TVD)	The vertical distance from the rig surface to a point in the well (usually the current or final depth) which makes it independent of the drilling path.
j	Demand For Increased Operational Safety	The need for improving the safe execution of operations on the rig by providing more safety through especially drilling systems (e.g. fail-safe).
k	Demand For Increased Uptime	The need of running drilling operations without breakdowns and disturbances.
l	Demand For Change Of Rate Of Penetration	The need of increasing the rate of penetration when drilling a borehole.
m	Demand For Increased Automation Level	The need of increasing the automated work content for rig operations.

Table 11-22 Considered System Requirements in FDO Execution Model

ID	System Requirement	Description
1	Active Heave Compensation [Capability]	The ability of performing Active Heave Compensation (AHC) which in contrast to Passive Heave Compensation is powered and has a control system to actively countersteer heave movements.
2	Electric Power [Constraint]	The available electric power capacity on the rig.
3	Hydraulic Power [Condition]	The required hydraulic power capacity for the hydraulic ringline system.
4	Maintenance While Operating [Capability]	The ability of maintaining topside equipment while operating.
5	Managed Pressure Drilling [Capability]	The ability of performing Managed Pressure Drilling (MPD) operations with better control of the annular pressure profile.
6	Mud Gas Transport [Condition]	The transported mud gas flow rate.
7	Mud Gas Separation [Condition]	The separation rate of gas from the mud return.

Table 11-23 Imported Objects into FDO Execution Model

ID	Object	Description
A	Drillers Control Cabin	The Drillers Control Cabin (DCC), also called DCR (Drilling Control Room) or Drillers Cabin, is a room on drillfloor where operators control drilling and (pipe) handling operations on the rig. It contains computer hardware and data processing systems with the room being usually pressurized to prevent gas influx.
B	Mud Gas Separator	The Mud Gas Separator (MGS) is designed for receiving mud returns from the Choke & Kill Manifold / Pressure Control Manifold and separates gas from the mud by flowing over baffle plates.
C	Hydraulic Power Unit	The Hydraulic Power Unit (HPU) is designed to supply hydraulic machines with hydraulic power through the hydraulic ringline system.
D	Power Generating Unit	The Power Generation Unit (PGU) generates electrical energy by diesel engines and an electric generator for primary and emergency / auxiliary power on the rig.
E	Power Cables	Power Cables are assemblies of one or more electrical conductors that are usually integrated in an overall sheath being used for the transmission of electrical power.
F	Hydraulic Pipes	Hydraulic Pipes are connected by flanges and guide oil to and from hydraulic machines on the rig.
G	Drillfloor Structure	Deck structure of most central work area where the rig crew conducts drilling and (tubular) handling operations.
H	Moonpool Structure	Deck structure for especially heavy equipment on the lower part of the rig (below drillfloor) with an opening in the hull to easily access the water below.
I	Buffer Manifold	Manifold to collect the various mud return flows and guide them to the Coriolis meter / Pressure Control Manifold.
J	Pressure Control Manifold	The Pressure Control Manifold (PCM) applies surface back pressure on the well bore by the use of chokes. It usually includes meters to measure the return fluid characteristics such as mass flow rate (Coriolis meter), pressure, density, temperature.
K	Back Pressure Pump	The Back Pressure Pump (BPP) is an automated on-demand pump to ensure sufficient fluid supply and provides an active means to control backpressure losses or reestablish backpressure by additional pumping of drilling fluid.

Table 11-24 Considered Change Enablers in FDO Execution Model

ID	Change Enabler	Description
1	COM_6; Object	Use standardized interfaces between Objects and their modules
2	COM_6; Manifolds	Use standardized interfaces between Objects and their modules
3	CON_3; Room	Design detachable bolted hatch in (room) structure for removal / integration of Object
4	CON_4; Change Object	Use bolts instead of welding for Object fixation
5	CON_9; Object	Put supply interfaces directly on Object
6	MOB_1; Change Object	Equip with lifting lugs / pad-eyes for Object handling
7	MOB_4; Change Object	Provide personnel mobility devices for access to Objects
8	MOB_8; Change Object	Equip with single lifting lug on centralized frame for ease of handling
9	MOB_9; Change Object	Aim for compact design for enhancing mobility
10	MOD_4; Object	Centralize connection points for hydraulic supply through manifold
11	MOD_7; Change Object	Design single centralized frame
12	MOD_12; Object	Reduce distance between connected Objects
13	MOD_13; Room	Assign area and interfaces to specific additional piping, cabling and ducting
14	MOD_14; Change Object	Split hoses from piping
15	SCA_3; Structure	Pre-install structure base for easing subsequent integration of Objects
16	SCA_4; Room	Provide space around Object for spatial expansion
17	SCA_16; Room	Assign dedicated areas on room ceiling for evolutionary development of piping, cabling and ducting
18	UNI_2; Change Object	Oversize with regard to stress / load cases
19	UNI_2; Structure	Oversize with regard to stress / load cases
20	UNI_4; Change Object	Oversize with regard to power / energy / capacity
21	UNI_4; Power Generation Unit (PGU)	Oversize with regard to power / energy / capacity
22	UNI_4; Hydraulic Power Unit (HPU)	Oversize with regard to power / energy / capacity
23	UNI_5; Change Object	Oversize with regard to throughput capacity
24	UNI_7; Room	Design higher room ceiling
25	UNI_13; Room	Provide space around Object for better accessibility

Table 11-25 Available Transitions

ID	Transition	Description
1	Passive	"No Transition" as Objects deliver its intended functionality sufficiently under varying conditions of operation.
2	Relocating	Change position and/or system configuration of Change Objects on the rig.
3	Partial Replacement	Replacement of larger subassemblies of Change Objects.
4	Entire Replacement	Replacement of entire Change Object.
5	Adding	Adding additional or new Objects (entire unit) to the system to address required functionality and capacity.
6	Reducing	Removing existing Objects (entire unit) from the system to get rid of unnecessary functionality and capacity.
7	Extending	"Partial adding" of subassemblies to an existing Object to address required functionality and capacity.
8	Contracting	"Partial reduction" of subassemblies from an existing Object to get rid of unnecessary functionality and capacity.

11.7.2 Transition-related DMMs M_H and M_I

As section 6.1 highlighted, M_H and M_I represent exceptions of the MDM-based meta-model which are not represented explicitly as matrices in the FDO Execution Model. Hence, in the following both the matrices M_H and M_I that are relevant for the use case are introduced separately. They are added on top of matrices M_D/M_E and M_F in the imported FDO Execution Model for the use case (appendix 11.7.4) as additional selections[358] enabling the generation of Flexible Design Concepts (stage II).

---

[358] In the Excel® based tool this is solved by drop-down menus.

