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A Method for Analyzing the Impact of Changes and their Propagation in Manufacturing Systems

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Editor's Preface

Production engineering is crucial for the advancement of our industrial society because the performance of manufacturing companies depends heavily on the equipment and resources employed, the production processes applied, and the established manufacturing organization. A company's full potential for corporate success can only be reached by optimizing the interaction between humans, operational structures, and technologies. Being able to remain competitive while balancing the varying and often conflicting priorities of complexity, cost, time, and quality requires constant thought, adaptation, and the development of new manufacturing structures. Thus, there is an essential need to reduce the complexity of products, manufacturing processes, and systems. Yet at the same time it is also vital to gain a better understanding and command of these aspects.

The objective of the research activities at the Institute for Machine Tools and Industrial Management (*iwb*) is to continuously improve product development and manufacturing planning systems, manufacturing processes and production facilities. A company's organizational, manufacturing, and work structures, as well as the underlying systems for order processing, are developed under strict consideration of employee-related requirements. Although an increasing degree of automation is unavoidable, labor will remain an important component in production processes. Thus, questions concerning the optimization of human involvement in the Idea-to-Offer process are of utmost importance.

The volumes published in this book series collate and report the results from the research conducted at *iwb*. Research areas covered stretch from the design and development of manufacturing systems to the application of technologies in manufacturing and assembly. The management and operation of manufacturing systems, quality assurance, availability, and autonomy are overarching topics, which affect all areas of our research. In this series, the latest results and insights from our application-oriented research are published. These will foster an improvement in the transfer of knowledge between universities and the wider industrial sector.

Gunther Reinhart *Michael Zäh*

Abstract

Manufacturing systems are subject to frequent changes caused by technology and product innovation, varying demand, shifted product mix, continuous improvement initiatives, or regular substitutions of outworn equipment and machines.

Elements within a manufacturing system are connected by a complex network of relations such as material flow, technological dependencies, and infrastructure. Depending on the scale of manufacturing changes, they may also interfere with business functions such as engineering, procurement, logistics, or even manufacturing strategy. The total impact in terms of expected costs and required effort for planning and implementation of those changes is usually hard to predict. Thus, the objective of this thesis is to enable a thorough analysis of change in socio-technical manufacturing systems and to provide a decision support for manufacturing change management.

Although the topic of change propagation received considerable attention in product development and systems engineering literature with regard to the prediction and assessment of engineering changes, comparable endeavors have not yet been made in the field of manufacturing science. Following a review of prevailing approaches, a model-based method for the prediction and assessment of change propagation in manufacturing systems is developed. Applied structural modeling techniques, the derived prediction algorithm, and the proposed procedure of the approach are described in detail.

Findings from three real-world industrial applications, carried out in different industry sectors, demonstrate the feasibility and effectiveness of the method in practice and are used to evaluate the approach. Application experiences are critically discussed to indicate opportunities for further improvements and future research.

Glossary

Changeability “An umbrella term comprising more specific properties describing a system’s ability to change its structure (incl. interfaces), form, and function at an acceptable level of valued resources (i.e., time and money).” (PLEHN et al. 2016)

Change impact Is the cost incurred by a change in terms of money and time due to any activities related to its planning and implementation.

Change propagation Describes the process by which a change to an existing system design triggers at least one additional change to the system or any associated activity, incident, or deliberate decision within the engineering system environment, that would not have otherwise been required.

Engineering Change (EC) An alteration made “to parts, drawings or software that have already been released during the product design process. The change can be of any size or type; the change can involve any number of people and take any length of time.” (JARRATT et al. 2011, p. 105)

Engineering system “A complex socio-technical system that is designed, developed, and actively managed by humans in order to deliver value to its stakeholders.” (BARTOLOMEI et al. 2006, p. 3)

Engineering Change Management (ECM) Refers to organizing and controlling the process of EC execution (JARRATT et al. 2011, p. 105).

Expert “A very skillful person who had much training and has knowledge in some special field. The expert is the provider of an opinion in the process of expert-opinion elicitation. Someone can become an expert in some special field by having the training and knowledge to a publicized level that would make him or her recognized by others as such.” (AYYUB 2001, p. 114)

Factory / manufacturing system Describes the spatial arrangement, relations, and properties of technology, personnel, and infrastructure in a differentiable subsection of a manufacturing plant, where the system boundary should be drawn depending on technological or product-oriented deliberations. (PLEHN et al. 2015b)

Manufacturing Change (MC) An alteration made "to the factory or its elements that have been released for or are already in operations. An MC can be of any size or type, it can involve any number of people, and take any length of time." (KOCH et al. 2016, p. 11)

Manufacturing Change Management (MCM) Refers to "organizing and controlling the process of making alterations to a factory. This includes the totality of measures to avoid and specifically front-load as well as efficiently plan, select, process, and control manufacturing changes." (KOCH et al. 2016, p. 11)

Mental model "A *mental model* of a dynamic system is a relatively enduring and accessible, but limited, internal conceptual representation of an external system (historical, existing or projected) whose structure is analogous to the perceived structure of that system." (DOYLE & FORD 1999)

Metamodel A description of "the abstract syntax of a language, capturing its concepts and relationships, using modeling infrastructure." (PAIGE et al. 2014)

Model-Based Systems Engineering (MBSE) Refers to "the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases." (INCOSE 2007)

Ontology Describes a "specification of a representational vocabulary for a shared domain of discourse – definitions of classes, relations, functions, and other objects [...]." (GRUBER 1993)

System "A set of interacting components having well-defined (although possibly poorly understood) behavior or purpose [...]" while a complex system is "a system with numerous components and interconnections, interactions or interdependencies that are difficult to describe, understand, predict, manage, design, and / or change." (MAGEE & DE WECK 2004)

Contents

1 Introduction

1.1 Motivation

1.1.1 Initial situation

Changes affect manufacturing companies on every system level—reaching from manufacturing technologies, equipment, and plants up to global supplier networks (WIENDAHL et al. 2007). A plethora of external and internal influences have been identified that are considered as *drivers of change*. Usually, the following aspects are named in literature: companies have to struggle with an increasing number of product variants (WANG et al. 2011), shortened and overlapping product life cycles (WIENDAHL et al. 2007) as well as tremendous uncertainty of future requirements (e.g., demand, product mix, new technologies, business models, and regulations) (FRICKE & SCHULZ 2005; ELMARAGHY 2014). Additional challenges are posed by the increasing importance of sustainable manufacturing (SELIGER et al. 2011) and the general cost pressure caused by fierce global competition. This so-called *turbulent manufacturing environment* leads to a high frequency of changes in manufacturing plants and also within the companies running them (NYHUIS et al. 2008).

However, "adding flexibility to a design in general adds costs" (DE NEUFVILLE 2004, p. 16), and the cost of highly changeable solutions are usually growing with the degree of uncertainty about future requirements, because a broader range of possible outcomes has to be thought ahead for which solutions have to be provided in the initial system design. Still, the capability to react rapidly to changing requirements at low cost is a competitive edge for 21st century agile manufacturing companies more than ever (GUNASEKARAN 2001; ELMARAGHY 2014). In order to tackle this challenge effectively, a variety of complementary strategies have been suggested in manufacturing, systems engineering, and product development research, which are outlined briefly in the following.

- *Design for Changeability (DfC).* Building changeability into manufacturing systems "admits the inability to accurately predict the future" (ROSS et al. 2008, p. 258). The design of flexible and reconfigurable manufacturing systems is one of the recent paradigms that have been developed as an answer to the high frequency of changing requirements, be it due to market volatility, technology evolution, or customization (ELMARAGHY & WIENDAHL 2009). It aims at reduced switching costs and effort for adapting a system to new requirements. DfC comprises a variety of design principles like simplicity, modularity, integrability, and scalability that support different aspects of a system's changeability (FRICKE & SCHULZ 2005). In manufacturing literature, these principles are also referred to as *changeability enablers*, which have a long tradition in the context of reconfigurable manufacturing systems (KOREN et al. 1999; DASHCHENKO 2006; ELMARAGHY 2009).

- *Agile systems engineering.* As a consequence of the increased frequency at which systems have to be designed and introduced, agile systems engineering aims at a more flexible and swift design as well as implementation of new products or engineered systems (HABERFELLNER & DE WECK 2005). In order to deal with the enduring uncertainties along the development process, methods such as Concurrent Engineering have been suggested (cf. e.g., YASSINE & BRAHA 2003).

- *Forecasting of change drivers.* Endeavors to anticipate future changes try to enable manufacturing companies to prepare solutions for changed requirements in due time. Manifold forecasting and monitoring methods have been proposed (e.g., Delphi method, scenario technique, time series analysis, and multiple regression) to effectively gather and interpret available information like market data. More recently, the cyclic behavior of relevant manufacturing influences (e.g., product and technology life cycles) has been analyzed to provide forecasting models in the context of strategic production planning (REINHART et al. 2009b; PLEHN et al. 2015a).

- *Change management.* Changeable manufacturing systems alone are not sufficient to overcome the challenges imposed on todays industrial companies. Successful change management in manufacturing may utilize the technical and organizational changeability potential by means of a process guiding required activities to

> plan, organize, and control manufacturing changes efficiently (KOCH et al. 2015). A reliable methodology for the *assessment of change impact* is indispensable to allow for a systematic management of changes in this context.

Evolving stakeholder needs and preferences, new operating conditions, technology innovation, and market volatility require a variety of changes which have to be implemented in manufacturing systems and related functions such as logistics planning, product development, and procurement (ELMARAGHY 2009). The consequences of these manufacturing changes are hard to predict since a change to one system element may result in one or more additional changes to the system, even though these might not have been required initially—this effect is commonly referred to as *change propagation* in literature (ECKERT et al. 2004; GIFFIN et al. 2009). Change propagation often happens unexpectedly, causing project delays and excessive cost (TERWIESCH & LOCH 1999). While DfC aims at *decreasing change effort*, agile systems engineering at *changing swiftly*, and forecasting at *being prepared*, change management strives for an increased *efficiency & effectiveness* in dealing with changes. This also includes making the right decisions when it comes to comparing alternative change options or to approve or reject change requests in advance of their implementation.

Since the early 2000s, engineering design and product development research has realized the existence of change propagation in complex products, which depends on the intensity and types of relations that constitute a product architecture (CLARKSON et al. 2004). Despite the large body of literature that has emerged in this domain dealing with the assessment of change impact in technical products (cf. HAMRAZ et al. 2013a), similar endeavors do not yet exist in manufacturing literature. However, due to the complexity of advanced manufacturing systems and plants, the assessment of change impact represents an ever more challenging task. Especially in early conceptual phases of change management, where decisions about alternative change options, project budgeting, and resource allocation have to be made, a reliable impact prediction is crucial (JARRATT et al. 2011, p. 106). But even the most experienced experts are not able to oversee and assess all possible chains of effects without appropriate supporting methods and tools (STERMAN 2002). DE NEUFVILLE (2002) states that in order to "engineer flexibility into systems, we must be able to measure alternative possibilities so that we can compare them analytically." Hence, this thesis aims at the development of a model-based method for change impact assessment for manufacturing systems to support an efficient and effective engineering change management in industrial practice and to improve changeability of systems in the long run.

1.1.2 Scientific environment and external interactions

This thesis is the result of the author's research activities at the Institute for Machine Tools and Industrial Management (*iwb*) of the Technical University of Munich (TUM) within the Collaborative Research Center (CRC)[1] 768 funded by the German Research Foundation (DFG)[2] since 2008 and his research visit at the Engineering Systems Division (ESD)[3] of Massachusetts Institute of Technology (MIT).

The CRC's general research area is the management of recurrent patterns in innovation processes of integrated goods and services based on technical products, also referred to as Product Service Systems PSS. The major objective of this project is to improve the effectiveness and efficiency of all phases during innovation processes, with a particular focus on manufacturing companies. Reflecting the broad range of skills required for this task, the CRC 768 is highly interdisciplinary involving engineering (manufacturing, product development, automation, and automatic control), computer and information science, business administration and management, sociology, and psychology. Especially, the collaboration between researchers from the domains of product development and manufacturing inspired the research questions tackled within this thesis.

Equally, the ESD is characterized by a strong transdisciplinary network of scientists dealing with complex socio-technical systems from the perspectives of engineering, management, and social sciences using advanced modeling techniques. In addition to the application of real options theory to value flexibility in engineering systems under uncertainty, the exchange of thoughts with researchers of the ESD who are dealing with theories and methods to assess and design strategic properties of engineering systems to increase their life cycle value (including methods for the assessment of changeability and the impact of changes) contributed to this thesis.

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[1] Sonderforschungsbereich 768, "Zyklenmanagement von Innovationsprozessen – verzahnte Entwicklung von Leistungsbündeln auf Basis technischer Produkte"

[2] Deutsche Forschungsgemeinschaft

[3] Since mid 2015 the ESD has become a part of MIT's Institute for Data, Systems, and Society (IDSS).

1.2 Elementary definitions

A variety of terms and concepts are used within this thesis, which have to be discussed and defined beforehand to avoid potential confusion and ambiguity. Starting from the types of systems considered, the applied understanding of changeability, engineering & manufacturing changes, change management, and change impact is made explicit.

1.2.1 Engineering system

Engineering systems are an umbrella term for socio-technical systems that have been designed for a specific purpose. The term is used in various disciplines including systems engineering, product development, manufacturing, management, and social sciences. Engineering systems are defined as a "class of systems characterized by a high degree of technical complexity, social intricacy, and elaborate processes, aimed at fulfilling important functions in society" (DE WECK et al. 2011, p. 31). BARTOLOMEI et al. (2006) complement this definition by describing the role of humans and by detailing their understanding of "important functions in society". Based on MAGEE & DE WECK (2004) they state that:

Definition: "An *engineering system* is a complex socio-technical system that is designed, developed, and actively managed by humans in order to deliver value to its stakeholders." (BARTOLOMEI et al. 2006, p. 3)

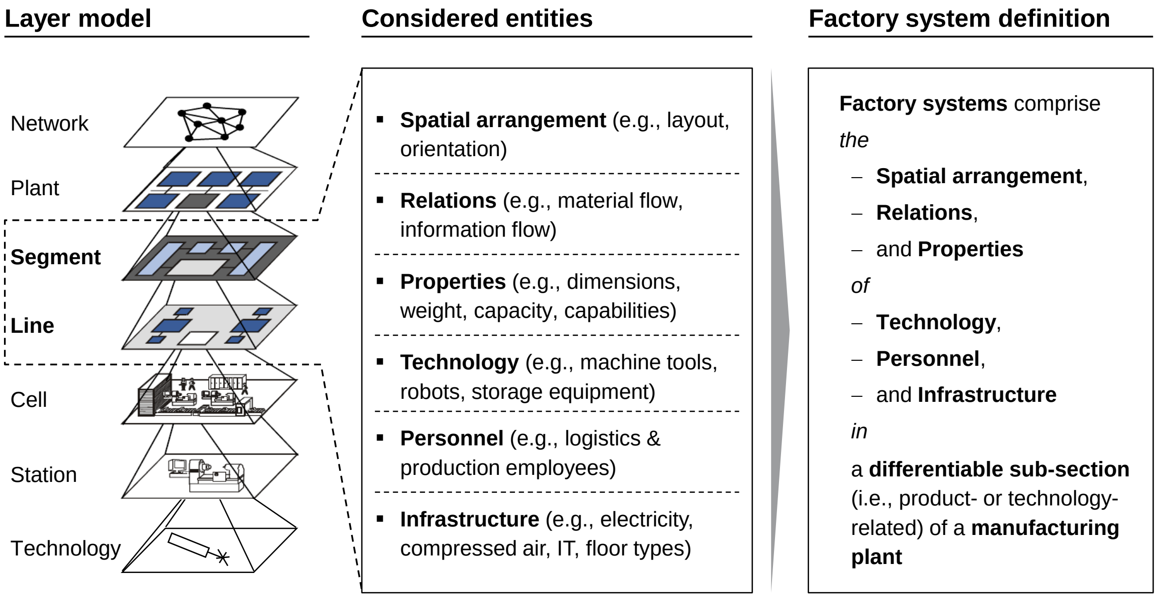
1.2.2 Factory and manufacturing system

According to the CIRP Dictionary of Production Engineering a *manufacturing system* is defined as a "system that includes all procedures and facilities to transform raw materials into final products" (BRAMLEY et al. 2011, p. 320). In manufacturing literature, the layer model of production is often referred to as a resource-based illustration of this broad definition (cf. e.g., WIENDAHL et al. 2007, p. 785). Figure 1.1 shows the resource view of the layer model distinguishing network, factory, segment, line, station, and technology level.

However, for the analysis of changes in manufacturing, this separation provides little guidance. Another issue arises from the original use of the "system" term as a layer of the model itself, while this concept should be thought of independent from the level of abstraction. Hence, the following definition for factory systems is proposed (cf. figure 1.1):

> **Definition:** *Factory systems* comprise the spatial arrangement, relations, and properties of technology, personnel, and infrastructure in a differentiable sub-section of a manufacturing plant, where the system boundary should be drawn depending on technological or product-oriented deliberations. (PLEHN et al. 2015b)

This definition is in accordance with earlier research contributions that are taking a structural perspective on factory design and reconfiguration planning.[4] However, following the general distinction between *structure* and *system* (LINDEMANN et al. 2009, pp. 22-24) the term factory system is used instead.



Considered entities

- **Spatial arrangement** (e.g., layout, orientation)
- **Relations** (e.g., material flow, information flow)
- **Properties** (e.g., dimensions, weight, capacity, capabilities)
- **Technology** (e.g., machine tools, robots, storage equipment)
- **Personnel** (e.g., logistics & production employees)
- **Infrastructure** (e.g., electricity, compressed air, IT, floor types)

Factory system definition

Factory systems comprise
the
- **Spatial arrangement**,
- **Relations**,
- and **Properties**

of
- **Technology**,
- **Personnel**,
- and **Infrastructure**

in
a **differentiable sub-section** (i.e., product- or technology-related) of a **manufacturing plant**

Figure 1.1: Factory system definition

Originally, the factory system definition was introduced to emphasize the difference between an individual manufacturing system and an entire section of a plant consisting

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[4] For instance, HARMS (2004, p. 12) suggest the term *factory structure*, while REINHART et al. (2009c, p. 9) use the term *production structure* instead.

of multiple manufacturing resources like machine tools, robots, and transportation equipment (PLEHN et al. 2015b). Although, factory systems are a subset of the broader manufacturing system definition, the terms are used synonymously within this thesis. Also note that manufacturing systems are often a specific class of engineering systems according to the definition stated above.

1.2.3 Changeability

Changeability is generally understood as an umbrella term for the concept of system change (HERNÁNDEZ 2002; ROSS et al. 2008; PACHOW-FRAUENHOFER 2012). Recognizing that the future is uncertain and that our capability to predict how it might look like are fairly limited, strategies for the effective and timely response to changing conditions are essential (DE NEUFVILLE & SCHOLTES 2011).

Besides the comprehensive management of engineering and manufacturing changes (cf. e.g., CLARKSON & ECKERT 2005; JARRATT et al. 2011; KOCH et al. 2016), incorporating changeability in the initial design of a system is often highly beneficial to increase lifetime value (DE NEUFVILLE 2003; ENGEL & BROWNING 2008; DE WECK et al. 2011). Being able to handle volatile demand, product variety, and shortened product life cycles has become a competitive edge for manufacturing companies already decades ago. Potentially, this is why "some of the most consistent and precise definitions of flexibility can be found in manufacturing engineering literature" (RYAN et al. 2013).

The ongoing industrial and academic interest in flexibility, robustness, adaptability, and many other properties closely related to changeability has not yet converged in a precise definition of terms. A recent survey of related literature by RYAN et al. (2013) shows that terminology is often carelessly employed, used in a casual sense and without providing explicit definitions. However, there is an agreement that these non-functional strategic properties are meant to achieve value robustness of engineering systems, protecting them against future uncertainty. *Value robustness* describes "a system's ability to maintain its perceived value to stakeholders, in spite of changes of its components, environment, or requirements. Value includes any form of utility to a stakeholder (monetary or non-monetary)" (ROSS 2006).

The history of flexibility in the economic literature dates back to the early 1920s (LAVINGTON 1921) and was first mentioned in the context of firm theory by STIGLER (1939). In the late 1970s and early 1980s academia recognized that the term *flexibility* encompassed two different aspects: SLACK (1983) distinguishes between response flexibility and range flexibility, which are referred to as dynamic and static aspects of flexibility by DE TONI & TONCHIA (1998). Two distinct concepts of flexibility emerged over time which lead to distinct but related terms. Firstly, "traditional" flexibility that can be defined as the ability of a system to be changed with little cost penalty but only within a predefined range (UPTON 1995). Secondly, the ability of a manufacturing system to exceed predefined functional ranges with acceptable effort and investments—in German factory design literature, this concept is often referred to as transformability (*"Wandlungsfähigkeit"*) to emphasize its relation to *changeability* (HERNÁNDEZ 2002; HEGER 2007). In international literature, however, the distinction of transformability and changeability is unusual. Instead, changeability is used as a generic term encompassing a variety of other change-related system properties. For the purpose of this thesis, this understanding is sufficiently concise. Hence, the following definition is suggested:

Definition: "*Changeability* is an umbrella term comprising more specific properties describing a system's ability to change its structure (incl. interfaces), form, and function at an acceptable level of valued resources (i.e., time and money)." (PLEHN et al. 2016)

As depicted in figure 1.2 on page 9, a variety of related concepts do exist, which may be useful to achieve value robustness depending on the specific circumstances. The following definitions are suggested by PLEHN et al. (2016):

- *Robustness*. Ability of a system, to maintain a given set of capabilities in spite of changes.
- *Resilience*. Ability of a system to recover its original structure and function after change-induced disturbances.
- *Flexibility*. Ability of a system to be modified based on pre-provisioned capability options in its initial design. External actuation is required.

- *Adaptability*. Ability of a system to autonomously modify its own capabilities based on pre-provisioned options in its initial design.
- *Transformability*. Ability of a system to embed new functions, exceeding its original range of capabilities. External actuation is required.
- *Intelligent Adaptability*. Ability of a system to autonomously embed new functions, exceeding its original range of capabilities.

Figure 1.2 visualizes the relationship of these changeability concepts, where vertical levels indicate the extent and ability of mechanisms provided by a system to encounter change. The framework reflects that the achievement of robust value delivery to system stakeholders requires both, highly changeable systems and effective change management.[5]

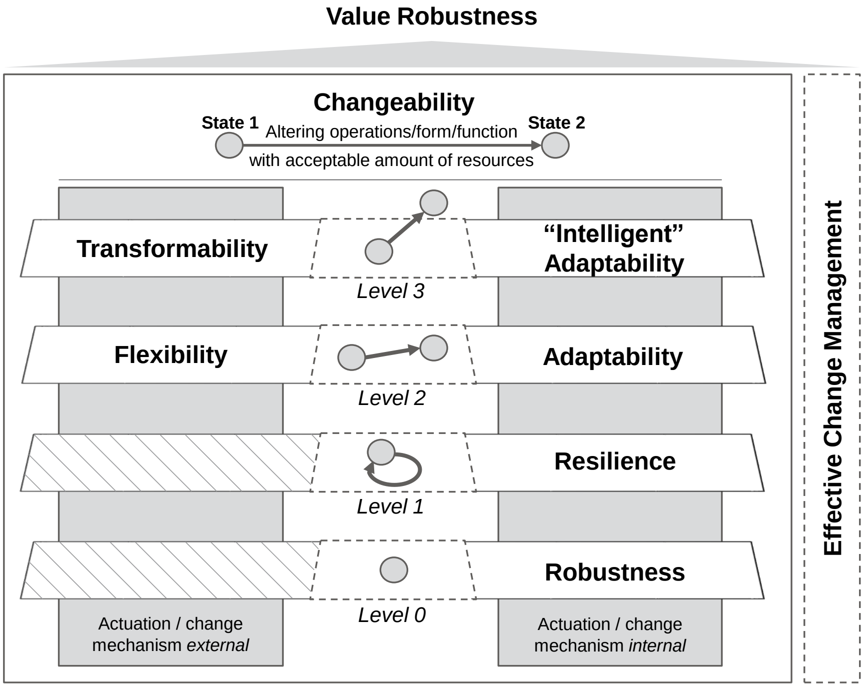

*Figure 1.2: Changeability and related properties as enablers for value robustness (*PLEHN *et al. 2016)*

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[5] For a detailed discussion of strategic system properties, also called *ilities*, the reader is referred to DE WECK et al. (2011) for a general introduction and to FRICKE & SCHULZ (2005), NILCHIANI & HASTINGS (2007), ROSS et al. (2008), RYAN et al. (2013), and CHALUPNIK et al. (2013) for detailed discussions.

1.2.4 Engineering and manufacturing change management

Following a review of current engineering design literature JARRATT et al. (2011) provide a comprehensive definition of engineering changes based on TERWIESCH & LOCH (1999), which shall be adopted here:

Definition: An *Engineering Change (EC)* is "an alteration made to parts, drawings or software that have already been released during the product design process. The change can be of any size or type; the change can involve any number of people and take any length of time." (JARRATT et al. 2011, p. 105)

HAMRAZ et al. (2013a, p. 475) extend the coverage of this definition, including changes made to the structure, behavior, or functions of a technical artifact. ECs are not limited to the design phase of the product life cycle. Thus, ECs also have an effect on downstream processes such as procurement, manufacturing, or after sales. It is common sense that the cost of change implementation is increasing along the way reflected by the "Rule of 10" as stated by K. B. CLARK & FUJIMOTO (1991). For the most part, Engineering Change Management (ECM) literature focuses on product related consequences of ECs when analyzing knock-on effects of changes in sub-systems, components, and parts, which might have to be redesigned due to, e.g., shared mechanical or electrical interfaces (CLARKSON et al. 2004).

Based on industrial case studies, FRICKE et al. (2000, p. 173) identify five strategies of successful ECM: less, earlier, effective, efficient, and better—i.e., "to aspire to have less changes, to front-load changes, to select necessary changes more efficiently, to perform the changes efficiently in terms of time, cost, and resources, and to learn continuously from changes to do it better in the next project." The following general definition summarizes the purpose of ECM:

Definition: *Engineering Change Management (ECM)* refers to organizing and controlling the process of EC execution (JARRATT et al. 2011, p. 105).

A high-level EC process is described by JARRATT et al. (2004), which encompasses six, partly iterative, steps for the management of EC requests (cf. figure 1.3). An important break point within this process is the *risk / impact assessment* phase, where the consequences of a potential EC implementation are scrutinized.

As already touched upon above, ECs may lead to changes within the manufacturing function. TERWIESCH & LOCH (1999) where one of the first authors to explicitly address potential “changes in production” due to engineering change orders. AURICH & RÖSSING (2007), RÖSSING (2007), MALAK et al. (2011), and WULF (2011) provide early contributions dedicated to the study of “technical changes”, their impact, and their efficient management from a manufacturing perspective.

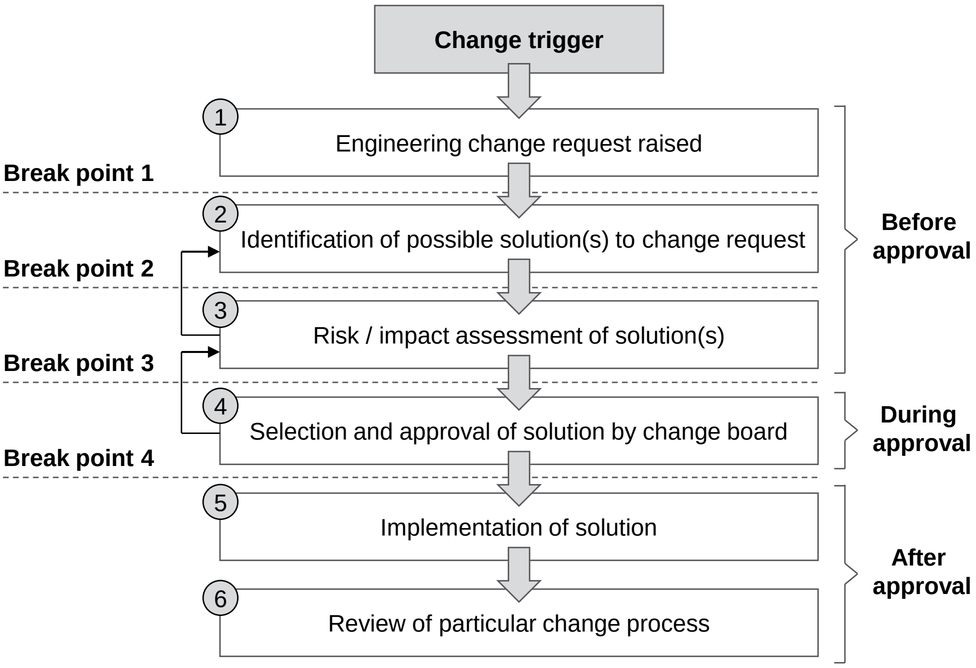

*Figure 1.3: A generic six-step engineering change process (*JARRATT *et al. 2004, p. 272)*

Based on REINHART et al. (2009a), MALAK et al. (2011) describe “engineering changes in manufacturing systems” as reconfigurations of factory objects (e.g., machines and work stations) due to any “addition, substitution, and removal of production objects; and changes to the structure of interrelationships between production objects.” The term *manufacturing change*, however, was first used explicitly by STANEV et al. (2008) in an attempt to integrate flexibility measurements in production into the manufacturing change process.

KOCH et al. (2015) find that only few authors deal with the topic of Manufacturing Change Management (MCM) up to now and that their contributions “usually refer to the ECM terminology and transfer it to the domain of manufacturing [. . .]”. Based on the established definition of ECs suggested by JARRATT et al. (2004), they define manufacturing changes as follows:

Definition: A *Manufacturing Change (MC)* is “an alteration made to the factory or its elements that have been released for or are already in operations. An MC can be of any size or type, it can involve any number of people, and take any length of time.” (KOCH et al. 2016, p. 11)

Common examples for manufacturing changes are layout adaptations, reconfigurations of manufacturing resources, modifications of assembly processes, or corrections of assembly instructions. Evidently, ECs may result in MCs, but also vice-versa: a new manufacturing technology can cause design modifications and thus trigger ECs. By analogy with the ECM definition:

Definition: *Manufacturing Change Management (MCM)* means “organizing and controlling the process of making alterations to a factory. This includes the totality of measures to avoid and specifically front-load as well as efficiently plan, select, process, and control manufacturing changes.” (KOCH et al. 2016, p. 11)

1.2.5 Change impact

Change impact predictions are an important element of ECM (HAMRAZ et al. 2013a). The economic viability of changes depends on the amount of valued resources consumed for their realization and on the expected benefit or utility the changed system provides to its stakeholders. Particularly, the resulting downside effects of changes are commonly subsumed under the term *change impact* in ECM literature. In general, “the verb impact has developed the transitive sense ’to have an impact or effect on’ [...] and the intransitive sense ’to have an impact or effect’ [...]. Although recent, the new uses are entirely standard and most likely to occur in formal speech and writing” (THESAURUS 2015). Within this thesis, ROSS et al. (2008, p. 249)’s framework for system change is adopted and completed by *change impact* in order to distinguish it from *change effects*, as illustrated in figure 1.4.[6]

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[6] Note that some authors use change effect and change impact synonymously as their intended meaning usually becomes evident when used in a specific context.

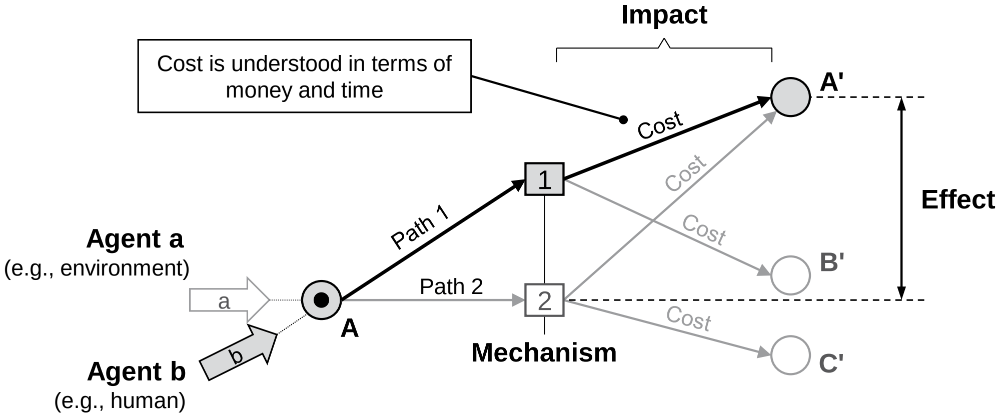

Figure 1.4: Elements of system change based on the framework of Ross *et al. (2008, p. 248)*

- *Change agent.* The force instigator for the change to occur, e.g., humans, software, Mother Nature etc. Often referred to as change cause or trigger.
- *Change mechanism.* The specific process causing the transition of a system from its prior to its post state, including conditions, resources, and constraints.
- *Change effect.* The difference in states before and after a change has taken place.
- *Change path.* Alternative paths for the system to change its state.

Impact can be quantified in various ways depending on the context of inquiry (e.g., technical, organizational, legal, ecological etc.). In the domains of manufacturing and product development it commonly refers to the objects affected and ultimately to the cost incurred by a change—either through investments (e.g., new machines) or labor (e.g., redesign of a product component). With respect to engineering design, Fricke et al. (2000, p. 172) also emphasize the significance of project delays caused by unplanned iterations of processes. Analogously, Aurich & Cichos (2014, p. 395) state that complications during the execution of manufacturing changes can cause high costs because of complex change impact interdependencies, iterations of planning processes, and postponed end dates. Summarizing, the following definition is used within this thesis:

Definition: *Change impact* is defined as the cost incurred by a change in terms of money and time due to any activities related to its planning and implementation.

1.2.6 Change propagation

The parts of a system are usually connected by different types of relations, transferring a triggered change through its network of dependencies—an element that is subject to change can become the cause of change itself. This phenomenon is commonly referred to as *change propagation* and has been studied especially in product development since the early Millennium years (cf. COHEN et al. 2000; SIMONS 2000; OLLINGER & STAHOVICH 2004; CLARKSON et al. 2004). Based on the work of ECKERT et al. (2004), change propagation is defined as the process by which a "change to one part or element of an existing system configuration or design results in one or more additional changes to the system, when those changes would not have otherwise been required" (GIFFIN et al. 2009, p. 2).

For the manufacturing domain, this definition has to be extended to include *activities* of a change process that need to be carried out due to previous activities, changes of system elements, or *incidents* within the manufacturing environment. Activities are not necessarily linked to a system change, but might require considerable investments or working hours in case they need to be executed. Hence, the following definition is suggested:

Definition: *Change propagation* describes the process by which a change to an existing system design triggers at least one additional change to the system or any associated activity, incident, or alteration within the system environment, that would not have otherwise been required.

1.3 Research scope

1.3.1 Objectives

In engineering design literature, ECs have been assessed on the parameter and component level since the early 2000s. Nonetheless, change impact analysis remains a "huge challenge for research" (HAMRAZ et al. 2013a, p. 488). Particularly, change assessment in manufacturing is still in its infancy, since "there has not been any publication focusing primarily on the impacts of ECs on manufacturing and post-manufacturing stages" (HAMRAZ et al. 2013a, p. 492).

However, a systematic and comprehensive assessment of manufacturing change impact is indispensable for effective and efficient MCM. Analogous to the established process of ECM (cf. figure 1.3 on page 11), the *risk / impact assessment* phase in the early stages of the MCM process determines further processing of a manufacturing change (e.g., its rejection). Experience from interviews with industrial experts further indicates that a method for change impact assessment in manufacturing also needs to incorporate *external effects* in neighboring functions such as procurement, logistics, and product development. Furthermore, such a method has to allow for uncertain information, various types of interdependencies, and complex cause and effect chains within engineering systems. Hence, the following primary objective has been set to contribute to the state of the art and to support industrial practice in an efficient management of manufacturing changes:

O.1 *Prediction of the impact of MCs.* Provide a method for a comprehensive assessment of change impact in manufacturing to enable a quantitative analysis of (alternative) MCs.[7] Based on the method, the user shall be able to compare and prioritize manufacturing changes quantitatively. For a comprehensive analysis, especially propagation effects, cross-domain cause and effect chains, and networked system structures need to be taken into account.

A reliable quantitative assessment of change impact in manufacturing systems provides side benefits for MCM. These secondary objectives are the following:

O.2 *Budget and capacity planning in MCM.* As explained earlier, important criteria for the evaluation of MCs are cost and time for their planning and implementation. In order to support budget planning and to enable an informed allocation of capacity in early phases of the MC process, this work strives to provide a prediction of expected change cost, required working time, and a quantitative assessment of the associated risk. The spread of cost and time predictions, as an indicator for risk, is considered as an important criterion for decision making.

O.3 *Focused MCM and the incorporation of changeability.* In general, changeable manufacturing systems are more costly than rigid solutions (DE NEUFVILLE

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[7] ECs are only considered if they are believed to cause related MCs.

2004, p. 16). The approach developed within this thesis shall support the identification of *change multipliers* in manufacturing systems, which generate more changes than they absorb and can amplify changes (ECKERT et al. 2004, p. 13). These entities should be focused in MCM to mitigate the impact of manufacturing changes. Besides, incorporating changeability into change multipliers can help to reduce future change cost efficiently (cf. also GIFFIN et al. 2009).

1.3.2 Key research questions

In order to achieve the aforementioned objectives, the research project is guided by five key research questions, which address the main aspects of method conception and detailed design. Research domains considered along the way include manufacturing systems and factory design, product development and engineering design, systems engineering, system modeling, structural complexity management, graph theory, multiple-criteria decision analysis, risk management, and real options.

Q.1 *Which promising approaches, methods, and techniques for change impact assessment are provided by engineering and manufacturing research?*

Q.2 *How do manufacturing systems have to be modeled such that the impact of manufacturing changes can be assessed in terms of time, cost, and associated risk?*

Q.3 *How can the tacit knowledge of system experts be formalized for the purpose of model-based impact analysis, also concerning inevitable uncertainties?*

Q.4 *How can change propagation in manufacturing systems be simulated using system models?*

Q.5 *How should the procedure of a model-based method for change impact analysis be designed to suite the requirements of users in practice?*

1.3.3 Research methodology

This research project is guided by the Design Research Methodology (DRM), documented by BLESSING & CHAKRABARTI (2009). According to the DRM framework, the research design at hand can be classified as a *Type 3*, where *Research Clarification* and *Descriptive Study I* are conducted review-based while *Prescriptive Study* and *Descriptive Study II* are performed comprehensively (cf. figure 1.5). In addition to a literature based approach, a comprehensive study requires "a study in which the results are produced by the researcher, i.e., the researcher undertakes an empirical study, develops support, or evaluates support" (BLESSING & CHAKRABARTI 2009). To enable a subsequent evaluation of results, the *success criterion* of this work is defined as *successful development of a method for manufacturing change impact analysis*. Figure 1.5 visualizes the iterative nature of the DRM and lists the main outcomes of each phase.

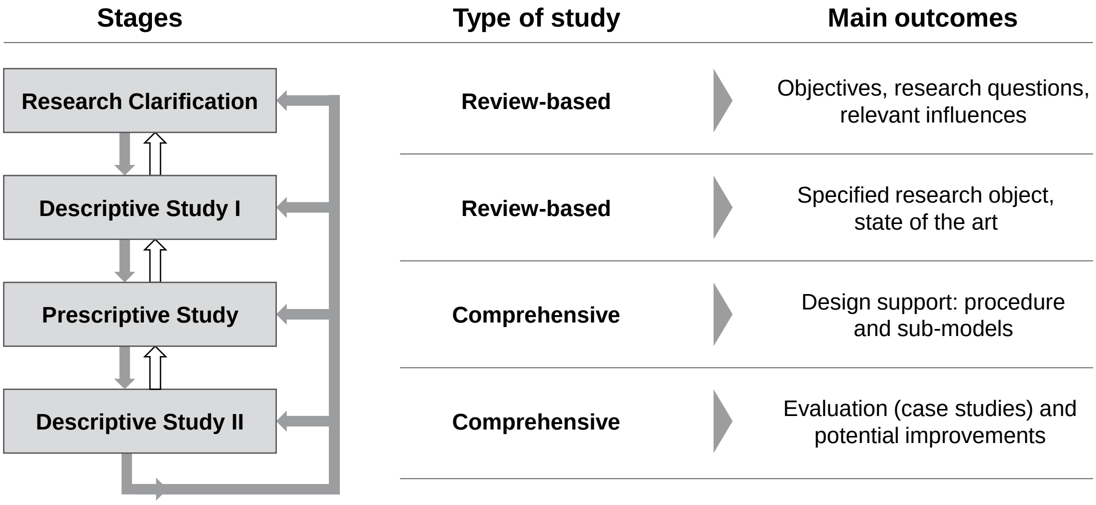

Figure 1.5: Design Research Methodology "Type 3" research project (cf. BLESSING & CHAKRABARTI *2009, p. 15)*

This research project aims at a practical goal (cf. section 1.3), i.e., to provide methodological support for industrial practice in the context of MCM. The Research Process of Applied Sciences (RAS) suggested by ULRICH & HILL (1976b) has been adopted to define the structure as well as the research activities to be carried out.[8] The major steps resulting from both research guidelines, DRM and RAS, shall be summed up briefly in the following. Details are depicted in figure 1.5 and figure 1.6, respectively.

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[8] ULRICH & HILL's approach is well established in German manufacturing science and has been used in a multitude of PhD projects in the field. For further details on the research process of applied sciences the reader is referred to ULRICH & HILL (1976a,b).

Knowledge synthesis

The phase of *Research Clarification*, which starts from the initial review-based identification and description of a theoretical problem, is complemented by expert interviews in order to check the problem's industrial relevance and relate it to a practical issue. Once a first draft of the objectives and research questions is formulated, an extensive literature review is conducted in the *Descriptive Study I* to identify relevant theories, concepts, and methods. During this phase, the focus will be on manufacturing and product development literature to identify the state of the art in the field and to derive deficits of current approaches.

Theory development

After relevant influences on the problem have been identified, *Descriptive Study II* aims at the conceptual design and the development of sub-models based on a profound theory. Theory development is guided by formulating assumptions about the object of inquiry and the specification of practical and formal requirements. During this phase, the researcher tries to transfer and extend concepts from other research domains to resolve existing deficits and to provide answers to the research questions stated earlier. Among others, results are the conceptual design, detailed design, and the procedure of the method. Moreover, a software tool may be required for practical experiments. A first definition of targeted use case scenarios supports the purposeful choice of industrial case studies.

Industrial application

Descriptive Study II is the final phase of the DRM and corresponds with the empirical-inductive evaluation (RAS) of the method using three case studies. The selection of cases is planned according to the guidelines of EISENHARDT (1989, p. 537) to increase the quality of insights gained from the *Descriptive Study II* as a feedback for theory building. Evidently, the case studies need to be conducted subsequently to allow for an iterative adaptation of the method. This "replication logic" is central to case based theory building and ensures that "each case serves as a distinct experiment that stands on its own as an analytic unit", while multiple cases serve as "replications, contrasts, and extensions to the emerging theory" (EISENHARDT & GRAEBNER 2007,

p. 25; YIN 1994). To enable an in-depth investigation of aspects that emerge from previous applications, the research focus or question may also shift between cases (EISENHARDT 1989, p. 536). According to EISENHARDT's guideline, the objective of case sampling is to choose cases which are either used to replicate findings or to extend theory development, which is in contrast to traditional hypothesis-testing by statistical sampling (EISENHARDT 1989, p. 537). Hence, cases are chosen from different manufacturing industries and the application examples vary with respect to the type of manufacturing change to be analyzed. That way, multiple levels of abstraction can be investigated to generalize research findings.