Table 11-26 DMM M_H for use case

Transition

Object

allows

		Transition 1 (Passive)	Transition 2 (Relocating)	Transition 3 (Partial Replacement)	Transition 4 (Entire Replacement)	Transition 5 (Adding)	Transition 6 (Reducing)	Transition 7 (Extending)	Transition 8 (Contracting)
		1	2	3	4	5	6	7	8
Drillers Control Cabin	A	O		O	O			O	O
Mud Gas Separator	B	O		O	O	O	O		
Hydraulic Power Unit	C	O	O	O	O	O		O	
Power Generating Unit	D	O							
Power Cables	E	O	O	O	O			O	O
Hydraulic Pipes	F	O	O	O	O			O	O
Drillfloor Structure	G	O		O				O	O
Moonpool Structure	H	O		O				O	O
Buffer Manifold	I	O	O	O	O	O	O		
Pressure Control Manifold	J	O	O	O	O	O	O		
Back Pressure Pump	K	O	O	O	O	O	O	O	O

Table 11-27 DMM M_I for use case

Change Enabler facilitates Transition

Change Enabler		Transition 1 (Passive) 1	Transition 2 (Relocating) 2	Transition 3 (Partial Replacement) 3	Transition 4 (Entire Replacement) 4	Transition 5 (Adding) 5	Transition 6 (Reducing) 6	Transition 7 (Extending) 7	Transition 8 (Contracting) 8
COM_6; Object	1			O				O	O
COM_6; Manifolds	2			O				O	O
CON_3; Room	3		O		O	O	O		
CON_4; Change Object	4		O	O	O	O	O		
CON_9; Object	5		O	O	O			O	O
MOB_1; Change Object	6		O		O	O	O		
MOB_4; Change Object	7		O	O	O	O	O	O	O
MOB_8; Change Object	8		O		O	O	O		
MOB_9; Change Object	9		O		O	O	O		
MOD_4; Object	10		O	O	O	O	O	O	O
MOD_7; Change Object	11		O		O	O	O		
MOD_12; Object	12		O	O	O	O	O	O	O
MOD_13; Room	13			O				O	
MOD_14; Change Object	14			O				O	O
SCA_3; Structure	15		O			O		O	
SCA_4; Room	16			O	O			O	
SCA_16; Room	17			O	O			O	
UNI_2; Change Object	18	O						O	
UNI_2; Structure	19				O			O	
UNI_4; Change Object	20	O							
UNI_4; Power Generating Unit (PGU)	21	O						O	
UNI_4; Hydraulic Power Unit (HPU)	22	O						O	
UNI_5; Change Object	23	O						O	
UNI_7; Room	24		O	O				O	
UNI_13; Room	25		O	O	O	O	O	O	O

11.7.3 Intermediate assessment of Flexible Design Concepts in use case

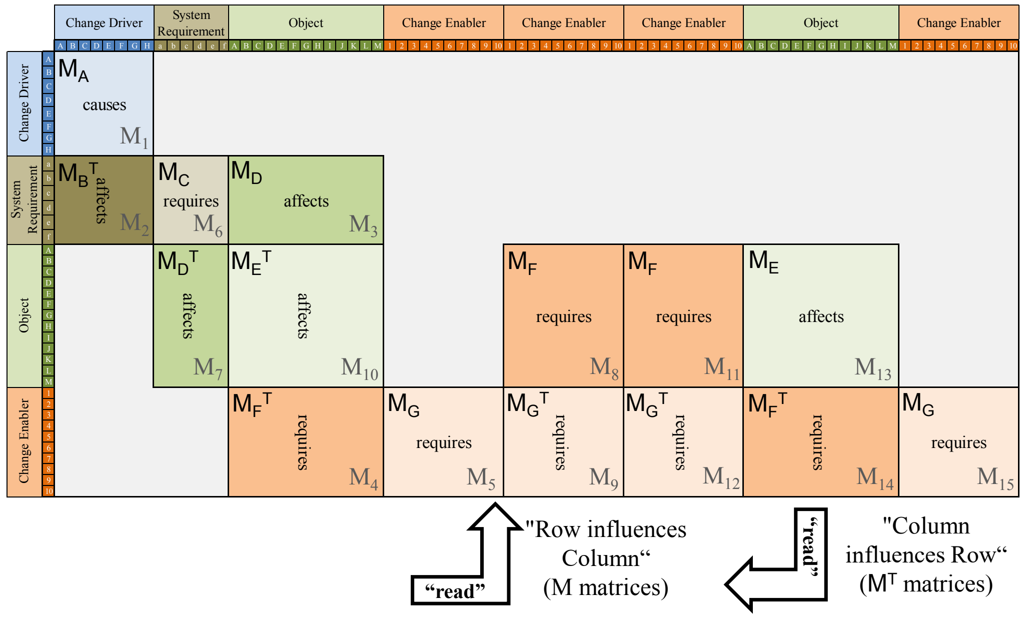
Table 11-28 Ratings and results of Change Enablers for MGS and Transitions "Adding" and "Passive"

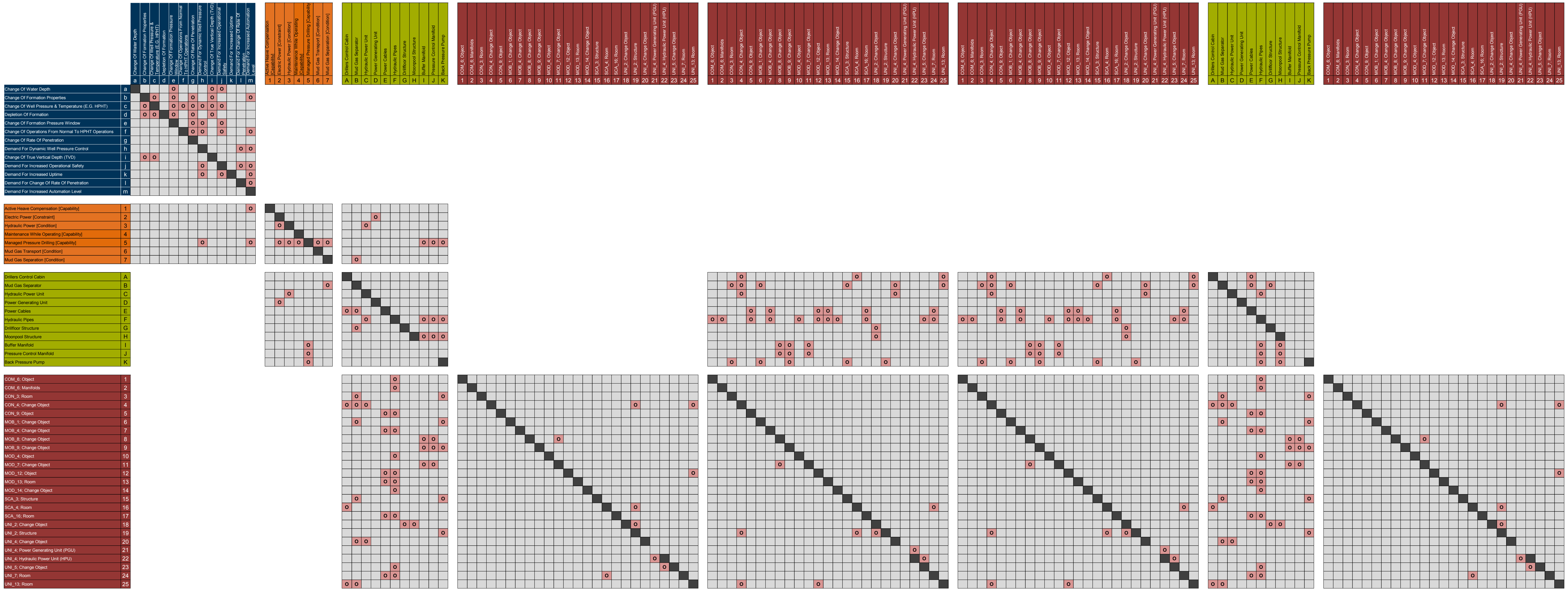
		Upfront effort				Upgrade effort					
	Change Enabler	Initial costs		One-time costs		Physical effort		Time-related effort		Opportunity costs	
		w/o weighting	w/weighting	w/o weighting	w/weighting	w/o weighting	w/weighting	w/o weighting	w/weighting	w/o weighting	w/weighting
ID	Weighting		3		3		3		3		9
3	CON_3; Room	2	6	1	3	-3	-9	-3	-9	-3	-27
4	CON_4; Change Object	1	3	0	0	-2	-6	-3	-9	-3	-27
6	MOB_1; Change Object	0	0	1	3	0	0	-2	-6	-2	-18
15	SCA_3; Structure	2	6	1	3	-1	-3	-2	-6	-2	-18
25	UNI_13; Room	1	3	0	0	-1	-3	-2	-6	-2	-18
20	UNI_4; Change Object	3	9	3	9	-3	-9	-3	-9	-3	-27

		Operational effort & losses									
	Change Enabler	Operational costs		Maintenance costs		Availability losses		Performance losses		Quality losses	
		w/o weighting	w/weighting	w/o weighting	w/weighting	w/o weighting	w/weighting	w/o weighting	w/weighting	w/o weighting	w/weighting
ID	Weighting		9		3		9		3		3
3	CON_3; Room	1	9	1	3	-2	-18	0	0	0	0
4	CON_4; Change Object	0	0	-2	-6	0	0	0	0	0	0
6	MOB_1; Change Object	0	0	1	3	-1	-9	0	0	0	0
15	SCA_3; Structure	0	0	0	0	0	0	0	0	0	0
25	UNI_13; Room	0	0	-2	-6	-2	-18	0	0	0	0
20	UNI_4; Change Object	2	18	1	3	0	0	0	0	0	0

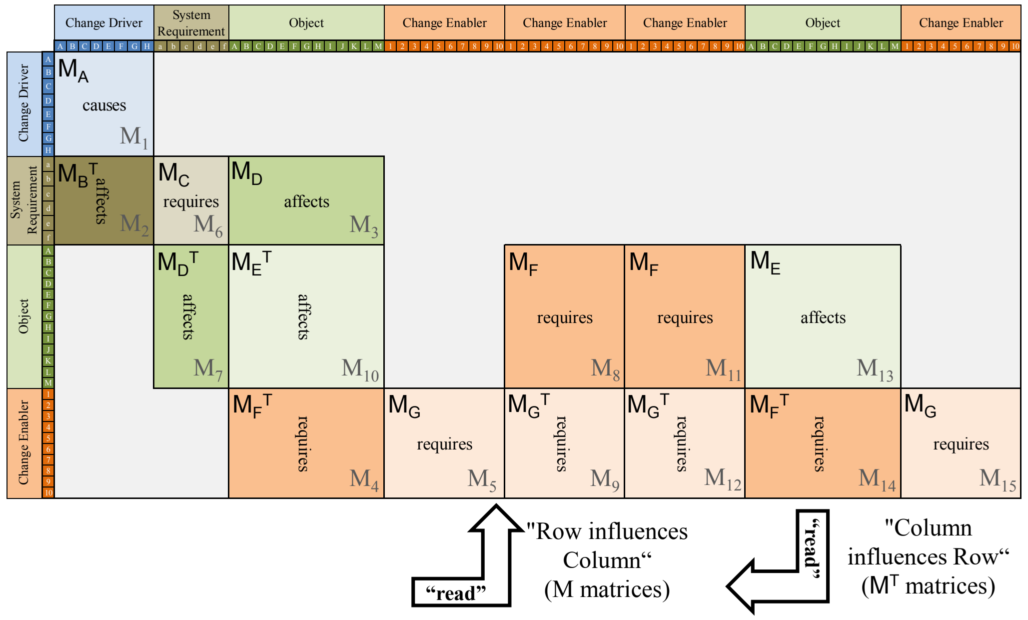
		Total score				
ID	Change Enabler	Upfront effort	Upgrade effort	Operational effort & losses	Perfor-mance rating	Ranking
3	CON_3; Room	1.50	-3.00	-0.22	-1.72	3
4	CON_4; Change Object	0.50	-2.80	-0.22	-2.52	1
6	MOB_1; Change Object	0.50	-1.60	-0.22	-1.32	4
15	SCA_3; Structure	1.50	-1.80	0.00	-0.30	5
25	UNI_13; Room	0.50	-1.80	-0.89	-2.19	2
20	UNI_4; Change Object	3.00	-3.00	0.78	0.78	6