1.4 Synopsis

The remainder of this thesis is structured as follows: in chapter 2, general and domain-specific modeling techniques are discussed, followed by a review of the state of the art in chapter 3. Approaches and methods for manufacturing and engineering change impact analysis are analyzed and discussed in order to identify promising approaches and current weaknesses. Besides the specification of requirements and assumptions, chapter 4 introduces the conceptual design of the approach. The detailed design is split up into three chapters: a graph-based domain-specific modeling language for manufacturing systems is presented in chapter 5, a method for formal expert knowledge (impact estimates) representation and an expert elicitation procedure are discussed in chapter 6, and the theory of model-based simulation of change impact is presented in chapter 7. Finally, the developed method is evaluated in chapter 8, using three case studies, before the thesis concludes with chapter 9, providing a critical discussion of the developed methodology as well as opportunities for future research. Figure 1.6 shows the structure of the thesis.

Type of research	Research process of applied sciences	Ch.	Short title
empirical-inductive	Identification and description of practical problems (e.g. expert interviews, literature)	**1**	Introduction
terminological-descriptive	Analysis of existing theories and methods	**2** **3**	System modeling State of the art
analytical-deductive	Specification of requirements and assumptions	**4**	Conceptual design
	Procedure and model construction, development of methodological support	**5** **6** **7**	Modeling approach Expert elicitation Change impact simulation
empirical-inductive	Application and evaluation of the method	**8** **9**	Application & evaluation Conclusion

Figure 1.6: Research methodology and structure of the thesis

2 Structural System Modeling and Analysis

> *"The whole is more than the sum of its parts. The part is more than the fraction of the whole."*
>
> —HALL 1989, Composition Laws

2.1 Chapter introduction

Manufacturing systems are complex engineering systems. Their elements are part of different domains, such as technology, personal, and infrastructure. Similarly, the linkages, which constitute the network of interdependencies between these elements, are heterogeneous. In technical systems, for instance, they may encompass energy, material, and signal flows. Due to their complicated nature, careful simplifications are required when modeling a real-world manufacturing system. For this purpose, a variety of system modeling languages and techniques have been suggested in literature. As this thesis aspires a model-based analysis of manufacturing change, the choice of an appropriate modeling language is fundamental. Thus, within this chapter, well-established modeling approaches will be presented and discussed. Furthermore, the reader is equipped with important basics required to understand the state of the art review of model-based change impact prediction and assessment (cf. chapter 3).

Since an in-depth understanding of promising approaches and current deficits is required to fully evaluate the potential benefits of a specific modeling language, only a preliminary comparison of modeling languages can be provided at this point. Based on the objectives stated in section 1.3—and in anticipation of the findings from the literature review—the following basic requirements are stated as characteristics of an ideal modeling approach for the purpose at hand: consideration of multiple object types, multiple relation types, manufacturing domain specifics, and of a system's structure, while providing a high degree of modeling flexibility, standardization, and information richness, and requiring little learning effort.

2.2 General system theory

According to MAGEE & DE WECK (2004, p. 2) a *system* is “a set of interacting components having well-defined (although possibly poorly understood) behavior or purpose [. . .]”, while a *complex system* is “a system with numerous components and interconnections, interactions or interdependencies that are difficult to describe, understand, predict, manage, design, and / or change.”

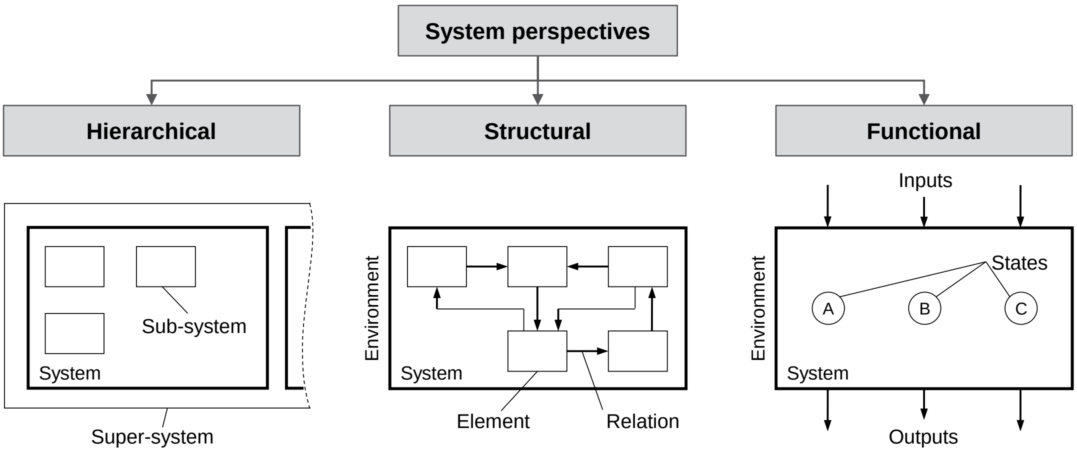

Figure 2.1: Concepts of general systems theory based on ROPOHL *(1999, p. 76)*

Systems theory takes three perspectives on a system, which are not mutually exclusive but complementary (cf. figure 2.1): the hierarchical, structural, and functional view (ROPOHL 1999, pp. 75-77). Each of these views may be given priority when analyzing a system—depending on the purpose of the analysis.

- *Hierarchical view*. The hierarchical perspective emphasizes the notion that a system can be considered as a part of a larger (super-)system. While a higher level of detail may provide more detailed explanations, insights with respect to a system’s purpose and context are often gained on a higher level of abstraction.

- *Structural view*. The system is recognized as the sum of its elements connected by a network of interdependencies among them, which may lead to system emergence[1].
- *Functional view*. The system is considered as a black box model abstracting from its internal structure. It is defined by the relationships of inputs, outputs, and state variables that can be observed from the outside.

Within this thesis, the hypothesis of structural complexity management is shared that function and even behavior of systems are strongly determined by their structure (LINDEMANN et al. 2009, p. 8). Hence, in the following sections, the main emphasis is put on structural modeling techniques.

2.3 Model-Based Systems Engineering

According to the International Council on Systems Engineering (INCOSE), Model-Based Systems Engineering (MBSE) "is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" (INCOSE 2007). Thereby, successful system realization and analysis "is driven by a model that comprises a coherent and consistent set of views that reflect multiple viewpoints of the system." (HOLT & PERRY 2014, p. 7). As the core of this thesis is, essentially, the analysis of complex systems, a short overview of two prominent modeling approaches of MBSE is provided in this section: SysML and OPM.

Systems Modeling Language

Systems Modeling Language (SysML) is a language profile of the Unified Modeling Language (UML), tailored for the specific area of Systems Engineering. It extends UML for the modeling of engineering systems as defined in section 1.2.1 (DE WECK

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[1] A *system of systems* that shows *emergent behavior* "performs functions and carries out purposes that do not reside in any component system. These behaviors are emergent properties of the entire system of systems and not the behavior of any component system" (SAGE & CUPPAN 2001, p. 326).

et al. 2011, p. 104). The Object Management Group (OMG) describes SysML as "a general-purpose graphical modeling language for specifying, analyzing, designing, and verifying complex systems that may include hardware, software, information, personnel, procedures, and facilities. In particular, the language provides graphical representations with a semantic foundation for modeling system requirements, behavior, structure, and parametrics, which is used to integrate with other engineering analysis models" (OBJECT MANAGEMENT GROUP 2015). It has been developed jointly by the OMG and the INCOSE.

The four pillars of SysML are its structure, behavior, requirements, and parametric diagrams (cf. figure 2.2). A system's structure can be modeled using block definition and internal block diagrams, while its static and dynamic behavior is represented using the activity, sequence, state machine, and use case diagram. SysML reuses many diagrams of UML, but also adds its own specifications (e.g., requirement and parametric diagram). However, some constructs and diagram types only required in software engineering have been omitted (e.g., communication and timing diagram).

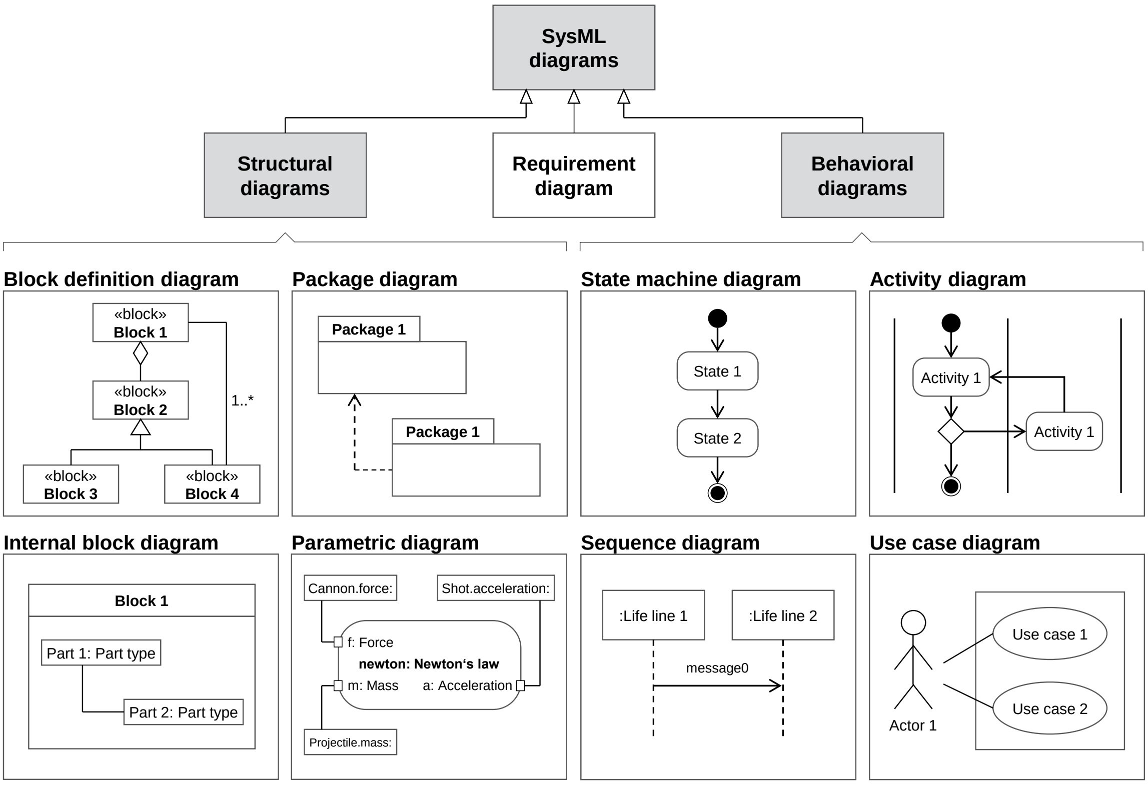


Figure 2.2: SysML diagram taxonomy based on HOLT & PERRY *(2014)*

Object-Process Methodology

The conceptual modeling language Object-Process Methodology (OPM), which was developed by DORI (2002), is a holistic formal graphical and textual approach for the representation, design, and analysis of complex systems. OPM enables representing function, behavior, and structure with a compact set of intuitive symbols for entities and relations in a single diagram type (YAROKER et al. 2013, p. 283). These diagrams can be organized hierarchically and navigated by the modeler to achieve a high-level overview and sufficient detail at the same time. As only a single diagram type is required, effort for generating, synchronizing and maintaining a plenitude of diagrams for system and function modeling—like in SysML—is cut down (DE WECK et al. 2011, p. 105).

Besides fundamental structural relations, such as aggregation and generalization, also known in UML and SysML, OPM extends the set of relation types (cf. figure 2.3). However, the language merely requires three types of entities: objects, processes, and states (DORI 2002, p. 5). A well-known IT-tool for OPM modeling is OPCAT, which allows different ways of model interaction (e.g., zooming in / out, displaying additional information). Although OPM has several advantages when an integrated system overview is desired, it is considered less code-oriented than UML (COHN & SOFFER 2007), which is a drawback in software engineering applications. Figure 2.3 illustrates some of the most important building blocks and links.

2.4 Structure matrices

Another technique to design, manage and analyze—particularly the structure of—complex engineering systems is the *Design Structure Matrix (DSM)*. The DSM "is a square $N \times N$ matrix, mapping the interactions among the set of N system elements" highlighting a system's architecture (EPPINGER & BROWNING 2012, p. 2). In order to increase system understanding using DSMs, the system is decomposed into subsystems and the relationships between them. Formally, all entities in a DSM belong to the same domain, which is why it is called an intra-domain matrix (LINDEMANN et al. 2009, p. 50).

Due to the straightforwardness and flexibility of its concept, the DSM is applied in a variety of domains. BROWNING (2001) provides a list of application examples in

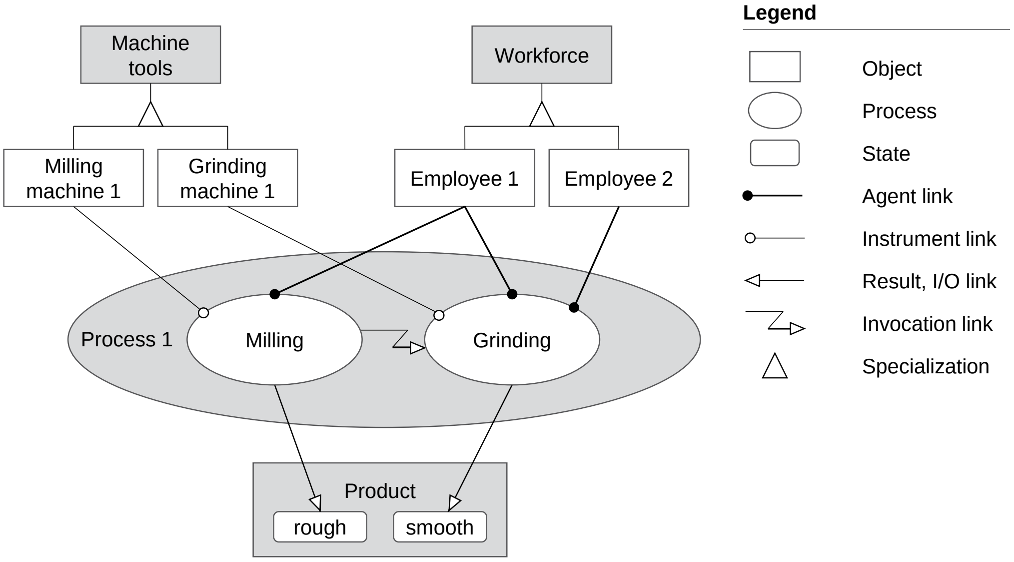
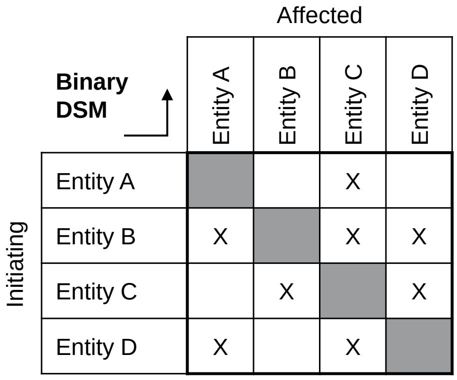


Figure 2.3: Example of an integrated representation of objects and processes in OPM

building construction, semiconductor, automotive, photographic, aerospace, telecom, small-scale manufacturing, factory equipment, and electronics industries. As four major types of DSMs, Browning (2001, p. 293) characterizes the component-based architecture DSM, the team-based or organization DSM, the activity-based or schedule DSM, and the parameter-based DSM.



	Entity A	Entity B	Entity C	Entity D
Entity A	▨		X	
Entity B	X	▨	X	X
Entity C		X	▨	X
Entity D	X		X	▨

Figure 2.4: Static binary DSM

Inter-domain matrices are used to map the relations of different domains such as components, processes, and organizational structures (Lindemann et al. 2009, p. 54). If only two domains are involved, the term *Domain Mapping Matrix (DMM)* is used, which was introduced by Danilovic & Browning (2004, 2007). The combination of DSMs and DMMs is defined as *Multiple Domain Matrix (MDM)* by MAURER & LINDEMANN (2007). Figure 2.5 gives an overview of all three structure matrix types.

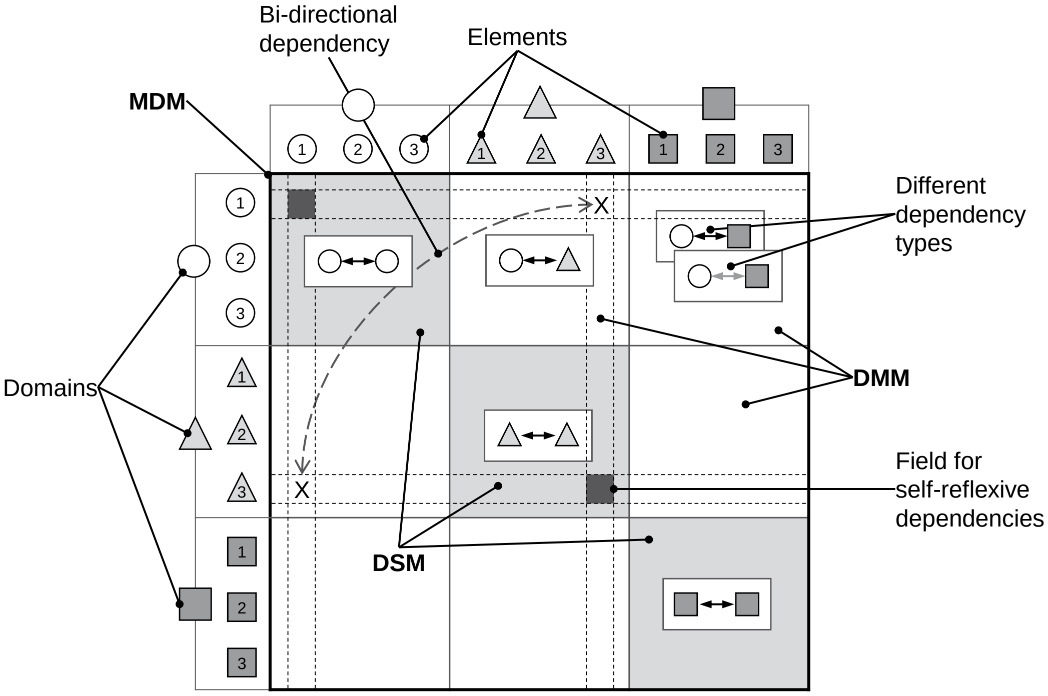
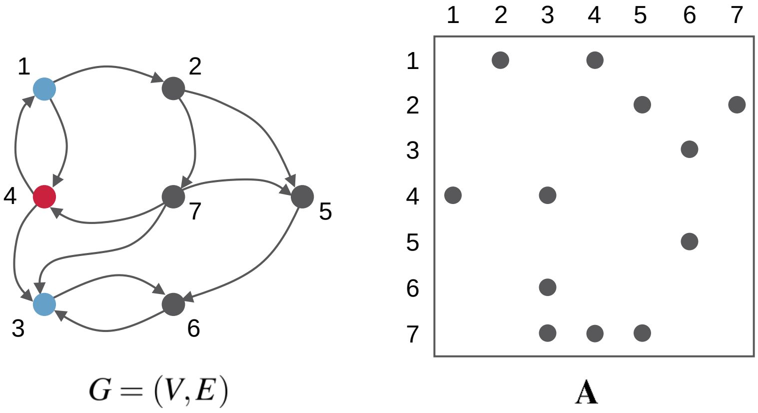


*Figure 2.5: Overview of generic structure matrices (*LINDEMANN *et al. 2009, p. 76)*

2.5 Networks and graphs

Network (referred to as graph in the following) and matrix approaches are dual formulations of a system's structure (KEPNER 2011, p. 5). Graphs consist of nodes and edges, which can be directed or undirected. Nodes represent entities, while edges are used to model various kinds of interrelations. In a *multi-graph*, also multiple relations between nodes are allowed. Usually, nodes of a graph are treated equally, resulting in a highly abstracted representation of a system, which is considered as a major drawback for the application in engineering. However, when it comes to visualization, statistical analysis, architectural properties (i.e., graph metrics), and big data, graph approaches demonstrate their benefits (cf. DE WECK et al. 2011). The level of detail and the potential explanatory power of the models can be increased when different domains are considered in a graph. For instance, Pasqual & de Weck (2012) state that their multilayer network model comprising the social, change, and product domain, provides a holistic, data-driven framework for the analysis and management of technical changes. However, the authors also note that better network visualization techniques are required to reveal patterns and other insights to the user. Other augmented network models are proposed by, e.g., Bounova & de Weck (2008) and Plehn et al. (2015b).

As illustrated in figure 2.6, the *adjacency matrix* $\mathbf{A}$ for a graph $G = (V,E)$ comprising the set V of nodes and the set E of edges has the property $\mathbf{A}(i,j) = 1$, if there is an edge $e_{ij} \in E$ linking nodes $v_i, v_j \in V$, and is zero otherwise. Note that graph algorithms can also be performed by linear algebraic operations as discussed in detail by Kepner & Gilbert (2011)—e.g., vector matrix multiply is dual with Breadth-First Search (BFS).



$G = (V,E)$

$\mathbf{A}$

Figure 2.6: Adjacency matrix $\mathbf{A}$ *and corresponding graph* $G = (V,E)$ *based on* Kepner *(2011, p. 4)*

Fuzzy Cognitive Maps

Fuzzy Cognitive Maps (FCMs) are “fuzzy-graph structures for representing causal reasoning” (Kosko 1986, p. 65). Cognitive maps were first used by the political scientist R. Axelrod (1976). Arrows are used to link concept variables indicating the direction of a causality (Hall et al. 1994, p. 341). Due to their graph structure, FCMs allow for a systematic analysis of causal propagation. Originally, their intended field of application were soft knowledge domains, like e.g., political science, international relations, and organization theory.

As an alternative to expert systems, FCMs represent knowledge and relate concepts like events, states, processes, actors, policies, goals, values, and trends in a uniform way using causal flow paths and fuzzy rules (AGUILAR 2005). Normalized edge weights $w_{ij} \in [-1, 1]$ represent the degree or strength of interaction between concepts and are stored in an adjacency matrix. Signs ($+$ or $-$) indicate causal increase or decrease. Thus, using the *fuzzy causal algebra* as described by KOSKO (1986), causal propagation effects can be analyzed quantitatively. Figure 2.7 shows an illustrative example of a FCM used to model survival tactics of dolphins.

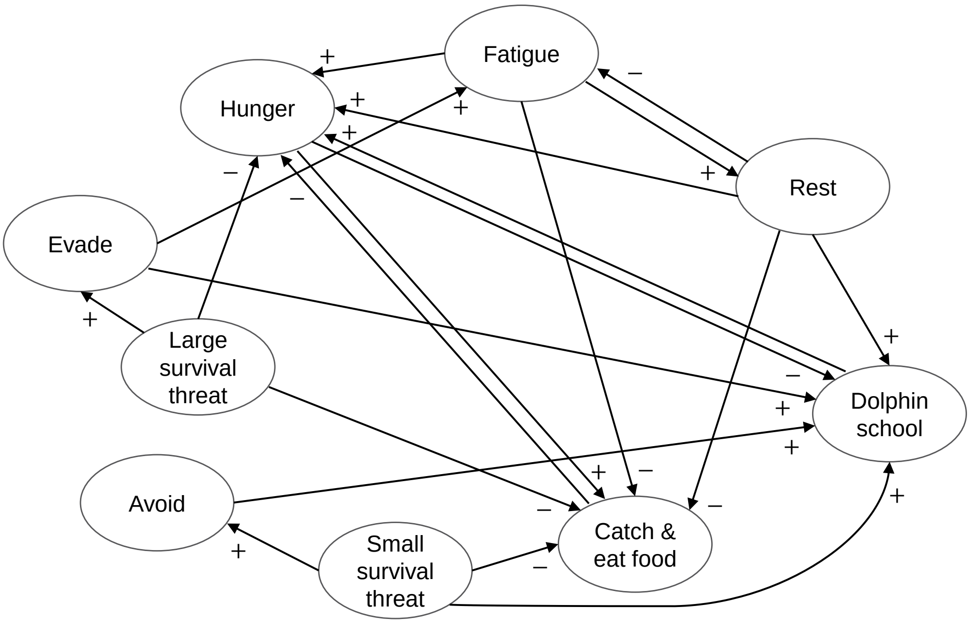


*Figure 2.7: A Fuzzy Cognitive Map illustrating dolphin survival tactics (*DICKERSON & KOSKO *1994, p. 184)*

System Dynamics

System dynamics is based on control theory and the modern theory of nonlinear dynamical systems (STERMAN 2002). It offers a set of conceptual tools (e.g., causal loop & stock and flow diagrams) that enable engineers and managers to understand “the structure and the dynamics of complex systems” to design more effective policies and to make informed decisions based on computer simulations (Sterman 2000, p. vii). One of system dynamics' main advantages compared with cognitive maps or simple causal loop diagrams is its ability to "capture the stock and flow structure of systems", which determines system behavior (Sterman 2000, p. 191).

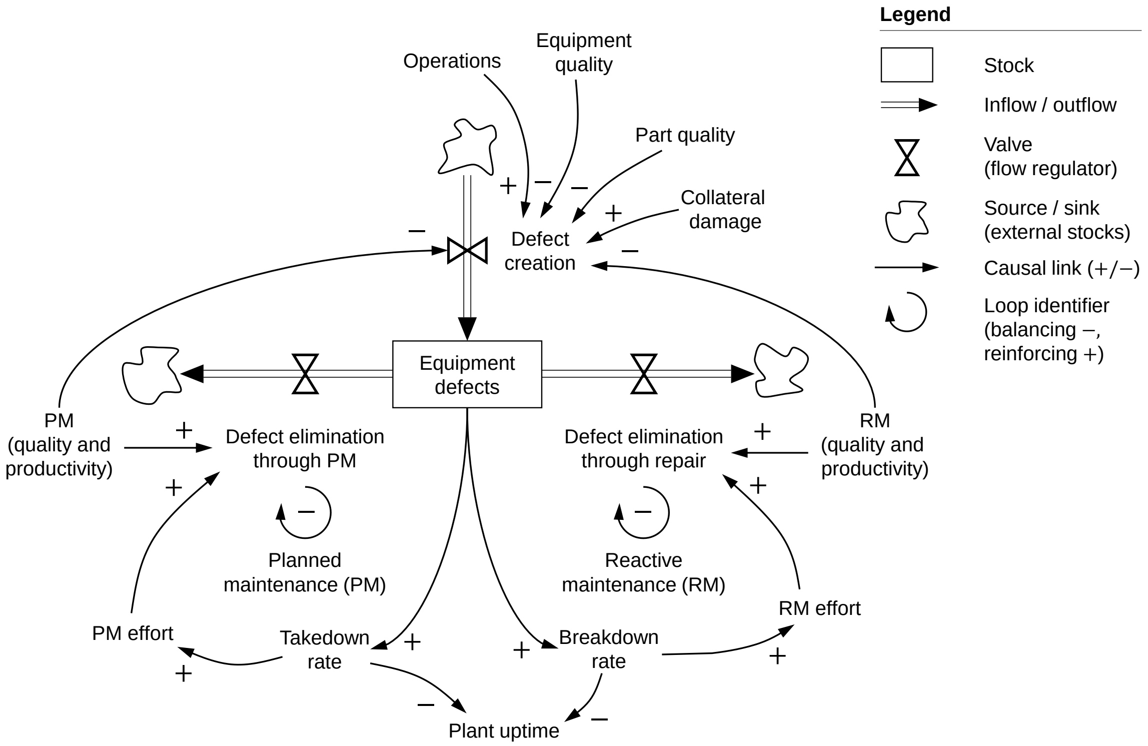


*Figure 2.8: System dynamics model of defect creation and elimination (*Sterman *2000, p. 68)*

This dynamical behavior of complex systems emerging from the interactions of agents and other sources of influence is modeled using stocks[2], flows[3], valves, sources, sinks, polar causal links, and feedback loops as illustrated in figure 2.8. By means of mathematical modeling—i.e., systems of integral and differential equations —the behavior of target variables can be simulated over time to gain valuable insights for system or strategy design. However, the required parameterization of the underlying

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[2] Stocks are accumulations that provide systems with inertia and memory and are the source of delays. They characterize the state of a system (Sterman 2000, p. 192).

[3] Inflows and outflows determine the rate of change of a stock. In general, flows are "functions of the stock and other state variables and parameters" (Sterman 2000, p. 194).

equations is a major challenge, in particular when formal models of socio-technical systems are aspired (cf. e.g., FORD & STERMAN 1998).

2.6 Conclusion

Within this chapter, promising modeling techniques for the analysis of complex systems have been presented to provide a basis for the state of the art review as well as the later design of the model-based method for change impact analysis. At the beginning of this chapter, characteristics of an ideal (in the context of this thesis) modeling approach have been suggested. Namely, the consideration of multiple object types, multiple relation types, manufacturing domain specifics, and the representation of a system's structure, while providing a high degree of modeling flexibility, standardization, and information richness, only requiring little learning effort. Table 2.1 shows a qualitative rating of each of the presented modeling approaches degree of fulfillment with respect to these characteristics.

Table 2.1: Qualitative comparison of system modeling approaches

	Characteristics							
Approaches	Multiple object types	Multiple relation types	Domain specifics	System structure	Modeling flexibility	Standardization	Information richness	Learning effort
Systems Modeling Language (SysML)	⬤	•	•	●	•	⬤	⬤	∙
Object-Process Methodology (OPM)	●	•	•	⬤	●	●	●	•
Design Structure Matrix (DSM)	∙	∙	●	●	⬤	∙	∙	⬤
Multiple-Domain Matrix (MDM)	⬤	●	⬤	⬤	⬤	∙	•	⬤
Fuzzy Cognitive Map (FCM)	•	∙	●	●	⬤	∙	∙	⬤
System Dynamics		∙	•	•	●	●	•	∙

⬤ very good ● good • fair ∙ poor not applicable

SysML—and OPM, to some extent—offer a broad spectrum of diagrams, are highly standardized, and allow to model a variety of object types. Using the package and block definition diagram, different classes of objects can be modeled in SysML. However, the broad spectrum of diagram types and potential information richness of this powerful *general purpose language* has to be confronted with the considerable experience and effort required for building and maintaining actual system models.

As directed and weighted graphs, FCMs are quite similar to DSMs. These approaches are most suitable for the analysis of the structure of a system, allowing for any domain-specific constructs and requiring little learning effort. However, neither multiple object nor relation types can be defined using these modeling techniques.

Essentially, the MDM can be considered as a domain-specific language, which makes use of the flexibility and simplicity of directed graphs, but increases their information richness. This is achieved by the domain-specific definition of node and edge classes for the constituents of a system, contrasting MDMs from DSMs and general-purpose languages like SysML (FRANCE & RUMPE 2005).

The use of a *domain-specific language* has several advantages. Firstly, the modeling language can be customized to a certain problem (GIACHETTI et al. 2009), thus its information content can be tailored according to the intended level of detail and to the relevant aspects of system analysis. Secondly, communication among users within a domain is simplified. Finally, domain-specific languages usually have a restricted semantic scope, reducing learning effort and leading to increased usability for domain expert groups. Drawbacks, on the other hand, are the limitation to a specific domain and the non-existence of standards (FRANCE & RUMPE 2005). As a consequence, to opt for a domain-specific language must be based on a comparison of learning effort, modeling effort, and the requirements of system analysis with a loss of general applicability and the non-existence of established standards.

3 Literature Review

3.1 Chapter introduction and methodology

The focus of this literature review is the discussion of contributions aiming at the analysis, prediction, and assessment of change impact in complex engineering systems. An extensive review was performed using the framework depicted in figure 3.1 (JAHANGIRIAN et al. 2010). Research articles of relevant journals and conference proceedings have been screened in the domains of manufacturing science, product development & engineering design, systems engineering, computer science & information systems, management science, and production economics. Three major research topics were taken into closer consideration:

- *Classification of changeability.* Refers to contributions defining changeability terms or proposing criteria for their distinction. This also includes work dealing with the definition of similar concepts (e.g., flexibility, adaptability, robustness, and agility) which have been studied, but will not be discussed in detail here.[1] Major insights gained from this review have been summarized in section 1.2.3 of the introductory chapter. The concise classification of changeability terminology ensures an objective comparison of contributions dealing with the assessment of changeability and change impact.
- *Evaluation of changeability.* The literature survey in the field of manufacturing science has shown that changeability enablers are considered crucial for the design of changeable manufacturing systems. There is a broad consensus among researchers concerning the relevance of five core concepts, namely: mobility, scalability, versatility, integrability, and modularity. Contributions dedicated to the evaluation of the *degree of changeability* and the *value of changeability* a

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[1] A review of changeability terminology is provided by PLEHN et al. (2016), submission in review.

system provides to its stakeholders have been reviewed to identify appropriate metrics for change impact quantification—as anticipated in section 1.2.5, these metrics are time and money. While the former contributions are generally characterized by an analytic bottom-up approach, the latter often take a more aggregate view on the system of interest. A review of this literature is presented in appendix A.1.2 for the sake of completeness.

- *Prediction of the impact of changes*. Starting from a sound understanding of changeable systems, contributions dealing with the analysis and prediction of change impact in engineering systems are the focus of this literature review. A variety of methods are identified, especially in the manufacturing, engineering design, and systems engineering domains. They are discussed separately depending on whether they are aiming at the analysis of manufacturing changes (section 3.2) or engineering changes (section 3.3).

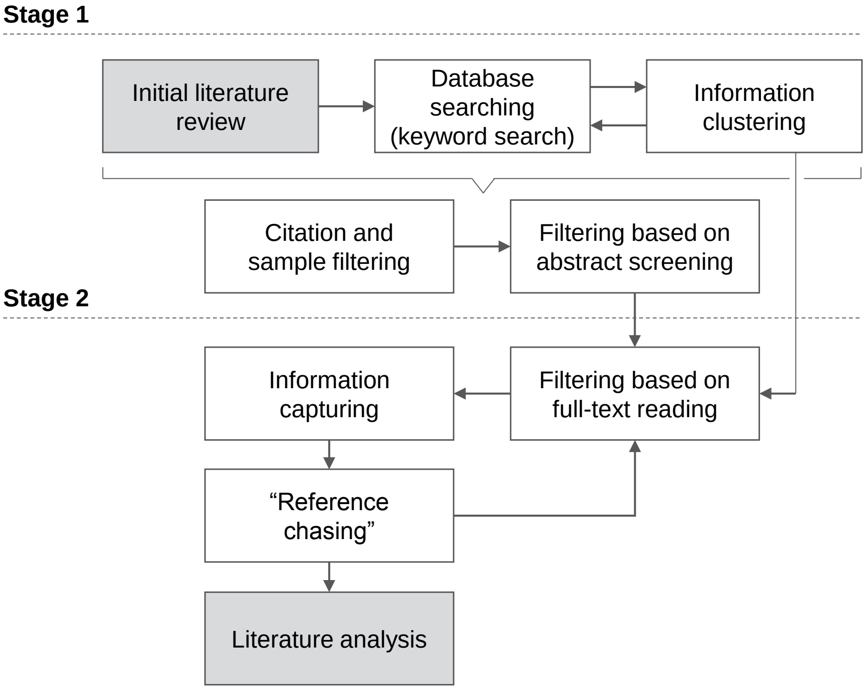

Figure 3.1: Literature review framework based on JAHANGIRIAN *et al. (2010, p. 2)*

A complete list of the screened academic journals and proceedings is provided in table A.1 of the appendix. Additionally, a structured keyword search was performed supported by methods of literature analysis such as forward search and the concept matrix as proposed by WEBSTER & WATSON (2002). Meta-search engines and data bases used include the following: Scopus®, Web of Science™, IEEE Xplore®, EBSCOhost™, and Google Scholar™.

The remainder of this chapter is structured as follows: section 3.2 presents approaches of the *manufacturing domain*, which cover the prediction of change impact in manufacturing systems. Three categories of approaches have been identified, corresponding with the framework of changeable manufacturing (cf. section 3.2.1), i.e., *change driver analyses*, methods for *reconfiguration planning*, and *dedicated impact analyses*. A preliminary discussion of findings is provided in section 3.2.5, before approaches dealing with engineering changes are reviewed in section 3.3. The state of the art review concludes with a summary of findings and research opportunities in section 3.4.

3.2 Manufacturing change

3.2.1 Overview: A framework for changeable manufacturing

As a framework to theorize about the "mechanisms required for manufacturing reconfiguration", AZAB et al. (2013) propose a conceptual *control loop model* (cf. figure 3.2). This framework, introduced by WIENDAHL et al. (2005) & NOFEN (2006), represents the relationships of change drivers (e.g., customer requirements, emerging technologies), system changeability, and the impact of change on a manufacturing system as the change object. Depending on the magnitude of change drivers, two classes of counter measures are distinguished, utilizing the system-inherent flexibility or reconfigurability. If a mere reconfiguration should not be sufficient for the manufacturing system to react to the imposed change drivers, restructuring as the most extensive consequence of manufacturing change has to be executed, having the biggest impact on a manufacturing plant.

For this review, the control loop model shall serve to illustrate the interdependencies of change drivers, strategic system properties (e.g., reconfigurability), and resulting changes of the manufacturing system over time. Three idealized perspectives of the manufacturing literature, touching upon the topic of change impact assessment, have been identified:

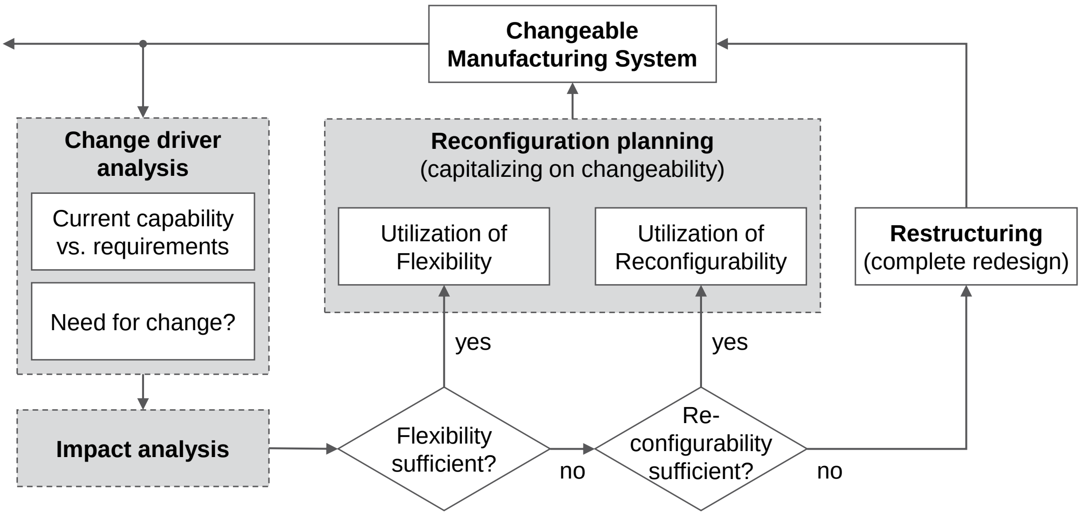

*Figure 3.2: Control loop of changeable manufacturing systems based on (*Azab *et al. 2013, p. 112)*

1. *Change driver analyses (section 3.2.2).* These contributions are devoted to the analysis of external and internal influences on a manufacturing plant. They are unified by the question, if the inherent changeability of the manufacturing system and its constituents is sufficient to react effectively and in due time to new requirements.

2. *Methods for reconfiguration planning (section 3.2.3).* In order to utilize the changeability potential of the manufacturing system, reconfigurations have to be planned according to the constraints and new requirements imposed on the system. A variety of planning procedures has been suggested, which are subsumed under this category.

3. *Dedicated impact analyses (section 3.2.4).* In an industrial context, change requests are usually evaluated in advance of their implementation to avoid wrong, and potentially costly, decisions. Dedicated methods for impact analyses have been developed in different contexts.

These perspectives are often *closely intertwined.* Note that the assignment of approaches in the following sections has been performed based on a subjective judgment. That is, an approach is categorized depending on its *thematic priority* with regard to the above mentioned perspectives.

3.2.2 Change driver analyses

VELKOVA (2014) develops a procedure for changeability analysis of manufacturing systems based on an expert team identifying endogenous and exogenous influences—i.e., change drivers—on the manufacturing system. Change drivers are identified by means of moderated workshops and brainstormings of system experts. Following, the factor's "effect direction" is determined and it is assigned to the four categories change initiators, change drivers, change enablers, and change inhibitors. Enablers and initiators are classified with regard to the company function they are related to, such as e.g., production, quality, and research & development.

The impact assessment is performed using a *reaction rate-flexibility diagram*, where the *reaction rate* quantifies the time required to implement a change and *flexibility* the number of options available to do so. Drawing from an early changeability definition by REINHART et al. (1999), the concept is based on the simplifying assumption that changeability can be expressed as a composition of reaction rate and flexibility. The expert team is finally asked to assess whether the change drivers have the potential to affect either reaction rate or flexibility factors. Additionally, pie and bar charts are used to analyze how enablers and inhibitors are distributed in terms of company functions and changeability types. According to VELKOVA (2014, pp. 79-87), the more factors are assigned to a category, the higher its impact on changeability should be assessed.

KLEMKE (2014) suggests a similar procedure model for changeability planning of factories consisting of two major steps (cf. figure 3.3): *change monitoring* and *changeability analysis*. The fundamental assumption of the approach is that the behavior and development of change drivers in the uncertain environment of manufacturing companies can be predicted. Forecasts, change impact analysis with regard to manufacturing cost, implementation time, and quality, as well as all other steps of the method are carried out by a multi-functional project team on a workshop basis.

Given the confidence that change drivers are predictable, the main objective is to figure out whether necessary changes can be implemented before their implementation is due. For monitoring, analysis, and planning of changes several methods are suggested (KLEMKE 2014, pp. 51-80): The *change dashboard* provides an overview of the elements and relations of a factory using five views depicting processes, layout, organization, logistics, and unit manufacturing cost. A collection of generic change drivers can be used by the project team to understand their impact in each of these

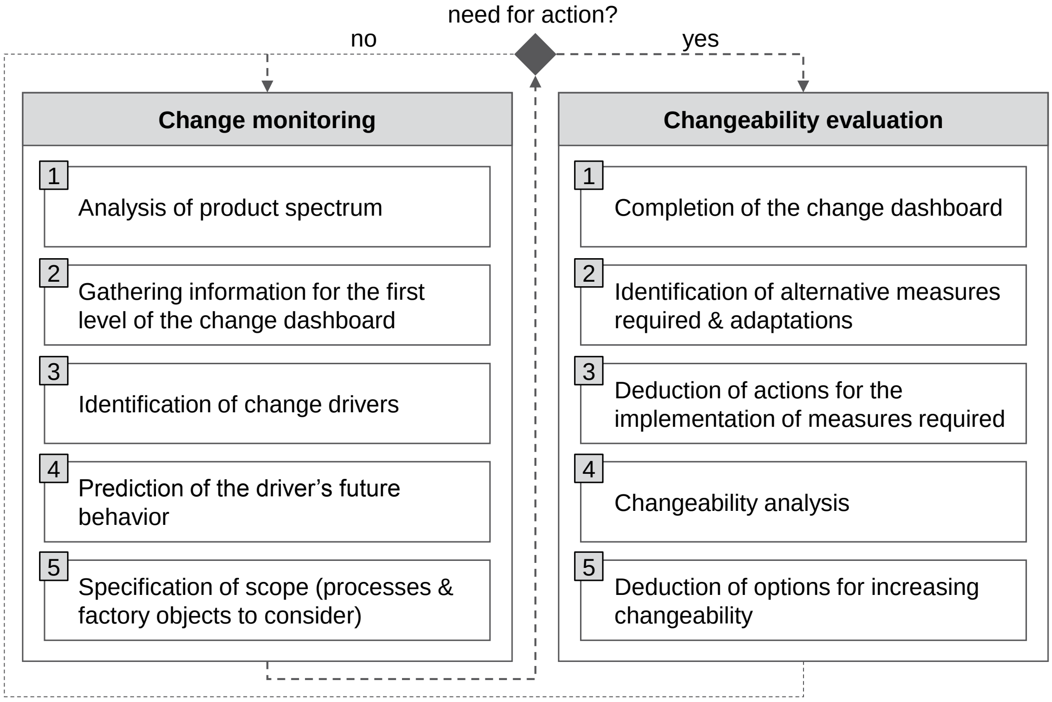

*Figure 3.3: Procedure model for changeability planning (*KLEMKE *2014, p. 83)*

categories. Future effects of change drivers on volume, product variants, and objectives are documented in *development sheets*. Based on the change dashboard and driver development sheets a *catalog of adaptations* is created, describing how factory elements could be adapted with respect to technology, staff, organization, and logistics. Finally, the *activity diagram*, which is basically a Gantt chart, sets the time line for the required activities to react to a future change to determine the total implementation duration.