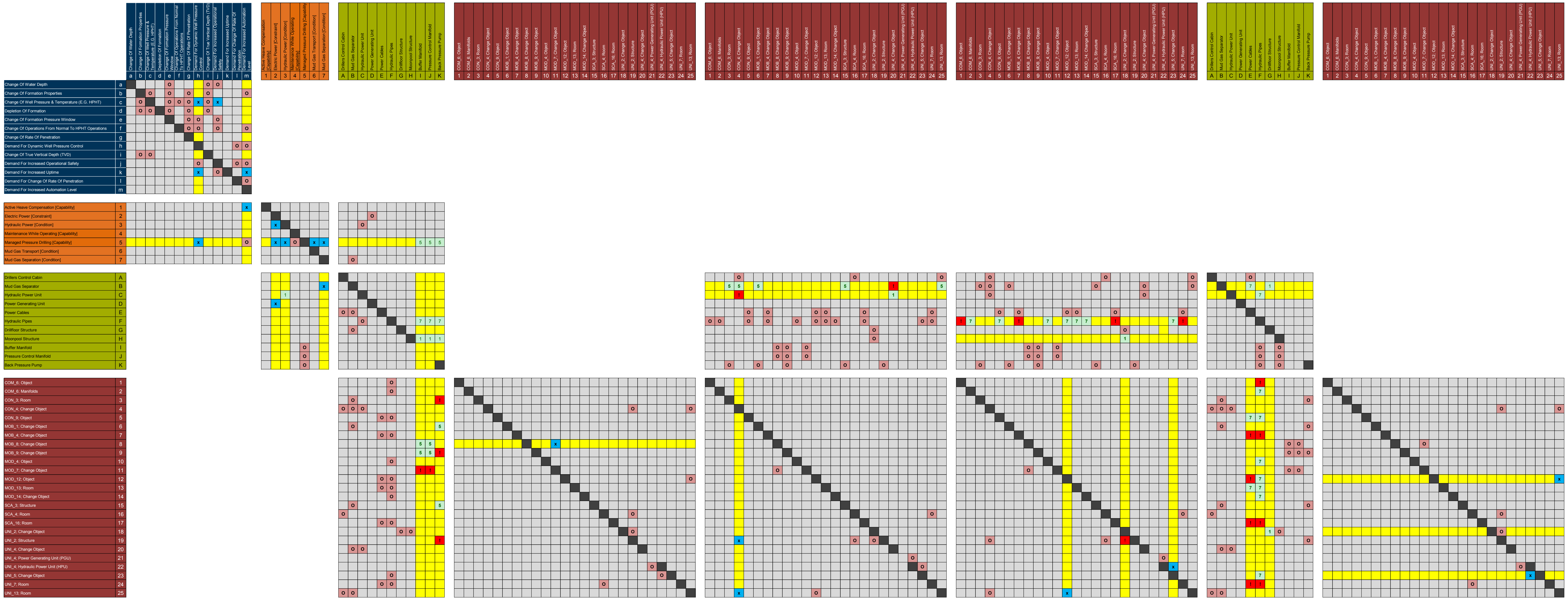
11.7.4 Imported FDO Execution Model





11.7.5 Run FDO Execution Model





11.8 Evaluation sheet

Basic requirement	FDO requirement	FDO requirement - Definition	Weighting FDO requirements				**Remarks** concerning **definition and weighting** of FDO requirements	FDO Execution								Database				Definition & structuring				FDO assessment & decision-making				FDO Facilitators					Rating fulfillment of FDO requirements				**Remarks** concerning **contributions** and **fulfillment** of FDO requirements
			1 = very low	2 = low	3 = high	4 = very high		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	1 = very low	2 = low	3 = high	4 = very high	
								Matrix-based approach	Multiple paths in FDO Execution Model	Reference and baseline design basis	Tracing and Back-Tracing capability	Gradual scenario building	Change trigger definition and application	Transition integration into FDO Execution Model	Transition vs. Enabler-driven approach	Pre-defined elements in domains	Pre-defined relations in matrices	Large scope of applicable change sources	Large scope of alternative design variables for possible Flexible Design Concepts	Split of FDO models	Syntax definition of domain elements	Categorization and hierarchization of domain elements	Differentiation of general and specific Change Enablers	Continuous assessment and decision making	Report-based assessment and decision-making	Criteria and stage-based assessment	Utility analysis and comparison of Flexible Design Concept performance	Objects classes	FDO Selection Constraints	Upgrade Risk Portfolio	Change Enabler Value-Effort Portfolio	Change Enabler Consistency Matrix					
I	R1	Ability to identify the relevant problem and solution space								x	x	x	x			x	x	x			(x)	x		x						x							
	R2	Ability to identify technically feasible solutions								x	x					(x)	x		x				(x)	x		x			x			x					
	R3	Ability to identify high-performing solutions								(x)						(x)	x		x					(x)	(x)	x	x				x	(x)					
	R4	Ability to reduce to effective and relevant solutions																						x	(x)	x	x		(x)	(x)	x	x					
	R5	Ability to reduce risk of offering non-profitable solutions from System Supplier's perspective								x							x		(x)				x		(x)	x	x				(x)	x					
II	R6	Comprehensive identification of change sources and Objects						(x)			x	x				(x)		(x)				x															
	R7	Comprehensive generation and representation of Flexible Design Concepts						(x)			x					(x)	(x)	(x)	x				(x)		x												
III	R8	Customer-dependent decision-making on relevant problem and solution space								(x)		x										(x)		x						x							
	R9	Customer-dependent decision-making on solutions																				(x)		x	(x)	x					x						
IV	R10	Efficient identification of Baseline Objects								x																				x							
	R11	Efficient identification of Change Sources and Objects						x	(x)		x	x	x			x	x	(x)				x		x													
	R12	Efficient identification of Flexible Design Concepts and solutions						x	(x)	x	x			x		x	x		(x)			x		x	x	x	x		x		x	x					
V	R13	Non-ambiguous and clear comprehension											x								x	x			x												
	R14	Simple traceability of selections and decisions						x			x		x	x			(x)				(x)	(x)			x				x	(x)	(x)	(x)					
	R15	Homogeneity of and within approach						x					x	x							x																
	R16	Ease of application						x					x	x							x				x				x								
	R17	Ease of managing models during execution												(x)		(x)				x	x	x															
VI	R18	Alternative entry or exit points							x		x	(x)																									
	R19	Ability of omitting or postponing step(s) and iteration(s)						(x)	x			x	x		x											x											
	R20	Ability of changing direction of identification						x			x																										
	R21	Scalability of complexity and comprehensiveness						(x)	x		x													x		x				x							
VII	R22	Efficient build-up of database														(x)				x	x	x						x									
	R23	Efficient maintenance of database						x								(x)	x			x	x	x						x									
	Added requirements																																				

12. List of dissertations

Chair of Product Development
Technical University of Munich, Boltzmannstraße 15, 85748 Garching
Dissertations supervised by:

- Prof. Dr.-Ing. W. Rodenacker,
- Prof. Dr.-Ing. K. Ehrlenspiel and
- Prof. Dr.-Ing. U. Lindemann

D1 COLLIN, H.:
Entwicklung eines Einwalzenkalanders nach einer systematischen Konstruktionsmethode. München: TU, Diss. 1969.

D2 OTT, J.:
Untersuchungen und Vorrichtungen zum Offen-End-Spinnen.
München: TU, Diss. 1971.

D3 STEINWACHS, H.:
Informationsgewinnung an bandförmigen Produkten für die Konstruktion der Produktmaschine.
München: TU, Diss. 1971.

D4 SCHMETTOW, D.:
Entwicklung eines Rehabilitationsgerätes für Schwerstkörperbehinderte.
München: TU, Diss. 1972.

D5 LUBITZSCH, W.:
Die Entwicklung eines Maschinensystems zur Verarbeitung von chemischen Endlosfasern.
München: TU, Diss. 1974.

D6 SCHEITENBERGER, H.:
Entwurf und Optimierung eines Getriebesystems für einen Rotationsquerschneider mit allgemeingültigen Methoden.
München: TU, Diss. 1974.

D7 BAUMGARTH, R.:
Die Vereinfachung von Geräten zur Konstanthaltung physikalischer Größen.
München: TU, Diss. 1976.

D8 MAUDERER, E.:
Beitrag zum konstruktionsmethodischen Vorgehen durchgeführt am Beispiel eines Hochleistungsschalter-Antriebs.
München: TU, Diss. 1976.

D9 SCHÄFER, J.:
Die Anwendung des methodischen Konstruierens auf verfahrenstechnische Aufgabenstellungen.
München: TU, Diss. 1977.

D10 WEBER, J.:
Extruder mit Feststoffpumpe – Ein Beitrag zum Methodischen Konstruieren.
München: TU, Diss. 1978.

D11 HEISIG, R.:
Längencodierer mit Hilfsbewegung.
München: TU, Diss. 1979.

D12 KIEWERT, A.:
Systematische Erarbeitung von Hilfsmitteln zum kostenarmen Konstruieren.
München: TU, Diss. 1979.

D13 LINDEMANN, U.:
Systemtechnische Betrachtung des Konstruktionsprozesses unter besonderer Berücksichtigung der Herstellkostenbeeinflussung beim Festlegen der Gestalt.
Düsseldorf: VDI-Verlag 1980. (Fortschritt-Berichte der VDI-Zeitschriften Reihe 1, Nr. 60).
Zugl. München: TU, Diss. 1980.

D14 NJOYA, G.:
Untersuchungen zur Kinematik im Wälzlager bei synchron umlaufenden Innen- und Außenringen.
Hannover: Universität, Diss. 1980.

D15 HENKEL, G.:
Theoretische und experimentelle Untersuchungen ebener konzentrisch gewellter Kreisringmembranen.
Hannover: Universität, Diss. 1980.

D16 BALKEN, J.:
Systematische Entwicklung von Gleichlaufgelenken.
München: TU, Diss. 1981.

D17 PETRA, H.:
Systematik, Erweiterung und Einschränkung von Lastausgleichslösungen für Standgetriebe mit zwei Leistungswegen – Ein Beitrag zum methodischen Konstruieren.
München: TU, Diss. 1981.