The *specific changeability* of a factory is eventually measured as a function of time and effort for implementing manufacturing changes: the more time is left between the detection of a required change and its due date and the lower the implementation effort, the higher the changeability of a manufacturing plant is assessed. KLEMKE (2014) provides diverse workshop-based tools for the documentation of a factory's "status quo" in order to enable experts to analyze the effects of changes and their interdependencies with respect to processes, technology, staff, organization, and logistics. The method does not provide a model-based analysis of changes, but depends strongly on the capabilities of project members to identify any relevant consequences due to their expertise.

3.2.3 Reconfiguration planning methods

Reconfiguration of factory structures

In a turbulent manufacturing environment, factory systems are under a permanent pressure for change (DASHCHENKO 2006). Thus, factory structures need to be adapted continuously to maintain high efficiency (ELMARAGHY & WIENDAHL 2009). While focusing on the factory system and workstation level, the approach of CISEK (2005) aims at the continuous identification of needs for reconfiguration to optimize the manufacturing and capacity structure and to evaluate structure alternatives[2] with respect to adaptation costs (CISEK 2005, pp. 8-10). The method proposed encompasses three successive modules: (1) *monitoring*: identification of need for manufacturing structure adaptation, (2) *planning*: development of alternative manufacturing layouts, and (3) *evaluation*: calculation of adaptation costs for possible structure alternatives.

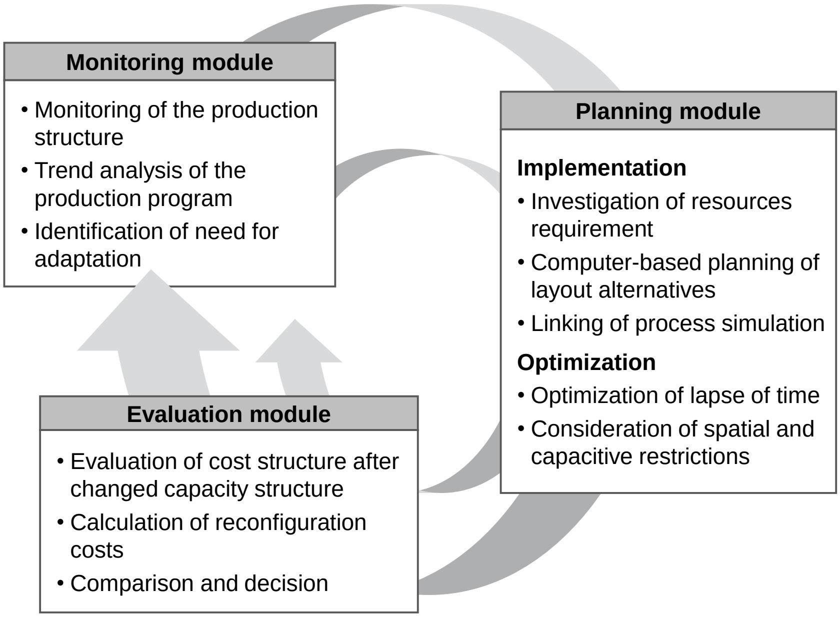

Figure 3.4: Method for the continuous reconfiguration of manufacturing structures (CISEK 2005, p. 56)

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[2] According to CISEK (2005, p. 53), the manufacturing structure defines type, amount, and spatial arrangement of manufacturing resources.

Using key figures for structure, performance, utility, and cost, the *monitoring module* serves to permanently oversee the efficiency of both, the current manufacturing structure and trends in the production program (e.g., introduction of new products, decreasing production volume). It is further used to initiate the planning module as well as to support identification of suitable measures for structure adaptation. The *planning module* is divided into two sub-modules serving the optimization of the existing manufacturing structure and the execution of reconfiguration processes. The former is approached formulating the arrangement of manufacturing resources as a mixed-integer problem and solving it with a genetic algorithm adapted from J. G. KIM & Y. D. KIM (2000). Reconfiguration processes deal with minimizing shortfall in production by coordinating the execution of reconfiguration measures. Within the *evaluation module*, profit or loss due to the changed manufacturing structure is calculated for the successive period. Doing so, saving potentials are estimated and set off against adaptation and investment costs (e.g., cost for disassembly or investments in new machines).

The work of CISEK (2005) offers a procedure for production system reconfigurations consisting of three steps. However, in terms of changes considered, the approach does only allow for varying production volume and product mix and their consequences for the factory structure's capacity.

POHL (2013) develops a method for the identification, conception, and assessment of manufacturing structure[3] adaptations taking product, technology, and manufacturing resource life cycles into account. The approach aims first and foremost at the identification of profitable time windows for the implementation of adaptations in a given manufacturing environment.

The method is based on three related models: elements of the manufacturing equipment, staff, or infrastructure domain as well as their attributes are captured by the *manufacturing structure model*. POHL (2013, p. 54) suggests to store this data in spreadsheets or alike. The *uncertainty model*, which is based on previous work of KREBS (2011), structures qualitative (linguistic) and quantitative (probabilistic) risks with respect to the identification of required adaptations, influences, and the later

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[3] A manufacturing structure describes the composition of individual elements, their arrangement, and their interconnectedness within a production system (POHL 2013, p. 2013).

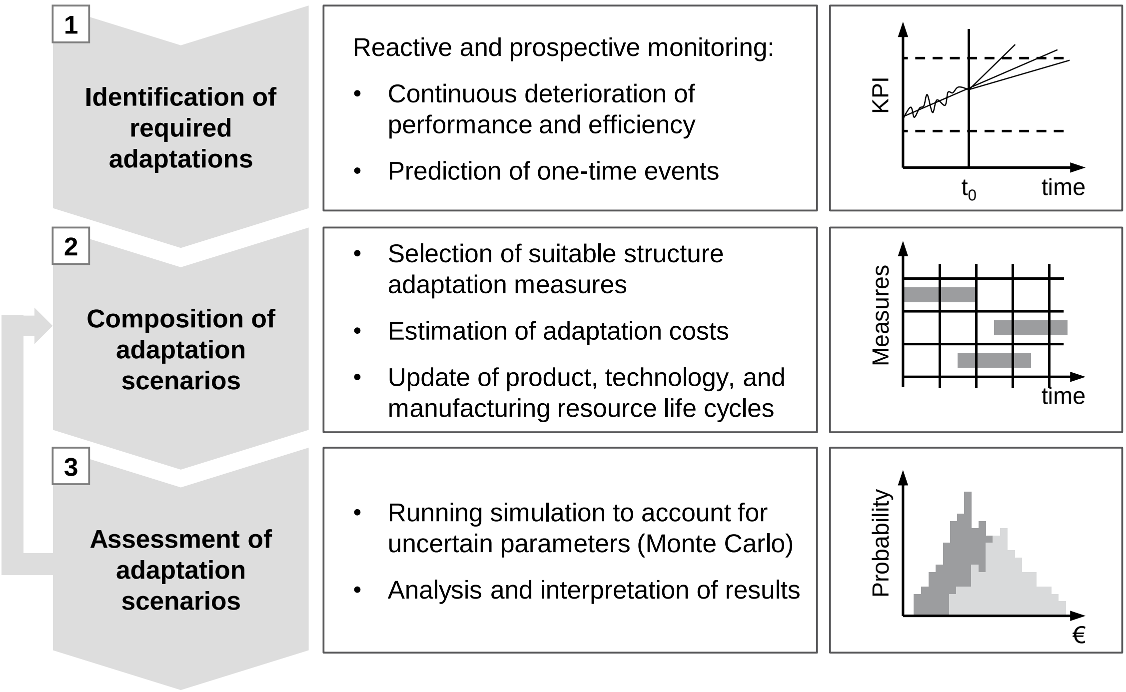

*Figure 3.5: Procedure model for manufacturing structure adaptations (*POHL *2013, p. 62)*

assessment of manufacturing structure alternatives (POHL 2013, p. 57). Finally, the *cost model*—consisting of a cost structure and cost elements—is designed to organize different types of cost resulting from activities required to plan and implement manufacturing structure adaptations (e.g., invest, ramp-up, redesign, and disposal). The cost structure is determined by the element causing the costs, their occurrence over time (life cycle), and the cost type.[4]

POHL's procedure comprises three phases, as shown in figure 3.5:

1. *Identification of required adaptations*. Monitoring of performance and efficiency of the current manufacturing structure using KPIs—i.e., delivery reliability, lead time, unit cost, resource utilization, resource availability, and maintenance cost. Besides, singular events are predicted based on product, technology, and manufacturing resource life cycles.

2. *Composition of adaptation scenarios*. Potential measures for structure adaptation (e.g., substitution, elimination, and parallelization) are derived from the type of

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[4] Cost types are adopted from BRIEKE (2009).

adaptation required. A scenario is defined by varied combinations of elementary structure adaptations within permissible windows of time. These are visualized using Gantt charts.

3. *Assessment of adaptation scenarios.* Analysis of alternatives and selection of the most profitable scenario according to company-specific target dimensions: POHL suggests the use of histograms, two-dimensional portfolios, cost structure diagrams, and sensitivity analyses.

In order to determine the cost of structure adaptation measures, expert estimations are requested (POHL 2013, pp. 85, 89). It is not specified, how this information should be acquired. However, the manufacturing structure and cost model are recommended as means to facilitate and organize the process of expert elicitation.[5]

RICHTER et al. (2014) propose an approach for structural modeling of production systems to enable a quick redesign of plant structures[6]. RICHTER et al. state that prevailing methods for factory modeling do not provide sufficient detail to map the variety of relations between structural elements within a manufacturing plant and are not suitable for predicting knock-on effects of changes. However, due to the interdependencies of the structural elements within a manufacturing plant, numerous other structural elements may be affected by an initiating change (RICHTER et al. 2014, p. 3296). In a *relational matrix*, change drivers are linked to structural elements based on a literature study and the authors' practical experiences. If a dependency is presumed, further details are provided including a brief *effect-description*. RICHTER et al. (2014) do neither provide a method for the analysis of knock-on effects between structural elements nor do they describe the impact of change drivers in quantitative terms.

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[5] Note that the method proposed by POHL (2013) does not use any structural models of factory layouts, but spreadsheet based data models.

[6] RICHTER et al. (2014) refer to the definition suggested by HARMS (2004, p. 12), who states that a "plant structure is formed by a factory's elements and their relations." As the most granular class of factory elements he considers manufacturing equipment such as machine tools and individual work stations.

Reconfiguration of manufacturing resources

KARL & REINHART (2015) present an approach to identify, plan, and evaluate reconfigurations of manufacturing equipment.[7] A reconfiguration is defined as the adaptation of several parts of a manufacturing resource, where adaptations are changes of individual parts in terms of exchange, removal, adjustment, or addition. The approach pursues the selection of favorable reconfiguration alternatives using structural metrics related to complexity[8] and economic criteria as proxy variables for reconfiguration cost. Four major steps constitute the proposed method:

1. *Documentation of current and future requirements / capabilities.* A set of 25 product, manufacturing structure / equipment, and employee related criteria are used for the requirement and capability models (e.g., product dimensions, mass, and mobility).
2. *Identification of required reconfigurations.* By comparison of available and desired capabilities (= requirements), necessary reconfigurations are identified.
3. *Generation of alternative reconfigurations.* Manufacturing resources are modeled using multiple part-to-part DSMs, each reflecting one of seven interdependency-types (mechanical, IT, electrical, fluids, thermal, logical, and functional). Based on these structural models, reconfiguration graphs are generated depicting directly and indirectly affected parts of a manufacturing resource. Reconfiguration costs are estimated accounting for labor (implementation & development), material, and downtime.
4. *Selection of favorable alternatives.* After filtering unsuitable alternatives by disqualifying criteria (e.g., acceptable cost thresholds), reconfiguration alternatives are compared based on structural metrics and reconfiguration cost. The lower the complexity of an alternative, the better it is rated.

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[7] According to KARL (2014, p. 5)—and in line with standard VDI 2815—manufacturing equipment comprises all systems, devices, and installations used for the production of goods and services. KARL (2014, p. 6) restricts this broad definition focusing on equipment capable to perform at least one primary manufacturing or assembly process (e.g., machining, joining, also cf. DIN 8580)

[8] As a proxy for complexity, several structural metrics are computed: number of adaptations, number of interdependencies, number of parts adapted, and percentage of parts adapted.

The structure of the approach is similar to the work of POHL (2013), but focused on a more granular factory level, i.e., manufacturing equipment. Analogous to the structural adaptation measures described by POHL (2013), KARL & REINHART (2015) also require experts to determine reconfiguration costs. In contrast, the approach of KARL & REINHART (2015) is characterized by an extensive utilization of structural models in order to identify directly and indirectly affected parts. Note, however, that only economic parameters are modeled uncertain while affected parts due to a change are considered entirely predictable, which is a questionable assumption in the context of complex systems.

3.2.4 Dedicated change impact analyses

Modeling of cause and effect chains

NOFEN (2006) describes a procedure to derive cause and effect chains for manufacturing changes as a sub-method for change planning of modular factory systems. Generic cause and effect chains for system elements and organizational aspects are characterized, separating directly and indirectly affected elements when planning changes of factory modules. However, indirect changes, which NOFEN describes as knock-on effects of initial desired changes—are neglected, because of their supposed minor importance (NOFEN 2006, pp. 79-91). During change planning, cause and effect chains are used to support the identification of affected objects to check if the time available for change implementation is sufficient. An approach to determine actual investments, labor cost, and time required to perform factory module changes is not provided, though.

WESTERMEIER et al. (2014) analyze the correlations of quality parameters such as material properties and process parameters in lithium-ion cell production to identify the most relevant influences on final product quality. The initial set of parameters and direct parameter correlations has been elicited from expert workshops using Failure Modes and Effects Analysis (FMEA). Based on this data, dependency matrices are constructed from which cause and effect chains of quality parameters for the entire production chain can be derived by matrix multiplication or path search. Cause and effect relations are characterized by the assumed impact magnitude (“severity”), the effect probability of occurrence, and a self-assessment of the expert’s level of confidence. Along a cause and effect chain, the mean values of these estimates are computed. In order to quantify the impact of a parameter on the final product quality, a *risk* measure is introduced as the product of *severity* and *probability*. If multiple paths link a parameter to final product quality, the one with the highest risk value is chosen. The approach of WESTERMEIER et al. (2014) shows the importance of indirect effects in complex manufacturing process chains. However, feedback loops are neglected because the process chain dealt with is strictly sequential.

Engineering Change Management for manufacturing systems

The Institute for Manufacturing Technology and Production Systems (FBK) of the University of Kaiserslautern has been dealing with Engineering Change Management (ECM) for manufacturing systems for more than ten years. Standing for the work of this group, the contributions of AURICH & RÖSSING (2007), MALAK et al. (2011), MALAK & AURICH (2013), and CICHOS & AURICH (2015) are reviewed here.[9]

AURICH & RÖSSING (2007) propose an approach for the management of multiple engineering changes and the assessment of their impact using a Virtual Reality (VR) environment. Manufacturing systems are modeled using UML[10] as a basis for VR visualization. Parameters (e.g., dimensions) of and relations between manufacturing system elements as well as their history are stored in a data base. Referring to the work of CLARKSON et al. (2001), the relations between production objects are captured in a change impact matrix to enable the calculation of similarity indices for manufacturing

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[9] The author is aware of the articles published in German by this research group. Because their core ideas and results are part of the work cited here, they have been omitted. Despite of the limited accessibility of these sources for non German speakers, the interested reader is referred to RÖSSING (2007), AURICH & MALAK (2010), MALAK (2013), and AURICH & CICHOS (2014) for the sake of completeness.

[10] BERGHOLZ (2006)'s software engineering inspired approach for object-oriented factory design also makes use of UML models. Besides, his work contributes to the definition of a high-level taxonomy for objects of and relations within factory systems. SCHADY (2008) develops this idea further and also suggests to use the resulting UML models to support change management in manufacturing (SCHADY 2008, pp. 122, 125-127). However, neither BERGHOLZ nor SCHADY provide a procedure for quantitative change impact analysis using UML models.

changes. The resulting similarity factor[11] is employed to bundle multiple matching changes in an engineering change project to enhance efficiency of change management. Within this procedure, the VR representation of the manufacturing system serves as a source of information for the user and as a means to support the identification of potential change impacts—i.e., activities required for change implementation.

MALAK et al. (2011), MALAK & AURICH (2013), and CICHOS & AURICH (2015) present refinements of AURICH & RÖSSING (2007)'s approach trying to minimize costly production downtime due to the implementation of (multiple) engineering changes. The analysis of change impact is based on a detailed description of changes and is performed in four areas (MALAK & AURICH 2013, p. 350):[12]

1. *Layout.* Checking of infrastructure requirements for the implementation of an engineering change. These comprise, e.g., fixtures, supply systems, dimensions, and load capacities of floor areas.
2. *Process chain.* Comparison of cycle times for machining, handling, transport, and storage before and after an EC implementation.
3. *Conflicts.* Potentially harmful interactions of machines are analyzed, e.g., heat emissions and vibrations.
4. *Interrelationships.* Are material flows interrupted, which might lead to a production shutdown?

The engineering change description contains information about the type of change (i.e., addition, removal, and relocation), the affected production object class (e.g., machine, layout, and transportation equipment), and the type of relation between objects (i.e., material & information flow and manufacturing interrelations). In order to enable an automated change planning based on historical data, generic implementation tasks

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[11] The comparison of different ECs is based on the amount of production objects affected by the triggering change and the overall impact they cause, where impact is measured numerically in terms of the distance between the triggering EC and the affected object (1st, 2nd, 3rd grade). For further details please refer to AURICH & RÖSSING (2007, p. 6).

[12] Unlike in product development literature, where an EC refers to a change of the product, MALAK et al. (2011) and MALAK & AURICH (2013, p. 349) describe ECs in manufacturing systems as "reconfigurations of production objects, as for example machines and working places; addition, substitution, and removal of production objects, e.g., machines or tools; changes to the structure of interrelationships between production objects."

are stored in a data base and complemented by information on required resources, estimated costs, and implementation time—however, the authors do not specify an approach for the prediction of these parameters. Finally, project plans can be derived based on required tasks and the present structure of the manufacturing system. Figure 3.6 shows a flow chart of the method's procedure.

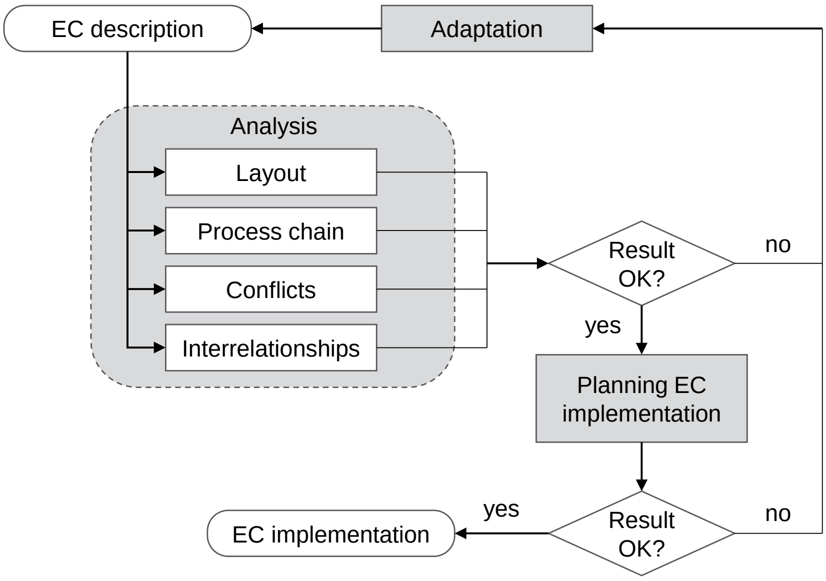

*Figure 3.6: Procedure for manufacturing change analysis (*MALAK *&* AURICH *2013, p. 350)*

Impact of new product and technology infusion

A procedure for the evaluation of the impact of new products and manufacturing technologies on factories is proposed by WULF (2011). The approach aims at the collaborative design of product, technology, and factory structure to mitigate unwanted effects of adaptations (WULF 2011, p. 119). Inspired by technology road maps, the *factory road map* is introduced as a tool to schedule and synchronize change activities due to technology and product adaptations. Essentially, the factory road map is a project plan, which emphasizes possible relations of singular activities in different swim lanes representing planning fields. The *influence level* depicts the occurrence of change drivers (e.g., strategic guidelines, product, technology) over time, while the *development level* contains factory planning fields in a stricter sense, i.e., building, organization, and manufacturing resources (WULF 2011, p. 91).

In addition to the road map, generic attributes of products, technologies, and factories are listed to characterize these factory objects. Information concerning the interdependencies (metric: low, medium, high) of object attributes are captured by the construction of *influence matrices*. WULF (2011, pp. 88, 121) states that the content of these influence matrices is heavily case specific and must be checked by a department-wide multi-hierarchy team for each application. The project team is also in charge of the factory road map and needs to make sure to gather relevant exogenous information regarding product and technology development early in the process.

The assessment of the impact of new products and technologies is performed for each factory object that is believed to be affected by changes. In order to identify these candidates, available and required capabilities—measured by object attributes—undergo a target-performance analysis for each factory object. Following, an expert team needs to judge the extent of necessary adaptations. Estimates for implementation time and cost are assigned to all required *transformation steps* of an object. Types of cost are classified according to BRIEKE (2009, p. 147), who proposed a framework for capital budgeting in factory planning. The resulting *migration path* can then be visualized in the factory road map to check whether the implementation is attainable until its planned due date (WULF 2011, p. 115). Change propagation phenomena, however, are not considered.

Compatibility analysis in mechatronic systems

The development of manufacturing plants requires integrated models allowing for the domain-specifics of mechanics, electrics / electronics, and software. As these systems have a long life cycle, they have to be changed due to evolving customer requirements and shorter update cycles of their sub-systems. KERNSCHMIDT & VOGEL-HEUSER (2013) developed the modeling approach SysML4*Mechatronics*, which is designed to provide a “detailed description of system elements in the different disciplines mechanics, electrics / electronics (E/E), and software as well as their port specifications” (KERNSCHMIDT et al. 2014, p. 149). Using the resulting models, an interdisciplinary analysis of change influences is enabled. The authors propose a procedure for an integrated model-based change analysis of mechatronic manufacturing plants, which "combines two perspectives of change influences, namely on the system structure and on the subsequent life cycle phases" (KERNSCHMIDT et al. 2014, p. 150). The objective is to compare alternative courses of action for engineering changes in early development phases. Future effects of changes are assessed by experts, which are selected according to the respective life cycle phase (e.g., product development and manufacturing). Checklists of common change effects compiled from a literature survey are provided as a guideline.

Focusing on the formal analysis of compatibility issues as a sub-category of change influences, FELDMANN et al. (2014) combine SysML4*Mechatronics* and the Web Ontology Language (OWL), extending the work of KERNSCHMIDT & VOGEL-HEUSER (2013). By appending the SysML-based approach with a semantic technology, (semi-) automatic compatibility checks are enabled through formal representations of the original model. The estimation of change cost or the prediction of knock-on effects is not addressed by this research group. However, KERNSCHMIDT et al. (2014, p. 153) call for methods for a quantitative estimation of engineering change effects that allow for their uncertain propagation behavior.

3.2.5 Interim conclusion

The literature reviewed within this section deals with both the impact of actual and potential manufacturing changes. Table 3.1 provides an overview and comprehensive assessment. All contributions are classified with respect to the system domains considered and the impact metric applied.

While most work is focused on the technical entities of manufacturing plants, the social domain (i.e., people, processes, and activities) is often neglected. Especially in reconfiguration planning, system drivers[13] such as, e.g., the environment, political factors, markets, and technologies are considered crucial. Knock-on effects of manufacturing changes (i.e., change propagation) and the uncertainty of expert judgment, however, are not sufficiently addressed up to now. With respect to change impact

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[13] System drivers are commonly subsumed under the term *turbulent manufacturing environment* (WIENDAHL et al. 2007, p. 783).

assessment, cost and time seem to be the predominant criteria, supporting the assertion stated earlier in section 1.2.5.

Table 3.1: Literature overview of change impact assessment in manufacturing

	Aspects							
	Model domains			*Consid. phenom.*		*Impact assessm.*		
Reference	Technical	Social	System drivers	Knock-on effects	Expert uncertainty	Cost	Implementation time	Associated risk
Change driver analyses								
Velkova (2014)	●	●	●		·	·	·	
Klemke (2014)	⬤		•			●	●	
Reconfiguration planning								
Cisek (2005)	●		•			●	•	
Pohl (2013)	⬤	·	●		·	⬤	•	●
Richter et al. (2014)	●	·	⬤	•		·	·	
Karl & Reinhart (2015)	⬤		•	●	·	⬤	·	●
Dedicated impact analyses								
Nofen (2006)	●	•	●	•		·	·	
Wulf (2011)	⬤	·	•			⬤	●	
Malak & Aurich (2013)	⬤		·	•		●	●	·
Westermeier et al. (2014)	⬤		·	●	●	·		
Kernschmidt et al. (2014)	⬤		•	·		·		

⬤ focus ● investigated • used/modeled · mentioned not considered

While most contributions rather emphasize the process steps required for change driver analysis and reconfiguration planning, Aurich & Rössing (2007) and Malak & Aurich (2013) introduced a model-based approach to manufacturing change analysis. It is broadly accepted that the impact of changes is hard to predict and a matter of uncertainty. Pohl (2013) and Karl & Reinhart (2015) partly tackle this problem by means of uncertain parameters in their cost models. It is striking, however, that manufacturing changes—also referred to as adaptations and reconfigurations—are assumed *static* by this strand of research, meaning that the effect of change propagation is neglected. Albeit, KARL & REINHART (2015) make use of structural models for manufacturing equipment in order to assess alternative reconfigurations, the impact of these changes is assumed predictable.

Another observation is that most authors refer to experts when estimates for change cost or the duration for change implementation are required in the course of their suggested procedures. However, the interdependencies between the models provided and the process of expert elicitation as well as the quality of elicited data remain unclear. Only WESTERMEIER et al. (2014) explicitly model the uncertainty of expert estimates by means of self-assessed confidence levels.

3.3 Engineering change

3.3.1 Introduction

Up to now, manufacturing literature has taken a rather process-oriented approach to the analysis of change impact, with only few exceptions (cf. section 3.2). In contrast, research in Engineering Change Management (ECM) has a long tradition in model-based change propagation analysis on the design parameter and product component level. Recently, HAMRAZ et al. (2013a) provided an up-to-date literature review of 427 publications in the field of ECM as a basis for a holistic categorization framework of ECM literature.[14] The framework encompasses three major phases of ECM: the *pre-change stage* (EC reduction), the *in-change stage* (EC handling), the *post-change-stage* (EC impact analysis)—and general studies & surveys. Besides publications associated to the post-change stage category, methods & tools dealing with change impact analysis during the pre- and in-change stage are especially relevant for this state of the art review. Publications identified during the literature study performed by the author of this thesis were complemented with those assigned to the aforementioned

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[14] The literature study of HAMRAZ (2013) extends existing surveys considerably. Two years earlier, JARRATT et al. (2011) published a review in the same field, comprising 128 references in total.

categories by HAMRAZ (2013, pp. 56-57).[15] Based on the guidelines of FRICKE et al. (2000), HAMRAZ subsumes most methods dealing with change impact under the topic of *more effective* ECM and provides a comprehensive list compiled from his survey.

After an abstract screening process, a total of 65 contributions was short-listed for the ECM domain either dealing with change impact or change propagation analyses. From the plenitude of contributions available, HAMRAZ (2013) identifies eight original comprehensive ECM methods: Change Favorable Representation (C-FAR) by COHEN et al. (2000), RedesignIT by OLLINGER & STAHOVICH (2004), Change Prediction Method (CPM) by CLARKSON et al. (2004), and ADVICE by KOCAR & AKGUNDUZ (2010), as well as the methods suggested by ROUIBAH & CASKEY (2003), CHEN et al. (2007), Y. MA et al. (2008), and REDDI & MOON (2009). However, this rather restricted selection is justified by specific ECM requirements, which are too narrow for the objective of this thesis.

Two of the first methods dealing with the phenomenon of change propagation on the design parameter and attribute level are C-FAR and RedesignIT. Paying tribute to their pioneering role in the field of change propagation research, they are outlined in section 3.3.2. The CPM can be considered as the most established approach for change propagation analysis and the first method dedicated to the product architecture level—including its original publication, 18 of the short-listed research articles are extensions or applications of this method. Thus, the CPM is presented in section 3.3.3, briefly discussing the various amendments published since its development in table 3.2. A classification of these methods is provided in table 3.3 on page 70.

Although the remaining 47 articles cannot be explained in same detail due to spatial limitations, major *methodological*, *system model*, or *design tool* innovations are discussed to thoroughly reflect the current state of knowledge. The review is structured in three categories according to their objects of inquiry, i.e., the *design parameter and attribute* domain (cf. section 3.3.2), the *system architecture* domain (cf. section 3.3.3), and *multi-domain* approaches (cf. section 3.3.5). In total, 38 contributions are assigned to these categories. Finally, 9 contributions dedicated to the *ex post* study of engineer-

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[15] If multiple publications by an author or by a group of authors report on the same method, only the main source is listed. If conference proceedings, a thesis, and a journal publication are available, the latter is referred to in the overview.

ing changes have been identified. These publications are clustered in section 3.3.6 independent from the above mentioned structure. For the sake of better readability, a separate overview of “non-CPM” methods is shown in table 3.4 on page 72.

Note that the framework used for the classification of ECM literature is different than the one used for methods from the manufacturing domain. On the one hand, this is due to the increased level of detail required to distinguish ECM contributions. On the other hand, aspects fulfilled by virtually all of them, e.g., the use of system models, or non of them, e.g., modeling expert uncertainty, are omitted to save table columns and improve clarity. This chapter concludes with a discussion of current deficits and research opportunities based on the reviewed manufacturing and ECM literature.

3.3.2 Design parameter and attribute domain

Change Favorable Representation (C-FAR)

One of the first engineering change propagation algorithms is C-FAR (COHEN 1997). It aims at the qualitative evaluation of Engineering Change (EC) impacts caused by changing the attributes of an initiating entity on the attributes of a target entity (COHEN et al. 2000, p. 322). Entities, such as parts and components of a product, are represented by vectors while the vector components describe the attributes of a particular entity (e.g., size, weight, or material). The number of attributes defines the dimension of a vector. C-FAR’s change propagation mechanism enables a qualitative assessment of relations between product components by matrix multiplication. A linkage matrix between two vectors describes the attribute-specific effect using qualitative descriptors elicited from a domain expert (i.e., high, medium, low). Because the effects are not symmetrical, two matrices have to be constructed for each pair of entities.

After change propagation paths have been defined, a set of vector-matrix multiplications, reflecting the series of relations between initiating and target entity, is performed. To allow for multiple influence paths between two entities, the impact is aggregated at intersections. Change impact of the individual paths is either assumed to be independent from one another (upper bound) or to be correlated (lower bound) to yield predictions for the total linkage value (COHEN et al. 2000, p. 329). The C-FAR algorithm also compensates redundancies that might occur due to correlated attributes by computing so-called orthogonality weights.

The considerable amount of effort needed for data gathering, linkage matrix, and vector construction, as well as multiplication limits C-FAR's applicability to small scale systems (also cf. JARRATT et al. 2011, p. 118). Furthermore, the algorithm is not suitable for graph structures that contain cycles (COHEN et al. 2000, p. 329). Note that the algorithm's purpose is not to predict the total cost of a change, but to analyze whether an entity is subject to change or not.

RedesignIT

RedesignIT is a method and algorithm for a model-based evaluation of redesign proposals (OLLINGER & STAHOVICH 2001, 2004). It is based on qualitative product models that focus on *physical quantities* and their causal relationships. Physical quantities can either describe the properties of a product's components (e.g., the volume of a cylinder) or its operation (e.g., the durability of an engine). Similar to C-FAR, the primary purpose of the algorithm is to automatically identify the parts, which will be impacted by a proposed engineering change (OLLINGER & STAHOVICH 2004, p. 216).

Physical quantities and their relations are modeled in a simplified, semi-quantitative causal influence graph, which captures the order of magnitude (10^0 = small, 10^1 = typical, 10^2 = large) and the causal direction (M^+ and M^-) of influences between design parameters. That way, change effects can be added and multiplied along deterministic causal paths in a propagation tree (cf. figure 3.7). M^+ and M^- describe the dependency of a target quantity as an increasing (or decreasing, respectively) monotonic function of an influencing quantity's magnitude. So-called exogenous quantities, like the piston stroke in figure 3.7, are not affected by any causal influence themselves.

Redesign plans are evaluated in terms of their implementation cost and overall benefit, taking undesirable side effects due to change propagation into account. The overall cost is assessed by total magnitude of unwanted change, the importance of quantity constraints that might be violated, and the implementation cost for initial changes induced by exogenous quantity modifications. As a proxy for benefit, the magnitude of all desired quantity changes is multiplied with their assigned importance and then summed up. Finally, the best redesign plan is selected according to the largest difference of total benefit and cost. Alternative redesign plans result from different combinations of exogenous quantities that lead to the intended changes of a target

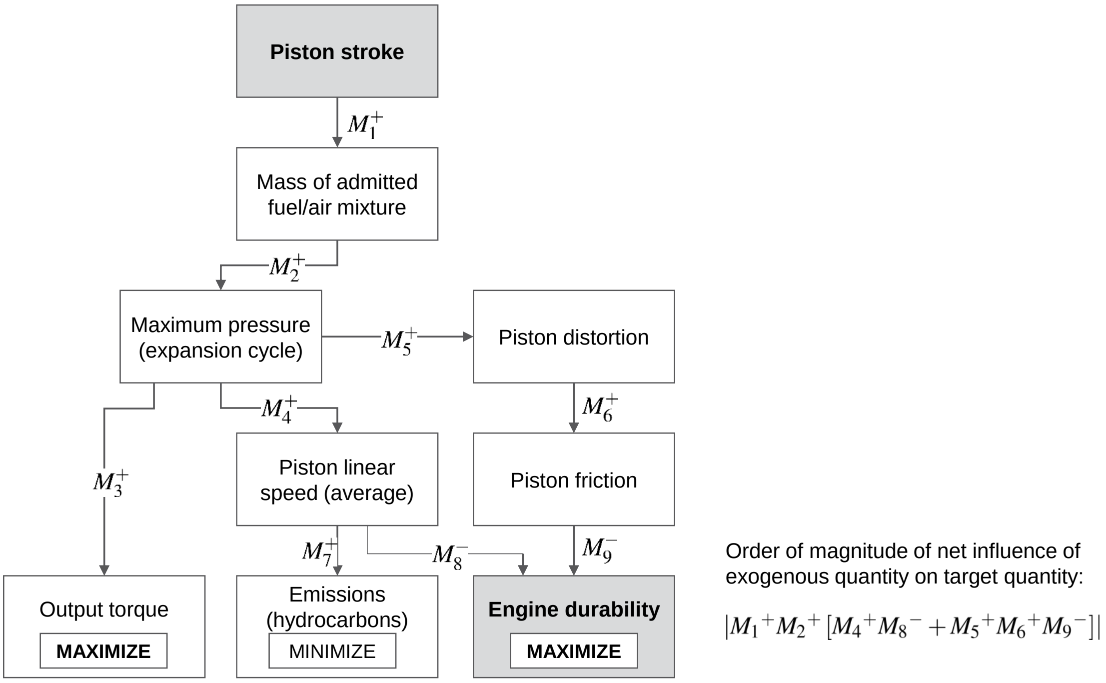

Figure 3.7: Illustration of a confluence of propagating causal influences emanating from exogenous quantity “piston stroke” (cf. OLLINGER & STAHOVICH *2004, pp. 211,212)*

quantity. Simultaneously induced changes and feedback loops of design parameters are not considered.

Other contributions

ROUIBAH & CASKEY (2003) present a procedure for tracking ECs in a concurrent engineering environment involving multiple companies (e.g., suppliers and engineering partners). A *design parameter network model* is built up to trace change impact through the product structure to identify responsible engineers, which have be notified of the change, and to derive a reasonable sequence of their approval. Design parameter relationships have to be identified beforehand during the design process or are based on experience from previous projects. The acceptable model size is limited by the fact that changes are propagated “by hand”.

The *Design Dependency Matrix (DDM)* suggested by CHEN et al. (2007) is a mapping between design parameters and functions. By transforming the DDM into a block-angular matrix[16] *redesign pattern* solutions can be identified. The objective is to isolate portions of a design, which are affected by changed requirements. That way, redesign effort and unwanted change propagation to further subsystems can be minimized. A quantification of change cost and implementation effort or the number of changed parts is not provided, though. An extension of this method, enabling the tracing of propagation paths in ECM, is offered by S. LI & RAJINIA (2010).

Combining the *Characteristics-Properties Modeling / Property-Driven Development (CPM/PDD)* theory for structural product modeling introduced by WEBER et al. (2003) with the *Failure Modes and Effects Analysis (FMEA)* as a well-established quality management tool, the Change Impact and Risk Analysis (CIRA) is suggested by CONRAD et al. (2007) for EC impact assessment. While *characteristics* describe the “shape and structure of a product” (e.g., its geometry), *properties* describe its behavior regarding attributes such as weight, functions, and cost. Properties and characteristics are then linked by relations. The CIRA comprises six steps including a CPM/PDD model-based impact analysis and a risk assessment. Risk is evaluated using a qualitative 1-10 rating scale to analyze the significance of the originally affected property, the likelihood of change success, and the likelihood of further changes. However, the authors admit that the procedure cannot be automated effectively (CONRAD et al. 2007, p. 10).

YANG & DUAN (2012) propose a new *parameter linkage network model* for the analysis of change propagation paths in technical products. The distinction of *fundamental linkages* based on physical laws (e.g., Newton’s laws of motion) and *constraint linkages* based on deliberate design decisions (e.g., function integration) is used to investigate different change propagation mechanisms. *Change routing* and *influence diffusion* between parent and child parameters are identified as major propagation patterns, which are related to four generic change path selection strategies for efficient product redesign (e.g., prioritization of paths with low expected change cost). However, a complete algorithm or tool support are not provided yet.

Generally, most approaches on the design parameter level have refrained from formulating explicit cost models for design changes. An exception is the economic design

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[16] A matrix is in block-angular form if it consists of independent blocks along the diagonal and a set of coupling rows or columns (ROSEN & R. S. MAIER 1990, p. 23).

change model of ROSER et al. (2003), which incorporates uncertain design change effectiveness for the computation of expected profits due to EC implementation.

3.3.3 System architecture domain

Change Prediction Method (CPM)

One of the most established methods for change prediction and the analysis of change propagation in ECM is the Change Prediction Method (CPM), which has been developed by researchers of the Cambridge Engineering Design Centre. The CPM is based on the work of SIMONS (2000) and is presented in detail by CLARKSON et al. (2001, 2004). As a variety of enhanced approaches build upon this method, it is presented in depth.

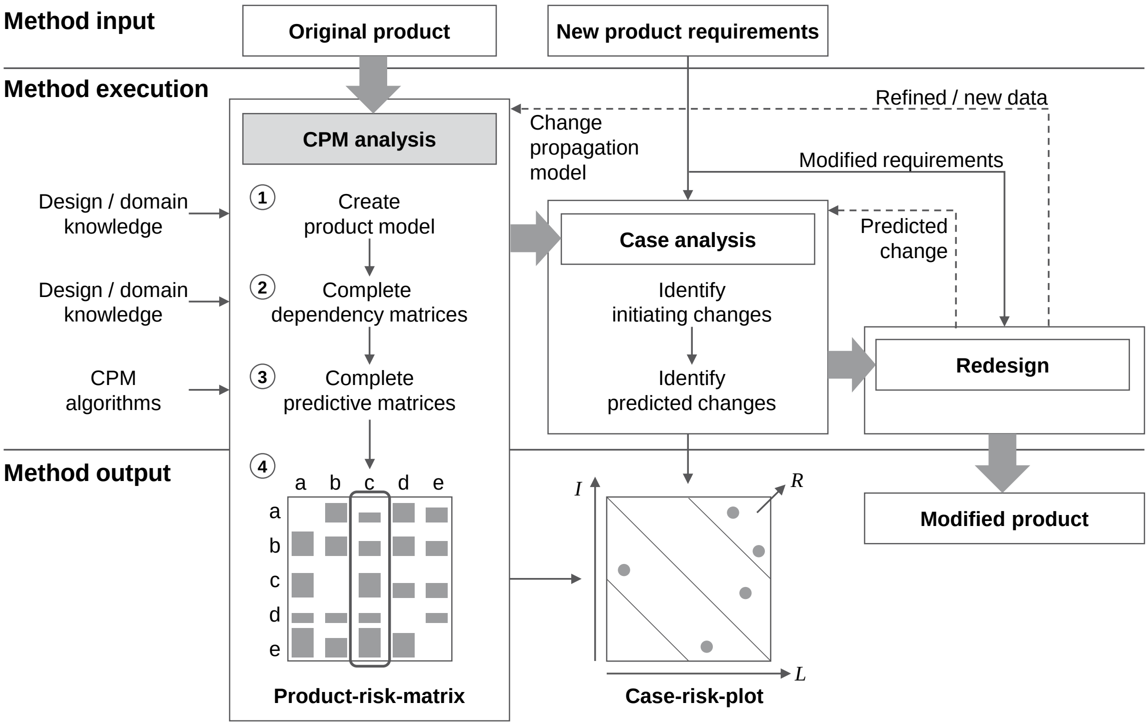

Figure 3.8: Product redesign using the Change Prediction Method (CPM), based on (CLARKSON et al. 2004, p. 791)

The CPM is structured into four major steps, visualized by the procedure of the CPM analysis depicted in figure 3.8:

1. *Creation of the initial product model.* The product is broken down into a suitable number of sub-systems on the component level. Since the modeling effort increases with the number of components n, CLARKSON et al. (2004) recommend to choose the model's granularity such that $n < 50$.

2. *Capturing direct component-component dependencies.* It is assumed that change only propagates along the linkages of a product's network model, which are captured in a component-based DSM. *Direct* dependencies of adjacent components are quantified in terms of direct likelihood and direct impact of change propagation. *Likelihood* is defined as "the average probability that a change in the design of one sub-system will lead to a design change in another" and *impact* as the "average proportion of the design that will need to be redone if the change propagates" (CLARKSON et al. 2004). The required information is elicited from engineers, which either draw from their system knowledge or from past experience about changes for their assessments. These experts also accompany the process of product model development to enhance the overall understanding of possible sub-system dependencies.

3. *Calculate "combined" change risk using the Forward CPM algorithm.* To gain a comprehensive insight of potential impact within a product architecture, all direct and indirect paths leading from all potentially initiating towards all potentially affected sub-systems have to be considered and aggregated in terms of combined change likelihood L, combined change risk R, and combined change impact I. For this purpose, the Forward CPM algorithm is used, which "applies stochastic intersection and union operators along possible change propagation paths to calculate path likelihoods and impacts while excluding self-dependencies and cyclic paths" (HAMRAZ et al. 2013d, p. 770). Figure 3.9 illustrates the logic of the Forward CPM algorithm.

4. *Visualize results in the Product-risk-matrix.* A graphical product risk matrix is derived from the matrices of combined likelihood L and impact I. As the combined risk R is defined as $L \times I$, R can be visualized as the area of a rectangle. The result is used to support the stakeholders of the ECM process in communicating and decision making.

Figure 3.9 shows a partial change propagation tree for three propagation steps starting from component a: along all potential propagation paths the total likelihood of a sub-system being affected is evaluated—i.e., the *combined likelihood*. *Combined risk* can be thought of as impact weighted by probability, which is similar to an expected value calculation.