D18 BAUMANN, G.:
Ein Kosteninformationssystem für die Gestaltungsphase im Betriebsmittelbau.
München: TU, Diss. 1982.

D19 FISCHER, D.:
Kostenanalyse von Stirnzahnrädern. Erarbeitung und Vergleich von Hilfsmitteln zur Kostenfrüherkennung.
München: TU, Diss. 1983.

D20 AUGUSTIN, W.:
Sicherheitstechnik und Konstruktionsmethodiken – Sicherheitsgerechtes Konstruieren.
Dortmund: Bundesanstalt für Arbeitsschutz 1985. Zugl. München: TU, Diss. 1984.

D21 RUTZ, A.:
Konstruieren als gedanklicher Prozess.
München: TU, Diss. 1985.

D22 SAUERMANN, H. J.:
Eine Produktkostenplanung für Unternehmen des Maschinenbaues.
München: TU, Diss. 1986.

D23 HAFNER, J.:
Entscheidungshilfen für das kostengünstige Konstruieren von Schweiß- und Gussgehäusen.
München: TU, Diss. 1987.

D24 JOHN, T.:
Systematische Entwicklung von homokinetischen Wellenkupplungen.
München: TU, Diss. 1987.

D25 FIGEL, K.:
Optimieren beim Konstruieren.
München: Hanser 1988. Zugl. München: TU, Diss. 1988 u. d. T.: Figel, K.: Integration automatisierter Optimierungsverfahren in den rechnerunterstützten Konstruktionsprozess.

Reihe Konstruktionstechnik München

D26 TROPSCHUH, P. F.:
Rechnerunterstützung für das Projektieren mit Hilfe eines wissensbasierten Systems.
München: Hanser 1989. (Konstruktionstechnik München, Band 1). Zugl. München: TU, Diss. 1988 u. d. T.: Tropschuh, P. F.: Rechnerunterstützung für das Projektieren am Beispiel Schiffsgetriebe.

D27 PICKEL, H.:
Kostenmodelle als Hilfsmittel zum Kostengünstigen Konstruieren.
München: Hanser 1989. (Konstruktionstechnik München, Band 2). Zugl. München: TU, Diss. 1988.

D28 KITTSTEINER, H.-J.:
Die Auswahl und Gestaltung von kostengünstigen Welle-Nabe-Verbindungen.
München: Hanser 1990. (Konstruktionstechnik München, Band 3). Zugl. München: TU, Diss. 1989.

D29 HILLEBRAND, A.:
Ein Kosteninformationssystem für die Neukonstruktion mit der Möglichkeit zum Anschluss an ein CAD-System.
München: Hanser 1991. (Konstruktionstechnik München, Band 4). Zugl. München: TU, Diss. 1990.

D30 DYLLA, N.:
Denk- und Handlungsabläufe beim Konstruieren.
München: Hanser 1991. (Konstruktionstechnik München, Band 5). Zugl. München: TU, Diss. 1990.

D31 MÜLLER, R.
Datenbankgestützte Teileverwaltung und Wiederholteilsuche.
München: Hanser 1991. (Konstruktionstechnik München, Band 6). Zugl. München: TU, Diss. 1990.

D32 NEESE, J.:
Methodik einer wissensbasierten Schadenanalyse am Beispiel Wälzlagerungen.
München: Hanser 1991. (Konstruktionstechnik München, Band 7). Zugl. München: TU, Diss. 1991.

D33 SCHAAL, S.:
Integrierte Wissensverarbeitung mit CAD – Am Beispiel der konstruktionsbegleitenden Kalkulation.
München: Hanser 1992. (Konstruktionstechnik München, Band 8). Zugl. München: TU, Diss. 1991.

D34 BRAUNSPERGER, M.:
Qualitätssicherung im Entwicklungsablauf – Konzept einer präventiven Qualitätssicherung für die Automobilindustrie.
München: Hanser 1993. (Konstruktionstechnik München, Band 9). Zugl. München: TU, Diss. 1992.

D35 FEICHTER, E.:
Systematischer Entwicklungsprozess am Beispiel von elastischen Radialversatzkupplungen.
München: Hanser 1994. (Konstruktionstechnik München, Band 10). Zugl. München: TU, Diss. 1992.

D36 WEINBRENNER, V.:
Produktlogik als Hilfsmittel zum Automatisieren von Varianten- und Anpassungskonstruktionen.
München: Hanser 1994. (Konstruktionstechnik München, Band 11). Zugl. München: TU, Diss. 1993.

D37 WACH, J. J.:
Problemspezifische Hilfsmittel für die Integrierte Produktentwicklung.
München: Hanser 1994. (Konstruktionstechnik München, Band 12). Zugl. München: TU, Diss. 1993.

D38 LENK, E.:
Zur Problematik der technischen Bewertung.
München: Hanser 1994. (Konstruktionstechnik München, Band 13). Zugl. München: TU, Diss. 1993.

D39 STUFFER, R.:
Planung und Steuerung der Integrierten Produktentwicklung.
München: Hanser 1994. (Konstruktionstechnik München, Band 14). Zugl. München: TU, Diss. 1993.

D40 SCHIEBELER, R.:
Kostengünstig Konstruieren mit einer rechnergestützten Konstruktionsberatung.
München: Hanser 1994. (Konstruktionstechnik München, Band 15). Zugl. München: TU, Diss. 1993.

D41 BRUCKNER, J.:
Kostengünstige Wärmebehandlung durch Entscheidungsunterstützung in Konstruktion und Härterei.
München: Hanser 1994. (Konstruktionstechnik München, Band 16). Zugl. München: TU, Diss. 1993.

D42 WELLNIAK, R.:
Das Produktmodell im rechnerintegrierten Konstruktionsarbeitsplatz.
München: Hanser 1994. (Konstruktionstechnik München, Band 17). Zugl. München: TU, Diss. 1994.

D43 SCHLÜTER, A.:
Gestaltung von Schnappverbindungen für montagegerechte Produkte.
München: Hanser 1994. (Konstruktionstechnik München, Band 18). Zugl. München: TU, Diss. 1994.

D44 WOLFRAM, M.:
Feature-basiertes Konstruieren und Kalkulieren.
München: Hanser 1994. (Konstruktionstechnik München, Band 19). Zugl. München: TU, Diss. 1994.

D45 STOLZ, P.:
Aufbau technischer Informationssysteme in Konstruktion und Entwicklung am Beispiel eines elektronischen Zeichnungsarchives.
München: Hanser 1994. (Konstruktionstechnik München, Band 20). Zugl. München: TU, Diss. 1994.

D46 STOLL, G.:
Montagegerechte Produkte mit feature-basiertem CAD.
München: Hanser 1994. (Konstruktionstechnik München, Band 21). Zugl. München: TU, Diss. 1994.

D47 STEINER, J. M.:
Rechnergestütztes Kostensenken im praktischen Einsatz.
Aachen: Shaker 1996. (Konstruktionstechnik München, Band 22). Zugl. München: TU, Diss. 1995.

D48 HUBER, T.:
Senken von Montagezeiten und -kosten im Getriebebau.
München: Hanser 1995. (Konstruktionstechnik München, Band 23). Zugl. München: TU, Diss. 1995.

D49 DANNER, S.:
Ganzheitliches Anforderungsmanagement für marktorientierte Entwicklungsprozesse.
Aachen: Shaker 1996. (Konstruktionstechnik München, Band 24). Zugl. München: TU, Diss. 1996.

D50 MERAT, P.:
Rechnergestützte Auftragsabwicklung an einem Praxisbeispiel.
Aachen: Shaker 1996. (Konstruktionstechnik München, Band 25). Zugl. München: TU, Diss. 1996 u. d. T.: MERAT, P.: Rechnergestütztes Produktleitsystem

D51 AMBROSY, S.:
Methoden und Werkzeuge für die integrierte Produktentwicklung.
Aachen: Shaker 1997. (Konstruktionstechnik München, Band 26). Zugl. München: TU, Diss. 1996.

D52 GIAPOULIS, A.:
Modelle für effektive Konstruktionsprozesse.
Aachen: Shaker 1998. (Konstruktionstechnik München, Band 27). Zugl. München: TU, Diss. 1996.

D53 STEINMEIER, E.:
Realisierung eines systemtechnischen Produktmodells – Einsatz in der Pkw-Entwicklung
Aachen: Shaker 1998. (Konstruktionstechnik München, Band 28). Zugl. München: TU, Diss. 1998.

D54 KLEEDÖRFER, R.:
Prozess- und Änderungsmanagement der Integrierten Produktentwicklung.
Aachen: Shaker 1998. (Konstruktionstechnik München, Band 29). Zugl. München: TU, Diss. 1998.

D55 Günther, J.:
Individuelle Einflüsse auf den Konstruktionsprozess.
Aachen: Shaker 1998. (Konstruktionstechnik München, Band 30). Zugl. München: TU, Diss. 1998.

D56 Biersack, H.:
Methode für Krafteinleitungsstellenkonstruktion in Blechstrukturen.
München: TU, Diss. 1998.

D57 Irlinger, R.:
Methoden und Werkzeuge zur nachvollziehbaren Dokumentation in der Produktentwicklung.
Aachen: Shaker 1998. (Konstruktionstechnik München, Band 31). Zugl. München: TU, Diss. 1999.

D58 Eiletz, R.:
Zielkonfliktmanagement bei der Entwicklung komplexer Produkte – am Bsp. PKW-Entwicklung.
Aachen: Shaker 1999. (Konstruktionstechnik München, Band 32). Zugl. München: TU, Diss. 1999.

D59 Stösser, R.:
Zielkostenmanagement in integrierten Produkterstellungsprozessen.
Aachen: Shaker 1999. (Konstruktionstechnik München, Band 33). Zugl. München: TU, Diss. 1999.

D60 Phleps, U.:
Recyclinggerechte Produktdefinition – Methodische Unterstützung für Upgrading und Verwertung.
Aachen: Shaker 1999. (Konstruktionstechnik München, Band 34). Zugl. München: TU, Diss. 1999.

D61 Bernard, R.:
Early Evaluation of Product Properties within the Integrated Product Development.
Aachen: Shaker 1999. (Konstruktionstechnik München, Band 35). Zugl. München: TU, Diss. 1999.

D62 Zanker, W.:
Situative Anpassung und Neukombination von Entwicklungsmethoden.
Aachen: Shaker 1999. (Konstruktionstechnik München, Band 36). Zugl. München: TU, Diss. 1999.

Reihe Produktentwicklung München

D63 Allmansberger, G.:
Erweiterung der Konstruktionsmethodik zur Unterstützung von Änderungsprozessen in der Produktentwicklung.
München: Dr. Hut 2001. (Produktentwicklung München, Band 37). Zugl. München: TU, Diss. 2000.

D64 Assmann, G.:
Gestaltung von Änderungsprozessen in der Produktentwicklung.
München: Utz 2000. (Produktentwicklung München, Band 38). Zugl. München: TU, Diss. 2000.

D65 Bichlmaier, C.:
Methoden zur flexiblen Gestaltung von integrierten Entwicklungsprozessen.
München: Utz 2000. (Produktentwicklung München, Band 39). Zugl. München: TU, Diss. 2000.

D66 Demers, M. T.
Methoden zur dynamischen Planung und Steuerung von Produktentwicklungsprozessen.
München: Dr. Hut 2000. (Produktentwicklung München, Band 40). Zugl. München: TU, Diss. 2000.

D67 Stetter, R.:
Method Implementation in Integrated Product Development.
München: Dr. Hut 2000. (Produktentwicklung München, Band 41). Zugl. München: TU, Diss. 2000.

D68 Viertlböck, M.:
Modell der Methoden- und Hilfsmitteleinführung im Bereich der Produktentwicklung.
München: Dr. Hut 2000. (Produktentwicklung München, Band 42). Zugl. München: TU, Diss. 2000.

D69 COLLIN, H.:
Management von Produkt-Informationen in kleinen und mittelständischen Unternehmen.
München: Dr. Hut 2001. (Produktentwicklung München, Band 43). Zugl. München: TU, Diss. 2001.

D70 REISCHL, C.:
Simulation von Produktkosten in der Entwicklungsphase.
München: Dr. Hut 2001. (Produktentwicklung München, Band 44). Zugl. München: TU, Diss. 2001.

D71 GAUL, H.-D.:
Verteilte Produktentwicklung - Perspektiven und Modell zur Optimierung.
München: Dr. Hut 2001. (Produktentwicklung München, Band 45). Zugl. München: TU, Diss. 2001.

D72 GIERHARDT, H.:
Global verteilte Produktentwicklungsprojekte – Ein Vorgehensmodell auf der operativen Ebene.
München: Dr. Hut 2002. (Produktentwicklung München, Band 46). Zugl. München: TU, Diss. 2001.

D73 SCHOEN, S.:
Gestaltung und Unterstützung von Community of Practice.
München: Utz 2000. (Produktentwicklung München, Band 47). Zugl. München: TU, Diss. 2000.

D74 BENDER, B.:
Zielorientiertes Kooperationsmanagement.
München: Dr. Hut 2001. (Produktentwicklung München, Band 48). Zugl. München: TU, Diss. 2001.

D75 SCHWANKL, L.:
Analyse und Dokumentation in den frühen Phasen der Produktentwicklung.
München: Dr. Hut 2002. (Produktentwicklung München, Band 49). Zugl. München: TU, Diss. 2002.

D76 WULF, J.:
Elementarmethoden zur Lösungssuche.
München: Dr. Hut 2002. (Produktentwicklung München, Band 50). Zugl. München: TU, Diss. 2002.

D77 MÖRTL, M.:
Entwicklungsmanagement für langlebige, upgradinggerechte Produkte.
München: Dr. Hut 2002. (Produktentwicklung München, Band 51). Zugl. München: TU, Diss. 2002.

D78 GERST, M.:
Strategische Produktentscheidungen in der integrierten Produktentwicklung.
München: Dr. Hut 2002. (Produktentwicklung München, Band 52). Zugl. München: TU, Diss. 2002.

D79 AMFT, M.:
Phasenübergreifende bidirektionale Integration von Gestaltung und Berechnung.
München: Dr. Hut 2003. (Produktentwicklung München, Band 53). Zugl. München: TU, Diss. 2002.

D80 FÖRSTER, M.:
Variantenmanagement nach Fusionen in Unternehmen des Anlagen- und Maschinenbaus.
München: TU, Diss. 2003.

D81 GRAMANN, J.:
Problemmodelle und Bionik als Methode.
München: Dr. Hut 2004. (Produktentwicklung München, Band 55). Zugl. München: TU, Diss. 2004.