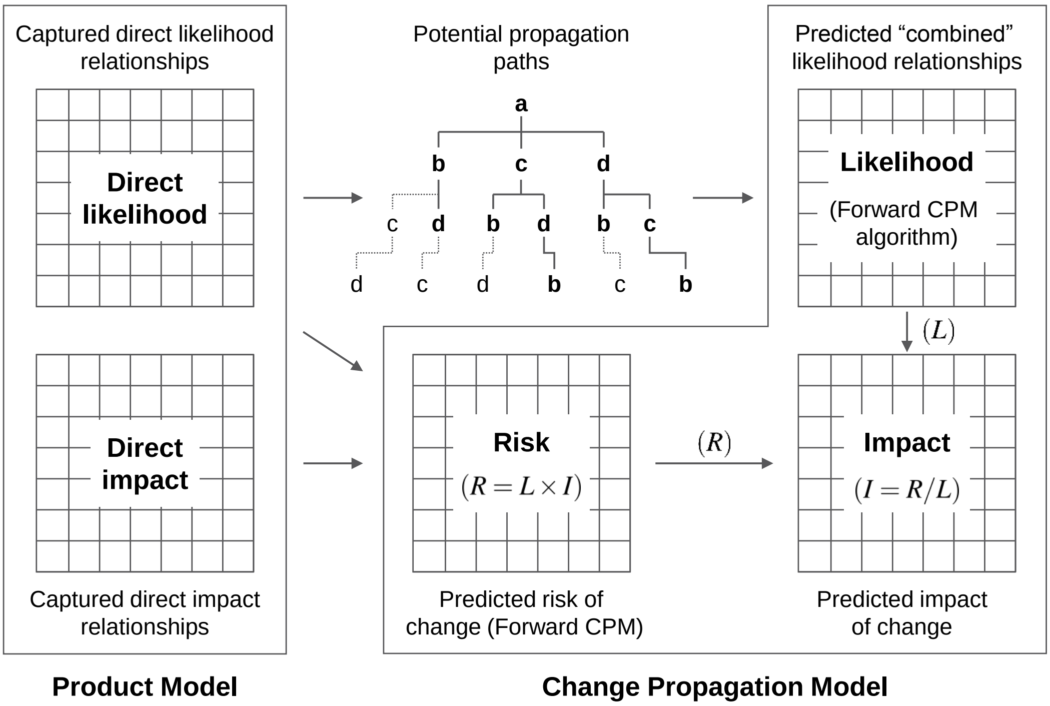

*Figure 3.9: Scheme of the CPM analysis (*CLARKSON *et al. 2004, p. 793)*

Beside the fact that the CPM is not designed to handle cyclic paths, its major drawbacks are that it cannot process multiple initiating changes at once (AHMAD et al. 2010)—which is likely to happen in real-world applications—and that its brute-force search algorithm has a considerable time complexity (cf. also HAMRAZ et al. 2013b, p. 187). Furthermore, the original CPM provides relative results $\in [0,1]$, which have to be multiplied by corresponding estimated design costs in a second step to obtain absolute values for, e.g., time and money. Finally, the uncertainty of input data (= expert estimations) is not incorporated by the model.

Amendments and applications of the CPM

Since its introduction in the early 2000s, various extensions of the CPM have been reported on. Improvements that have been aimed at include (but are not limited to) the complexity of the baseline models, the algorithm, the process of data gathering, and visualization techniques. Additionally, some application examples are available that also address research questions beyond the original purpose of change impact assessment. A full review of these contributions exceeds the spatial limitations and the focus of this thesis. Nevertheless, a brief presentation is provided by table 3.2 and a structured overview can be found in table 3.3 at the end of this chapter.

Table 3.2: Extensions and applications of the CPM

Reference	**Description**
FLANAGAN et al. (2003)	Consideration of change propagation through the linkages between functions and components.
ARIYO (2007) & ARIYO et al. (2008)	Guidelines for hierarchically structured product models enabling a multi-level product decomposition and analysis.
KELLER et al. (2007)	Combination of the CPM with the Contact & Channel Model (C&CM), introduced by MATTHIESEN (2002), to assess change risk. The C&CM is a function-component mapping consiting of abstract Working Surface Pairs (WSP) and Channel and Support Structures (CSS).
KELLER et al. (2008)	An algorithm for determining the cost optimal change freeze order of product components based on simulated annealing.
KELLER et al. (2009)	Visual analysis of change propagation risk in conceptual design based on node-link representations of product architectures.
AHMAD et al. (2010) & AHMAD et al. (2013)	MDM-based approach to manage engineering change processes across multiple domains (requirements, functions, components, and activities) of the design process. Introduction of the Information Structure Framework (ISF) and implementation of a tool support generating dynamic check lists to assess change impact. Consideration of multiple initiated changes and cross-domain impact.

Table 3.2: (continued)

Reference	Contribution
HAMRAZ et al. (2012), HAMRAZ et al. (2013c), HAMRAZ & CLARKSON (2015), HAMRAZ et al. (2015)	Introduction of the Function-Behavior-Structure (FBS) Linkage Ontology for modeling hidden dependencies and cross-domain impact within the structure of a technical artifact. Combination of the Function-Behavior-Structure model by GERO (1990) and the CPM algorithm.
KOH et al. (2012)	Combination of the House of Quality (HAUSER & CLAUSING 1988) with the CPM to analyze the performance of alternative change options regarding the fulfillment of product requirements.
HAMRAZ et al. (2013b)	Algorithm for change propagation analysis based on matrix algebra suitable for an implementation in Microsoft Excel®.
KOH et al. (2013)	CPM-based technique to assess the changeability of complex engineering systems by means of the Incoming Change Likelihood and Impact as well as the Outgoing Change Risk indices.
WYNN et al. (2010)	Comparison of alternative prioritization policies for ECM.

Other contributions

SMALING & DE WECK (2007) investigate the architectural invasiveness of infusing a new technology into an existing product. The authors suggest the *Technology Invasiveness (TI)* index to measure the amount of redesign cost and effort of a technology infusion. In order to obtain the data required for this index, a change Design Structure Matrix, coined ΔDSM, is introduced to capture the number of new, removed, or redesigned components as well as to model changed interconnections of mass, energy, or signal / data flows by comparison of the original and the planned system architecture (SMALING & DE WECK 2007, p. 5). Monte Carlo Simulation is used to model the uncertainty of important design variables. SUH et al. (2010) extend this method and apply it to a printing system, suggesting the *expected* ΔNPV and its standard deviation to evaluate the financial consequences of a technology infusion.

A design tool for the identification of affected parts to ECs and their respective propagation paths is implemented by REDDI & MOON (2009). Attribute-component and component-component relationships have to be captured during the design phase of a product and stored in a *dependency data base*. An EC is characterized by its initiator, its target, its type, and the likeliness of a change to be transferred from initiator to target. Using the dependency data base, parts affected by an initial EC can be identified automatically level by level of a hierarchical product structure. Simultaneously induced changes are not considered and parts are only allowed to be changed once.

H. LEE et al. (2010) use a generalization of the *Analytic Hierarchy Process (AHP)* by T. L. SAATY (1980) based on module-part dependency network models of products. That way, the relative importance of changes to a module or a part for the whole product can be derived. It is expressed by the *Relative Change Impact (RCI)* index. Due to the tremendous effort required for pairwise comparisons within the AHP, which are used to systematically prioritize modules and parts, the approach is limited to small and thus tractable models.

A *weighted product network model* allowing for multiple interaction types is suggested by CHENG & CHU (2012). Based on "structured interviews with experienced engineers and design documentation data" the model is built. Interaction types comprise specification flows[17] as defined by MARTIN & ISHII (2002) as well as spatial, energy, material, and information flows. The weight of an edge within the network depends linearly on the number of links between part i and part j and, thus, reflects the presumed strength of their connection (CHENG & CHU 2012, p. 1421). Three graph theoretic centrality measures are proposed to assess change impact: *degree-changeability*, *reach-changeability*, and *between-changeability*. However, estimates for effort and cost of a design change are not derived from these measures.

3.3.4 Process and activity domain

Using activity-based DSM models of *process networks*, BROWNING & EPPINGER (2002) investigate the impact of alternative architectures on the duration and cost of

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[17] Specification flows are defined as "the design information that must be passed between designers to design their respective components." (MARTIN & ISHII 2002, p. 218)

product development processes. By means of combining discrete event and Monte Carlo simulation, distributions for cumulative cost and duration of the entire process are generated. The uncertainty of activity durations is modeled through *triangular distributions*, constructed based on best, most likely, and worst case estimates. Learning effects for rework are accounted for by an *improvement curve*, which is assumed to have the form of a step function. The approach of BROWNING & EPPINGER (2002) provides sophisticated modeling techniques, which are also valuable for EC impact models. However, propagation phenomena within the process network are not considered. An extension is provided by CHO & EPPINGER (2005), who also consider multiple activity iterations, their overlapping, and resource constraints. LUKAS et al. (2007) and GÄRTNER et al. (2008) report on an application of this approach for the analysis of process alterations on the duration and cost of a development process for a power-train control unit in automotive industry.

A similar approach is adopted by W. LI & MOON (2012), who use *discrete event simulation* to analyze the dependencies of the ECM and the New Product Development (NPD) process to gain insights with respect to their mutual impact and "how these interactions eventually affect the lead time, cost, and quality of a new product development project" (W. LI & MOON 2012, p. 863). The model accounts for rework, process iterations, the uncertainty of EC occurrence, activity durations, and the "completeness" of a design solution. Further applications of discrete event simulations are provided by J. F. MAIER et al. (2014) and WYNN et al. (2014). Aiming at an analysis of progressive iterations, rework, and change propagation in design processes to prioritize design tasks, J. F. MAIER et al. (2014) also allow for the consideration of learning curve effects and a part maturity metric in their model. WYNN et al. (2014) focus on the prediction of resource requirements and schedule risk of change processes. Similarly to J. F. MAIER et al. (2014), iterations during design work flows are being modeled. A significant improvement, compared to most contributions discussed here, is the consideration of multiple sources of change.

Change impact analysis is not limited to conventional product development processes. For instance, ZHAO et al. (2010) apply activity based DSMs to model the information flows between influencing factors and changes for planning complex construction projects. Again, the uncertainty of activity durations caused by rework are generated using Monte Carlo Simulation. Change propagation phenomena are not considered.

3.3.5 Multi-domain approaches

While the vast majority of approaches discussed in the previous sections is dedicated to modeling the dependencies of objects that belong to a single domain (e.g., design attributes or components), this section presents more recent work dealing with inter-domain linkages. AHMAD et al. (2013, p. 220) state that "there has been growing recognition that information from multiple domains of design can be used to more fully understand and manage change propagation." A recent CPM-based multi-domain model has been developed by HAMRAZ et al. (2012, 2015) using the *Function-Behavior-Structure (FBS)* framework introduced by GERO (1990). Figure 3.10 shows the *FBS linkage ontology* network model by HAMRAZ et al. (2015) as an exemplary visualization of an advanced multi-domain approach for ECM.

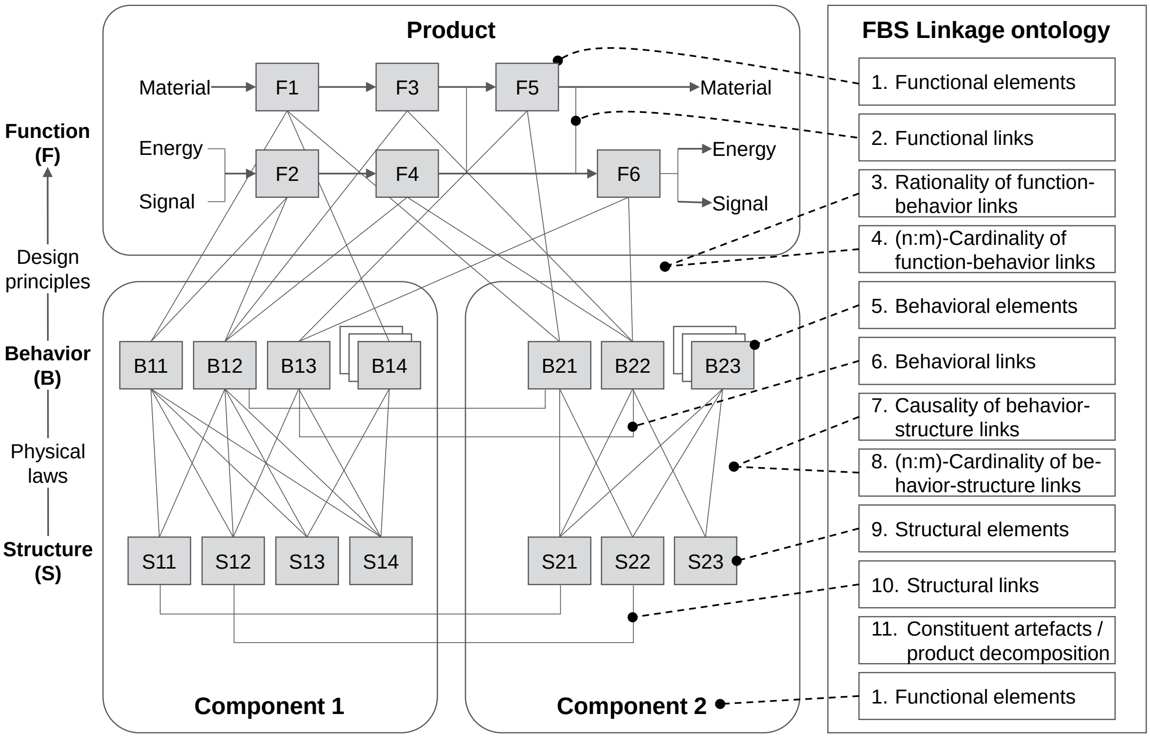

Figure 3.10: FBS Linkage network model and corresponding ontology assumptions (HAMRAZ et al. 2015, p. 15)

One of the very first contributions dealing with multi-domain engineering change assessment is provided by S. MA et al. (2003). An integrated design information model is developed, which combines product (components), process (activities), and resource (people) data by linking them with *design constraint, precedence, and responsibility interdependencies*. That way, changes to the product can be navigated through an integrated model of the design process to identify all affected entities. Furthermore, a task duration computation algorithm is conceptualized (S. MA et al. 2003, p. 5). It is noteworthy that a variety of sophisticated model features such as rework iterations, learning curve effects, uncertain activity durations, task sequencing, cross-domain impact, and the use of historic EC data are already touched upon by this early contribution.

Based on their previous conceptualization of a *cross-domain model for engineering systems* (RUTKA et al. 2006), which is intended to capture the viewpoints of requirements, product architecture, and design activities, LEMMENS et al. (2007) suggest a prototype software environment for deterministic change propagation analysis. A novelty of their approach is the consideration of *linguistic change magnitude qualifiers* (i.e., high, medium, low) between two entities and the possibility of filtering for predefined types of change. These options are used to control the propagation behavior of ECs in the engineering system; e.g., simulating the fact that performing only slight changes to a part does not necessarily require changes of connected parts.

RAFFAELI et al. (2007) suggest a graphical tool for modeling products based on functions, components, and their attributes. The resulting network representations are intended to support the ex ante comparison of alternative implementation options for ECs through an analysis of their resulting change propagation paths. A similar approach is developed by OUERTANI & GZARA (2008) to “assess impacts and study change feasibility.” The so-called *Dependencies Network (DEPNET)* captures the dependencies of product specifications in a graph model. These specifications denote, among others, structural, functional, behavioral, and geometrical properties defined during the design process. Using data captured in a repository throughout the design process, the DEPNET can be automatically generated by a set of SQL queries. By propagating a potential change through the network, a “list of the product specifications to be modified is established as well as a list of the activities for applying these modifications” (OUERTANI & GZARA 2008, p. 835).

The *unified feature modeling scheme* by Y. MA et al. (2008) is proposed to maintain the validity and consistency of product models in concurrent engineering. A unified feature is defined as “a combination of geometric references, non-geometric attributes as well as explicitly defined inter- or intra-feature relations" (Y. MA et al. 2008, p. 111). Features are the basis of the *Justification-based Truth Maintenance System (JTMS)* dependency network model covering functions, constraints, justifications, and properties of a product. A change propagation algorithm is developed for constraint checking and consistency control within this model. The algorithm makes use of a numerical constraint solver and a rule-based expert system reflecting experts' decision heuristics. Since the model is intended for the analysis of geometric modifications, the level of detail is inappropriate for a complex engineering system. Cost or effort predictions for geometric modifications are not considered.

FEI et al. (2011) state that effective change impact assessment during the design phase should involve both the modeling of functional requirements and the physical domain, i.e., the components of a product. In order to create a *composite matrix*[18] of the relationships between functional requirements and the physical structure, SysML block definition diagrams (for function-function relations), CAD models (for spatial relations), and SysML internal block diagrams (for function-component relations) are required. Changes are manually traced through a product design using the composite matrix.

Aiming at the quantification of overall impact in terms of *design project delay*, CHUA & HOSSAIN (2012) present an integrated model of redesign activity change propagation and its scheduling. Similar to the CPM, a *transition matrix* is used to capture the probabilities that change will propagate from one activity to another. However, the approach also accounts for the "degree of change initiated in the upstream activity" based on the assumption that it is more likely that a successor will be affected severely if its predecessor's degree of change is high.

3.3.6 Data-based engineering change analysis

In contrast to the work discussed so far, this section briefly summarizes research into *past* Engineering Changes (ECs). The primary objective of such approaches is usually to reveal patterns in historic data to gain insights regarding the behavior and impact

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[18] The composite matrix is basically a Multiple-Domain Matrix (MDM) for functions, components, and different flow types connecting the elements of these domains.

of ECs that may be useful for the management and assessment of present or future ECs.

Do et al. (2008) propose a product data model that is used to record the structure-oriented *change history of a product*, which also contains information about possible configurations and their assembly structure. The suggested EC propagation procedure uses information on past changes to maintain data consistency. Different data views are suggested for design, manufacturing, and customer support.

Kocar & Akgunduz (2010) develop the *Active Distributed Virtual Change Environment (ADVICE)* as a data-based approach to manage Engineering Change Requests (ECRs). Applying sequential pattern mining techniques on the history of similar changes stored in a data base, ECRs can be prioritized depending on their assumed impact in terms of the expected design work that needs to be redone if an ECR should be implemented. Historic change data is also used to predict change propagation, which is assessed based on probability values that quantify the likelihood of "an attribute change to serve as a basis for triggered changes." An advantage of this approach is that a prior recording of functional dependencies of attributes or system components is not a prerequisite.

In order to understand "how and why changes propagate during engineering design", Giffin et al. (2009) analyze 41,500 change request over a period of 8 years, which have been documented in the course of a complex defense sensor system design. They identify different types of patterns composed of parent, child, and sibling changes by *statistical and time-lapse analyses*, which are described as elementary *change motifs*. Based on the work of Suh et al. (2007), the normalized *Change Propagation Index (CPI)* is applied to identify change multipliers, absorbers, and carriers within the engineering system. That way, the propensity of a system element to "act as a propagator of change" can be quantified objectively. This data-driven approach is amended by Pasqual & de Weck (2012), who suggest a *multilayer network model* integrating the product layer (affected components), the change layer (required changes), and the social layer (responsible engineers) as a comprehensive representation of ECM processes.

Another a posteriori analysis of engineering change data was performed by Siddiqi et al. (2011). In the context of a "multi-billion dollar development project of an offshore oil and gas production system", insights for effective design and management strategies—such as the identification of *change hotspots*—are derived from the analysis of cost, project time, and location of changes.

MEHTA et al. (2010) develop a data-driven approach to compute *similarity* between proposed and past ECs to derive impact estimations. In order to predict the impact of a proposed change, *empirical probability distributions* of impact are linked to a multitude of attribute values of ECs.

Knowledge management for "achieving efficient retrieval and reuse of past engineering changes" has also been studied by H. J. LEE et al. (2006) in the context of a Korean automobile manufacturer. The authors state that conventional ECM systems merely support the processing of ECs (e.g., issuing and approval of EC orders) and the storage of related documents. They suggest an automated *Collaborative Environment for Engineering Change Management (CECM)* to retrieve and reuse knowledge of past ECs for efficient ECM applying an *information-based similarity measure*.

3.4 Summary and research opportunities

In this chapter, procedure models, algorithms, simulation models, and methods in the context of change impact assessment have been discussed to identify promising research paths for this project. While section 3.2 is devoted to the analysis of manufacturing changes, section 3.3 is focused on ECM methods and the analysis and prediction of engineering changes. Summarizing, the following general conclusions can be drawn from both parts of the literature review:

1. The *heterogeneity of contributions* dealing with manufacturing change is generally higher than in the field of ECM. Three different streams of literature could be identified in the context of manufacturing change research: change driver analyses (section 3.2.2), reconfiguration planning (section 3.2.3), and dedicated change impact analyses (section 3.2.4).
2. Virtually all ECM approaches are based on *structural modeling techniques*—in particular, the Design Structure Matrix—and a large proportion of articles is devoted to the prediction of *change propagation phenomena*. Starting from the design parameter and system architecture perspective on technical products, the focus of research activities recently shifted to *multi-domain models* covering

dependencies among attributes, components, functions, requirements, and design activities. However, non of the reviewed work is comprehensive in this respect, i.e., only a subset of these domains is being dealt with.

3. While the predominant *metrics for impact quantification* in manufacturing are cost and time, ECM approaches much rather aim at the identification of affected parts than to provide an aggregate impact estimate. Information on expected cost and duration of implementing a change as well as the associated risk are considered highly valuable for decision making, though.

4. ECs are a major trigger for manufacturing changes—i.e., product-induced effects of changes in manufacturing systems. Yet, non of the 65 reviewed publications deals with this kind of *cross-domain impact analysis*, which confirms the previous research of HAMRAZ et al. (2013a, p. 492), who states that "there has not been any publication focusing primarily on the impacts of ECs on manufacturing and post-manufacturing stages."

5. Both manufacturing and ECM literature recognize the *uncertainty of change impact* predictions. Albeit, all non-data-based approaches rely strongly on the knowledge, experience, and judgments of experts, only very few contributions deal with the inherent uncertainty of these sources. Eliciting and formalizing expert opinion in this context still remains a research path that should be pursued.

6. The technique applied most often to model uncertain parameters, factors, and mechanisms is *Monte Carlo Simulation (MCS)*. With very few exceptions, the underlying probability density functions from which samples are drawn presume normally distributed data. In contrast, BROWNING & EPPINGER (2002) favor the use of positively skewed beta distributions while W. LI & MOON (2012) suggest Erlang distributions for modeling uncertain activity durations.

ECM approaches reviewed have been clustered depending on their targeted domains, i.e., design parameters, system architecture, or processes & activities. Besides, also multi-domain and data-based approaches have been identified. As some of the multiple-domain models involve functions and requirements, this column has been added to table 3.3 and table 3.4.

Table 3.3: Literature overview of CPM extensions and applications

	Aspects										
	Model domains					*Consid. phenom.*			*Impact assessm.*		
Reference	Design parameters	Product components	Functions & requirements	Process & activities	System drivers	Cyclic structures	Simultaneous changes	Propagation behavior	Cost	Implementation time	Associated risk
Method / algorithm											
CLARKSON et al. (2004)		⬤						·	·	·	•
KOH et al. (2012)	·	●	●				●		·	·	
AHMAD et al. (2013)	●	●	●	●			⬤		·	●	•
HAMRAZ et al. (2013b)		⬤							·	·	•
System model											
FLANAGAN et al. (2003)		●	●					·			
KELLER et al. (2007)	·	⬤	●								
ARIYO et al. (2008)		⬤							·	·	
HAMRAZ et al. (2015)		●	⬤					•	·	·	•
Visualization											
KELLER et al. (2009)		⬤						·	·	·	●
Alternative use case scenarios											
KELLER et al. (2008)		⬤							●	•	•
WYNN et al. (2010)		⬤				●		●		•	·
KOH et al. (2013)		⬤						·	·	·	•

⬤ focus ● investigated • used/modeled · mentioned not considered

The salient role of the Change Prediction Method by CLARKSON et al. (2004) could be confirmed, with 12 extensions reported on in a total of 18 research articles (cf. table 3.3). Although HAMRAZ et al. (2015) apply the CPM algorithm to Function-Behavior-Structure models of technical products, the main focus of CPM applications remains the analysis of change impact in component-component dependency networks.

However, simulating *simultaneously initiated changes*, which are triggered through different elements of a system, cannot be tackled effectively yet. Partial solutions to this problem are suggested by KOH et al. (2012) and AHMAD et al. (2013). Beyond that, *cyclic system structures* of engineering systems are generally prohibited—meaning that re-changing objects or redoing activities cannot be simulated using the CPM.

Table 3.4 shows an overview of all "non-CPM" methods reviewed in section 3.3. Looking at this table, it is striking that none of the research performed so far explicitly accounts for the influence of external *system drivers*, although their importance for product development and systems engineering is generally recognized in literature (cf. e.g., FRICKE & SCHULZ 2005). The overview also supports the assertion that the *quantification of change impact* in terms of cost, time, and risk is deemed important: roughly 66% of contributions at least mention the relevance of predicting change cost (18 of 27) and implementation time (17 of 27). The spread—i.e., the associated risk—of at least one of these metrics is addressed or modeled by about 41% of reviewed approaches. Nevertheless, a comprehensive assessment is only provided by BROWNING & EPPINGER (2002), W. LI & MOON (2012), and S. MA et al. (2003).

Finally, it must be noted that the *variety of relation types* between the entities of multiple-domain models is not yet accounted for. While single-domain models such as the CPM only consider one type of linkage (e.g., component-component interactions), multiple-domain models are characterized by a variety of interdependency types. None of the work reviewed, however, offers modeling guidelines for manufacturing systems and their socio-technical characteristics. A selection of *technical dependency* types like energy, signal, and material flows are addressed by KARL & REINHART (2015), SMALING & DE WECK (2007), and CHENG & CHU (2012). The development of such guidelines is an indispensable prerequisite for well-founded model-based impact analyses in this domain. The method developed in this thesis tries to resolve the described research challenges. Promising methods and techniques suggested by both manufacturing and ECM research, will be taken into account for the conceptual design presented in the following chapter. In particular, this includes the adoption of structural modeling to represent the underlying engineering system and Monte Carlo Simulation to capture the uncertainty of change propagation and its impact—since these methods have proven their potential in a broad spectrum of applications.

Table 3.4: Literature overview of change impact assessment in ECM

	Aspects										
	Model domains					*Consid. phenom.*			*Impact assessm.*		
Reference	Design parameters	Product components	Functions & requirements	Process & activities	System drivers	Cyclic structures	Simultaneous changes	Propagation behavior	Cost	Implementation time	Associated risk
Method / algorithm											
Cohen et al. (2000)	⬤	·				·	●				
Browning & Eppinger (2002)				⬤		●		•	●	●	●
Roser et al. (2003)	●								●		●
Rouibah & Caskey (2003)	⬤	·		•							
Ollinger & Stahovich (2004)	⬤	·					●				
Chen et al. (2007)	⬤	·	⬤				●		·	·	
Lemmens et al. (2007)		●	●	●		•		●	·	·	
Smaling & de Weck (2007)	•	⬤					•		·	·	●
H. Lee et al. (2010)	·	●	·								●
Suh et al. (2010)	•	⬤					•		●	·	⬤
W. Li & Moon (2012)				⬤		·		•	•	●	●
J. F. Maier et al. (2014)		•		⬤		●		⬤	·	●	
Wynn et al. (2014)				⬤		●	●	●	·	⬤	●
System model											
S. Ma et al. (2003)	·	●	·	●					●	●	•
Rutka et al. (2006)		●	●	●		·			·	·	·
Conrad et al. (2007)	●	·	●						·		•
Chua & Hossain (2012)	●			⬤	·			●	·	⬤	
Y. Ma et al. (2008)	●	●	●	•			•				
Fei et al. (2011)		●	●					·			
Cheng & Chu (2012)		⬤				·					
Yang & Duan (2012)	⬤	·						⬤	·	·	
Tool support											
H. J. Lee et al. (2006)		●		●					•	·	
Raffaeli et al. (2007)	●	●	●							·	
Ouertani & Gzara (2008)	•	●	•	●		●			·	·	
Reddi & Moon (2009)	·	⬤		•					·		
Kocar & Akgunduz (2010)	●	●	·	•					·	⬤	
Zhao et al. (2010)				⬤						●	●

⬤ focus ● investigated • used/modeled · mentioned not considered

4 Conceptual Design of the Method

4.1 Chapter introduction

The main objective of this thesis is to design a model-based method for analyzing the impact of changes and their propagation in manufacturing systems. Based on the literature study performed in the previous chapter and first interviews with industrial experts, targeted use case scenarios and potential users of the method are defined in section 4.2. Following, general (substantive) and model (normative) requirements of the method are stated in section 4.3, and the underlying assumptions of the approach are clarified in section 4.4, before the conceptual design is presented in section 4.5.

4.2 Targeted use case scenarios

The method to be developed in this contribution is designed to support engineers in charge of or taking part in all activities that are concerned with technical changes in manufacturing companies. Above all, this includes the following functions: change management, simultaneous engineering, product development, technology management, plant design, production controlling, and manufacturing strategy. Since the quality of results obtained by using the method relies strongly on the quality of expert knowledge, it is recommended to install a cross-functional team for the change impact assessment on a project basis. Evidently, not all above mentioned functions are required at any time or to the same extent (e.g., some experts will merely be consulted to elicit their judgment).

1. *Enhancement of system understanding and stakeholder communication.* The assessment of change impact in manufacturing systems prior to change implementation is a challenging task in industrial practice. Unexpected propagation effects of changes can significantly increase required efforts and costs. On the

one hand, it is crucial to improve system understanding and the awareness for change propagation in complex manufacturing systems. On the other hand, transparent and applicable techniques for change impact assessment are required, which also enhance communication among all relevant stakeholders that have to deal with manufacturing change (e.g., at the interfaces of product development, technology management, and manufacturing). Factory and change managers need to be provided with the ability to assess the impact of changes and the risk associated with them in advance of their implementation.

2. *Comparison of alternative change options.* In engineering and manufacturing change management, alternative concepts should be compared already in early conceptual phases to avoid unfavorable decisions. A quantitative comparison should be performed with respect to required investments, implementation effort, and associated risk (i.e., the potential spread of results). In the context of technology management, alternative technologies might be interesting for future applications or to reduce manufacturing cost. In order to assess such a "portfolio of technology investments, one would like to position different technologies in terms of invasiveness, associated risk, and value" (SUH et al. 2010, p. 187). The assessment of changes induced by product or manufacturing technology infusion supports this task. Because of inevitable imprecision of data and simplifying assumptions, results of model-based analyses have to be interpreted as approximate values. Nevertheless, set in relation to each other, they are still very useful for decision making (DE NEUFVILLE 2003).

3. *Supporting capacity planning and resource allocation.* Changes in complex manufacturing systems can be costly and time-consuming—especially, if unexpected change propagation effects occur—and might require production downtime. If changes have to be implemented, it will be important to know the range of possible outcomes with respect to required resources for the implementation of manufacturing changes to carry out capacity and budget planning. Worst case scenarios are often underestimated due to a lack of knowledge about possible change propagation paths that might enlarge the scale of a change project considerably (TERWIESCH & LOCH 1999).

4. *Focusing of change management efforts.* Beside the comparison of alternative change options, the identification of change-critical elements, and change propa-

gation is valuable information for manufacturing change management. Knowing about the influence of changes can help to focus change management efforts. According to ECKERT et al. (2004, p. 13) "systems and parts respond to change in different ways, ranging from systems that do not pass on change to those that amplify change. This change propagation behavior is dependent upon the particular change situation." Based on change impact analysis, four types of change propagation behavior can be distinguished, i.e., constants, absorbers, carriers, and multipliers.[1] Apparently, multipliers are most critical as they can lead to *snowball effects* and *change avalanches* (ECKERT et al. 2004, p. 18).

5. *Efficient incorporation of changeability*. As manufacturing systems evolve over time, changeability is a beneficial property to reduce switching costs, e.g., due to new products or process changes. However, it is a challenging task to decide where to embed flexibility to maximize cost efficiency. Identifying system elements, which should incorporate changeability equals searching opportunities for real options in a system (DE NEUFVILLE 2002). As SILVER & DE WECK (2007, p. 175) put it, "a real option can be framed simply as a feature embedded 'in' or 'on' an initial design configuration to lower future switching costs." Change impact analysis can help to make informed decisions about how and where to embed changeability to enable system evolution most efficiently. Furthermore, such an analysis can also serve as a justification for investments in flexible solutions.

6. *Potential and feasibility studies*. Potential and feasibility studies, where a complex network of uncertain interlinked effects needs to be considered, are a further important use case scenario. Although the focus of the approach developed here is on manufacturing systems, it might be applicable for feasibility studies in the broader context of engineering systems, where the level of abstraction is virtually unlimited. For instance, an investment in a disruptive manufacturing technology may also be accompanied by business model alterations and organizational changes that have to be evaluated.

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[1] Also cf. the Change Propagation Index by GIFFIN et al. (2009), which is suitable for the formal differentiation of these types of behavior based on in- and out-degree calculation.

4.3 Requirements specification

General requirements

R.1 *Enhancement of system understanding*. The complex nature of interdependencies within manufacturing systems requires a structural modeling technique, which allows to analyze potential change propagation effects. Relevant objects, relations, and attributes of manufacturing systems have to be considered on a suitable level of granularity to be concise but also flexible, depending on the amount of reliable information available. The process of model building and expert elicitation should increase system understanding of stakeholders to ensure that no crucial dependencies are missed.

R.2 *Consideration of uncertain change propagation*. Even the most knowledgeable experts experience uncertainty when asked to assess the probability of a change to happen and to predict its impact in terms of necessary investments and time for implementation. Hence, these uncertainties have to be considered by the approach to attain sound results. As mentioned earlier, propagation phenomena of changes in highly interconnected engineering systems are the rule, not the exception. Thus, a useful method needs to take change propagation into account to be able to quantify the full extent of potential change impact.

R.3 *Consideration of cross-domain effects*. It is understood that changes in manufacturing may affect other domains, like e.g., procurement, logistics, distribution, or product development. Thus, the method needs to incorporate the interdisciplinary nature of manufacturing changes when striving for a comprehensive assessment of change impact. Hence, a sufficient degree of freedom is required with respect to the types of relations and entities considered in structural models of the system of inquiry.

R.4 *Provision of decision support*. The paramount objective of the approach is to provide decision support for practitioners in manufacturing companies in charge of potentially complex (investment) decisions. Hence, the analysis must be based on quantitative decision criteria to capture the consumption of valued resources (i.e., time and money) and to evaluate the associated risk. Numerical values need to be interpretable and of utility to stakeholders to decide upon manufacturing changes to prioritize, compare, or discard them. Evidently, this also implies the need for valid and accurate results.

R.5 *Justifiable level of effort.* In order to achieve a reasonable benefit-to-cost ratio, a low effort for collecting required data, building the model, and computing results is favorable. Hence, an appropriate trade-off between modeling effort and model detail has to be chosen. As a means to increase the efficiency of model building, guidelines for system model development should be provided.

Model requirements

R.6 *Flexible, adaptable, and reusable models.* As the approach shall be designed to cope with a multitude of change types, it needs to be flexible in this regard. System models might evolve over time due to the successful implementation of changes, which is why they should be adaptable to allow for a reuse in different contexts.

R.7 *Transparency.* The entire procedure leading to numerical results has to be transparent and comprehensible to decision makers. This also applies to any tool support and visual information that might be provided.

R.8 *Synchronous processing of multiple changes.* A system may be affected by multiple changes at once. Hence, the approach needs to be able to process different initiating changes simultaneously and to evaluate their joint impact on the system.

R.9 *Cyclic system structures.* Propagation effects of changes can lead to cyclic structures in real-world applications. When assuming a conventional propagation tree structure, cycles cannot occur. However, in some cases, a repeated change of an object or performing a sequence of activities iteratively can make sense in reality and should thus be included to the model. Excluding cycles results in underestimations of change impact.

R.10 *Propagation behavior.* For the most part, current approaches dealing with change propagation phenomena in engineering systems (cf. section 3.3) do not characterize the behavior of how changes actually spread out. In real-world applications, humans with individual preferences are involved in change processes. A simple subjective decision heuristic of responsible change managers could be to favor change paths with low expected impact over rather costly options. Furthermore, potential revisiting of system elements or redoing of activities due to cyclic structures (cf. R.9) depends on the specific use case scenario. Being able to configure this behavior is, thus, desirable.

4.4 Assumptions

The purpose of this section is to unveil formal limitations of the approach and to clarify its range of validity. A characteristic property of models is that they abstract from the complexity of real-world systems to formally analyze phenomena of interest. This process includes simplifications, which have to be weighed up carefully against the loss of information during model generation so that insights gained from a model-based analysis do not lose their explanatory power when used for decisions pertaining to the real-world system. In the following, these assumptions are listed and briefly discussed:

A.1 *Suitability of structural models.* It is assumed that complex manufacturing systems can be modeled as linked subsystems consisting of different types of objects (nodes) and relations (edges). This fundamental assumption has proven to be appropriate in product-related change propagation literature, where product models are commonly constructed as component level DSMs (cf. e.g., SIMONS 2000; CLARKSON et al. 2004; KELLER et al. 2007; KOH et al. 2012). Multiple Domain Matrices (MDMs) also allow to include relations between entities of different domains, such as social and technical. Recently, the function-behavior-structure ontology has been proposed by HAMRAZ et al. (2015). Because the system is modeled by means of nodes and edges, changes are assumed to propagate only along the interdependencies of system elements (also cf. HAMRAZ et al. 2013b). This restriction is acceptable since most influences can be thought of in terms of interactions or cause-and-effect relationships that can be captured by this modeling approach.

A.2 *Conceivability of direct change probability and impact.* System experts are assumed to be capable to provide estimations of direct change impact and its probability. For larger systems, which can consist of complex subsystems, different experts might be consulted for knowledge elicitation. Often, a senior engineer is capable to provide a high-level overview of a system, while specialists are required to assess interactions between subsystems and their immediate environment (CLARKSON et al. 2004, p. 790). This assumption also articulates the implicit belief that an analytic bottom-up approach will yield more precise results than a comprehensive estimation of change impact for a non-trivial system—which is supported by common faults in practice when predictions for required resources due to changes have to be made (KELLER et al. 2007).

A.3 *Model reduction.* Multiple relation types between the entities of the system model can be aggregated by experts for parameter estimation. In order to simplify structural modeling and to cut down the effort of model population, multiple types of relations that might exist between a potentially change initiating node i and a potentially affected node j are only represented by a single transition probability p_{ij} and a single impact measure c_{ij} (same applies for capturing required implementation time t_{ij}). It follows from this assumption that experts need to be capable of synthesizing different interactions for specific cases and that the parameterized reduced system model is only valid for a specific change scenario.

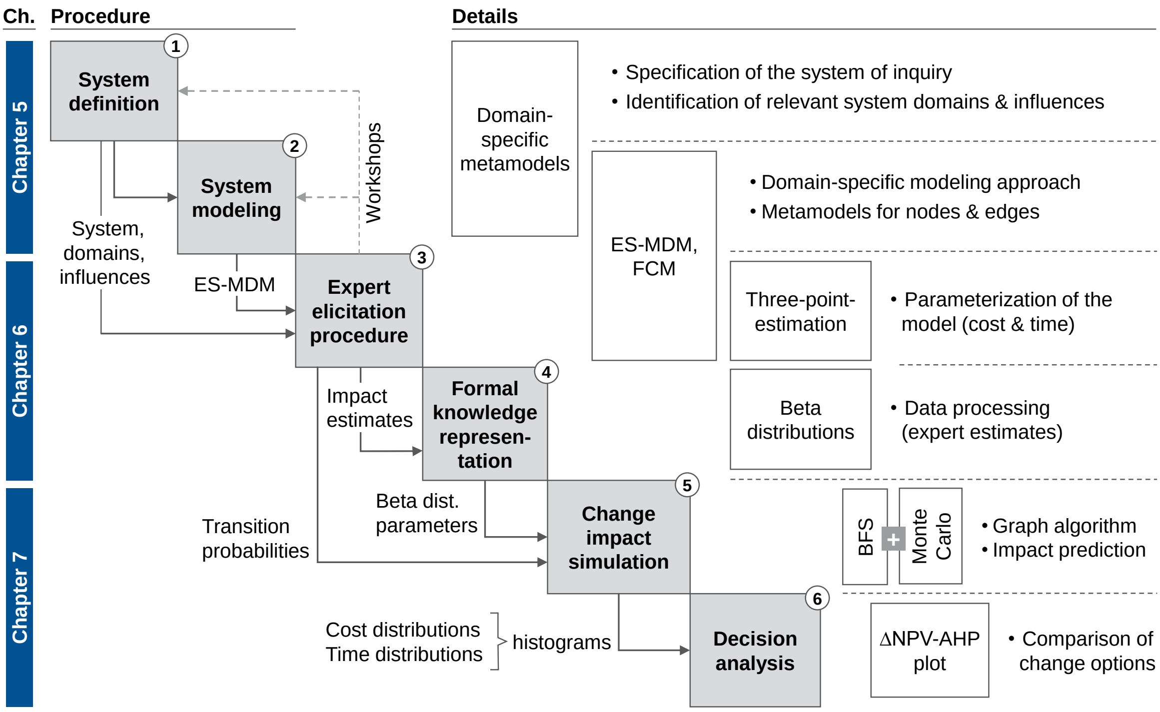
A.4 *Stochastic independence of changes, activities, and incidents.* The transition likelihood (i.e., the direct likelihood) of change propagation as well as the estimates for investment and time between each pair of nodes are assumed stochastically independent. Conditional probabilities are not considered.

4.5 Procedure

4.5.1 Overview

Prevailing methods refrain from providing guidelines for modeling the baseline system in change propagation analysis. Many approaches rely mostly on standard structural modeling techniques like the DSM to capture system architectures (cf. e.g., CLARKSON et al. 2004; KOH et al. 2013). The absence of a modeling guideline is particularly true for the manufacturing domain where change propagation research is still in its infancy. Furthermore, current methods are focused on the calculation of expected values and do not provide information on the spread of results—although, expert estimates are prone to flaws such as individual biases and the degree of uncertainty about the topic at hand (AYYUB 2001, cf. e.g.,).

In the following, the concept of the approach will be presented, which tries to resolve the issues mentioned above. It is structured in six consecutive steps. Figure 4.1 illustrates the structure of the approach. On the right-hand side, details of each step, such as the methods applied, are shown. Arrows indicate outputs and inputs of each step. Note that the framework depicted in figure 4.1 has two semantic levels. Firstly, it serves as a procedure model of the analysis reflecting the idealized sequence of steps to be carried out. Secondly, the framework provides an overview of the topics addressed by the theoretical body of this thesis, i.e., structural system modeling (chapter 5), expert elicitation & formal knowledge representation (chapter 6), and change impact simulation (chapter 7).