D82 PULM, U.:
Eine systemtheoretische Betrachtung der Produktentwicklung.
München: Dr. Hut 2004. (Produktentwicklung München, Band 56). Zugl. München: TU, Diss. 2004.

D83 HUTTERER, P.:
Reflexive Dialoge und Denkbausteine für die methodische Produktentwicklung.
München: Dr. Hut 2005. (Produktentwicklung München, Band 57). Zugl. München: TU, Diss. 2005.

D84 FUCHS, D.:
Konstruktionsprinzipien für die Problemanalyse in der Produktentwicklung.
München: Dr. Hut 2006. (Produktentwicklung München, Band 58). Zugl. München: TU, Diss. 2005.

D85 PACHE, M.:
Sketching for Conceptual Design.
München: Dr. Hut 2005. (Produktentwicklung München, Band 59). Zugl. München: TU, Diss. 2005.

D86 BRAUN, T.:
Methodische Unterstützung der strategischen Produktplanung in einem mittelständisch geprägten Umfeld.
München: Dr. Hut 2005. (Produktentwicklung München, Band 60). Zugl. München: TU, Diss. 2005.

D87 JUNG, C.:
Anforderungsklärung in interdisziplinärer Entwicklungsumgebung.
München: Dr. Hut 2006. (Produktentwicklung München, Band 61). Zugl. München: TU, Diss. 2006.

D88 HEẞLING, T.:
Einführung der Integrierten Produktpolitik in kleinen und mittelständischen Unternehmen.
München: Dr. Hut 2006. (Produktentwicklung München, Band 62). Zugl. München: TU, Diss. 2006.

D89 STRICKER, H.:
Bionik in der Produktentwicklung unter der Berücksichtigung menschlichen Verhaltens.
München: Dr. Hut 2006. (Produktentwicklung München, Band 63). Zugl. München: TU, Diss. 2006.

D90 NIẞL, A.:
Modell zur Integration der Zielkostenverfolgung in den Produktentwicklungsprozess.
München: Dr. Hut 2006. (Produktentwicklung München, Band 64). Zugl. München: TU, Diss. 2006.

D91 MÜLLER, F.:
Intuitive digitale Geometriemodellierung in frühen Entwicklungsphasen.
München: Dr. Hut 2007. (Produktentwicklung München, Band 65). Zugl. München: TU, Diss. 2006.

D92 ERDELL, E.:
Methodenanwendung in der Hochbauplanung – Ergebnisse einer Schwachstellenanalyse.
München: Dr. Hut 2006. (Produktentwicklung München, Band 66). Zugl. München: TU, Diss. 2006.

D93 GAHR, A.:
Pfadkostenrechnung individualisierter Produkte.
München: Dr. Hut 2006. (Produktentwicklung München, Band 67). Zugl. München: TU, Diss. 2006.

D94 RENNER, I.:
Methodische Unterstützung funktionsorientierter Baukastenentwicklung am Beispiel Automobil.
München: Dr. Hut 2007 (Reihe Produktentwicklung) Zugl. München: TU, Diss. 2007.

D95 PONN, J.:
Situative Unterstützung der methodischen Konzeptentwicklung technischer Produkte.
München: Dr. Hut 2007 (Reihe Produktentwicklung) Zugl. München: TU, Diss. 2007.

D96 HERFELD, U.:
Matrix-basierte Verknüpfung von Komponenten und Funktionen zur Integration von Konstruktion und numerischer Simulation.
München: Dr. Hut 2007. (Produktentwicklung München, Band 70). Zugl. München: TU, Diss. 2007.

D97 SCHNEIDER, S.:
Model for the evaluation of engineering design methods.
München: Dr. Hut 2008 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2007.

D98 FELGEN, L.:
Systemorientierte Qualitätssicherung für mechatronische Produkte.
München: Dr. Hut 2007 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2007.

D99 GRIEB, J.:
Auswahl von Werkzeugen und Methoden für verteilte Produktentwicklungsprozesse.
München: Dr. Hut 2007 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2007.

D100 MAURER, M.:
Structural Awareness in Complex Product Design.
München: Dr. Hut 2007 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2007.

D101 BAUMBERGER, C.:
Methoden zur kundenspezifischen Produktdefinition bei individualisierten Produkten.
München: Dr. Hut 2007 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2007.

D102 KEIJZER, W.:
Wandlungsfähigkeit von Entwicklungsnetzwerken – ein Modell am Beispiel der Automobilindustrie.
München: Dr. Hut 2007 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2007.

D103 LORENZ, M.:
Handling of Strategic Uncertainties in Integrated Product Development.
München: Dr. Hut 2009 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2008.

D104 KREIMEYER, M.:
Structural Measurement System for Engineering Design Processes.
München: Dr. Hut 2010 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2009.

D105 DIEHL, H.:
Systemorientierte Visualisierung disziplinübergreifender Entwicklungsabhängigkeiten mechatronischer Automobilsysteme.
München: Dr. Hut 2009 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2009.

D106 DICK, B.:
Untersuchung und Modell zur Beschreibung des Einsatzes bildlicher Produktmodelle durch Entwicklerteams in der Lösungssuche.
München: Dr. Hut 2009 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2009.

D107 GAAG, A.:
Entwicklung einer Ontologie zur funktionsorientierten Lösungssuche in der Produktentwicklung.
München: Dr. Hut 2010 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2010.

D108 ZIRKLER, S.:
Transdisziplinäres Zielkostenmanagement komplexer mechatronischer Produkte.
München: Dr. Hut 2010 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2010.

D109 LAUER, W.:
Integrative Dokumenten- und Prozessbeschreibung in dynamischen Produktentwicklungsprozessen.
München: Dr. Hut 2010 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2010.

D110 MEIWALD, T.:
Konzepte zum Schutz vor Produktpiraterie und unerwünschtem Know-how-Abfluss.
München: Dr. Hut 2011 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2011.

D111 ROELOFSEN, J.:
Situationsspezifische Planung von Produktentwicklungsprozessen.
München: Dr. Hut 2011 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2011.

D112 PETERMANN, M.:
Schutz von Technologiewissen in der Investitionsgüterindustrie.
München: Dr. Hut 2011 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2011.

D113 GORBEA, C.:
Vehicle Architecture and Lifecycle Cost Analysis in a New Age of Architectural Competition.
München: Dr. Hut 2011 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2011.

D114 FILOUS, M.:
Lizenzierungsgerechte Produktentwicklung – Ein Leitfaden zur Integration lizenzierungsrelevanter Aktivitäten in Produktentstehungsprozessen des Maschinen- und Anlagenbaus.
München: Dr. Hut 2011 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2011.

D115 ANTON, T.:
Entwicklungs- und Einführungsmethodik für das Projektierungswerkzeug Pneumatiksimulation.
München: Dr. Hut 2011 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2011.

D116 KESPER, H.:
Gestaltung von Produktvariantenspektren mittels matrixbasierter Methoden.
München: Dr. Hut 2012 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2012.

D117 KIRSCHNER, R.:
Methodische Offene Produktentwicklung.
München: TU, Diss. 2012.

D118 HEPPERLE, C.:
Planung lebenszyklusgerechter Leistungsbündel.
München: Dr. Hut 2013 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2013.

D119 HELLENBRAND, D.:
Transdisziplinäre Planung und Synchronisation mechatronischer Produktentwicklungsprozesse.
München: Dr. Hut 2013 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2013.