Legend

AHP	Analytic Hierarchy Process
BFS	Breadth-First Search
ES-MDM	Engineering System Multiple Domain Matrix
FCM	Fuzzy Cognitive Maps
NPV	Net Present Value

Figure 4.1: Framework of the method for change impact prediction

4.5.2 System definition

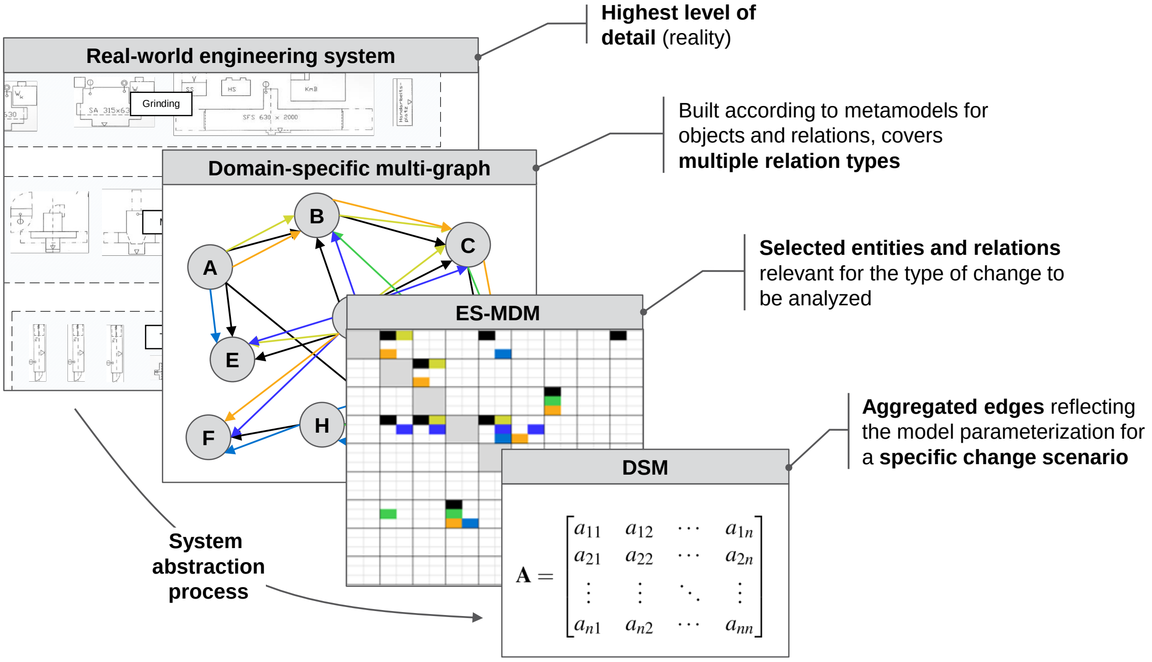
In every use case scenario, the first step of the approach is a thorough specification of the *system of inquiry*. The system boundary should be drawn according to the purpose and scope of the analysis, carefully weighing the risk of leaving out important sub-systems, system domains, or elements with the increased complexity and effort accompanied by their inclusion. General system theory suggests functional, hierarchical, and structural reasoning to gain a complete understanding (ROPOHL 1999). This process can be amended by a listing of general *internal and external influences* (system drivers) that are believed to affect the level of impact with respect to the initial changes to be analyzed. Within the first step, it is also recommended to clarify relevant *system and impact domains* using logic trees or other problem structuring techniques. The list of influences as well as the impact domains will be used during expert elicitation to improve the quality of background knowledge available to system experts and thus to enhance the quality of their estimates (AYYUB 2001).

4.5.3 System modeling: a domain-specific approach

The starting point of system modeling is to capture the real-world manufacturing system in a *domain-specific graph model*. As a guideline for system modeling, *metamodels* for objects and relations within manufacturing systems will be developed in chapter 5 as a formalized ontology of relevant entities and interdependencies within this domain (cf. GRUBER 1993). This work will be carried out using the established *Ontology Development Guide* by NOY & MCGUINNESS (2001).

In order to allow for more flexibility with respect to manufacturing-external interactions, also general *cause and effect relations* need to be considered. Although the metamodels are designed highly adaptable, these types of relations are not part of them, but are captured using modified *Fuzzy Cognitive Maps (FCMs)*. Combining structural manufacturing system and knowledge-based cause and effect models that are also able to capture activities and events within the system environment, a systematic and comprehensive identification of change impact is enabled (also cf. SCHADY 2008, p. 122). Evidently, the resulting model must be able to cover various socio-technical domains on different levels of abstraction. According to the definition of engineering systems provided earlier (cf. section 1.2.1), the resulting system model representation is termed *Engineering Systems Multiple-Domain Matrix (ES-MDM)*. This conceptual modeling framework was first introduced by BARTOLOMEI (2007) as a methodology for engineers to organize systems engineering data (BARTOLOMEI et al. 2012, p. 41).

Figure 4.2 shows the process of successive system abstraction starting from the original, which is modeled as a multi-graph. The ES-MDM is an equivalent representation of the multi-graph. It is preferable for the analysis of individual interdependencies in complex systems. Based on the ES-MDM, the *reduced graph model* (not shown) is derived for a specific change scenario. In the course of this process, multiple relations between system elements are aggregated and parameterized by system experts. The reduced graph model is equivalent to a Design Structure Matrix (DSM) of the system, also referred to as an adjacency matrix.



Highest level of detail (reality)

Built according to metamodels for objects and relations, covers **multiple relation types**

Selected entities and relations relevant for the type of change to be analyzed

Aggregated edges reflecting the model parameterization for a **specific change scenario**

Figure 4.2: Illustration of real-world system abstraction in four steps

4.5.4 Expert elicitation

The process of *expert elicitation* is based on the assumption that system experts are capable to assess the probability and magnitude of direct change transition, i.e., the effect of changing one element or subsystem on another directly connected entity (cf. A.2). Due to the complexity of interactions within larger subsystems, these effects cannot be predicted without appropriate methodological support. As CLARKSON et al. (2004) point out, complex systems are not governed by a single engineer. While a chief engineer might have a high-level overview of the interplay of subsystems, subsystem experts should be interviewed to elicit detailed knowledge about direct interactions inside those fractions of the entire system. CLARKSON et al. (2004, p. 792) further recommend to give more weight to the views of experts in their own area of expertise, while also considering the group opinion.

"Designers often fail to realize what changes of the subsystem they are responsible for may affect others" (CLARKSON et al. 2004). One way to support the process of accurately capturing knowledge about the interactions within a system is to provide experts with a model of the system they are asked to analyze. The purpose of these models is twofold: engineers are supported in thinking about possible connections between sub-systems and their mental models are made explicit for other participants of the expert group. The process of expert elicitation is improved by providing suitable models of the system to support human memory and thus to enable more complete assessments. In the manufacturing domain, a similar effect has been reported on by SCHADY (2008).

Since expert estimations are usually given without complete information (of the system and its environment) and because the true outcome of the considered process may be affected by unknown influences, it is reasonable to refer to the full range of possibilities rather than to a single average value. To account for this expert uncertainty, three-point-estimations are elicited for the parametrization of random beta distributed estimates. This formal representation of expert knowledge is explained in the next section.

4.5.5 Formal knowledge representation

The influence of uncertain expert estimates is taken into account by constructing *beta distributions* for every edge of the model according to the elicited expert judgment for cost and implementation time. Deriving beta distributions from *three-point-estimations* is adopted from the *Program Evaluation and Review Technique (PERT)*. Originally, these so-called PERT-beta distributions were used in operations research to account for uncertain activity times in stochastic critical path computation (MALCOLM et al.

1959; C. E. CLARK 1962). Beta distributions can be constructed based on the *best case*, *worst case*, and *most likely* estimates for an interdependency as shown in figure 4.3. Regarding the estimates of valued resources like money and time, best case refers to the left endpoint A and worst case to the right endpoint B of the interval, while the relation $A < M < B$ holds for the most likely value M.

The resulting PERT-beta distributions will be used during the *Change Impact Simulation (CIS)* to model the uncertain actual outcomes of required investments and time for a change in each *Monte Carlo Simulation (MCS)* trial. External relations and general cause and effect chains are captured using modified Fuzzy Cognitive Maps, where the edges are parameterized with the expected effect direction (e.g., investments vs. cost savings), the direct change transition probability, and the three-point-estimates for cost & implementation time.

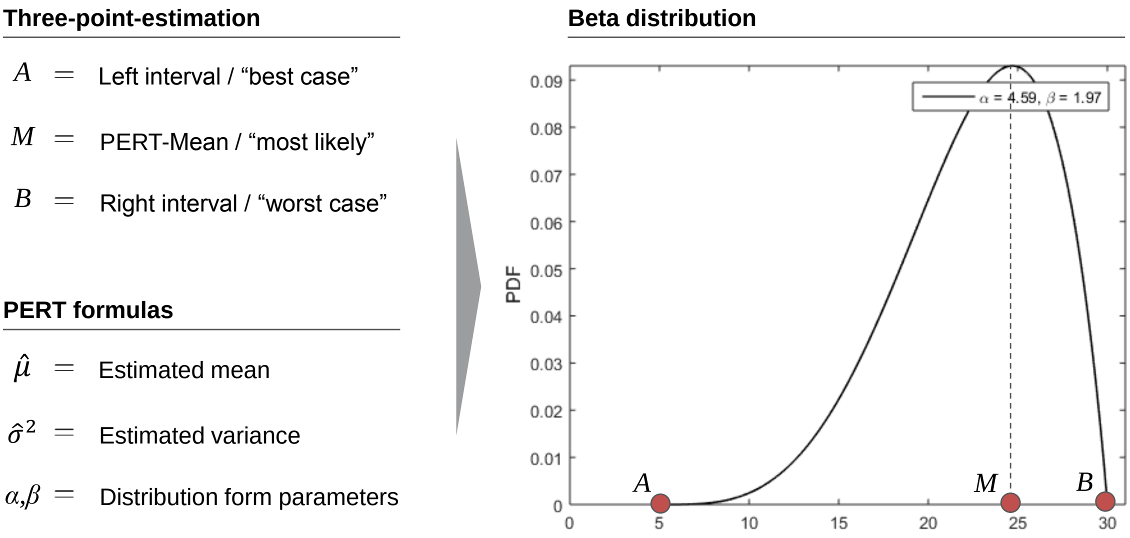


Figure 4.3: Three-point-estimation and parametrization of beta distributions

4.5.6 Change impact simulation

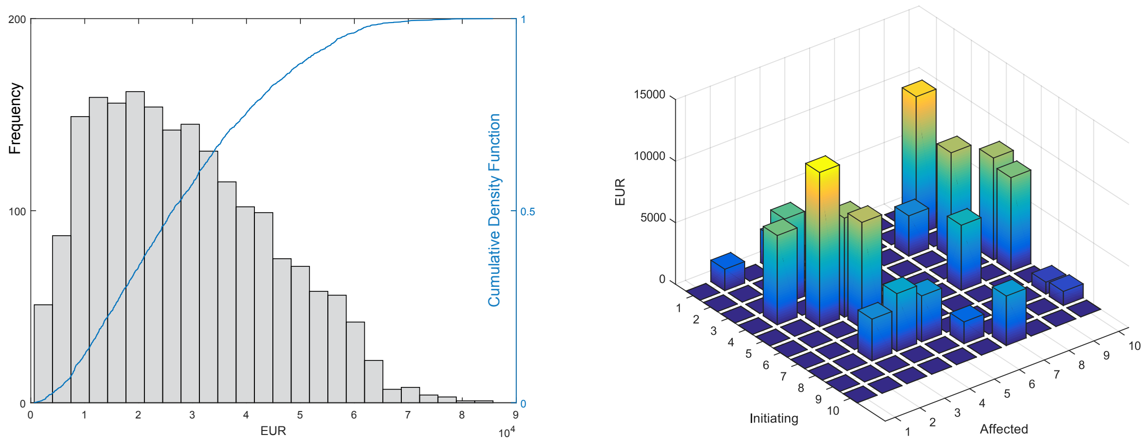
4.5.6.1 Change propagation in engineering systems

Change propagation aggravates the impact of initially desired alterations, making a system change surprisingly costly. However, cost is not the only performance measure of interest in an operations or business context. Due to the unexpected complexity of the changes to be carried out, change propagation can also cause severe delay of project schedules because of lacking capacity for change implementation. The effective time for change implementation is required for a reliable capacity planning in change projects. Within this thesis, change propagation is modeled stochastically based on the data gathered from system experts. The formal knowledge representation of transition probabilities and impact estimates is described in chapter 6. Transition probabilities and impact estimates serve as input for the CIS algorithm.

4.5.6.2 Simulation model and algorithm

The *Change Impact Simulation Graph Algorithm (CISGA)* is based on *Breadth-First Search (BFS)* and Monte Carlo Simulation (MCS). BFS, which has been invented by MOORE (1959), is used to model how changes spread to adjacent entities within a system. MCS accounts for the uncertainty of expert judgment with respect to estimates of cost and required implementation time for direct changes. This is done by drawing from beta distributions, which have to be parameterized for every edge of the reduced graph model. Thus, it can be simulated whether change is transferred from one system element to another in each simulation trial. By comparing a uniformly distributed random variable $u \sim U(0,1)$ with the estimated transition probability p_{ij} between a pair of nodes i and j, the uncertainty of change propagation is modeled. For $u < p_{ij}$, change is assumed to propagate and a random impact is drawn from the above mentioned distributions. In BFS, closest neighbors are visited first. Hence, the total path probability is decreasing with increasing distance from the route node, i.e., the location of the change trigger, modeling higher order change propagation.

BFS has several desirable properties: firstly, multiple route nodes (i.e., initial changes) can quite easily be dealt with. Secondly, cyclic system structures can be handled by the search algorithm—nodes can also be revisited if required, e.g., when multiple changes to system elements or a repeated execution of activities make sense in a specific use case. Thirdly, the search depth can be used as a termination condition of the algorithm, limiting the maximum amount of propagation steps. This accounts for the fact that even in complex systems, changes are not allowed to propagate infinitely in practice. Finally, BFS is a very efficient search method. Its worst case time complexity only depends on the propagation depth and the average out-degree of all nodes (BERWICK



(a) Histogram *(b)* Heat map

Figure 4.4: Result statistics of the change impact simulation (illustration)

2003). The Change Impact Simulation Graph Algorithm (CISGA) is described in chapter 7.

4.5.7 Decision analysis

The CISGA yields result statistics for total cost and working time for a quantitative impact evaluation. Using *histograms*, also the spread of these results can be taken into account as an indicator for risk. *Total cost* is modeled as the sum of investments (i.e., non-recurring cost) and labor cost, which is effective working time multiplied by an hourly rate. *Implementation time* is also computed in order to provide information for capacity planning, e.g., to answer questions like “How probable is it that change implementation takes longer than *X* days?” Additionally, change *impact heat maps* for cost and time, which show how severely sub-systems, elements, or activities of the system are affected by a change, can indicate what kind of experts will be needed in the course of the project and where additional capacity should be allocated.

Figure 4.4 illustrates a total cost histogram and a matrix-based change impact heat map (3D bar chart) for required invest due to a manufacturing change. The histogram depicted is skewed right, indicating a high probability of excessive cost. This information is valuable, e.g., for budget planning, risk management, and finally, the decision about the implementation or rejection of a manufacturing change request.

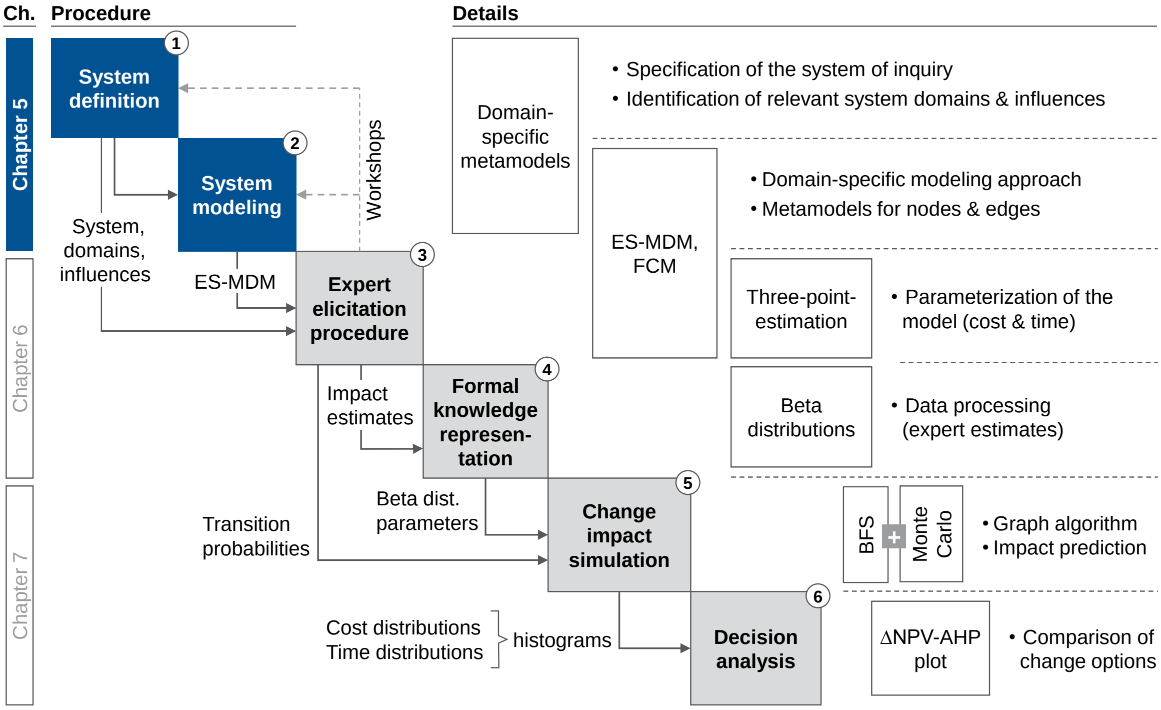
Note that the CISGA does only account for one-time cost and effort. The simulation is used to predict the magnitude of initial expenses that have to be weighed up against long-term benefits—both, monetary (e.g., cost savings) and non-monetary (e.g., increased customer satisfaction) within the time horizon considered. In section 7.5, a simple discounted system cost model is constructed to evaluate changes of expected future cash flows, while the Analytic Hierarchy Process (AHP) is suggested to incorporate qualitative decision criteria. Furthermore, as a concept for the comprehensive comparison of alternative change options, the *ΔNPV-AHP diagram* is suggested.

4.6 Summary

Within this chapter, the conceptual design of a model-based method for the analysis of change impact and change propagation in manufacturing systems is described. Several targeted use case scenarios, substantive and normative requirements, as well as the underlying assumptions have been discussed, before the six-step procedure model of the method was explained.

The framework shown in figure 4.1 will be used as an orientation guide throughout the remainder of the theoretical body of this thesis, which is structured as follows: the domain-specific structural modeling approach for manufacturing systems is introduced in chapter 5. Chapter 6 deals with steps 2 and 3 of the procedure in reverse order for the sake of comprehensibility. Section 6.3 presents the PERT methodology and explains its transfer to the formalization of expert estimates for change impact analyses. A formal expert elicitation procedure is suggested in section 6.4. Expert elicitation is not only required for the parameterization of system models with regard to transition probability and impact estimates, but also for system definition and knowledge-based model building (steps 1 and 2). Chapter 7 elaborates on the CISGA, which is based on BFS and MCS, and concludes with propositions for quantitative decision analysis for the comparison of alternative change options.

5 A Domain-Specific Structural Modeling Approach



Legend

AHP	Analytic Hierarchy Process
BFS	Breadth-First Search
ES-MDM	Engineering System Multiple Domain Matrix
FCM	Fuzzy Cognitive Maps
NPV	Net Present Value

Figure 5.1: Chapter 5 addresses steps 1 and 2 of the procedure

5.1 Chapter introduction

Based on the preliminary comparison of system modeling languages (cf. chapter 2) and the insights gained from the state of the art review (cf. chapter 3), the development of a domain-specific modeling language for manufacturing systems will be pursued in chapter 5. Beside the specification of a suitable modeling technique, the construction of metamodels for entities and relations of manufacturing systems, used as a guideline for system abstraction, is described in this chapter. On the one hand, tangible technical system elements like manufacturing equipment, on the other, intangible concepts such as change activities and incidents within the manufacturing environment have to be considered. They are linked by a complex cause and effect network composed of a variety of relation types.

The domain-specific system modeling approach is based on the Engineering Systems Multiple-Domain Matrix (ES-MDM) by Bartolomei et al. (2012) and modified Fuzzy Cognitive Maps (FCMs). In order to benefit from the advantages of structure matrices and graph models, both representations will be employed depending on the requirements of the respective use case scenario. For "soft" knowledge domains, which cannot be framed in precise class structures for nodes and edges with reasonable effort, cognitive mapping has shown great potential. Thus, this technique shall be applied where no modeling guidelines are readily available. In the following, a short introduction to the ES-MDM is provided before the metamodel development and implementation is described in sections 5.3 and 5.4.

5.2 Engineering Systems Multiple-Domain Matrix

The Engineering Systems Multiple-Domain Matrix (ES-MDM) is a promising approach for modeling the technical and social aspects of manufacturing systems, which are a specialization of general engineering systems. The ES-MDM is a modeling framework designed to organize information, supporting engineers to collect, store, process, and analyze systems engineering data (Bartolomei et al. 2012). Five domains are part of this conceptualization, which are relevant for the description of complex socio-technical systems: the social, technical, functional, process, and environmental domain. Like any MDM, the ES-MDM is an *edge-labeled multi-graph*, which implies that the corresponding graph model contains different classes of nodes, that there are interactions between different classes of nodes, and that multiple (types) of edges may exist between nodes (Bartolomei 2007, p. 72). Snapshots of the system, can be used to document its evolution over time (cf. figure 5.2).

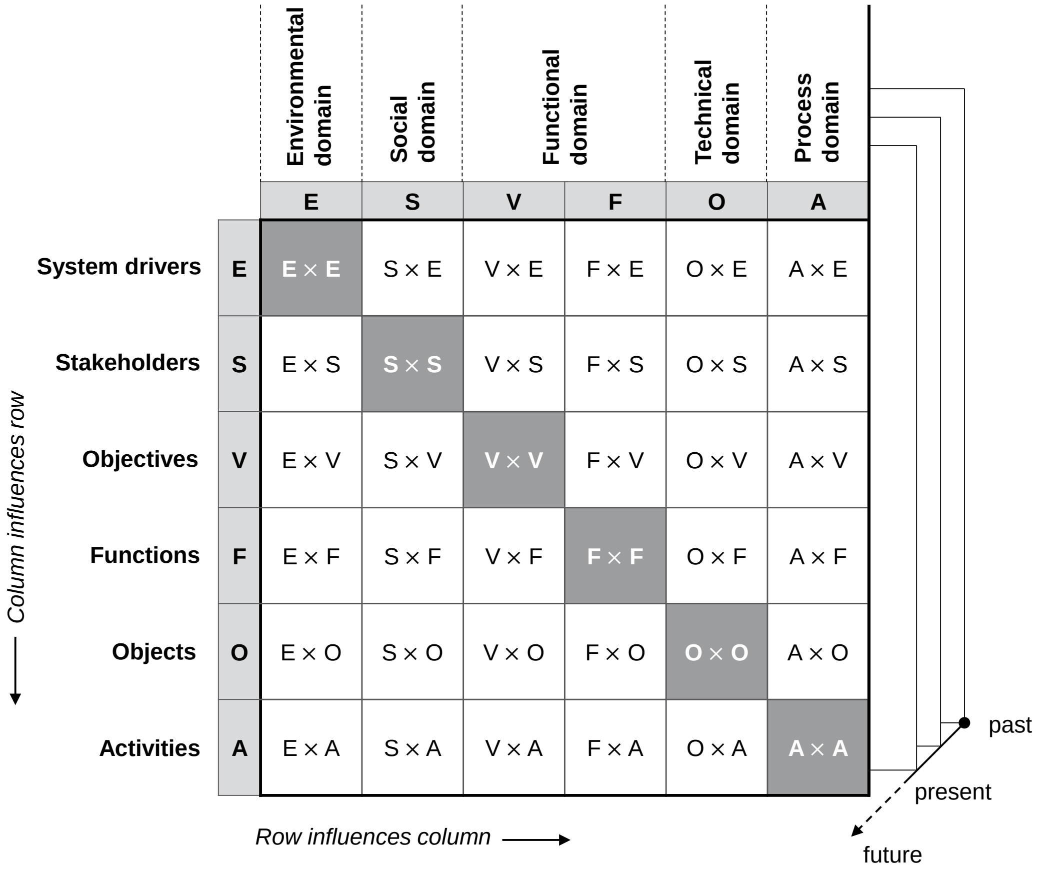


*Figure 5.2: Conceptualization of the Engineering Systems Multiple-Domain Matrix (*BARTOLOMEI *et al. 2012, p. 84)*

5.2.1 Tangible elements & intangible cause and effect networks

Particularly in the object domain of the ES-MDM, a variety of tangible system elements are conceivable. Within this thesis, a special emphasis is on manufacturing systems and hence, on the classes of entities and relations occurring in these systems. Different types of employees (e.g., operators, machinists, and logistics personal) have to be considered as well, since they are important stakeholders of the system. As already mentioned before, a variety of relation types occurs in a socio-technical system, like e.g., material, energy, and information flows. Both, for entities and relations, metamodels are constructed as class structures in section 5.3.4.2 and section 5.3.4.3. However, not all imaginable classes of objects and relations can be defined with reasonable effort in advance. Hence, it is important to consider flexible cause and effect relations between sub-systems (e.g., new machine), people (e.g., employee trainings), activities (e.g., layout planning), and events (e.g., jump in demand) within the manufacturing environment that are related to manufacturing changes. As figure 5.3

shows, the complexity of causal interdependencies arises from multiple-stages, cross-links, and feedbacks, which make the total impact of a change to an element hard to predict without suitable methodological support.

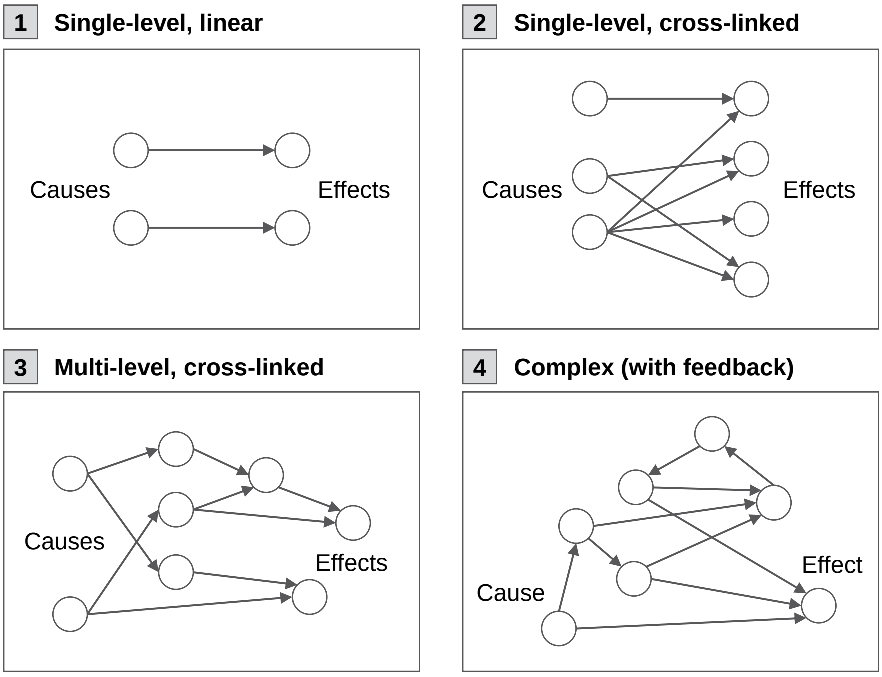


*Figure 5.3: Basic types of cause and effect interdependencies (*DAENZER & HUBER *1997, p. 118)*

In section 2.5, Fuzzy Cognitive Maps (FCMs) have been introduced as graph structures for causal reasoning and for a systematic analysis of causal propagation. They arise from the mental models of domain experts and represent the dependencies of intangible and often fuzzy phenomena. Effect directions and edge weights are usually assigned to the links of such a map to express the order of magnitude of interaction between constructs. For the representation of change propagation, *transition probabilities* are used as edge weights.

The constructs interlinked by causal relations in an FCM may be assigned to the domains of the ES-MDM, if possible. Unused domains of the ES-MDM can be omitted to reduce the size of the matrix. Figure 5.4 illustrates the equivalence of a domain-specific multi-graph model and the ES-MDM. Relation types have been color coded in both representations.

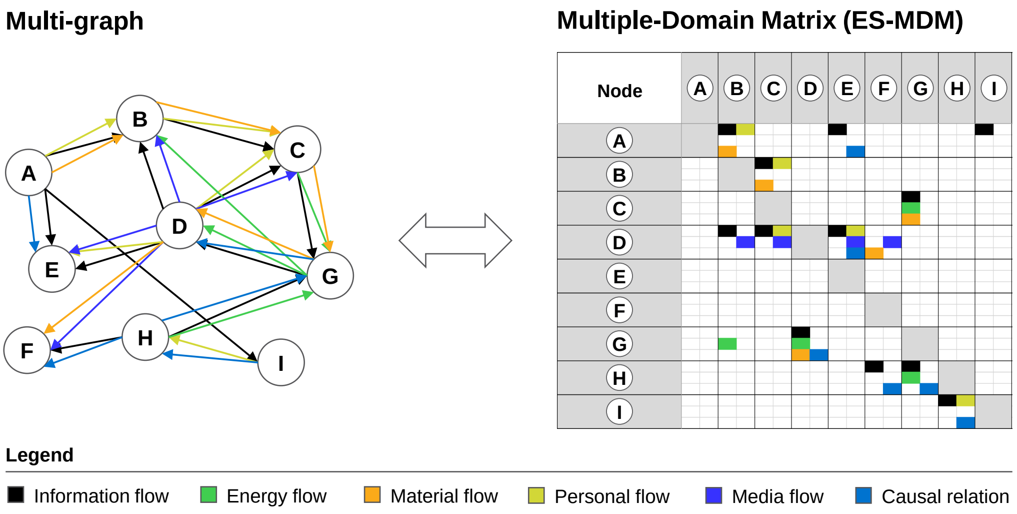


Figure 5.4: Equivalence of multi-graph and ES-MDM

5.3 Ontology-based metamodel development

5.3.1 Metamodel and ontology definition

According to PAIGE et al. (2014) “a model is a formal description of phenomena of interest, constructed for a specific purpose, and amenable to manipulation by automated tools.” In other words, models are tools to describe the structure, behavior, and other properties abstracting from the real world, considering specific phenomena (SPRINKLE et al. 2010). The same abstraction procedure can be applied, in turn, for the model itself. In that case, a so-called *metamodel* expresses certain properties of a model and “makes statements about what can be expressed in the valid models of a certain modeling language” (SEIDEWITZ 2003). Within this thesis, the following basic definition is adopted:

Definition: A *metamodel* is “a description of the abstract syntax of a language, capturing its concepts and relationships, using modeling infrastructure.” (PAIGE et al. 2014)

The definition implies that a metamodel is responsible for the *abstract syntax* of a language, i.e., it defines the allowed constructs, but it does not provide information about their application (JEUSFELD 2009). In contrast, *ontologies* are used to describe relevant concepts of a domain of discourse for a particular purpose. The definition of classes of concepts (e.g., objects, relations, attributes) and their taxonomic hierarchy supports the construction of metamodels.

Definition: An ontology describes a "specification of a representational vocabulary for a shared domain of discourse—definitions of classes, relations, functions, and other objects [...]." (GRUBER 1993)

Generally speaking, metamodels can be understood as formalized ontologies. A detailed discussion of the relation of ontologies and metamodels can be found in, e.g., HENDERSON-SELLERS (2011) and HENDERSON-SELLERS et al. (2014).

5.3.2 Motivation for the use of metamodels

Providing metamodels has several advantages: they document and support language evolution over time, foster creation of well-formed models, support model-transformations, and formal checking of model properties (PAIGE et al. 2014). Furthermore, metamodels determine the aspired level of abstraction and thus the granularity of later models (HENDERSON-SELLERS & GONZALEZ-PEREZ 2010). That way, the modeling approach can be tailored to system specifics or requirements of increased *information richness*. This is important, as the required semantic scope may differ in later applications. Hence, the metamodels are designed to be easily adaptable to the desired level of detail.

5.3.3 Methodology for metamodel design

Given the variety of objects, relations, and attributes within the manufacturing domain, it is reasonable to make use of guidelines for the design of ontologies to prepare for metamodel development. In software engineering, the process of ontology design is started with an ontology requirements specification (SURE et al. 2009). It specifies the purpose of the ontology, sketches the domain of discourse and application, guides the "inclusion and exclusion of concepts and relations and the hierarchical structure of the ontology." This approach is used to capitalize on the advantages of thoroughly designed ontologies, such as the explicit formulation of the structure of information of a domain, enabling reuse of domain knowledge (NOY & MCGUINNESS 2001). Using the ontology development guide of NOY & MCGUINNESS (2001), steps 1 to 5 have been carried out:

1. Determining the domain and scope,
2. Searching for opportunities to reuse existing ontologies,
3. Enumerating important terms for specified domain,
4. Defining classes and the taxonomic hierarchy, and
5. Defining the properties of classes.

In order to support steps 1 and 2, existing frameworks, taxonomies, and descriptions for categorizing factory objects, relations, and attributes—with a focus on factory planning and manufacturing system design literature—have been screened.

5.3.4 Manufacturing system metamodels

5.3.4.1 Review of extant ontologies

In accord with NOY & MCGUINNESS (2001), SURE et al. recommend to search for reusable ontologies during the initial stage of ontology design (SURE et al. 2009, p. 140). The corresponding metamodels define at least in part the granularity of later models (HENDERSON-SELLERS & GONZALEZ-PEREZ 2010). Hence, the desired level of abstraction has to be taken into account during steps 1 and 2. SCHADY (2008) recommends a medium level of granularity for change management applications compared to the model granularity required for factory planning and operations (cf. figure 5.5). In order to determine an appropriate level of granularity, three activities have been carried out iteratively:

- Initial specification of the domain of discourse reflected by the definition of manufacturing systems (cf. section 1.2.2) and manufacturing changes (cf. section 1.2.4) as the research objects,
- Specification of the aspired method's purpose (cf. section 4.2), which is the analysis of change impact in manufacturing systems, and
- Review and synthesis of extant ontologies and classifications of objects & relations in factory and manufacturing system design literature.

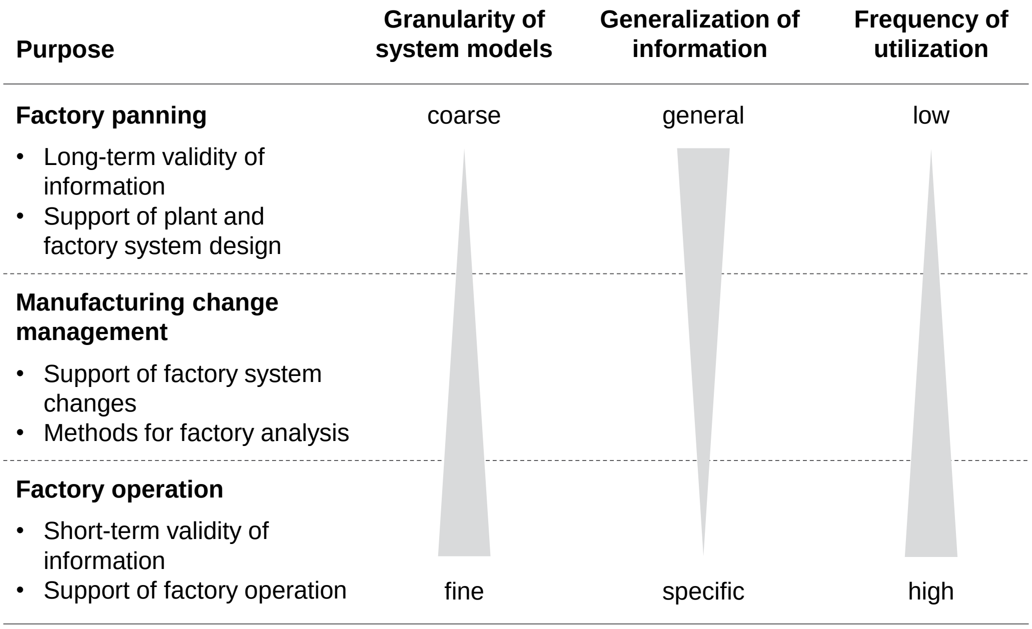


*Figure 5.5: Granularity of knowledge based factory system models (*SCHADY *2008, p. 122)*

Starting from manufacturing systems as the indented domain of discourse, suitable literature has been identified. Note that the selected literature has almost entirely been published by researchers of leading German manufacturing science institutions, reflecting their pioneering role in applied factory design research. Existing classifications of factory objects in HERNÁNDEZ (2002), HARMS (2004), BERGHOLZ (2006), NOFEN (2006), HEGER (2007), SCHADY (2008), and KLEMKE (2014) have been synthesized to identify relevant terms according to step 3 of the ontology development guide. This preparatory task is the foundation for the definition of classes and their taxonomic hierarchy (step 4) as well as the definition of required attributes (step 5).

5.3.4.2 Metamodel of nodes

The nodes metamodel consists of four layers characterized by an increasing level of detail from top to bottom (cf. table 5.1). Nevertheless, it is not mandatory for every branch to comprise all layers. Super-classes, like e.g., *Technology* are often *abstract*, meaning that a concrete node of this class will not appear in later models but is made available for the sake of *inheritance*. Besides, each class may contain a variety of attributes. Generally, attributes describe the properties of nodes and edges. They are useful to enrich the information content of the resulting model. By means of

Specifications and *Attributes*, the abstract *Domains* and *Types* can easily be extended, if additional detail should be required.

Table 5.1: Metamodel of nodes with exemplary specifications

Domain	**Technology**	**Personal**	**Infrastructure**
Type	Machinery Manual workstations Measuring & testing Transportation Supply / waste management	Operative Management	Storage & buffers Building services Social facilities IT Type of area
Specification (examples)	Machine tool Robot Assembly station Belt conveyor	Manufacturing Logistics Assembly Quality	Storage type Floor type Sanitary facilities Computer Compressed air De-watering Electricity
Attributes (examples)	Dimensions Position Capacity Availability Productivity	Qualification Affiliation Span of control	Dimensions Capacity Pressure Temperature

Table 5.1 shows exemplary sub-classes of the domains *Technology*, *Personal*, and *Infrastructure*. Due to spatial restrictions, the table does not show the taxonomic hierarchy of these classes and their full list of attributes. However, an illustration is provided in figure 5.6 for the infrastructure domain, using a UML class diagram.

5.3.4.3 Metamodel of edges

The metamodel of edges represents an ontology of relationships between different entities of the manufacturing domain. It is assumed that the relationships between factory objects can be described with four major types of flows: *Information*, *Personal*, *Energy*, and *Material*. Again, these domains can be detailed further, as shown in table 5.2 from top to bottom. In contrast to the nodes metamodel, all edge classes have

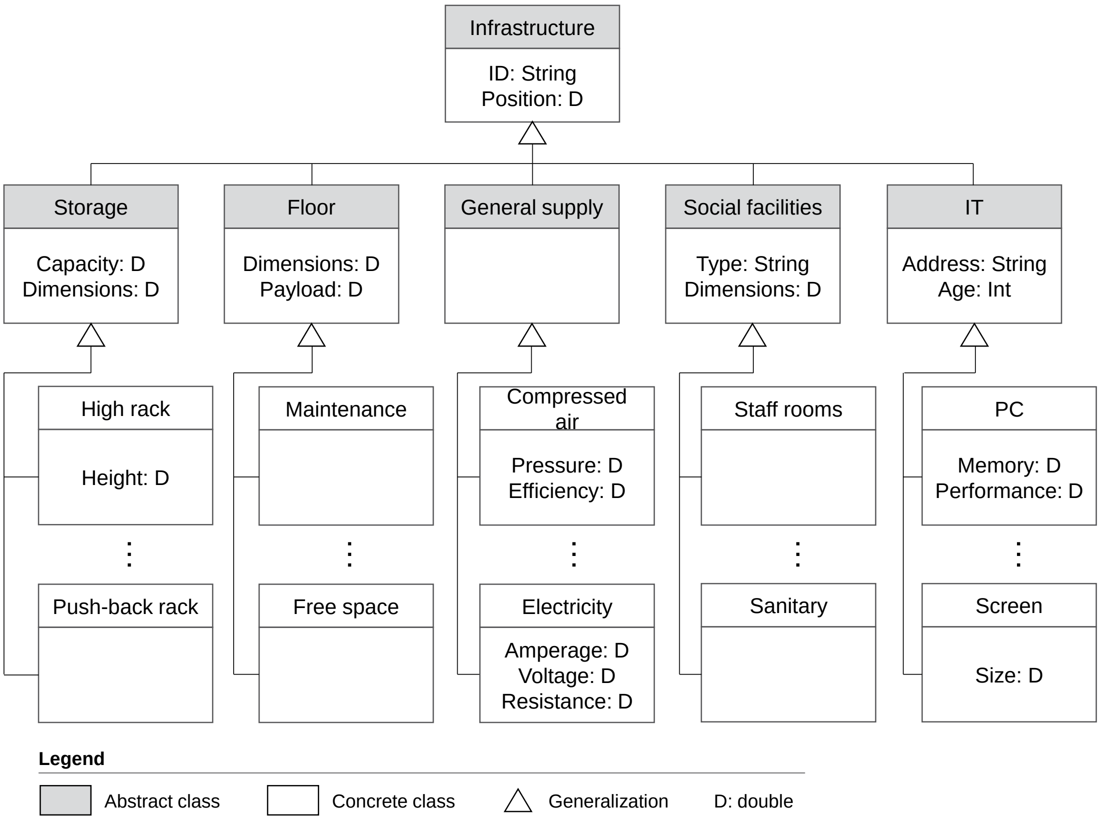


Figure 5.6: Infrastructure domain UML class diagram (nodes metamodel excerpt)

been classified as *concrete*. Hence, the user is not obliged to specify the types of flows in more detail than the domain level. This is due to the fact that in most applications no further specification of flows is required (cf. chapter 3). Defining edge (or node) classes as *abstract* implicitly sets the level of detail for a domain because abstract classes cannot be used for modeling.

5.4 Metamodel implementation and design tool

The metamodels have been implemented in Soley Studio, a software tool, which is based on the work of HELMS (2013) on object-oriented graph grammars and GrGen.NET, a programming productivity tool for graph transformations that has been developed at the Karlsruhe Institute of Technology. GrGen.NET provides "declarative languages for graph modeling, pattern matching, and rewriting, as well as rule control [...]", which facilitates the modification of graph-based representations at various levels of abstraction (cf. GOOS 2015). The user is further enabled to define simple scripts to carry out automated visual analyses. For example, nodes can be resized

Table 5.2: Metamodel of edges with exemplary specifications

Domain	**Information flow**	**Personal flow**	**Energy flow**	**Material flow**
Type	Signal Data Communication	Operation Affiliation Supervision Route	Electrial Mechanical Thermal Volumetric	Raw material Intermediate goods Final product
Specification (examples)	Verbally Hard copy Electronically		Substance Interface type Conveyance type (e.g., pipe)	Serial number Condition Transport structure (e.g., pallet)
Attributes (examples)	Frequency Content Duration Data type Band width	Number Distance	Voltage Amperage Torque Mass Pressure Temperature	Number of units Mass Dimensions Distance

depending on their attribute values, e.g., the size of a machine node may be scaled depending on its dimensions.

Figure 5.7 shows an illustrative example of a small-scale manufacturing system, which is modeled according to the developed metamodels. GrGen.NET also allows to define the shapes and their coloring in the metamodels. On the upper left side of figure 5.7 the node classes are shown and the edge types can be chosen below. The organic layout of the multi-graph is generated automatically based on force directed algorithms (LINDEMANN et al. 2009, p. 49). In these organic layouts, strongly interlinked nodes are pulled closer towards each other.

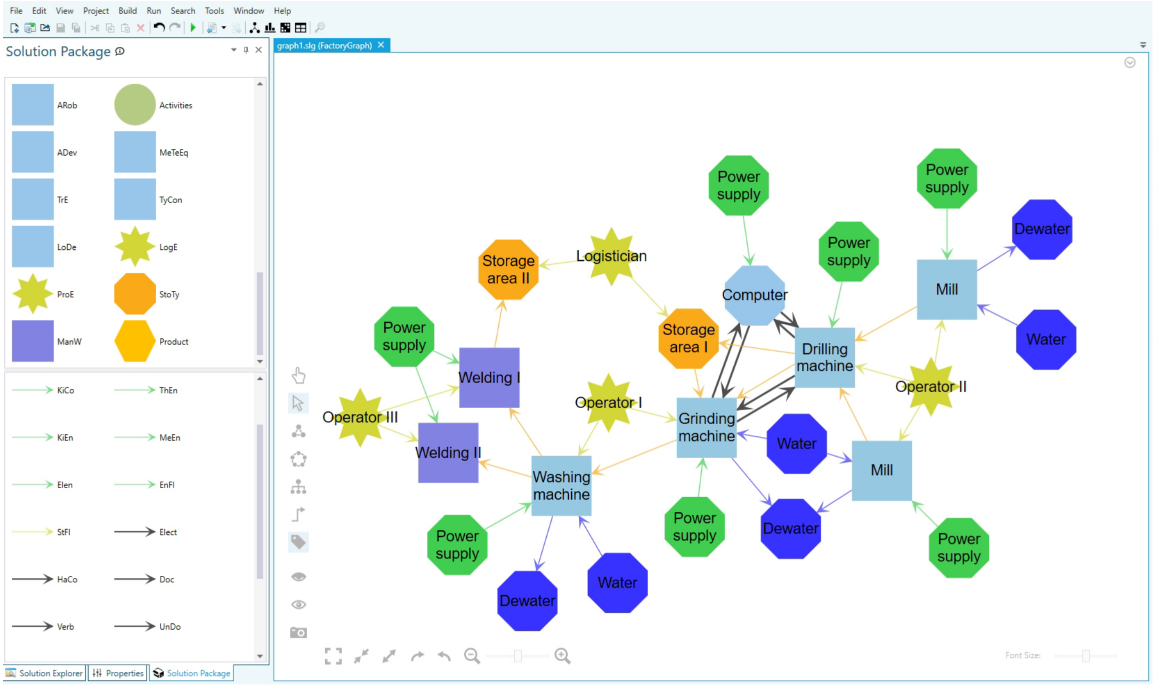
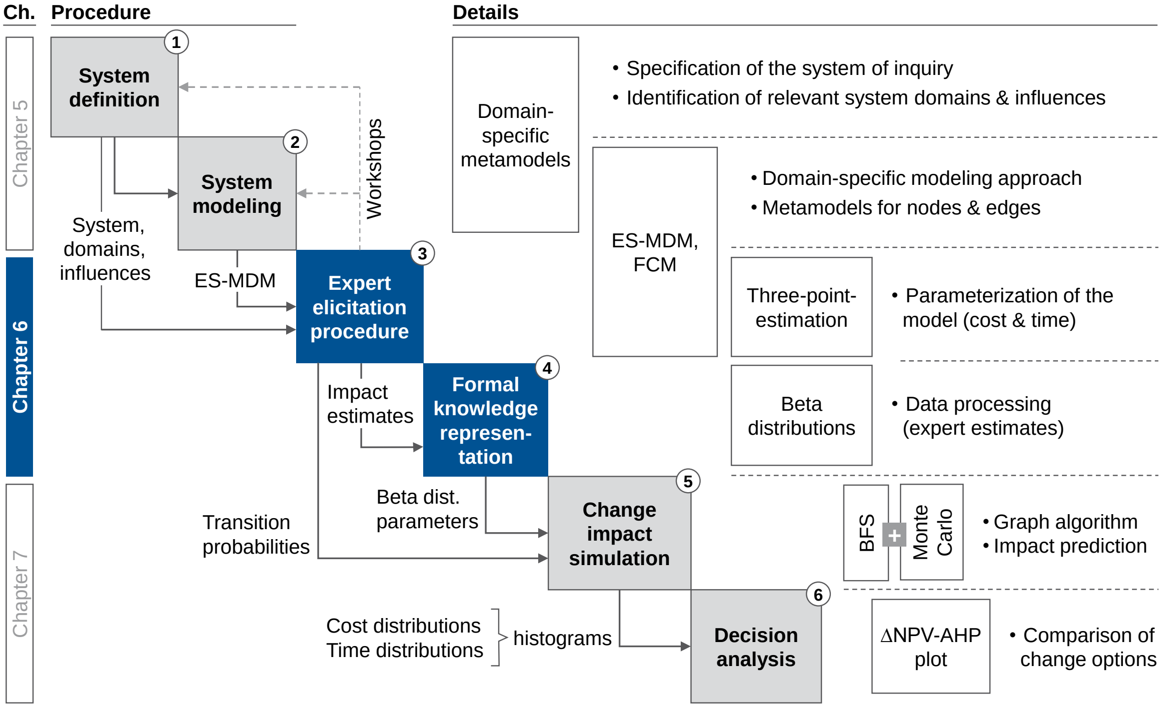


Figure 5.7: Node and edge classes specified by the metamodels in use (Soley Modeler)

6 Knowledge Representation and Expert Elicitation



Legend

AHP	Analytic Hierarchy Process
BFS	Breadth-First Search
ES-MDM	Engineering System Multiple Domain Matrix
FCM	Fuzzy Cognitive Maps
NPV	Net Present Value

Figure 6.1: Chapter 6 addresses steps 3 and 4 of the procedure

6.1 Chapter introduction

In the previous chapter, the domain-specific structural modeling approach for manufacturing systems has been presented. By means of metamodels for objects and relations of the manufacturing domain and Fuzzy Cognitive Mapping, the Engineering Systems

Multiple-Domain Matrix (ES-MDM) has been amended. The super classes of the constructed nodes metamodel are *technology*, *personal*, and *infrastructure*, while the super classes of the edges metamodel are *information*, *personal*, *energy*, and *material* flows. These classes have been broken down further in a taxonomic hierarchy and extend the social and technical domain of the ES-MDM. Fuzzy Cognitive Mapping is used to represent *intangible concepts* from the environmental, functional, and process domains of the ES-MDM, which can be linked by *causal relations*.[1] FCMs extend the ES-MDM and are used because of their high degree of modeling flexibility. Both modeling approaches can be represented as directed graphs or (adjacency) matrices.

This chapter is divided into two major parts. On the one hand, section 6.4 elaborates on the expert elicitation procedure, which is required for both *knowledge-based system modeling* and model *parameterization* (cf. step 4 in figure 6.1). On the other hand, the Program Evaluation and Review Technique (PERT) and three-point-estimation are explained and used for the *formal representation* of required model parameters in section 6.3 (cf. step 3 in figure 6.1). Note that the order of steps 3 and 4 has been switched in this chapter, as it is important to understand which data needs to be elicited in what form before the corresponding expert elicitation procedure can be designed.

In step 3 of the method for change impact analysis, the baseline model of the engineering system—represented by the ES-MDM—is parameterized for the specific change scenario of interest to the user. For this purpose, the variety of edge types in the complete multi-graph (corresponding to the ES-MDM) are *aggregated* during the elicitation process, yielding the *reduced graph model*. The selection of relation types and their synthesis depend on the judgment of system experts regarding which relation types play a vital role for the analysis of a specific change scenario. This step is required to reduce the complexity of the structural model in order to diminish the effort of model population to an acceptable level. Hence, after the phase of parameter estimation, the resulting *mental model* of system experts could be represented by a simple directed graph or adjacency matrix. This reduced graph model is then parameterized with transition probabilities and impact estimates according to the change scenario at hand.

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[1] Metamodels or ontologies for these domains are not in scope of this thesis.

6.2 Model parameters: transition probability, cost, and time

For the Change Impact Simulation Graph Algorithm described in chapter 7, estimates for change transition probability[2], cost, and implementation time are required. A suitable means for processing this information also considering uncertainty with respect to the estimates and possible actual outcomes of change impact are probability distributions. As mentioned earlier (cf. section 4.5.5), the approach suggested here is motivated by the Program Evaluation and Review Technique (PERT), which was first used to formally model uncertain activity durations (cf. MALCOLM et al. 1959). It is described in the following section.

6.3 Formalization of expert estimates

6.3.1 Program Evaluation and Review Technique

Originally, PERT analysis has been used for computing the expected duration of complex projects. For the analysis, a project is broken down into elementary activities and their interdependencies or prerequisites are determined, resulting in a flow plan of the project. Estimates for the required time of each activity have to be obtained from informed experts (C. E. CLARK 1962, p. 406). As "expected values and variances seem too complex for immediate appraisal", most likely and extreme times (worst and best case) are requested instead. Given this information, the estimated mode and range of a distribution can be converted into an expected value and variance, although assumptions have to be made concerning the distributions of activity times (C. E. CLARK 1962, p. 406).

The beta distribution is suggested with a standard deviation of one-sixths of its range as a first simple model, given the following assumptions (MALCOLM et al. 1959, p. 651): the distribution of activity times has a peak (most probable time estimate m) and the chance of realizing either the optimistic or pessimistic estimates is small. Figure 6.2 illustrates the assumed PERT-beta distribution and the time estimates a, b and m for

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[2] The terms transition probability / likelihood as well as direct change probability / likelihood are used synonymously throughout this thesis.

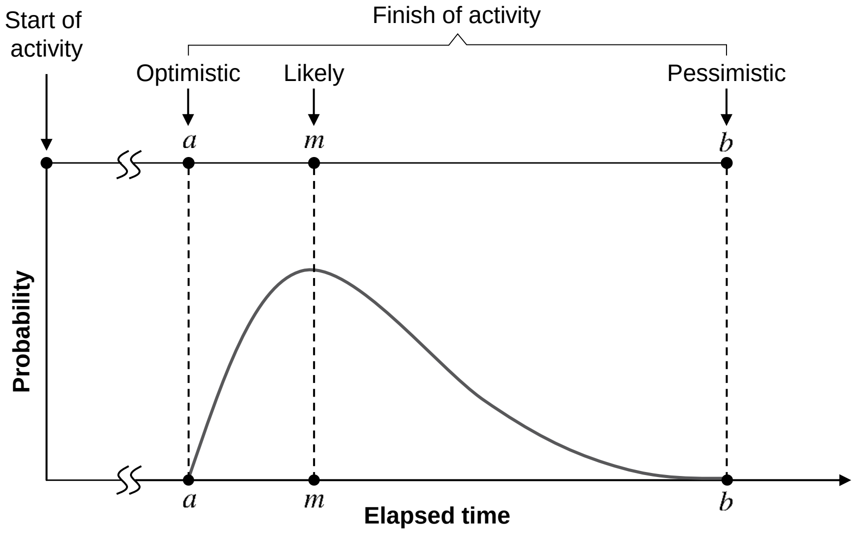

*Figure 6.2: Assumed elapsed time distribution in PERT (*MALCOLM *et al. 1959, p. 652)*

an activity or event. Using the above mentioned assumptions, the estimated mean $\hat{\mu}(t_e)$ and variance $\hat{\sigma}^2(t_e)$ of the distribution for the elapsed time t_e of an activity can be formulated as follows (MALCOLM et al. 1959, p. 652):

$$\hat{\mu}(t_e) = \frac{1}{3}\left[2m + \frac{1}{2}(a+b)\right] = \frac{a+4m+b}{6}, \tag{6.1}$$

$$\hat{\sigma}^2(t_e) = \left[\frac{1}{6}(b-a)\right]^2 = \frac{(b-a)^2}{36}. \tag{6.2}$$

6.3.2 Estimating the parameters of beta distributions

Two distributions are constructed for each edge e_{ij} of the reduced graph model to formalize the estimates for cost and working time. Variables $[c_a, c_m, c_b]_{ij}$ denote best, likely, and worst case estimates for cost (or investments) and $[t_a, t_m, t_b]_{ij}$ estimates for effective working time accordingly for an individual relation within the model.

The adjacency matrix of the reduced graph model $G(V, E, p_{ij})$, i.e., the transition probability matrix $\mathbf{P}$, also determines the structure of the cost estimate matrices $\mathbf{C}_a, \mathbf{C}_m, \mathbf{C}_b$ and the working time estimate matrices $\mathbf{T}_a, \mathbf{T}_m, \mathbf{T}_b$. These matrices contain all estimates of the reduced model, as exemplified by the $N \times N$ transition matrix $\mathbf{P}$, with N being the number of nodes in $G(V,E,p_{ij})$.

$$\mathbf{P} = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1N} \\ p_{21} & p_{22} & \cdots & p_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ p_{N1} & p_{N2} & \cdots & p_{NN} \end{bmatrix} \tag{6.3}$$

The beta distribution Beta(α,β) of a random variable $X \in [0,1]$, with form parameters $\alpha,\beta > 0$ is a continuous probability distribution. Its Probability Density Function (PDF) has the form

$$f(x;\alpha,\beta) = \frac{x^{\alpha-1}(1-x)^{\beta-1}}{\mathrm{B}(\alpha,\beta)}, \tag{6.4}$$

with the beta function $\mathrm{B}(\alpha,\beta)$ as a normalization coefficient (ASKEY & ROY 2010). When defined on the interval $[0,1]$, the formulas for mean and variance are given as

$$\mathrm{E}[X] = \mu = \frac{\alpha}{\alpha+\beta} \quad \text{and} \tag{6.5}$$

$$\mathrm{Var}[X] = \sigma^2 = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}. \tag{6.6}$$

However, as shown in figure 6.2, the beta distribution has to be defined on the interval $[a,b]$ with $a \neq 0$ and $b-a \neq 1$. Thus, the distribution needs to be shifted by a and scaled with $(b-a)$, yielding

$$\mu = a + (b-a)\frac{\alpha}{\alpha+\beta} \tag{6.7}$$

for the mean value based on equation 6.5. Using the basic variance properties

$$\mathrm{Var}[X+\eta] = \mathrm{Var}[X], \tag{6.8}$$

$$\mathrm{Var}[\eta X] = \eta^2 \mathrm{Var}[X], \tag{6.9}$$

$$\text{with } \eta \in \mathbb{R}, \tag{6.10}$$

the adapted variance formula is

$$\sigma^2 = \frac{(b-a)^2\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)} = \frac{\alpha}{\alpha+\beta} \cdot \frac{\beta}{\alpha+\beta} \cdot \frac{(b-a)^2}{\alpha+\beta+1}. \tag{6.11}$$

Solving equation 6.7 for $\alpha/(\alpha+\beta)$ and $\beta/(\alpha+\beta)$ and inserting into equation 6.11 yields the required formulas for $\alpha(a,b,\mu,\sigma)$ and $\beta(a,b,\mu,\sigma)$,

$$\alpha = \frac{\mu - a}{b - a}\left(\frac{(\mu - a)(b - \mu)}{\sigma^2} - 1\right), \tag{6.12}$$

$$\beta = \frac{b - \mu}{b - a}\left(\frac{(\mu - a)(b - \mu)}{\sigma^2} - 1\right). \tag{6.13}$$

Finally, inserting the expressions for PERT mean $\hat{\mu}$ (equation 6.1) and PERT variance $\hat{\sigma}$ (equation 6.2) into equation 6.12 and equation 6.13, the PERT beta distribution parameters α and β can be computed based on the estimates a, b and m alone:

$$\alpha = \frac{2}{3} \cdot \frac{b + 4m - 5a}{b - a}\left(1 + \frac{4(m - a)(b - m)}{(b - a)^2}\right), \tag{6.14}$$

$$\beta = \frac{2}{3} \cdot \frac{5b - 4m - a}{b - a}\left(1 + \frac{4(m - a)(b - m)}{(b - a)^2}\right). \tag{6.15}$$

Now, for every relation of the reduced model, the corresponding distribution form parameters of cost and implementation time distributions are stored in the form parameter matrices $[\boldsymbol{\alpha}^{N\times N}, \boldsymbol{\beta}^{N\times N}]_C$ and $[\boldsymbol{\alpha}^{N\times N}, \boldsymbol{\beta}^{N\times N}]_T$.[3] Depending on which kind of value is to be drawn from the distributions, a, b, m are free variable parameters for c_a, c_m, c_b and t_a, t_m, t_b in equations 6.14 and 6.15.

6.4 Expert elicitation procedure

6.4.1 Introduction

6.4.1.1 Expert definition

Expert judgment is time- and context-dependent. It is described as a snapshot of the expert's knowledge at a point in time (KEENEY & WINTERFELDT 1989) and may change due to updated or new information. MEYER & BOOKER (2001, p. 6) describe expert judgment as the result of "high-level thought processing, also called knowledge-based cognition", which is interpretive or analytic thinking, required when people

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[3] Generally, bold upright letters are used for matrix notation in this text. The superscript $N \times N$ is added, whenever a special emphasis is needed to avoid confusion between scalars and matrices.

are confronted with new and uncertain situations. Among others, expert judgment is used whenever other sources of information are unavailable in due time or with reasonable effort to "provide estimates on new, rare, complex, or otherwise poorly understood phenomena" (MEYER & BOOKER 2001, p. 4). An *expert* is characterized by the following traits:

Definition: An *expert* is "a very skillful person who had much training and has knowledge in some special field. The expert is the provider of an opinion in the process of expert-opinion elicitation. Someone can become an expert in some special field by having the training and knowledge to a publicized level that would make him or her recognized by others as such." (AYYUB 2001, p. 114)

This understanding is also shared by MEYER & BOOKER (2001, p. 3), albeit, they state that mere *substantive expertise*—here, the expert's knowledge about and experience with the engineering system of inquiry—is not sufficient. A suitable expert needs to be capable of the response modes required in a study, e.g., probability estimation and basic mathematical or logical rules. A lack of this *normative expertise* can seriously deteriorate the quality of elicited data (MEYER & BOOKER 2001, p. 86).

6.4.1.2 Mental models of experts

AYYUB (2001, p. 38) defines knowledge in engineering and the sciences as "a body of justified true beliefs, such as laws, models, objects, concepts, know-how, processes, and principles, acquired by humans about a system of interest [...]." It can be acquired by cognition (human senses), deduction (logical reasoning), beliefs, and conjectures (inference). JOHNSON-LAIRD (1983, pp. 126-127) states that both, explicit (conscious) and implicit (unconscious) inference are based on *mental models* according to general inference theory. NORMAN (1983, p. 7) notes that mental models are "naturally evolving" through a person's interaction with a target system. They do not need to be "technically accurate (and usually are not), but they must be functional" and are modified by a person's interaction with the target system until that is the case. NORMAN (1983) names four aspects to be clearly distinguished in this context:

- *Target system.* A system that a person is learning or using.

- *Conceptual model.* A model invented by designers, scientists, or engineers to provide an appropriate representation of the target system.
- *Mental model.* Representation of a thing or process in a person's mind.
- *Scientist's conceptualization.* A model of the mental model.

Here, the definition by DOYLE & FORD (1999, p. 414) is adapted. It has been formulated for the field of system dynamics applications, where both conceptual and formal modeling play a vital role:

Definition: "A *mental model* of a dynamic system is a relatively enduring and accessible, but limited, internal conceptual representation of an external system (historical, existing or projected) whose structure is analogous to the perceived structure of that system." (DOYLE & FORD 1999)

Mental models have a variety of undesirable properties: they are incomplete, cannot always be applied effectively by a person, are unstable over time (human memory), do not have firm boundaries, can be directed by opportunistic behavior patterns (people want to save effort), and often oversimplify reality (NORMAN 1983, p. 8). These aspects need to be taken into account when trying to ensure a high quality of elicited data by means of a suitable elicitation procedure. Furthermore, it must be noted that the subjective assessment of humans is generally flawed due to systematic biases (cf. e.g., TVERSKY & KAHNEMAN 1973, 1974, 1981), abstraction, and ignorance (blind and conscious) issues (AYYUB 2001, pp. 49, 101-107). Although the discussion of these phenomena lies beyond the scope of this thesis, they should be kept in mind for expert elicitation in practice. In the following, the expert elicitation procedure is presented, which is used to capture the knowledge and mental models of experts.

6.4.2 Positioning phase: system definition & problem description

The objective of the elicitation procedure is to capture tacit expert knowledge (mental models of system experts) explicitly and to formalize this information about a system's structure and its reaction to change. The approach proposed here is based on well established system dynamics conceptual and formal model-building procedures—in particular those of RICHARDSON & PUGH (1981), VENNIX et al. (1990), and FORD

& STERMAN (1998). According to VENNIX et al. (1994), five factors should guide the process of expert elicitation, as summarized by FORD & STERMAN (1998, p. 311), which should be explained during the initial group meeting:

- The purpose of the modeling effort,
- the current phase of the model-building process and type of task being performed (e.g., elicitation, exploration or evaluation),
- the number of people involved in the elicitation process (and their roles, tasks, and responsibilities),
- the time available for model-building, and
- the cost of the elicitation methods

Within the positioning phase, the *facilitator*, whose main role is to moderate and manage the structured workshop, describes the purpose of the modeling effort. He has to make sure that the experts involved have a clear understanding of the engineering system to be modeled, which level of granularity is to be aimed at, and how the system boundary is drawn in order to target the most relevant system domains. If necessary, also the time horizon for the analysis should be specified. The most important task during this step is to make the expert group familiar with the method to understand the objective and to ensure high motivation. For this purpose, the author achieved good results by giving a short (approximately 10 minutes) slide presentation. Furthermore, it is generally advisable to provide the expert group manager with a list of information beforehand that might be needed during the following workshop sessions (e.g., process documentations, technical data, ROI calculations, layout plans etc.). Table 6.1 gives an overview of the elicitation procedure, while figure 6.3 shows an exemplary project schedule. Obviously, the amount of workshops depends on the complexity of the system to be modeled and the level of detail chosen for its analysis.

6.4.3 Conceptualization phase: model-building

During the conceptualization phase, the project team progressively builds up the structure of the model consisting of nodes and edges. In this phase, the facilitator is supported by the *modeler*, whose task is to draw the graph model on a sufficiently large piece of paper, e.g., two or more flip chart sheets placed on a conference table.

Table 6.1: Overview of the expert elicitation procedure

Phases	**Positioning** (system definition)	**Conceptualization** (model building)	**Discussion** (formalization)
Activities	• Clarify the purpose of model building • Presentation of the method for impact analysis • Discussion of system bourdary, domains, and initial changes	• Clarify level of granularity • List relevant subsystems, elements, activities etc. • Building up the model and mapping of relations • Listing of general influences	• Clarify response modes • Briefing on assessment biases and how they can be countered effectively • Parameter estimation • Consistency analysis
Results	• System boundary • Problem domains • Initial changes	• Multi-graph model of the system • List of general influences (internal & external)	• Reduced system model • Matrices for transition probabilities and all impact estimates

In order to stimulate the model building process, the modeler prepares a preliminary model-based on the information acquired in the first meeting. This preliminary model is presented and explained to the group. For a shared understanding of the level of granularity and to reduce adjustments of the model during the workshop, it is recommended to write down subsystems, elements, activities, and events on a separate flip chart visible to all participants. These constructs can be encouraged by thinking about the system as a whole, starting from initial (desired) changes, or moving sequentially along a change process the studied organization might have installed (cf. e.g., KOCH 2016). FORD & STERMAN (1998) refer to this step as "description phase", where visual, verbal, textual, and graphic representations of the experts' mental models are shared.[4] "Differences in the mental models of team members can constrain progress and lead to conflict" slowing down the elicitation procedure (FORD & STERMAN 1998). The step-wise paper based modeling approach helps to involve all participants

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[4] FORD & STERMAN (1998, p. 315) focus on mathematical modeling (e.g., the shape of a function graph). They require experts to "use their own images" before interacting with their peers.

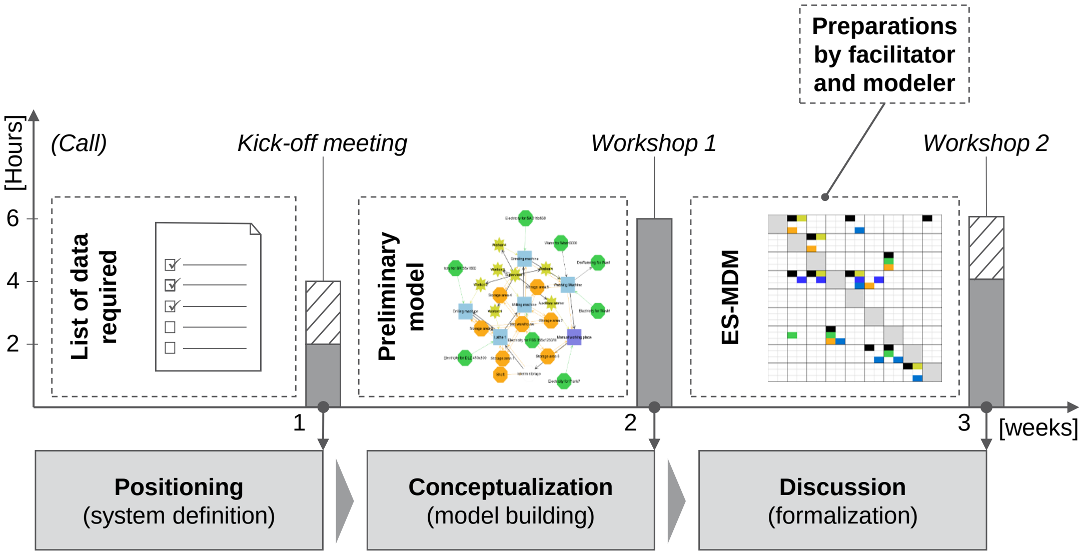


Figure 6.3: Exemplary project schedule

regardless of their expertise with digital modeling tools. Both, facilitator and modeler are actively involved in the discourse and, thus, serve as interviewers in this phase.

6.4.4 Discussion phase: Formalization and synthesis

The discussion phase usually takes place during the second structured workshop. The major objective of this phase is the elicitation of expert judgment on direct transition probabilities between the nodes of the model and the corresponding three-point-estimations for cost and implementation time (cf. section 6.3.2). According to FORD & STERMAN (1998, p. 317), it is the responsibility of the facilitator to direct the experts to identify and investigate the causes of different opinions that might arise from distinctive roles, functional affiliations, and organizational structures.

At first, the response modes for parameter estimation need to be clarified. A flip chart is suitable to provide basic explanations on probability and three-point-estimation, as illustrated in figure 6.4. MEYER & BOOKER (2001, p. 169) recommend to ask sample questions first to avoid misunderstandings and get used to the response mode. As discussed earlier (cf. section 6.4.1.2), humans are prone to a variety of biases like anchoring, availability, representativeness, and perceived control. A means to reduce these effects is to brief the experts on biases that are likely to occur in the given situation and to explain how tendencies toward them can be countered effectively (see MEYER & BOOKER 2001, pp. 170, 131-139; AYYUB 2001).

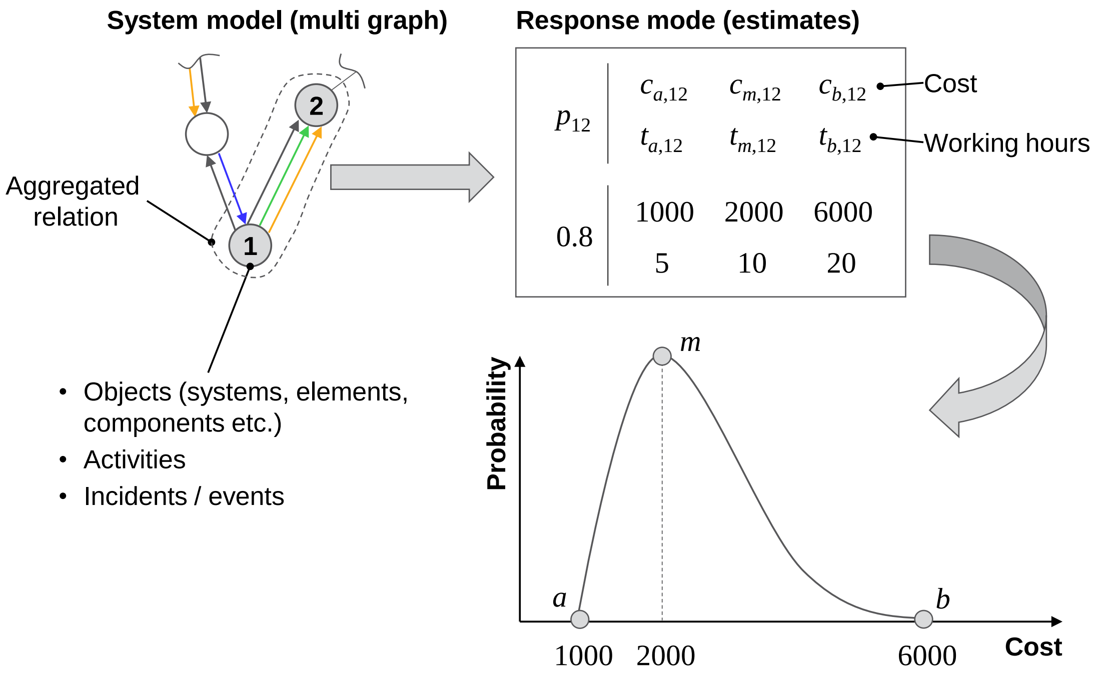
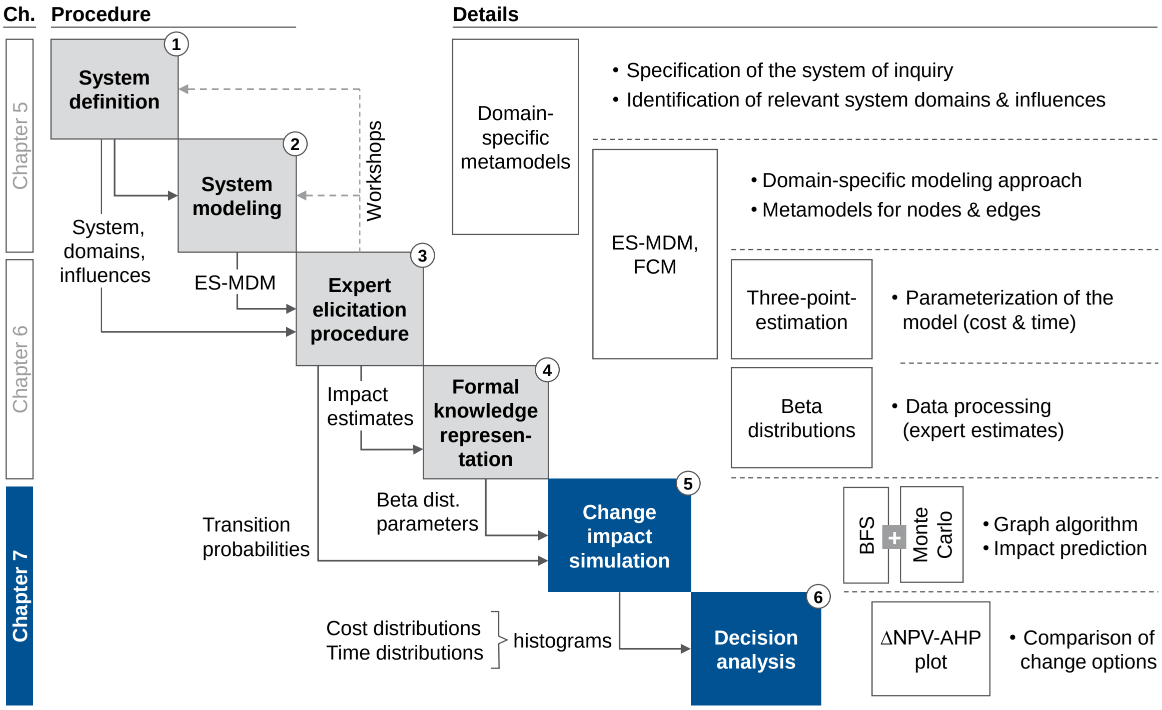


Figure 6.4: Flip chart illustration of the response modes required

Depending on the complexity of the paper based graph model it can be helpful to supplement it by a matrix representation as “a way of focusing on one relationship at a time” (DESTHIEUX et al. 2010, p. 173). The ES-MDM is implemented as an MS Excel® template with a color coding for different types of relations. It is populated beforehand with the data elicited during the conceptualization phase. The experts are required to reduce the multi-graph model to a simple directed graph—the *reduced graph model*—reflecting their mental model of the given change scenario. This trade-off between additional model precision and the effort required for its population is important for practical applicability. Hence, the time and cost for expert elicitation have to be compared with expected additional insights and explanatory power of the resulting model. If the level of detail chosen for causal mapping during the conceptualization phase appears too granular and does not significantly increase the quality of probability, cost, and time estimates, sub-systems should be clustered to simplify the model. Facilitator and modeler need to make sure that this structural synthesis is not driven by opportunistic behavior patters of the expert group, like e.g., the desire to save mental effort.

7 Change Impact Simulation and Decision Analysis

> *"La science est l'asymptote de la vérité. Elle approche sans cesse et ne touche jamais."*[1]
>
> —VICTOR HUGO (1864)



Legend

AHP	Analytic Hierarchy Process
BFS	Breadth-First Search
ES-MDM	Engineering System Multiple Domain Matrix
FCM	Fuzzy Cognitive Maps
NPV	Net Present Value

Figure 7.1: Chapter 7 addresses steps 5 and 6 of the procedure

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[1] Translation: Science is the asymptote of truth. It approaches constantly and never touches it.

7.1 Chapter introduction

In the previous chapter (cf. chapter 6), a technique for formal knowledge representation has been described, which is used to model expert uncertainty and to parameterize the *reduced graph model* derived from the ES-MDM. While the reduced graph model is represented by the (direct) transition probability matrix $\mathbf{P}$, the three-point-estimates for best case (a), most likely (m), and worst case (b) direct change cost and effective implementation time are stored in their corresponding estimate matrices $\mathbf{C}_a, \mathbf{C}_m, \mathbf{C}_b$ and $\mathbf{T}_a, \mathbf{T}_m, \mathbf{T}_b$, respectively. Using the PERT formulas[2], the form parameter matrices $\alpha^{N \times N}$ and $\beta^{N \times N}$ are computed based on this data, specifying beta distributions for direct change cost and implementation time between each pair of nodes i and j of the reduced model. Moreover, an *expert elicitation procedure* has been suggested based on conceptual and formal model building methods. The procedure is used to support both knowledge-based system modeling and parameter estimation.

Chapter 7 now deals with steps 5 and 6 of the method for change impact analysis, i.e., the Change Impact Simulation Graph Algorithm (CISGA) and decision analysis (cf. figure 7.1). The algorithm is used to simulate the total impact of a manufacturing change in terms of *investment cost*, *labor cost*, and *implementation time*. Beyond that, also the joint impact of multiple, simultaneously triggered changes can be simulated. The main inputs of the CISGA are the estimated transition probabilities for the change scenario to be analyzed, stored in $\mathbf{P}$, as well as the impact estimate matrices $\mathbf{C}_a, \mathbf{C}_m, \mathbf{C}_b$ and $\mathbf{T}_a, \mathbf{T}_m, \mathbf{T}_b$, as described in chapter 6. For the comparison of alternative change options, a simple system cost model and a comprehensive decision framework, coined *ΔNPV-AHP diagram*, are suggested.

The remainder of this chapter is structured as follows: section 7.2 provides an introduction to Breadth-First Search (BFS), before the basic idea of the CISGA is outlined. The main algorithm is presented in section 7.3, also discussing *node revisiting* and *propagation priority rules* for the specification of *change propagation behavior*. Since the CISGA is used for Monte Carlo Simulation (MCS), section 7.4 explains the statistics required to derive total *impact histograms* and *impact heat maps*. Finally, propositions for monetary and qualitative decision analysis are provided in section 7.5.

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[2] That is, the presumed mean and variance of direct change cost and implementation time, which reflect the uncertainty of expert estimates (cf. section 6.3.2).

7.2 Elementary principles

7.2.1 Breadth-First Graph Traversal

Breadth-First Search (BFS) is a graph traversal algorithm, which was first described by MOORE (1959). All nodes reachable from a root vertice s are visited in "breadth-first" order, i.e., all adjacent nodes (direct neighbors) of s are visited before proceeding to next level neighbors. The worst case performance for visiting all nodes within the distance of d edge traversals from the root node s for a graph $G(V,E)$ with a set of vertices V, edges E, and an average out-degree b is $O(|E|) = O(b^{d+1})$ (BERWICK 2003, p. 2). Generally, BFS implementations make use of queues for the nodes to be visited next. Algorithm 1 shows the pseudo code for BFS.

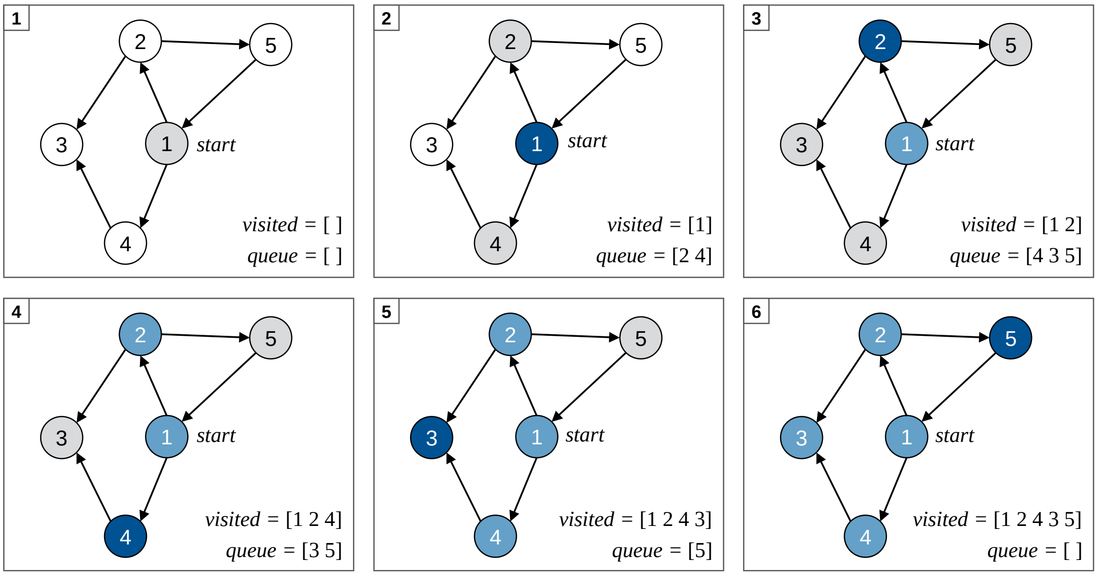

Figure 7.2: Illustration of breadth-first graph traversal

7.2.2 Basic idea of Change Impact Simulation

The theory of change propagation implies that changes only propagate along the interdependencies of a system, i.e., along the relations that constitute its structure (HAMRAZ et al. 2013b, p. 188). Here, this structure is modeled using adjacency matrices or directed graphs. In this context, initial changes correspond with the entries

```
Input  : Graph $G(V,E)$ with set of nodes $V$, $v,w \in V$, edges $E$, root node $s \in V$
Output : All vertices that can be reached from $s$
BreadthFirstSearch($G(V,E),s$)
begin
    $Q \leftarrow$ empty queue
    $Q.enqueue(s)$
    $\forall v \in G : visited(v) \leftarrow$ false
    $visited(s) \leftarrow true$
    while $\neg empty(Q)$ do
        $i \leftarrow dequeue(Q)$
        for $\forall w \in neighbors(i)$ do
            if $visited(w) =$ false then
                $Q.enqueue(w)$
                $visited(w) \leftarrow$ true
            end
        end
    end
end
```

Algorithm 1: Breadth-First Search

s_k of a root node vector[3] **s**. Thus, multiple changes can be processed simultaneously by breadth-first graph traversal. While basic BFS visits all nodes within the neighborhood of a root node s, change propagation is probabilistic with respect to the likelihood of change transition from one entity of the system to another as well as regarding the impact it generates in terms of cost and implementation effort. As explained earlier (cf. section 6.3.2), the latter uncertainty is modeled by the parameterization of beta distributions $\forall$ edges $e_{ij} \in E$. However, the most likely estimates can also serve as input for an expected value calculation when no assumptions on the distribution of estimates shall be made.

On the one hand, a deterministic expected impact calculation based on BFS can be performed by computing the combined impact for every node in the neighborhood of s (cf. section A.2). This method is very similar to the Forward CPM algorithm for "combined risk" as described by CLARKSON et al. (2004). On the other hand,

---

[3] In computer science, a vector denotes an array-like data structure, which allows dynamical allocation of memory. New data elements can be added at the end as well as at the front of a vector.

uncertain change transition can be modeled by means of Monte Carlo Simulation (MCS) combined with BFS. In this case, the direct transition likelihood p_{ij} from node i to node j is compared with a uniformly distributed random variable $u_{ij} \sim U(0,1)$, similar to a coin toss. If $u_{ij} < p_{ij}$, which is true in $p_{ij}\%$ of cases, change is assumed to propagate, else BFS terminates. By running a large number (e.g., $n > 2000$) of simulation trials, impact distributions for cost, total cost, and working time can be computed (cf. section 7.3.1). This algorithm is preferred here because it enables the user to analyze the spread of results, which provides additional insights for risk management. In the following, the probabilistic algorithm is presented. For the deterministic version the reader is referred to appendix A.2. Furthermore, different configurations with regard to node revisiting in section 7.3.2 (no revisiting, once per path, and unrestricted) and change transition priority rules in section 7.3.3 (e.g., most likely neighbor is visited first) are explained to provide options for their use in practical applications.

7.3 Change Impact Simulation Graph Algorithm

7.3.1 Main algorithm

In this section, the main Change Impact Simulation Graph Algorithm (CISGA) procedure `ChangeImpactMCS` is described, which is run n times in a Monte Carlo Simulation. As explained in section 6.3.2, the structure of the reduced graph model $G(V,E,p_{ij})$ is determined by the direct transition probability matrix $\mathbf{P}$. Alongside $\mathbf{P}$, the cost estimate matrices $\mathbf{C}_a, \mathbf{C}_m, \mathbf{C}_b$, the time estimate matrices $\mathbf{T}_a, \mathbf{T}_m, \mathbf{T}_b$, and the vector of initial changes $\mathbf{s}$ with $s_k \in V$ are the main parameters of `ChangeImpactMCS`. Table 7.1 provides an overview of all variables used within the procedure. While the complete pseudo code of the procedure is given in algorithm 2 on page 120, it shall be explained using the simplified illustration in figure 7.3 on page 119.