D120 EBERL, T.:
Charakterisierung und Gestaltung des Fahr-Erlebens der Längsführung von Elektrofahrzeugen.
München: TU, Diss. 2014.

D121 KAIN, A.:
Methodik zur Umsetzung der Offenen Produktentwicklung.
München: Dr. Hut 2014 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2014.

D122 ILIE, D.:
Systematisiertes Ziele- und Anforderungsmanagement in der Fahrzeugentwicklung.
München: Dr. Hut 2013 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2013.

D123 HELTEN, K.:
Einführung von Lean Development in mittelständische Unternehmen - Beschreibung, Erklärungsansatz und Handlungsempfehlungen.
München: Dr. Hut 2015 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2014.

D124 SCHRÖER, B.:
Lösungskomponente Mensch. Nutzerseitige Handlungsmöglichkeiten als Bausteine für die kreative Entwicklung von Interaktionslösungen.
München: TU, Diss. 2014.

D125 KORTLER, S.:
Absicherung von Eigenschaften komplexer und variantenreicher Produkte in der Produktentwicklung.
München: Dr. Hut 2014 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2014.

D126 KOHN, A.:
Entwicklung einer Wissensbasis für die Arbeit mit Produktmodellen.
München: Dr. Hut 2014 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2014.

D127 FRANKE, S.:
Strategieorientierte Vorentwicklung komplexer Produkte – Prozesse und Methoden zur zielgerichteten Komponentenentwicklung am Beispiel Pkw.
Göttingen: Cuvillier, E 2014. Zugl. München: TU, Diss. 2014.

D128 HOOSHMAND, A.:
Solving Engineering Design Problems through a Combination of Generative Grammars and Simulations.
München: Dr. Hut 2014 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2014.

D129 KISSEL, M.:
Mustererkennung in komplexen Produktportfolios.
München: TU, Diss. 2014.

D130 NIES, B.:
Nutzungsgerechte Dimensionierung des elektrischen Antriebssystems für Plug-In Hybride.
München: TU, Diss. 2014.

D131 KIRNER, K.:
Zusammenhang zwischen Leistung in der Produktentwicklung und Variantenmanagement – Einflussmodell und Analysemethode.
München: Dr. Hut 2014 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2014.

D132 BIEDERMANN, W.:
A minimal set of network metrics for analysing mechatronic product concepts.
München: TU, Diss. 2015.

D133 SCHENKL, S.:
Wissensorientierte Entwicklung von Produkt-Service-Systemen.
München: TU, Diss. 2015.

D134 SCHRIEVERHOFF, P.:
Valuation of Adaptability in System Architecture.
München: Dr. Hut 2015 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2014.

D135 METZLER, T.:
Models and Methods for the Systematic Integration of Cognitive Functions into Product Concepts.
München: Dr. Hut 2016 (Reihe Produktentwicklung).

D136 DEUBZER, F.:
A Method for Product Architecture Management in Early Phases of Product Development.
München: TU, Diss. 2016.

D137 SCHÖTTL, F.:
Komplexität in sozio-technischen Systemen - Methodik für die komplexitätsgerechte Systemgestaltung in der Automobilproduktion.
München: Dr. Hut 2016 (Reihe Produktentwicklung).

D138 BRANDT, L. S.:
Architekturgesteuerte Elektrik/Elektronik Baukastenentwicklung im Automobil
München: TU, Diss. 2017.

D139 BAUER, W.:
Planung und Entwicklung änderungsrobuster Plattformarchitekturen
München: Dr. Hut 2016 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2016.

D140 ELEZI, F.:
Supporting the Design of Management Control Systems In Engineering Companies from Management Cybernetics Perspective
München: TU, Diss. 2015.

D141 BEHNCKE, F. G. H.:
Beschaffungsgerechte Produktentwicklung – Abstimmung von Produktarchitektur und Liefernetzwerk in frühen Phasen der Entwicklung
München: TU, Diss. 2017.

D142 ÖLMEZ, M.:
Individuelle Unterstützung von Entscheidungsprozessen bei der Entwicklung innovativer Produkte.
München: Dr. Hut 2017 (Reihe Produktentwicklung).

D143 SAUCKEN, C. C. V.:
Entwicklerzentrierte Hilfsmittel zum Gestalten von Nutzererlebnissen.
München: Dr. Hut 2017 (Reihe Produktentwicklung).

D144 KASPEREK, D.:
Structure-based System Dynamics Analysis of Engineering Design Processes
München: TU, Diss. 2016.

D145 LANGER, S. F.:
Kritische Änderungen in der Produktentwicklung – Analyse und Maßnahmenableitung
München: Dr. Hut 2017 (Reihe Produktentwicklung).

D146 HERBERG, A. P.:
Planung und Entwicklung multifunktionaler Kernmodule in komplexen Systemarchitekturen und –portfolios – Methodik zur Einnahme einer konsequent modulzentrierten Perspektive
München: TU, Diss. 2017.

D147 HASHEMI FARZANEH, H.:
Bio-inspired design: Ideation in collaboration between mechanical engineers and biologists
München: TU, Diss. 2017.

D148 HELMS, M. K.:
Biologische Publikationen als Ideengeber für das Lösen technischer Probleme in der Bionik
München: TU, Diss. 2017.

D149 GÜRTLER, M. R.:
Situational Open Innovation – Enabling Boundary-Spanning Collaboration in Small and Medium-sized Enterprises
München: TU, Diss. 2016.

D150 WICKEL, M. C.:
Änderungen besser managen – Eine datenbasierte Methodik zur Analyse technischer Änderungen
München: TU, Diss. 2017.

D151 DANIILIDIS, C.:
Planungsleitfaden für die systematische Analyse und Verbesserung von Produktarchitekturen
München: TU, Diss. 2017.

D152 MICHAILIDOU, I.:
Design the experience first: A scenario-based methodology for the design of complex, tangible consumer products
München: TU, Diss. 2017.

D153 SCHMIDT, D.M.:
Increasing Customer Acceptance in Planning Product-Service Systems
München: Dr. Hut 2017 (Reihe Produktentwicklung). Zugl. München: TU, Diss. 2017.

D154 ROTH, M.:
Efficient Safety Method Kit for User-driven Customization
München: Dr. Hut 2017 (Reihe Produktentwicklung).

D155 PLÖTNER, M.:
Integriertes Vorgehen zur selbstindividualisierungsgerechten Produktstrukturplanung
TU München: 2017. (als Dissertation eingereicht)

D156 HERBST, L.-M.:
Entwicklung einer Methodik zur Ermittlung raumfunktionaler Kundenanforderungen in der Automobilentwicklung
München: Dr. Hut 2017 (Reihe Produktentwicklung).

D157 KAMMERL, D. M. A.:
Modellbasierte Planung von Produkt-Service-Systemen
München: Dr. Hut 2018 (Reihe Produktentwicklung).

D158 MÜNZBERG, C. H. W.:
Krisen in der Produktentwicklung und ihre operative Bewältigung
München: TU, Diss. 2018.

D159 HEIMBERGER, N.:
Strukturbasierte Koordinationsplanung in komplexen Entwicklungsprojekten
München: TU, Diss. 2018.

D160 Lang, A.:
Im Spannungsfeld zwischen Risiken und Chancen – Eine Methode zur Ableitung von Handlungsempfehlungen zur Öffnung der Produktentwicklung
München: Dr. Hut 2018 (Reihe Produktentwicklung).