Table 7.1: Nomenclature of the CISGA

Variable	**Type**	**Description**
$\mathbf{P}$	matrix	Transition probability matrix, stores direct change likelihoods p_{ij} between each pair of the N entities that constitute the system
$\mathbf{C}_a, \mathbf{C}_m, \mathbf{C}_b$	matrix	Best (a), most likely (m), and worst case (b) cost estimate matrices

Table 7.1: (continued)

Variable	Type	Description
$\mathbf{T}_a, \mathbf{T}_m, \mathbf{T}_b$	matrix	Best (a), most likely (m), and worst case (b) working time estimate matrices
$\mathbf{s}$	vector	Vector containing all change initiating system elements s_k
depth	scalar	Assumed propagation depth, which equals the search depth of BFS
visited	vector	Contains all nodes that have been visited (i.e., changed)
startnodes	vector	Contains all nodes that are currently active, is initialized with **s**
startpaths	matrix	Contains all paths corresponding with the current nodes in *startnodes*, nodes of a path are stored in the sequence they have been visited
$I_{neighbors}$	vector	Index set, contains the indices of all neighbors
neighbors	vector	Nodes in the neighborhood of all current nodes
parentnodes	vector	Expansion of *startnodes*; has the size of *neighbors*; assigns current nodes to their respective neighbors
parentpaths	matrix	Expansion of *startpaths*; has as many columns as *neighbors*; assigns paths to all nodes in *neighbors*
probslist	vector	Contains direct transition likelihoods $p_{ij} \in \mathbf{P}$ of all current nodes to their neighbors; has the size of *neighbors*
$\sigma(I_{neighbors})$	vector	Permutation σ of the index set $I_{neighbors}$ representing the application of priority rules for processing changes
cost	scalar	Random cost drawn from the estimated beta distribution; simulates the cost incurred if change propagates from current node to one of its neighbors
time	scalar	Random time drawn from the estimated beta distribution; simulates the required working time if change propagates from current node to one of its neighbors
total	scalar	Total cost incurred if change propagates from current node to one of its neighbor; computed based on *cost* and *time*

After the *startnodes* have been initialized with **s**, the first **for**-loop is executed, iterating the search depth. By means of the functions `GenerateNeighbors`, `GenerateParentNodes`, and `GenerateParentPaths` the *startnodes* [4, 5, 6] and their corresponding paths are expanded to match the vector of all current neighbors [7, 8, . . . , 12] (also cf. lines 8 to 11 of algorithm 2). The variables *startnodes, parentnodes, neighbors*, and *probslist* can be visualized as row vectors, whereas

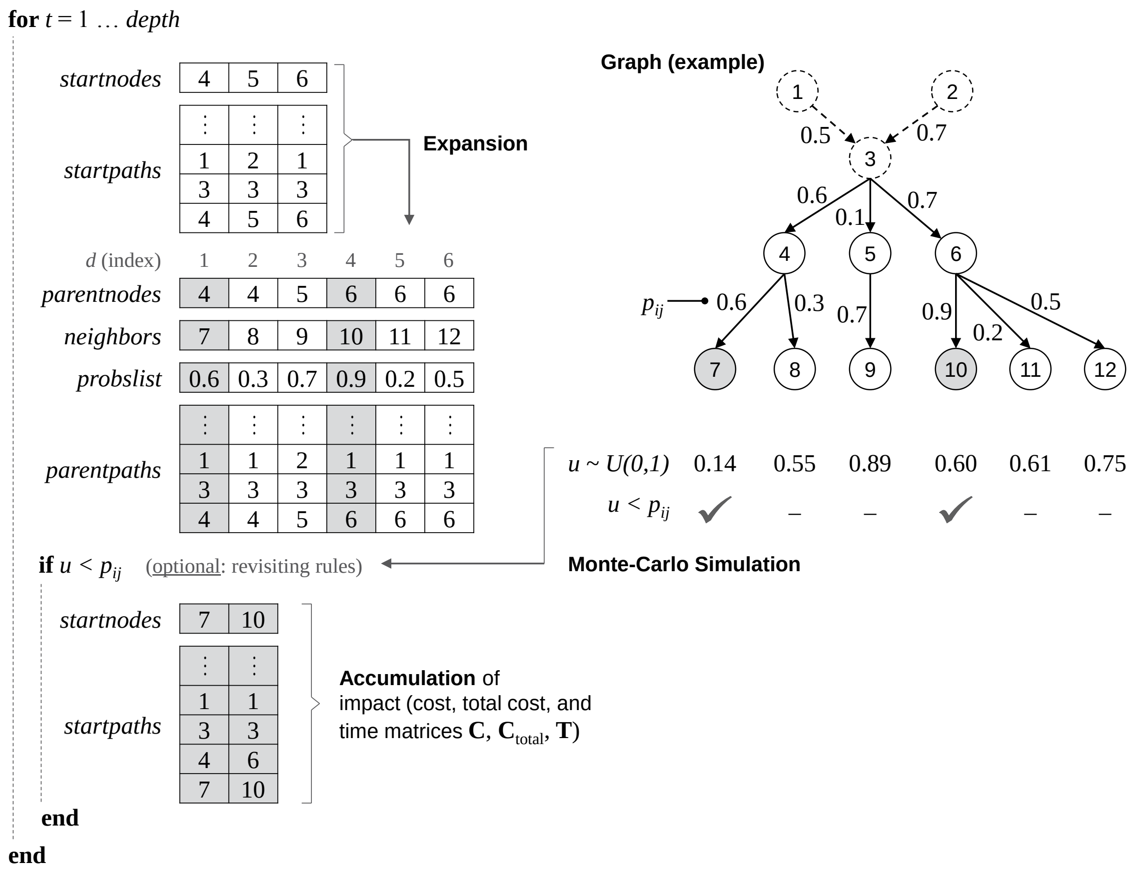

Figure 7.3: Illustration of the Monte Carlo CISGA

startpaths and *parentpaths* can be imagined as merged column vectors; i.e., matrices. Following, the uncertainty of change propagation is simulated for all neighbors n_d. As explained earlier, change is propagated only if the uniformly distributed random variable $u < p_{ij}$ ($= probslist_d$). If this condition is met—like for nodes [7, 10] in the example—random values for cost and time will be drawn from their respective PERT-beta distributions using the functions `DrawCostPERT` and `DrawTimePERT`. As described in section 6.3.2, the input parameters for these functions are the estimate matrices $\mathbf{C}_a, \mathbf{C}_m, \mathbf{C}_b$ and $\mathbf{T}_a, \mathbf{T}_m, \mathbf{T}_b$, respectively. Total cost is computed based on *cost* and *time* as $total = cost + c_t \cdot time$, where c_t is an hourly rate for labor cost. Finally, cost, time, and total cost are accumulated and stored in the result matrices $\mathbf{C}, \mathbf{T}$ and $\mathbf{C}_{total}$ before the depth-iteration proceeds to the next level (cf. lines 16 to 21 in algorithm 2). Note that the index set $I_{neigbors}$ is arranged according to the permutation σ in line 14 of algorithm 2 to simulate *priority rules* for change processing, like e.g., to work on the most probably affected system elements first. These priority rules are explained in detail in section 7.3.3. Propagation behavior with regard to revisiting of nodes—e.g, due to cycles or intersections of paths—can be adjusted as described in section 7.3.2.

```
Input  : Graph $G(V,E,p_{ij})$ with direct transition probabilities $p_{ij} \in \mathbf{P}$, cost
         estimates $c_{a,ij} \in \mathbf{C}_a$, $c_{m,ij} \in \mathbf{C}_m$, and $c_{b,ij} \in \mathbf{C}_b$, working time estimates
         $t_{a,ij} \in \mathbf{T}_a$, $t_{m,ij} \in \mathbf{T}_m$, and $t_{b,ij} \in \mathbf{T}_b$, hourly rate $c_t$, propagation $depth$,
         and the initial change vector $\mathbf{s}$ with $s_k \in V$
Output : Aggregated cost $c_{ij}^{(n)}$, working time $t_{ij}^{(n)}$, and total cost $c_{total,ij}^{(n)}$ incurred
         $\forall$ edges $e_{ij} \in E$ of the $n$-th MCS trial stored in $\mathbf{C}^{(n)}$, $\mathbf{T}^{(n)}$, and $\mathbf{C}_{total}^{(n)}$
ChangeImpactMCS ($\mathbf{P}, \mathbf{C}_a, \mathbf{C}_m, \mathbf{C}_b, \mathbf{T}_a, \mathbf{T}_m, \mathbf{T}_b, \mathbf{s}, depth, c_t$)
begin
    $\mathbf{C}, \mathbf{C}_{total}, \mathbf{T} \leftarrow [\,]$
    $visited \leftarrow [\,]$
    $startnodes \leftarrow \mathbf{s}$
    $startpaths.init(\mathbf{s})$
    for $t \leftarrow 1 \ldots depth$ do
        $\left\{parentpaths_i \in V^t \mid i \in I_{neighbors}\right\} \leftarrow$
          GenerateParentPaths ($\mathbf{P}, startnodes, startpaths$)
        $\left\{parentnodes_i \in V \mid i \in I_{neighbors}\right\} \leftarrow$
          GenerateParentNodes ($\mathbf{P}, startnodes$)
        $\left\{neighbors_i \in V \mid i \in I_{neighbors}\right\} \leftarrow$
          GenerateNeighbors ($\mathbf{P}, startnodes$)
        $\left\{probslist_i \in \mathbb{R} \mid i \in I_{neighbors}\right\} \leftarrow$
          $\left\{\left(\mathbf{P}_{u_i,v_i}\right)_i \mid u_i \in parentnodes, v_i \in neighbors, i \in I_{neighbors}\right\}$
        $startnodes \leftarrow [\,]$
        $startpaths \leftarrow [\,]$
        for $n_d \in neighbors, d \in \sigma\left(I_{neighbors}\right)$ do
            if $rand(0,1) < probslist_d$ and $\neg visited.contains(n_d)$ and
              $\neg parentpaths.contains(d, n_d)$ then
                $cost \leftarrow$ DrawCostPERT ($parentnodes_d, n_d, \mathbf{C}_a, \mathbf{C}_m, \mathbf{C}_b$)
                $time \leftarrow$ DrawTimePERT ($parentnodes_d, n_d, \mathbf{T}_a, \mathbf{T}_m, \mathbf{T}_b$)
                $total \leftarrow cost + time \cdot c_t$
                $\mathbf{C}_{parentnodes_d,n_d} += cost$
                $\mathbf{T}_{parentnodes_d,n_d} += time$
                $\mathbf{C}_{total,parentnodes_d,n_d} += total$
                $startnodes.append(n_d)$
                $visited.append(n_d)$
                $startpaths.append(parentpaths_d, n_d)$
            end
        end
    end
end
```

Algorithm 2: Change Impact Simulation (Monte Carlo)

7.3.2 Node revisiting modes

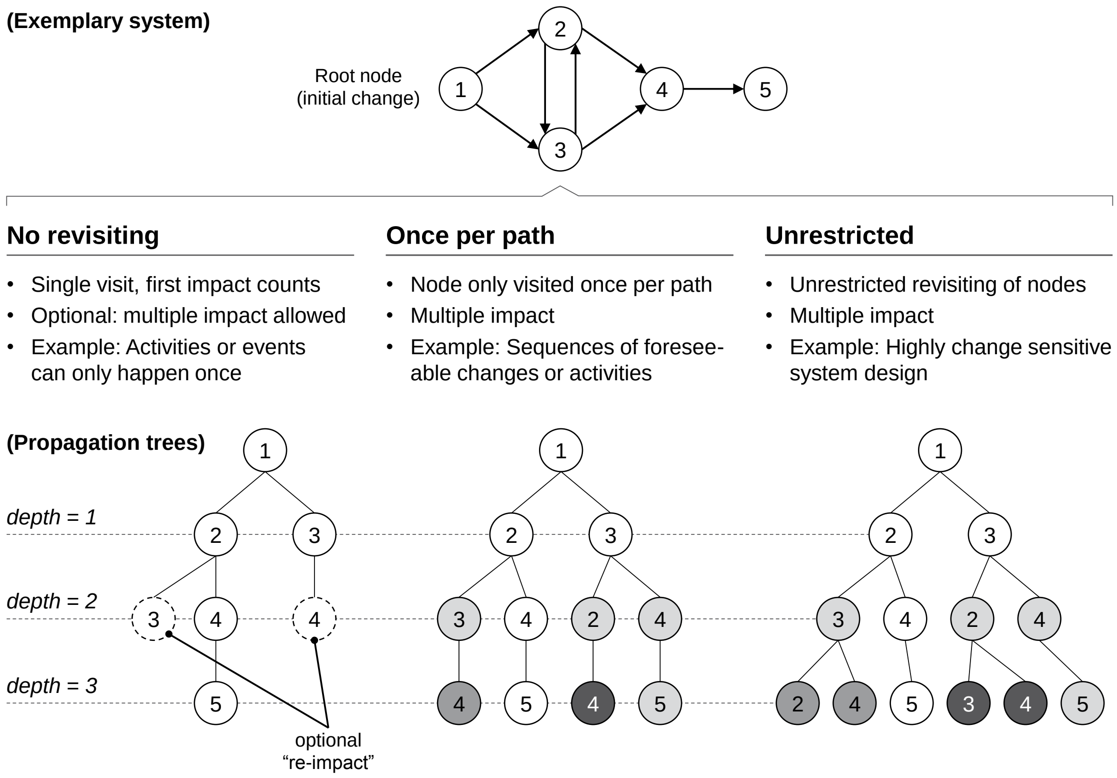

Figure 7.4: Implemented configurations for node revisiting BFS

Depending on the system of inquiry and the types of change to be analyzed, re-changing of system elements or redoing activities may have to be considered. Revisiting of nodes can be required due to elements with multiple incoming edges, cyclic structures or when more than one change is initiated at a time. To allow for these phenomena, three distinct revisiting modes have been implemented by adjusting the **if**-condition in line 15 of algorithm 2 on page 120 (cf. figure 7.4). They are not required for the deterministic algorithm described in appendix A.2.

- *No revisiting*. Every node may only be visited once, which is the default setting formulated in line 15. Nevertheless, it may be purposeful to allow for "re-impact". That is, the consideration of incoming edges—and therefore, impact on the node—without revisiting. Consider for example a cycle between two nodes i and j. With some probability, change that has propagated from i to j may require an adaptation of i again. If re-impact is allowed, it can be thought of as additional cost for the redesign of i to avoid further knock-on effects. This adjustment is achieved by moving the second part of the **if**-condition in line 15 (i.e., $[\neg visited.contains(n_d)$ and $\neg parentpaths.contains(d, n_d)]$) below line 21.

- *“Once per path”*. While the “no revisiting” mode controls whether a node has been visited before anywhere in the entire graph, this mode only prohibits revisiting in the same propagation *path*. If two paths lead to a connecting node, change may propagate “downstream” multiple times. This mode is activated by omission of $[\neg visited.contains(n_d)]$ in line 15. Analogously to the default mode, re-impact is considered by moving the adjusted **if**-condition below line 21.
- *Unrestricted.* In highly change sensitive systems, multiple redesign iterations are possible. The last mode does neither restrict multiple visiting nor the aggregation of incoming impact. The simulation is only stopped by means of the termination conditions, i.e., max. propagation depth reached or $u \nless p_{ij}$. This mode is activated by omission of $[\neg visited.contains(n_d)$ and $\neg parentpaths.contains(d, n_d)]$ in line 15.

7.3.3 Change propagation priority rules

By default, BFS (cf. algorithm 1) and thus also the `ChangeImpactMCS` algorithm (cf. algorithm 2) list the neighbors to be visited in the next depth iteration in ascending numerical order. For graph traversal this order has no relevance at all. CIS, however, is path dependent, i.e., the resulting impact is determined by the predecessors that propagate change to an entity. Three priority rules are suggested for algorithm 2 to allow for different configurations.

These rules are modeled by permutations $\sigma(1,\ldots,n)$ of the set $I_{neighbors}$, whose members are the indices d of all neighbors n_d (cf. line 14 in algorithm 2). Consider for example $I_{neighbors} = \{1,2,3,4\ldots\}$ with the exemplary permutation $\sigma(I_{neighbors}) = \{7,4,2,5,\ldots\}$. Figure 7.5 shows an illustrative example of the priority rules:

- *Ascending numerical order* $(\sigma_{indentity})$. The “natural” order of BFS. Regardless of transition probabilities, neighbors are visited in ascending numerical order of their index $d \in I_{neighbors}$. Thus, $\sigma_{Indentity}$ is the identity function $\sigma(d) = d$.

- *"Most probable first"* $\left(\sigma_{maxprob}\right)$. In order to simulate a simple change prioritization policy of manufacturing change managers (cf. WYNN et al. 2010), this rule permutes the index set $I_{neighbors}$ according to the direct transition probability between parent and neighbors in descending order.
- *Randomized* (σ_{rand}). If no change management policy can be thought of, a randomized order is preferable. In this case, a random permutation is applied to the members of the index set.

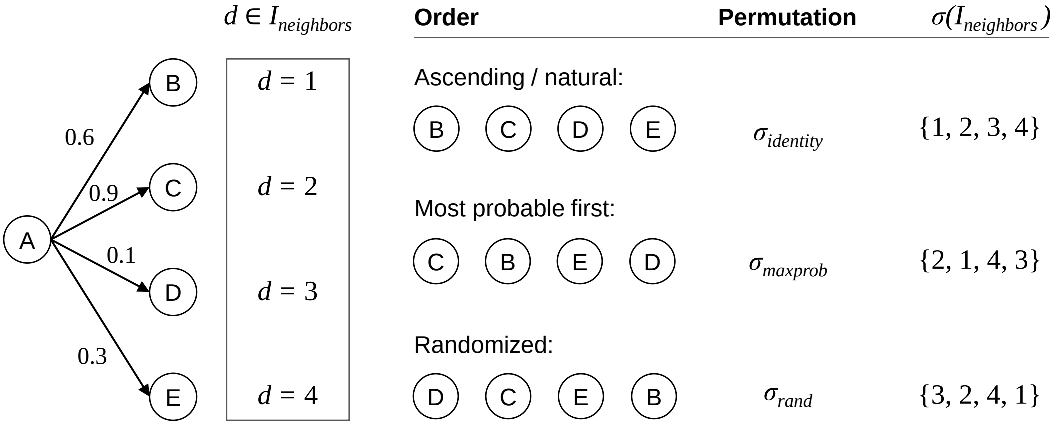

Figure 7.5: Priority rules for change transition to adjacent nodes

7.4 Result statistics

The procedure `ChangeImpactMCS` is run n times in Monte Carlo Simulation. For each of these trials the impact matrices $\mathbf{C}^{(n)}, \mathbf{T}^{(n)}, \mathbf{C}^{(n)}_{total} \in \mathbb{R}^{N \times N}$ store the accumulated impact in terms of cost $c^{(n)}_{ij}$, implementation time $t^{(n)}_{ij}$, and total cost $c^{(n)}_{total,ij}$ for every edge of the graph model $G(V, E, p_{ij})$. Because the deterministic procedure `ChangeImpactExp` (cf. appendix A.2) is only run once, n equals 1 and the index (n) can be omitted in equations 7.1 and 7.7. The sample means and the corresponding standard deviations defined in equations 7.2 to 7.4 are only required for the Monte Carlo algorithm.

The aggregated impact for each trial, i.e., the sum of all matrix elements, is computed using equations 7.1. Subsequently, the arithmetic sample means and standard deviations can be calculated based on equations 7.2 to 7.4.

$$C^{(n)} = \sum_{i=1}^{N}\sum_{j=1}^{N} c_{ij}^{(n)}, \quad T^{(n)} = \sum_{i=1}^{N}\sum_{j=1}^{N} t_{ij}^{(n)}, \quad C_{total}^{(n)} = \sum_{i=1}^{N}\sum_{j=1}^{N} c_{total,ij}^{(n)} \tag{7.1}$$

$$\overline{C} = \frac{1}{n}\sum_{i=1}^{n} C^{(i)} \quad \text{and} \quad \sigma_C = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(C^{(i)} - \overline{C}\right)^2}, \tag{7.2}$$

$$\overline{T} = \frac{1}{n}\sum_{i=1}^{n} T^{(i)} \quad \text{and} \quad \sigma_T = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(T^{(i)} - \overline{T}\right)^2}, \tag{7.3}$$

$$\overline{C}_{total} = \frac{1}{n}\sum_{i=1}^{n} C_{total}^{(i)} \quad \text{and} \quad \sigma_{C_{total}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(C_{total}^{(i)} - \overline{C}_{total}\right)^2}. \tag{7.4}$$

In order to enable a statistic analysis of the Monte Carlo samples, histograms and empirical Cumulative Distribution Functions (CDFs) for cost, time, and total cost can be plotted (cf. figure 7.6). The bin size of the histograms has to be computed dynamically depending on the number of trials. Here, the TERRELL-SCOTT rule is applied, which recommends $k = \lceil 2n^{1/3} \rceil$ for the number of bins (SCOTT 2009, p. 305).

The arithmetic mean of the impact propagated on all edges e_{ij} of the model—visualized by the change impact heat map shown in figure 7.7—can be used to identify change cost drivers, which is valuable information for manufacturing change management. For instance, this analysis reveals candidates for the implementation of additional changeability in order to lower future change cost. Edge-wise mean impact is calculated using equations 7.5 to 7.7.

$$\overline{\mathbf{C}}^{N\times N} = \frac{1}{n}\sum_{i=1}^{n} \mathbf{C}^{(i)}, \tag{7.5}$$

$$\overline{\mathbf{T}}^{N\times N} = \frac{1}{n}\sum_{i=1}^{n} \mathbf{T}^{(i)}, \tag{7.6}$$

$$\overline{\mathbf{C}}_{total}^{N\times N} = \overline{\mathbf{C}} + c_t \cdot \overline{\mathbf{T}} = \frac{1}{n}\sum_{i=1}^{n} \mathbf{C}_{total}^{(i)} \tag{7.7}$$

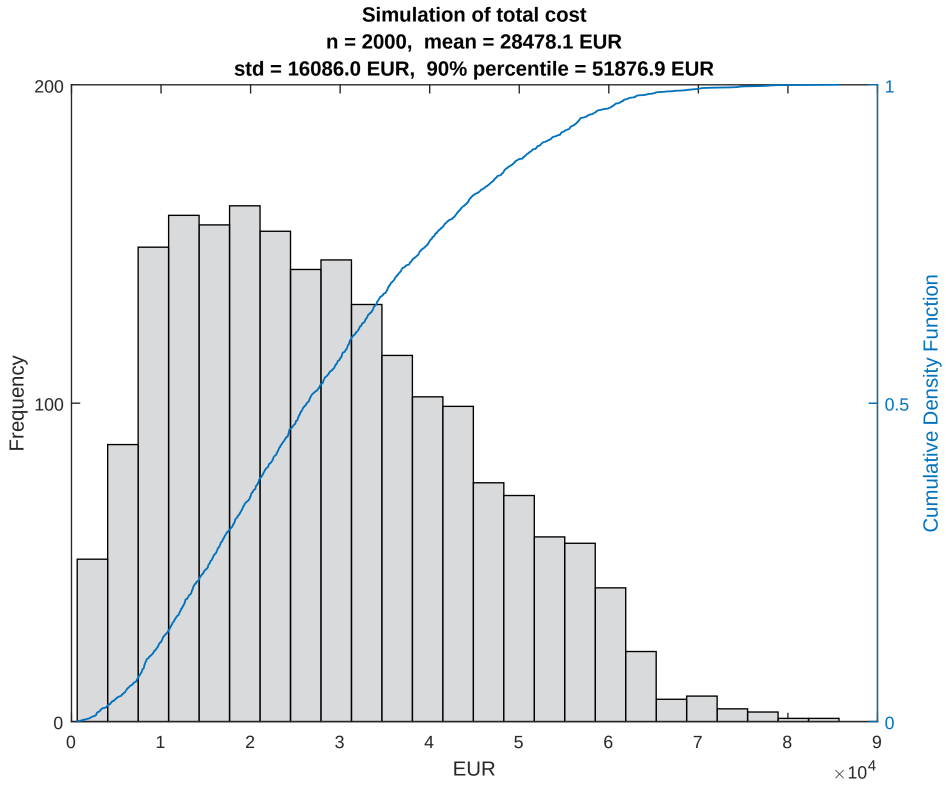

Figure 7.6: Exemplary total impact histogram and corresponding CDF

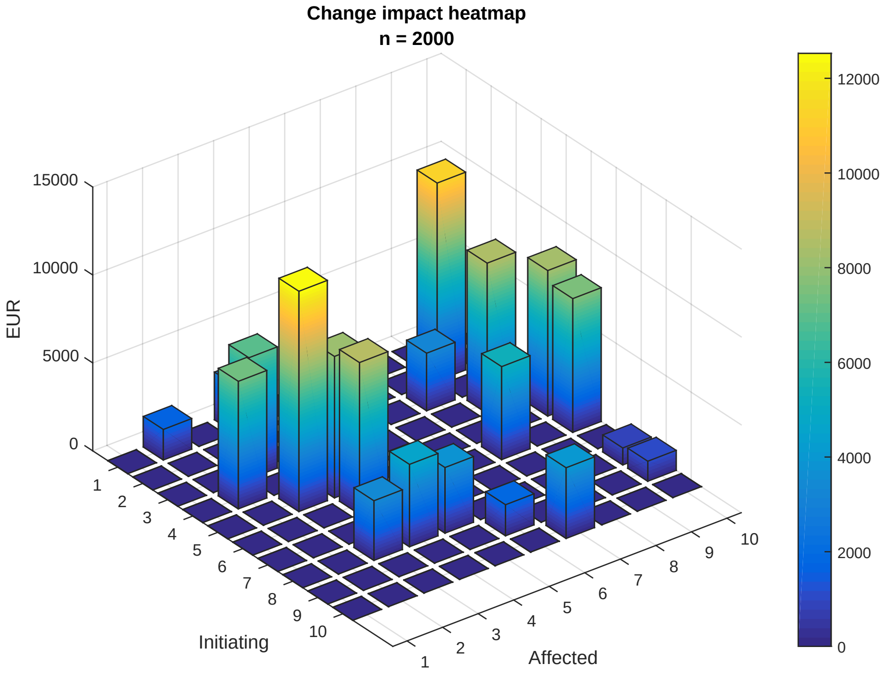

Figure 7.7: Exemplary change impact heat map showing aggregated impact by edge

7.5 Propositions for comprehensive decision analysis

7.5.1 Monetary criteria

For quantitative decision analysis, the CISGA yields the predicted total cost and working time due to initial changes, which are presented as histograms. Evidently, the impact simulation does only allow for one-time cost by design, which is the focus of this thesis. Nonetheless, the initial expenses I_0 for a desired change option have to be weighed up against recurring benefits, both, monetary and non-monetary, as well as against recurring costs within the time horizon considered.

For this purpose, the widely accepted Net Present Value (NPV) calculation shall be applied based on a simple system cost model. However, the results may also be used as a basis for more advanced valuation techniques such as real options analysis that also recognizes the ability of managers to influence the outcome of a change project by their choices over time (de Neufville 2002, p. 3). The NPV of a payment series is defined as (cf. e.g., Pyles 2014)

$$NPV = \sum_{t=1}^{\tau} \frac{C_t}{(1+r)^t} - C_0, \tag{7.8}$$

where:

t = Payment period (e.g., years)
τ = Time horizon, last payment period
C_0 = Cash outflow in t_0
C_t = Net cash flow (inflow minus outflow) in t
r = Discount rate[4] (e.g., risk free rate, WACC).

If an assessment of changed system costs is required, standard life cycle costs are suitable. Here, the model of Silver & de Weck (2007, p. 170) for life cycle cost of a system design is adapted (cf. 7.9). Discounted life cycle costs C_{LCC} are determined by fixed recurring costs $C_{F,t}$, the number of periods τ, and the discounted variable

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[4] See e.g., Guerard & Schwartz (2007) for detailed information on determining the cost of capital for a firm.

recurring costs $C_{V,t}(x)$, which depend on each period's demand x_t. C_D is the initial cost for a system design.

$$C_{LCC}(x,\tau,r) = C_D + \sum_{t=1}^{\tau} \frac{C_{V,t}(x) + C_{F,t}}{(1+r)^t} \tag{7.9}$$

Equation 7.9 yields the *absolute* discounted life cycle costs. For the purpose at hand *delta* cost due to a change or multiple changes is sufficient to determine whether a change is economically beneficial for a company. For the most part, manufacturing changes aim at a reduction of manufacturing cost. Nevertheless, also benefits like increased product quality have to be considered. In the simple ΔNPV model derived from equation 7.9 it is assumed that manufacturing changes affect product volume x and price p as well as fixed recurring costs $C_{F,t}$ in future periods. The initial non-recurring cost for the changes, which is the output of CISGA, is represented by the investment I_0. Thus, ΔNPV is given as

$$\Delta NPV(x,p,\tau,r) = \sum_{t=1}^{\tau} \frac{\Delta C_{V,t}(x,p) + \Delta C_{F,t}}{(1+r)^t} - I_0 \tag{7.10}$$

$$= \sum_{t=1}^{\tau} \frac{(\Delta p - \Delta c_V)_t \cdot (x + \Delta x)_t + \Delta C_{F,t}}{(1+r)^t} - I_0. \tag{7.11}$$

In equation 7.11, "Δ" refers to the difference of product price Δp, variable / fixed cost $\Delta c_V / \Delta C_F$, and volume Δx compared to their values for an unchanged system, all else being equal. Besides ΔNPV calculation, the model can also be used to determine the payback period of a system change using the static or dynamical pay-off method. It must be noted that the prediction of long-term effects of a change is a major challenge in itself—which is not in scope of this thesis—as price and demand variability are significant factors of uncertainty. Furthermore, costs due to organizational change should be taken into account.

7.5.2 Non-monetary criteria

Complex decisions may involve economic, technical, social, and environmental criteria, which cannot be appropriately represented by cash flow analysis alone (ZOPOUNIDIS & PARDALOS 2010). A variety of multi-attribute decision making techniques, which are suitable for the evaluation of "soft" decision criteria exist, such as cost-utility analysis, SWOT analysis, ranking method, and argument table. Two theoretically well-grounded techniques are the Analytic Hierarchy Process (AHP) by T. L. SAATY (1980) and the Relative Value Index (RVI). The latter has been developed more recently by DOWNEN et al. (2005) as a value assessment method for the "fuzzy front-end" of product development processes. Because of its prevalence in manufacturing literature, here, the AHP is suggested as a hierarchic scoring model for non-monetary decision criteria. For a detailed explanation the reader is referred to R. W. SAATY (1987) & T. L. SAATY (1990).

7.5.3 Comparison of multiple change options

To enable a comprehensive comparison of multiple change options, the ΔNPV-AHP plot is proposed as a tool for decision making (cf. figure 7.8) based on the data provided by the CISGA result statistics and equation 7.11. The ΔNPV of a change option A_i can be depicted as a *box plot* to visualize the variability of I_0. Whiskers[5] extending the boxes to the left and to the right mark the 2nd and 91st percentile of the total cost distribution—after summation of the ΔNPV—while a vertical line within the box is used for the mean value. The width of the box itself is defined by the 1st and 3rd quartile of the underlying distribution. For the AHP priority score $\in [0,1]$ of an alternative, a small dot is drawn on the vertical line representing the mean. The height of the box plot correlates linearly with the implementation time $\overline{T}$ required for an alternative (cf. equation 7.3 on page 124). That way, cost, time, and priority score are visualized in just one diagram for an intuitively accessible comparison.

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[5] Whiskers are thin lines extending the boxes of the box plot. They may also be used to represent other percentiles or the standard deviation.

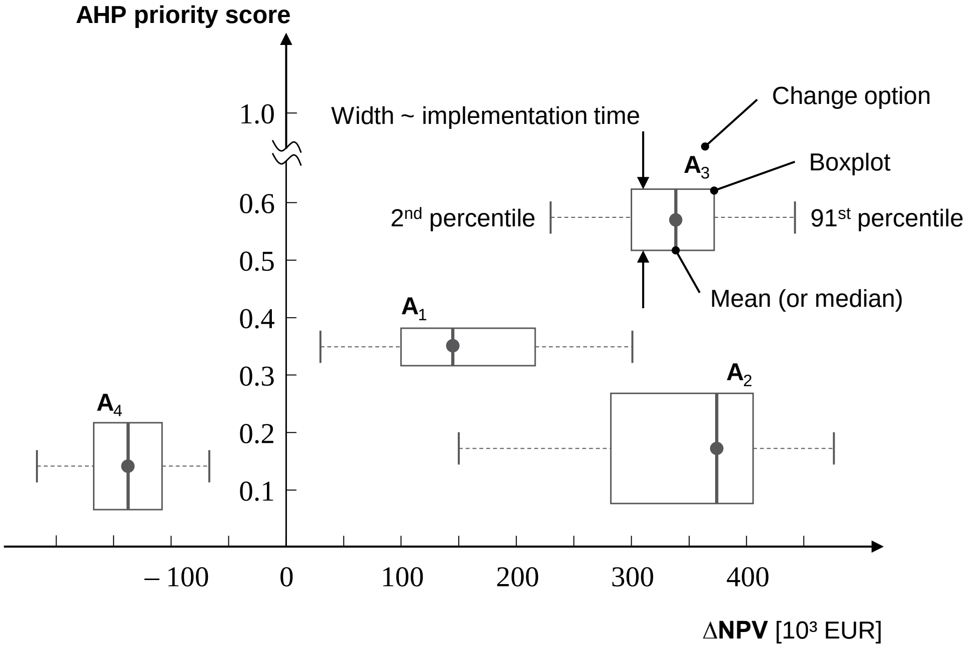

Figure 7.8: Illustration of the ΔNPV-AHP diagram

7.6 Summary

In this chapter, the CISGA was described as a means for the model-based simulation of change impact in manufacturing systems. This chapter completes the theoretical body of this thesis, encompassing the domain-specific structural modeling approach (cf. chapter 5), the formal representation of knowledge using PERT (cf. section 6.3), the procedure for the elicitation of expert judgment used for model-building and formalization (cf. section 6.4), and finally the graph-based model of change propagation behavior, its algorithmic description, as well as a model for decision analysis when facing alternative change options. In the following chapter, the method is applied and evaluated using three industrial case studies. Insights gained from the practical application of the method have been used as feedback for a continuous improvement of the approach. That is, a deliberate overlap of method development and application existed.

8 Application and Evaluation

8.1 Chapter introduction

According to the Engaged Scholarship Model described by VAN DE VEN (2007, p. 101), theory building arises from an iterative cycle of three activities: (1) conceiving, (2) elaborating, and (3) evaluating the theory. The latter requires inductive reasoning to assess “how the empirical ‘truth’ of a theory is evaluated in terms of how well the operational model of a theory fits observations of the world” (VAN DE VEN 2007, p. 102).

Over a period of six months, the method has been applied sequentially to three change scenarios in different industry sectors following the guidelines of EISENHARDT (1989) and EISENHARDT & GRAEBNER (2007) described in section 1.3.3: A medium-sized supplier of structural components for aerospace industry (substitution of a grinding machine), a small medical technology manufacturer (die redesign for an injection molding plant), and a large machinery and plant engineering company (feasibility study for additive manufacturing).

The degree of abstraction varies strongly among the case studies to investigate the general applicability of the approach. Experiences drawn from the practical applications have been used as feedbacks for a continuous improvement and extension of the methodology. These insights are discussed briefly after each case study. Due to spatial limitations, not all case data and result statistics are shown in the text, but can be found in the appendix. The transition probability matrices, impact histograms, and impact heat maps are shown in appendix section A.3.[1]

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[1] Note that all commercially sensitive data has been omitted or obscured.

8.2 Industrial applications

8.2.1 Case 1: Substitution of a grinding machine

Case description

The λ Inc. is a manufacturer of structural components and assemblies in the aerospace industry. In order to decrease production cost of a complex oil flow control sleeve made of stainless steel, a new grinding technology has been identified. Cost savings are expected due to shortened cycle times, the omission of process steps (e.g., deburring), and the replacement and disposition of less efficient machine tools. The chosen machine is capable of grinding a variety of high-precision circumferential grooves at the same time. Its replacement value is € 690,000[2]. The static payoff-period had been determined to be 2.6 years based on the expected cost savings. However, the general manager for technical methods of the λ Inc. asked for an independent retrospective assessment because the original analysis was suspected to not fully reflect the real change impact. Hence, the CIS methodology has been applied in cooperation with an expert team of the λ Inc. The results are described in the following sections. Table 8.1 provides an overview of the case data.

Table 8.1: Overview of case 1

Industry sector	Aerospace, structural components and assemblies
Number of employees	2,200
Change type	Replacement investment, new grinding technology
Perspective	Retrospection
Expert group	Senior production planner Operations manager General manager technical methods (occasional)
Project duration	Three project meetings, 16 hours on-site per person

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[2] Commercially sensitive data has been obscured and all financial values have been changed.

System specification, modeling, and parameterization

During a five-hour kick-off meeting the affected manufacturing system was identified by the expert group and the team of modeler and facilitator. The control sleeve is a part of a higher level component, which is manufactured in a production line layout. Beside a layout plan, a complete list of manufacturing equipment, routing sheets, technical drawings, and the original payoff-period calculation was provided by the λ Inc. Additionally, an on-site analysis of the production line was performed to ensure a comprehensive understanding. The main concern was the identification of potential technological interdependencies with up- and downstream processes. Since the substitution of the existing grinding machine had no such interactions within the production line, the focus of the analysis was shifted towards manufacturing external interactions such as production planning and quality. The latter function is of utmost importance because of the rigorous requirements for safety-relevant parts in aerospace industry.

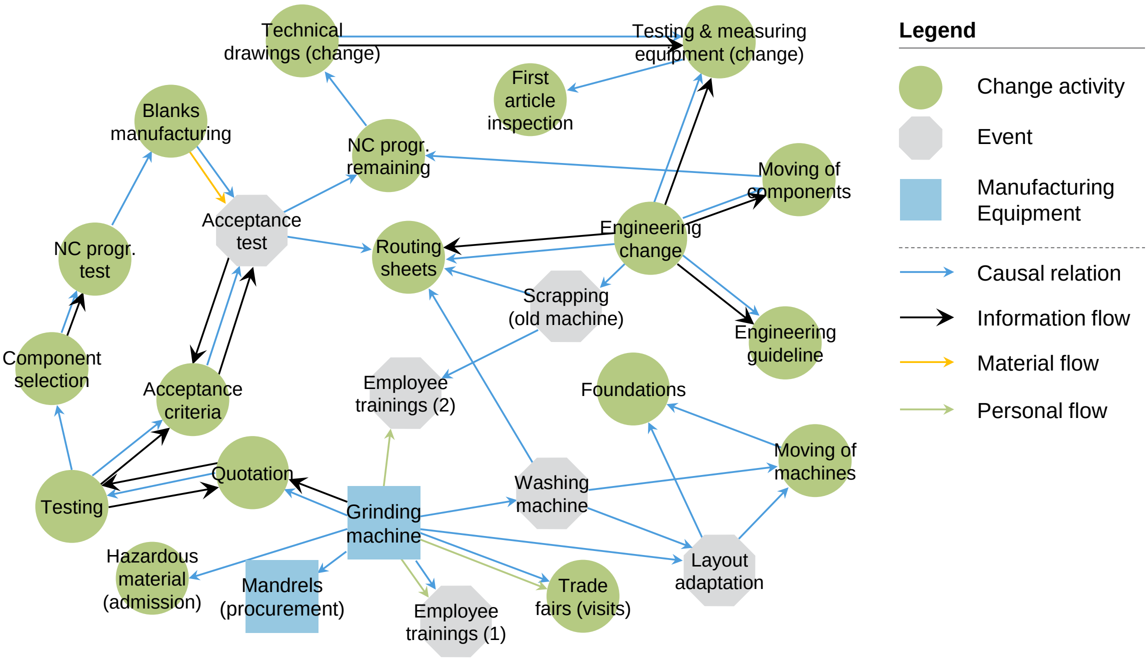

Figure 8.1: Multi-graph of the retrospective replacement investment analysis

The system modeling procedure was performed by a senior production planner of the λ Inc. in a consecutive six-hour modeling workshop. Starting from the investment decision for the new grinding machine, the creative process of model-building was performed based on six problem domains that were identified in advance: manufacturing, logistics, procurement, quality assurance, legal, and industrial engineering. This process was guided by the official processes of the λ Inc. for technical investments. Due to the strong process-orientation, the expert followed paths of sequentially impacted nodes in many cases before thinking about potential cross-links. Figure 8.1 shows the multi-graph model of the technology substitution. In total, 26 nodes have been identified during the conceptualization phase. A synthesis of sub-systems was not required.

For the discussion phase, which took place in a third four-hour workshop, the ES-MDM for the change impact analysis was prepared in advance to support parameter estimation (cf. figure A.5). The actual cost and implementation time estimates are confidential information. Still, the transition probability matrix $\mathbf{P}_\lambda$ can be found in table A.3 in the appendix in order to show the structure of the reduced system model.

Change impact simulation and decision analysis

Table 8.2: Simulation parameters for case 1

Node revisiting	No revisiting, but multiple re-impact
Simulation algorithm	`ChangeImpactMCS` (algorithm 2, p. 120)
Priority rule	Natural ascending numerical order
MCS trials	$n = 10{,}000$
Propagation depth	$t = 1 \longrightarrow \infty$
Initial changes	$\mathbf{s} = [15, 23]$
Labor cost	$c_{t,\lambda} = 70$ €/hour

Using the elicited data, the CIS is run with the configuration listed in table 8.2. In this case, most change activities are not iterative; thus, node revisiting is disabled. The expert recommended to check the activities in the order he named them, which is why the priority rule was set to ascending numerical order. A restriction of propagation depth is not required. The reason why node 23 (engineering change) has been considered as an initial change beside node 15 (grinding machine) is that 23 is a “source”—i.e., it only has outgoing edges—and would not be affected otherwise. The first case study was performed from an ex-post perspective. Hence, the original decision can only be carefully evaluated in the light of the revisited analysis.

Figures 8.2 and 8.3 summarize the total cost and implementation time histograms, depicted in figure A.6 and figure A.7 of the appendix. The baseline investment of € 690,000 is not part of the simulation because it is certain (an inclusion would deform the total cost histogram). As shown in figure 8.2, the mean impact almost doubles the originally assumed investment (+85.6%). In 90% of cases, total cost does not exceed € 1,650,699 (+139.2%). The coefficient of variation is 45.3%, reflecting the considerable spread of the distribution. With the assumed hourly labor cost rate of $c_t = 70$ € per hour, the mean labor cost of € 25,130 is comparatively low.

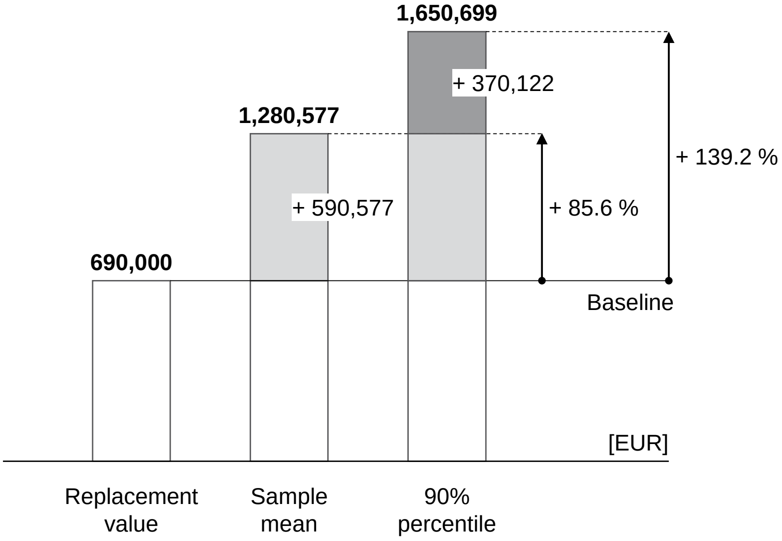

Figure 8.2: Additional (expected) cost identified by the change propagation analysis

The general manager of λ Inc. was particularly interested in a re-assessment of the payoff-period using the results of the impact simulation. Figure 8.3 shows the payoff-period for different interest rates $i \in [2\%, 3\%, 5\%]$. For the sample mean of the total cost distribution the payoff-period would increase from the initially assumed 2.6 to, e.g., 5.1 years for a dynamic computation with $i = 2\%$.

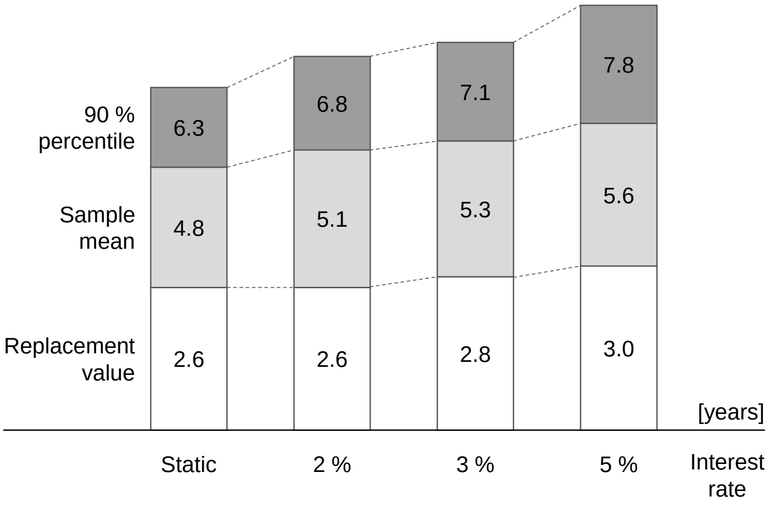

Figure 8.3: Payoff-period of the replacement investment based on the result statistics

Application experiences

The first application of the change impact assessment methodology provided several insights. Firstly, the importance of a deep understanding of the method by the involved experts was revealed. This learning was valuable feedback for the improvement of the elicitation procedure. Secondly, the inclusion of general cause-and-effect dependencies was encouraged by the unexpected shift of the impact analysis towards manufacturing external interactions that were not part of the metamodels designed for manufacturing systems. Furthermore, this case study also confirmed that the model-building process itself is valuable for the involved experts to gain a comprehensive understanding of the change scenario, as the following statement of the senior production planner indicates: "*Now one can see how complex the technical investment process for new manufacturing equipment is. This complexity is not realized by upper management at all.*" The total effort of 48 person-hours (4 persons) appears reasonable when compared with the adjusted mean of the *additional* total cost impact of € 590,577.

8.2.2 Case 2: Analysis of a polymer injection molding plant

Case description

The φ Inc., a medium-sized medical technology manufacturer, wants to assess the consequences of redesigning the die of a customized polymer injection molding machine because of a planned engineering change and increasing demand. The manufacturing system consists of an assembly station, the machine, the tool itself, robots, and measurement and control technology (MCT). Due to previous experiences with surprisingly costly and time consuming change projects, the company asked for an assessment of expected costs and working hours and the associated risk for the desired change. Thus, case 2 is an ex-ante analysis of change impact. The involved expert group consisted of a senior engineer and the factory manager. Four structured workshops were conducted for this project including a kick-off meeting (6 hours) as well as the positioning (4 hours), conceptualization (6 hours), and formalization workshops (6 hours). Since no changes in recurring costs were expected and no alternative change options were available, only the non-recurring costs were analyzed.

Table 8.3: Overview of case 2

Industry sector	Medical technology
Number of employees	≈ 400
Change type	Technical changes of polymer injection molding plant
Perspective	Prospection
Expert group	General manager production planning Project leader manufacturing technology
Project duration	Four project meetings, 22 hours on-site per person

System specification, modeling, and parameterization

Following the procedure described in section 6.4, the multi-graph model (cf. figure A.9 of the appendix) and the ES-MDM (cf. figure 8.4) of the injection molding system were elicited. The system boundary was drawn around the manufacturing system because no significant interactions with other equipment could be observed. In total, 18 nodes have been modeled.

Determining a suitable level of abstraction was already identified as a major challenge during the kick-off meeting because of the machine's internal complexity. In consultation with the expert team, four primary sub-systems were chosen, which should be modeled on a coarse component level: machine, die, automation equipment, and product. Thus, the modeler prepared a preliminary model and a list of components in advance of the conceptualization workshop in order to facilitate the system abstraction and structural model-building process.[3] The required information was acquired during an on-site inspection after the first project meeting. Technical drawings or further documentation of the manufacturing system were not made available.

During the model-building procedure, no restrictions were posed upon the experts with regard to the analytic detail. At the beginning of the discussion phase, however, some elements have been synthesized, e.g., the individual tool drives. This was done because individual impact assessments were deemed too expensive. The multi-graph model and ES-MDM show the resulting model used for parameter estimation.

Change impact simulation and decision analysis

Table 8.4: Simulation parameters for case 2

Node revisiting	Unrestricted revisiting
Simulation algorithm	`ChangeImpactMCS` (algorithm 2, p. 120)
Priority rule	Randomized
MCS trials	$n = 10{,}000$
Propagation depth	$t = 1, \dots, 7$
Initial change	$\mathbf{s} = [2]$
Labor cost	$c_{t,\varphi} = 110$ €/hour

Driven by their previous experiences with expensive change projects, the φ Inc. requested an impact analysis for decision making as well as for risk management and capital budgeting. The initial change is induced by the redesign of the mold (die), i.e., $\mathbf{s} = 2$. Since no information regarding the propagation behavior is available, the randomized priority rule is applied. Revisiting of nodes within an assumed propagation depth of 7 steps (also cf. GIFFIN et al. 2009) is unrestricted to allow for potential re-impact

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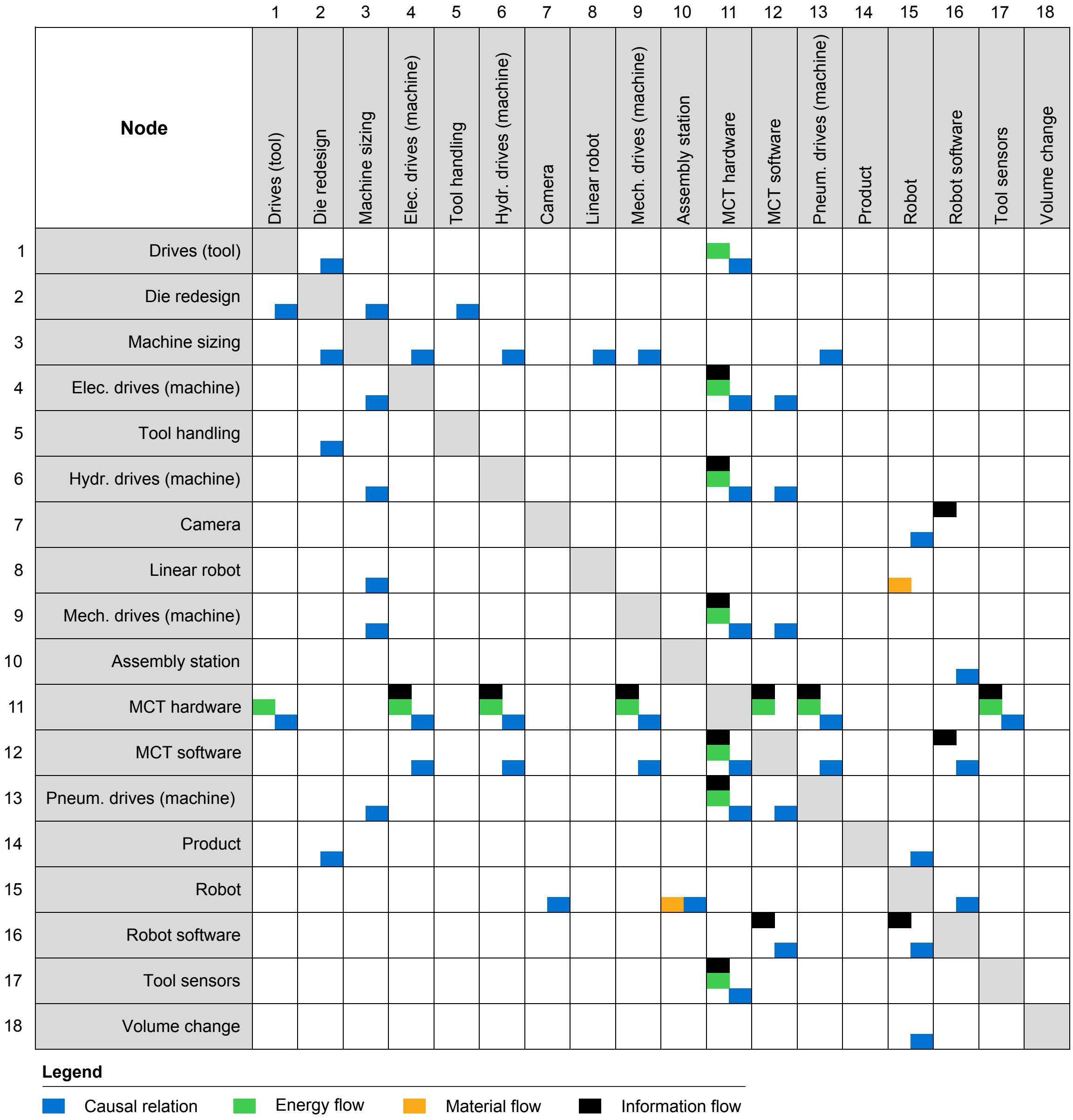
[3] Note that the method allows different levels of granularity even within the same node-domain.



	Node	1 Drives (tool)	2 Die redesign	3 Machine sizing	4 Elec. drives (machine)	5 Tool handling	6 Hydr. drives (machine)	7 Camera	8 Linear robot	9 Mech. drives (machine)	10 Assembly station	11 MCT hardware	12 MCT software	13 Pneum. drives (machine)	14 Product	15 Robot	16 Robot software	17 Tool sensors	18 Volume change
1	Drives (tool)		🟦									🟩🟦							
2	Die redesign	🟦		🟦		🟦													
3	Machine sizing		🟦		🟦		🟦		🟦	🟦				🟦					
4	Elec. drives (machine)			🟦								⬛🟩🟦	🟦						
5	Tool handling		🟦																
6	Hydr. drives (machine)			🟦								⬛🟩🟦	🟦						
7	Camera															🟦	⬛		
8	Linear robot			🟦												🟧			
9	Mech. drives (machine)			🟦								⬛🟩🟦	🟦						
10	Assembly station																🟦		
11	MCT hardware	🟩🟦			⬛🟩🟦		⬛🟩🟦			⬛🟩🟦			⬛🟩	⬛🟩🟦				⬛🟩🟦	
12	MCT software				🟦		🟦			🟦		⬛🟩🟦		🟦			⬛🟦		
13	Pneum. drives (machine)			🟦								⬛🟩🟦	🟦						
14	Product		🟦													🟦			
15	Robot							🟦			🟧🟦						🟦		
16	Robot software												⬛🟦			⬛🟦			
17	Tool sensors											⬛🟩🟦							
18	Volume change															🟦			

Legend

🟦 Causal relation 🟩 Energy flow 🟧 Material flow ⬛ Information flow

Figure 8.4: ES-MDM of the injection molding manufacturing system

due to the change sensitive customized design of the machine. The configuration of the simulation is summarized in table 8.4.

The CIS yields € 494,013 as mean value of total cost. However, the 90% percentile of € 1,173,178 and the right tailed distribution of simulation results shown in the total cost histogram in figure 8.5 indicate a significant risk of excessive cost. In total, 478 person-hours are expected for planning and implementation with the 90% percentile being 1,143 hours (cf. figure A.10 of the appendix).

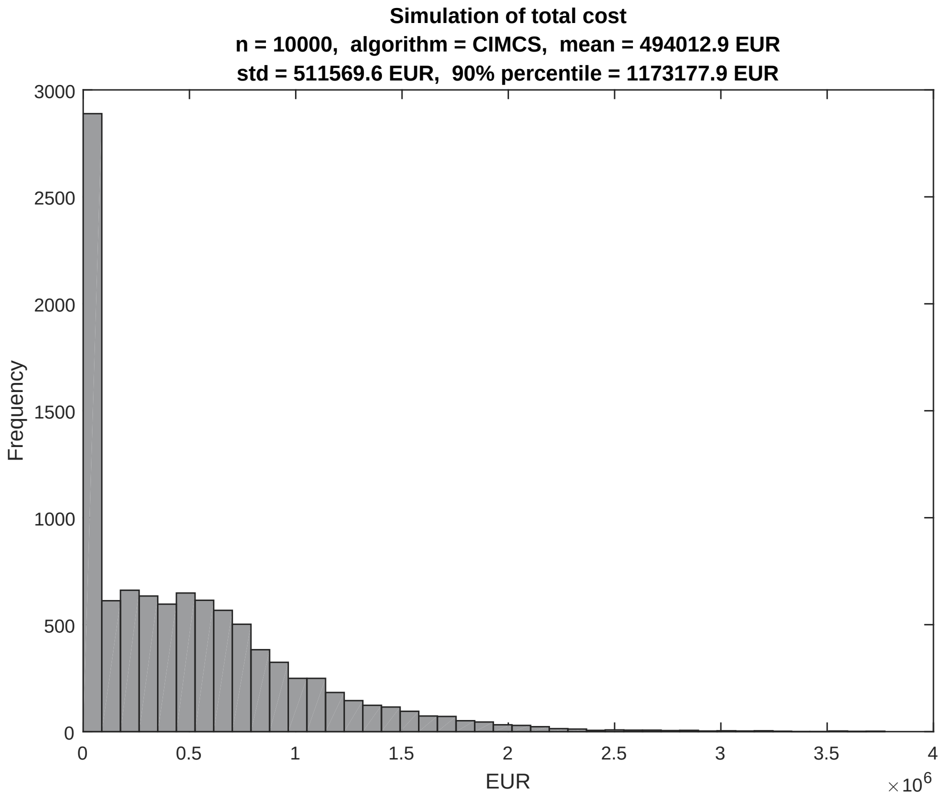


Figure 8.5: Total cost distribution for the impact of a die redesign

Application experiences

MEYER & BOOKER (2001, p. 86) state that sufficient normative expertise with respect to the response modes required is absolutely indispensable to achieve a high quality of results. Although the methodology and the expert elicitation procedure were explained in detail, the response modes had to be recapitulated several times due to obvious misunderstandings. If these had not been clarified, the results would have been severely deteriorated.

The preliminary system model provided by the modeler proved to be highly valuable for the process of specifying a suitable level of system abstraction. However, the expert group also named a variety of general influences that neither could be modeled as entities nor as relations (e.g., communication, market power of suppliers, internal prioritization, and lack of professional competence). This may be due to the fact that the experts had not been trained sufficiently in the use of the structural modeling guideline.

Furthermore, the great number of relations within the model relative to the amount of nodes was remarkable in this case study. This could indicate that the level of granularity was chosen too coarse, because the variety of different relation types actually related to distinct elements of a sub-system. With respect to the parameter estimation workshop it was helpful that at least two experts attended the discussions permanently. These “internal” discussions enabled a deeper understanding of technical dependencies compared to an exclusive moderation by the “external” facilitator.

8.2.3 Case 3: Introduction of additive manufacturing

Case description

Within the market of machinery and plant engineering the κ Inc. aspires to maintain their competitive edge in spare parts services by further reduction of lead time. Because of the enormous diversity of spare parts arising from their customized long-life capital goods, it is not economically sensible to have all of them in stock. In order to reduce capital lockup due to stored parts and to ensure a best in class lead time, the κ Inc. contemplates to introduce additive manufacturing for a range of polymer spare parts with exceptionally complex geometries. For this purpose, the investment in a Selective-Laser-Sintering (SLS) machine shall be analyzed as a major manufacturing change. Since no previous experiences with this manufacturing technology exist, this case study is to be understood as a feasibility study for a technology introduction. Outsourcing is not considered an option as the company also strives for technology leadership in this promising market.

Four structured workshops were required for this project including the kick-off (3 hours), positioning (5 hours), conceptualization (3 hours), and formalization workshop (2.5 hours). Table 8.5 summarizes important information at a glance.

System specification, modeling, and parameterization

In consultation with a senior operations manager of the κ Inc., the analysis was confined to a single manufacturing location in Germany. Furthermore, the study was restricted to the above mentioned range of selected complex Polyamide (PA) parts. Based on extensive technology know-how of the responsible project leader for strategic technology planning, SLS was chosen as the most promising additive manufacturing

Table 8.5: Overview of case 3

Industry sector	Machinery and plant engineering
Number of employees	≈ 12,000
Change type	Technology introduction, additive manufacturing
Perspective	Prospection
Expert group	Senior operations manager Project leader strategic technology planning
Project duration	Four project meetings, 13.5 hours on-site per person

technology for the intended field of application. Ahead of the conceptualization workshop, it was agreed to adjust the level of granularity of the analysis to the company-specific process framework of technology investments. This includes activities such as "budget release", "procurement", and "employee trainings".

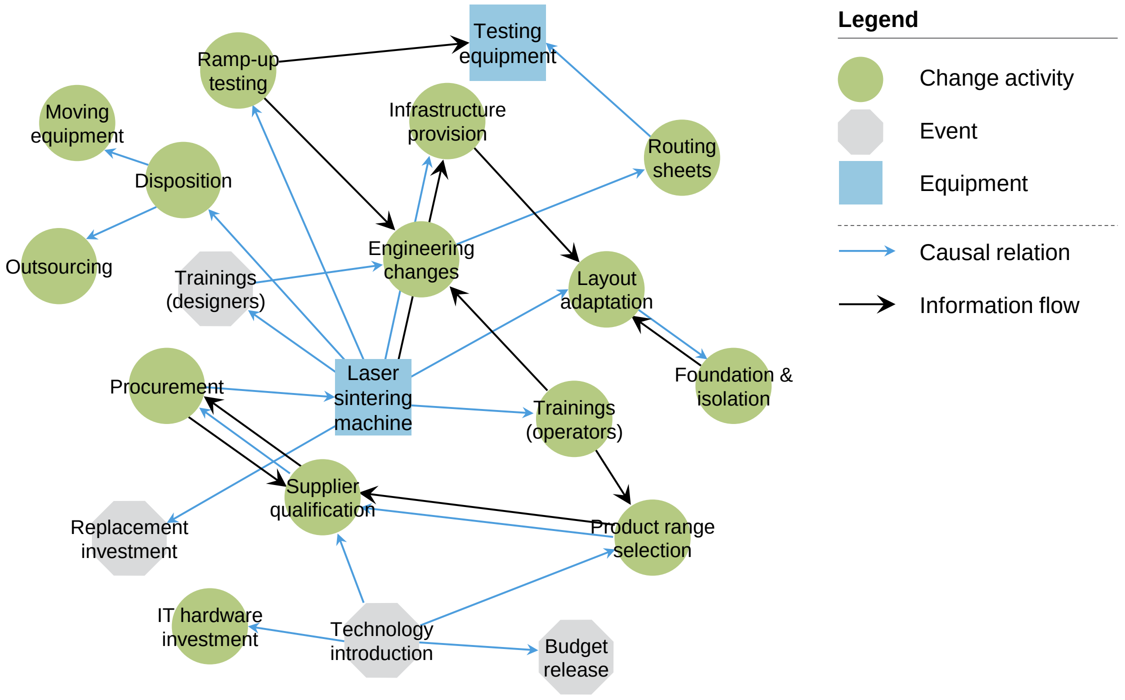


Figure 8.6: Multi-graph of the technology introduction feasibility study

Altogether, 28 nodes have been modeled. However, 8 nodes were eliminated from the model in advance of the formalization phase. A brainstorming session of the expert group, moderated by the modeler and the facilitator was performed beforehand to prepare a list of potentially affected entities. This greatly accelerated the conceptualization phase, since the remaining time was almost entirely used for contemplating the network of relations. Figure 8.6 shows the resulting multi-graph, while the corresponding ES-MDM can be found in appendix A.12.

Due to the perceived uncertainty and the comparatively low level of detail chosen for the analysis, the experts opted for the use of more general relation types to save effort required for a detailed specification. This may explain the dominance of causal relations and information flows is the models.

Change impact simulation and decision analysis

Similarly to the first case study, the transition probability matrix $\mathbf{P}_\kappa$ (cf. table A.5 of the appendix) contains a considerable amount of definite transitions, i.e., $p_{ij} = 1$. Nevertheless, the impact of these transitions remains uncertain due to the range of possible outcomes within the estimated interval. Definite transitions result from a variety of mandatory process steps, e.g., the formal release of an investment budget. This strong process orientation could also be observed in the first case study. Due to the similarity between both case studies, the simulation parameters are chosen identical, except for the priority rule, which was changed because the experts were unsure whether a deterministic propagation policy would reflect the change scenario appropriately (cf. table 8.6).

Table 8.6: Simulation parameters for case 3

Node revisiting	No revisiting, but multiple re-impact
Simulation algorithm	`ChangeImpactMCS` (algorithm 2, p. 120)
Priority rule	Randomized
MCS trials	$n = 10{,}000$
Propagation depth	$t = 1 \longrightarrow \infty$
Initial change	$\mathbf{s} = [18]$
Labor cost	$c_{t,\kappa} = 55$ €/hour

The CISGA yields the total cost histogram shown in figure 8.7 with a sample mean of € 1,070,204 (the SLS machine's expected price was set to € 400,000). For the mean effort of planning and implementation the simulation yields 6,299 hours (cf. figure A.13 of the appendix). With $c_{t,\kappa} = 55$ €/hour, labor cost amounts to € 346,445.

The right-skewed shape of the total cost distribution presumably results from the many definite transitions directly initiated by the technology introduction. Hence, some of the most costly activities always happen early in the course of the change process. This is confirmed by the impact heat map shown in figure A.14 of the appendix: particularly the relations between nodes 5 (procurement process) and 12 (investment in SLS machine) and nodes 12 and 10 (provision of required infrastructure) contribute to the total impact—albeit, this is no surprising result in this context.

In collaboration with the expert team, a variety of expected benefits of the technology introduction was also acquired to evaluate whether the investment in the new manufacturing technology is justified. These benefits are summarized in table 8.7.

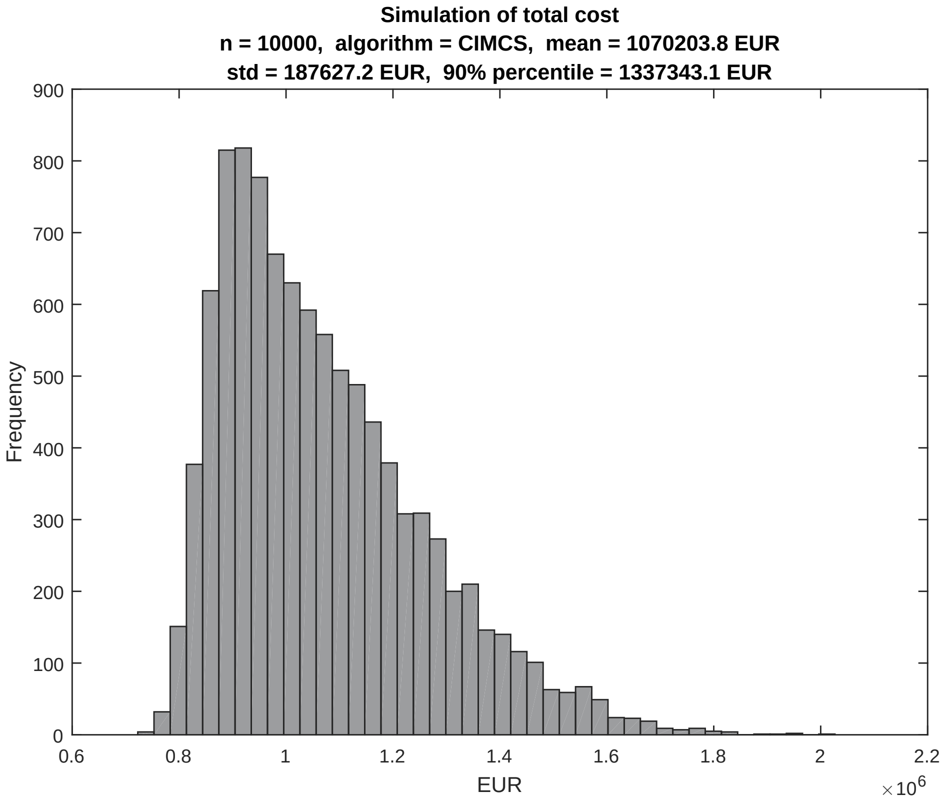


Figure 8.7: Total cost distribution for the technology introduction

Table 8.7: Overview of expected benefits due to the technology introduction

Short-term	Medium-term	Long-term
• Manufacturing of complex part geometries and multi-material designs • Economic viability of "lot size 1" (simultaneous generation of different parts) • Reduction of lead time in spare parts business	• Reduction of storage cost • Simplified disposition of orders • Strongly simplified manufacturing process and industrial engineering (less process steps) • Increased customer satisfaction	• Increased degree of automation • Lowered labor costs • Elimination of redundant conventional machine tools (reduced capital lockup) • Maintaining technology leadership in the target market • Economization of logistics cost and import duties

Application experiences

In advance of this case study, the response mode visualization presented in figure 6.4 on page 112 was designed. This improved notation was helpful to ensure a better comparability of expert estimates because the overview was facilitated. Two weeks passed between the conceptualization and formalization workshops. As it turned out, this helped the technology expert to further reflect the system model and to discuss specific questions with other employees of his company. Presumably, this also accelerated the following parameter estimation procedure.

Again, the expert group especially welcomed the procedure for structural modeling and the estimation technique for uncertain ranges of costs. Put in the words of the project leader, the results of the methodology are *"A very good arrangement, which provides an excellent overview of all relevant elements and also their complex dependencies."* Furthermore, the encouragement of interdisciplinary communication within the company was judged favorably.

For the first time, non-recurring *benefits* have been considered in this case study, which can simply be processed as negative costs (e.g., sale of outworn equipment). However, another problem was encountered during the formalization workshop: the experts asked for the consideration of *waiting time* such as lead times of suppliers. Currently, the methodology is not capable to process this kind of information as waiting time is not additive like cost and effective working hours—it can be parallelized. Hence, within probabilistic simulation trials the correct "total waiting time" cannot be determined without additional data.

8.3 Evaluation of the approach

8.3.1 Fulfillment of requirements

In this section the method's requirements are revisited in order to assess their fulfillment. They are discussed in the order they have been listed in section 4.3, separating general (substantive) and model (formal) requirements. Because of its pivotal role for industrial applicability, R.5—*justifiable level of effort*—is discussed separately in section 8.3.2.

General requirements

R.1 *Enhancement of system understanding*. A thorough investigation of interdependencies within the system and its environment is achieved through the step-wise elicitation procedure that encourages experts to think about the system boundary, relevant problem domains, sub-systems, activities, events, internal & external influences, the mapping of relations between these constructs, and the probability and magnitude of impact in case change propagates along the linkages of the system model. The effectiveness of the developed approach was confirmed by system experts.

R.2 *Incorporation of uncertain change propagation*. The prediction of knock-on effects of changes and how strongly they affect the system in terms of cost and implementation time are characterized by uncertainty. Knowledge-based modeling, however, also has to deal with the uncertainty of involved sources of information—the expert group. On the one hand, a breadth-first traversal graph algorithm and Monte Carlo Simulation have been used to simulate the uncertainty of change propagation within the system. On the other hand, Three-Point-Estimation and PERT have been applied to support experts in expressing their beliefs concerning the range of possible outcomes with regard to change impact. The elicitation procedure was designed to mitigate effects of subjective assessment biases by encouraging interdisciplinary discussions of experts and modeling interdependencies transparently and comprehensibly. Still, a basic level of experience is required in probability theory and logic inference to ensure a consistent quality of parameter estimations (i.e., sufficient normative expertise).

R.3 *Consideration of cross-domain effects*. A domain-specific structural modeling approach for manufacturing systems has been suggested combining the ES-MDM with Fuzzy Cognitive Mapping. Beside the technical (objects), social (stakeholders), environmental (system drivers), functional (functions), and process (activities) domain, also intangible constructs linked by general cause-and-effect dependencies can be processed effectively. The extended ES-MDM is both a multi-graph and a hyper-graph containing different node classes, cross-domain linkages, and multiple (types of) edges between nodes. Hence, also cross-domain effects of manufacturing changes can be captured and predicted.

R.4 *Provision of decision support*. The targeted use case scenarios of the developed methodological support range from the early phases of manufacturing change management to potential and strategic feasibility studies. In most cases, decision support suitable for practical applications has to involve an evaluation of the economical consequences of a decision in terms of time, money, and associated risk. Here, *decision* pertains to choosing between alternative change options or between implementation or rejection of the manufacturing change to be analyzed. The result statistics of the CISGA have been designed to fulfill this requirement by providing total cost and working time histograms as well as impact heat maps. A deeper understanding of potential benefits is also supported through the system modeling procedure.

Model requirements

R.6 *Flexible, adaptable, and reusable models*. Flexibility with respect to the types of manufacturing changes considered and the granularity of system models could be confirmed during the case studies. Nevertheless, the class structure of metamodels designed for the manufacturing domain can be extended easily to increase the level of detail, if required. Although the reusability of system models is given, it must be noted that the parameterization would have to be redone for a different change scenario. This recurring effort took between 2.5 and 6 hours in the presented application examples. Additionally, structural system models may also be useful in a different context, like e.g., the analysis of uncertainty proliferation in factory planning projects (HAWER et al. 2016).

R.7 *Transparency*. Model building and model parameterization are guided continuously by the responsible expert group. Within the limits of human imaginative power also the graph algorithm and the Monte Carlo Simulation approach are transparent. However, every simulation procedure that cannot be run by ones own mind lies beyond complete human control. In this case, only the underlying assumptions, which will be discussed in section 8.4, can add to the level of factual and perceived transparency.

R.8 *Synchronous processing of multiple changes*. This requirement has been fulfilled by means of the CISGA. Multiple initial changes can be processed simultaneously by the graph algorithm and handed over to the main function in a vector data structure. The effect of multiple changes can be imagined as a nucleation process where changes represent nucleation sites within the system.

R.9 *Cyclic system structures*. The implemented algorithm does not require the graph model to be acyclic. Different configurable modes for node revisiting have been suggested to adjust change propagation behavior to the situation at hand (cf. R.10).

R.10 *Propagation behavior*. While the mode *unrestricted revisiting* allows the algorithm to run a cycle more than once—in case the termination conditions are not met—*no revisiting* yields an acyclic propagation tree. *Once in every path* permits multiple impact on a system element, but since a node can only be visited once per path, a cycle can never be closed entirely, albeit the re-impact is actually taken into account (cf. section 7.3.2). By means of index permutations, propagation priority rules have been suggested, which can be used to further specify propagation behavior (cf. section 7.3.3).

8.3.2 Benefit-to-cost ratio

The developed methodology for change impact analysis is mainly intended for risky decisions and the comparison of alternative courses of action for changes in complex manufacturing systems. It is designed to provide a comprehensive understanding of the system and relevant influences to support a more reliable prediction of cost and effort caused by changes. Requirement R.5 of the methodology, stated in section 4.3, is a justifiable benefit-to-cost ratio, which shall be discussed in this section. Benefit and cost are defined in the context of the method beforehand:

- *Benefit.* A benefit is considered as "an advantage or profit gained from something" (STEVENSON 2010). When the analysis of change impact is aspired, this pertains to the following insights: an increased system understanding, a reliable assessment of cost and implementation time for decision making, indications of what system elements should be handled with special care, and where an implementation of flexibility could improve future changeability of the manufacturing system.

- *Cost.* In general, cost describes the "effort, loss, or sacrifice [...]" of resources such as time and money "[...] necessary to achieve or obtain something" that is perceived valuable (STEVENSON 2010). Here, the time spent to perform the methodology is the main driver of cost since no further investments are required.

The value of a more reliable impact assessment can hardly be quantified monetarily. An exception, however, is the comparison of two change options A and B. Theoretically, using the system cost model presented in section 7.5, the NPV of the cost minimizing decision *D* can be quantified, albeit, the quantification of changed recurring costs is highly uncertain:

$$NPV(D) = \left|I_{0,A} - I_{0,B}\right| + \sum_{t=1}^{T} \frac{\left|\Delta C_{t,A} - \Delta C_{t,B}\right|}{(1+r)^t} - \rho \cdot \overline{c}_L \cdot T_{Method} - C_{F,Method} \qquad (8.1)$$

where:

$I_{0,A}, I_{0,B}$ = Total non-recurring cost simulated by the CISGA
$\Delta C_{t,A}, \Delta C_{t,B}$ = Difference of variable recurring cost compared with the unchanged system
τ = Time horizon, last payment period
r = Discount rate
ρ = Number of people permanently involved (cost effective capacity)
$\overline{c}_L$ = Average labor cost of team members
T_{Method} = Duration of the analysis
$C_{F,Method}$ = Fixed expenses for the method (e.g., software).

Unfortunately, in non of the case studies such a comparison could be applied because no alternative options had to be assessed. Although a financial quantification of benefits was not feasible, the experts involved confirmed the usefulness of the method as reflected by their statements mentioned earlier. Using the nomenclature of equation 8.1, the additional cost C_{Method} of the method can be expressed as

$$C_{Method} = \rho \cdot \overline{c}_L \cdot T_{Method} + C_{F,Method}. \tag{8.2}$$

As the CISGA has already been implemented in MATLAB®, no initial investment for software engineering is required. The fixed expenses for a company that wishes to apply the method are limited to the license fees for MATLAB®, currently in the amount of € 3,000 for an individual commercial license including the "Statistics and Machine Learning Toolbox". Note, however, that the source code is easily portable to the free software GNU Octave. Thus, $C_{F,Method} = 0$ is neglected in table 8.8. An application of the method is recommended in three cases:

1. *$NPV(D) \geq 0$.* An application of the method is generally advisable if $NPV(D) \geq 0$. Hence, if the cost of the method is assumed lower than the roughly estimated difference of the financial consequences of two change options, an application is economically justified. As shown in table 8.8, C_{Method} ranges between € 4,050 and € 6,600.

2. *Ad-hoc cost estimate $E[I_0] \geq$ cost threshold $\hat{C}$.* The order of magnitude with respect to the anticipated costs for the implementation of a change can often be determined roughly without detailed analyses. A common policy in MCM is

to relate the steps required for a change release with a cost threshold. If $I_0 \geq \hat{C}$, then a complete change impact assessment should be performed.

3. *High-risk change projects.* As a generalization of 2., other attributes of the manufacturing change could require a thorough risk assessment. Examples are any manufacturing changes resulting in production downtime or that affect product liability and working safety.

Note that the above mentioned list does not consider any non-monetary benefits of the change impact analysis. Evidently, such benefits can justify the effort required taken by themselves, even though a valuation is not attempted here. For instance, the resulting impact heat maps are an instrument for an efficient mitigation of change risk, which may reduce future change cost. Comparing the predicted means of total cost and implementation time with C_{Method}, the additional cost appears justifiable for all three case studies. Table 8.8 provides an overview of the simulated change impact, the model size, and method cost.

8.4 Limitations

The underlying assumptions of the approach have been stated in section 4.4 to specify the range of validity of the approach. Possible restrictions due to simplifications are discussed in this section to evaluate the explanatory power of results derived based on the developed methodological support.

A.1 *Suitability of structural models.* It is assumed that complex systems can be modeled as multi-graphs based on different node and edge classes. This implies that change can only be propagated along the dependencies that have been captured during model building. If important relations are left unrecognized, the quality of the impact prediction is affected. The modeling approach was designed to support a thorough identification of relevant (possibly hidden) interdependencies. However, there is no guarantee for a complete mapping of relations and thus a risk of underestimating the impact of a change remains.

A.2 *Conceivability of direct change probability and impact.* Experience from industrial practice motivated the assumption that experts are capable to assess the probability of change transition and the direct impact between pairs of system

Table 8.8: Cost of method application opposed to the simulated change impact

	Unit	**Case 1** (λ **Inc.**)	**Case 2** (φ **Inc.**)	**Case 3** (κ **Inc.**)
Change impact				
Total cost ($\overline{C}_{total}$)	[€]	1,280,577	494,013	1,070,204
Working hours ($\overline{T}$)	[h]	359	478	6,299
System model size				
Nodes	-	26	18	20
Edges	-	49	79	31
Cost of the method				
Preparation / kick-off	[h]	4	6	3
Positioning	[h]	5	4	5
Conceptualization	[h]	4	6	3
Formalization	[h]	3	6	2.5
Total duration T_{Method}	[h]	16	22	13.5
Labor cost (c_L)	[€/h]	75	75	75
Experts (ρ)	-	$2+2^*$	$2+2^*$	$2+2^*$
C_{Method}	[€]	4,800	6,600	4,050

* Modeler (author) and facilitator (student assistant)

elements for a specific change scenario. Experience gained during the case studies confirmed this assumption, albeit, the quality of estimates may vary from case to case due to diverging professional and normative expertise.

A.3 *Model reduction*. During the formalization phase, i.e., the parameter estimation workshop, experts are provided with the multi-graph model to support their mental model of a given change scenario. It was assumed that the entirety of relation types can be aggregated to a single edge of the reduced graph model, parameterized with an estimate for direct transition probability and three-point-estimates for impact in terms of cost and time. This reduction of analytic detail was suggested to decrease the effort of model population. Case study experience also showed that the additional detail offered by a possible parameterization of multiple links between two system entities is not required to reflect the experts' mental models. This may be due to the fact that it is too complicated to weigh up the importance of different types of relations ad hoc. Theoretically, a differentiation of relation types could add to the precision of the model in the sense that change propagation also depends on the type of relation transferring it. However, rules would have to be implemented to specify this behavior. Currently, the variety of possible scenarios is only reflected by the estimated impact range.

A.4 *Changes, activities, and incidents are stochastically independent.* The methodology is based on the assumption that the changes, activities, and incidents within the system environment are independent events. Hence, conditional probabilities are not considered. Although this assumption is also stated by others, such as CLARKSON et al. (2004) and HAMRAZ (2013), it remains a simplification that is not always true. However, the mistake resulting from this assumption cannot be evaluated in general terms.

Beside the above mentioned assumptions, *beta distributions* have been used to represent the uncertainty of expert estimates. They have been derived from three-point-estimates, assuming the validity of the PERT mean and variance formulas.[4] Beta distributions are established for the modeling of uncertainty in activity cost and duration, cf. e.g., BROWNING & EPPINGER (2002, p. 432) and GOLENKO-GINZBURG (1989, p. 393). Their shape is a plausible representation of expert judgment in this respect. Nevertheless, beta distributed change impact remains a simplifying presumption and no sufficient data is currently available to assess its validity.

Finally, it must be noted that the case studies need to be understood as an *application evaluation* of the method, where user feedback and required effort are used to critically appraise the usefulness of the method. The data made available by the manufacturing companies and the selected research design are neither sufficient to prove nor to assess the *validity* of the method for change impact assessment in a scientific sense.[5] For a

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[4] Alternatives to the traditional PERT formulas are discussed, e.g., in GOLENKO-GINZBURG (1988), KEEFER & VERDINI (1993), and HERRERÍAS-VELASCO et al. (2011).

[5] "Validation in research involves close scrutiny of logical arguments and the empirical evidence to determine whether they support theoretical claims" (TAYLOR 2013, p. 2).

validation of the approach, a medium-term and a long-term study would have to be conducted:

- *Medium-term.* Two independent expert groups would be required, which are instructed to assess the impact of a planned manufacturing change. One group would have to use the provided method, while the other serves as a control group, applying any current best practice for the assignment. After the manufacturing change is fully implemented, the actual cost incurred would have to be identified and compared with the predictions of both groups. However, even in the a posteriori study (cf. section 8.2.1) a comparison of the original change impact estimate with the results of the method application is problematic. On the one hand, this is due to the lack of reliable cost accounting in change management and the (understandable) reluctance of industrial companies to share this sensitive data. On the other hand, non of the companies were willing or able to provide a second group of experts as a control group because of capacity restrictions or a lack of redundant professional experience.
- *Long-term.* In case of a comprehensive implementation of the method for change impact assessment in a manufacturing company, key performance indicators of change management could be compared with historic data. For instance, the difference between planned cost—e.g., represented by budget releases for manufacturing changes—and actual cost could be compared to evaluate the predictive power of the method. Evidently, this also requires a thorough accounting of change cost, which is a challenging task in itself.

Both set-ups can only be based on an intense cooperation with one or more manufacturing companies. Unfortunately, at the time of this application evaluation, no future manufacturing change could be identified at any of the companies involved, whose implementation was planned for the short-term, i.e., in less than one year from the present day.

9 Conclusion

9.1 Summary

Purpose

Within this thesis a methodology for model-based change impact analyses in manufacturing systems has been developed, which is intended to support change managers to perform a comprehensive assessment of manufacturing changes in advance of their implementation. The approach allows for change propagation phenomena that are caused by the complex network of interdependencies in engineered socio-technical systems. One the one hand, a quantitative comparison of alternative change options is enabled. On the other hand, budget and capacity planning of change projects is provided with a prediction of cost, required implementation time as well as their associated risk. Moreover, change multipliers can be identified using impact heat maps. This information provides insights for focused change management and changeable manufacturing system design.

Methodology

The principal research design of this thesis draws from the Design Research Methodology (DRM) and the Research Process of Applied Sciences (RAS). Theory building from case study research was based on the guidelines of EISENHARDT (1989) and the Engaged Scholarship Model of VAN DE VEN (2007). Starting from a synthesis of knowledge with regard to the review and discussion of relevant system modeling techniques and the state of the art in changeability and change impact assessment, the conceptual design of the method was elaborated. Finally, an application evaluation was performed based on three industrial case studies.

Contributions

Five research questions had to be answered in order to resolve theoretical deficits as well as shortcomings of change impact assessments in industrial practice. They shall be revisited in the light of the experiences gained from the elaboration of the method and its industrial application.

Q.1 *Which promising approaches, methods, and techniques for change impact assessment are provided by engineering and manufacturing research?*

This thesis provides a comprehensive review and critical discussion of the state of the art in change impact assessment. The literature review reported on in chapter 3 revealed the heterogeneity of approaches in manufacturing literature, which emphasize the procedures rather than the system models used for impact assessments. In constrast, Engineering Change Management (ECM) literature is dominated by model-based methods, which often lack sufficient practical guidelines and are characterized by a high level of abstraction. Although the existence of change propagation effects in manufacturing systems is recognized by some manufacturing researchers (cf. RICHTER et al. 2014; MALAK & AURICH 2013), no methodological support for their systematic analysis is provided yet. The CPM by CLARKSON et al. (2004) is considered as the most established tool for change impact analysis in ECM (HAMRAZ et al. 2013d) and a multitude of extensions has been developed over the last decade. However, the method is focused on component-component relationships and does not provide any guidelines for modeling manufacturing systems. Furthermore, the simultaneous analysis of multiple initiating changes within complex engineering systems as well as the analysis of cyclic structures are still problematic.

Q.2 *How do manufacturing systems have to be modeled such that the impact of manufacturing changes can be assessed in terms of time, cost, and associated risk?*

The second research question has been tackled by the design of a domain-specific structural modeling approach, based on a synthesis of Engineering Systems Multiple-Domain Matrix (ES-MDM), Fuzzy Cognitive Map (FCM), and metamodels for manufacturing systems. The modeling approach allows to capture entities of tangible and intangible engineering system domains and the multitude of relation types that reflect the interdependencies of these constructs. Tangible domains encompass objects (technical) and stakeholders (social), while intangible domains comprise system drivers (environmental), objectives & functions (functional), and activities (process). Metamodels have been designed for the technical domain of manufacturing systems comprising factory objects, relations, and their attributes. The design of metamodels was based on the ontology development guide by NOY & MCGUINNESS (2001) and a review of existing frameworks for factory object classification, published mostly in factory planning literature.

Q.3 *How can the tacit knowledge of system experts be formalized for the purpose of model-based impact analysis, also considering inevitable uncertainties?*

Three-point-estimation and PERT are used to formalize the tacit knowledge of system experts about the impact of manufacturing change in terms of cost and implementation time. PERT has been adopted from operations research, where it was used originally to model probabilistic activity durations for critical path computations. System experts are enabled to express their judgments with regard to change impact as ranges rather than single expected values. Using their estimates, beta distributions for cost and implementation time are modeled for every relation of the reduced graph model, which is defined by a direct transition probability matrix for each specific change scenario. Moreover, an expert elicitation procedure has been designed based on established conceptual and formal modeling guidelines from system dynamics and general theory on expert opinion elicitation. The procedure comprises three consecutive phases: Positioning (system definition), conceptualization (model building), and formalization (parameter estimation & discussion). By means of an effective elicitation procedure, the quality of elicited data for model building and model parameterization can be improved.

Q.4 *How can change propagation in manufacturing systems be simulated using system models?*

Based on a large body of literature in engineering design and product development, the theoretical background of change propagation, its mechanisms, and prevailing analytic approaches have been discussed in detail. Based on the knowledge acquired through the review of state of the art methods for system modeling and change propagation analysis, the Change Impact Simulation Graph Algorithm (CISGA) was designed. The algorithm is based on Breadth-First Search and Monte Carlo Simulation, simulating both, the uncertain behavior and impact of change propagation. Revisiting modes and prioritization rules have been designed to further customize the simulation to the specific change scenario at hand. A variety of existing deficits have been resolved, such as the consideration of simultaneously induced changes, cyclic system structures, and cross-domain change propagation. As instruments for a comprehensive decision analysis, total cost and implementation time histograms, change impact heat map, and ΔNPV-AHP diagram have been suggested.

Q.5 *How should the procedure of a model-based method for change impact analysis be designed to suite the requirements of users in practice?*

The conceptual design of the method is based on a specification of targeted uses case scenarios as well as general and formal requirements. They have been identified both in literature and in interviews with industrial experts. Assumptions were further stated to clarify potential limitations of the approach. Six steps constitute the method for change impact analysis: (1) system definition, (2) system modeling, (3) expert elicitation, (4) formal knowledge representation, (5) change impact simulation, and (6) decision analysis. In order to adapt the design of the method according to the requirements of industrial users, the application and evaluation of the approach have been performed sequentially. Three industrial case studies were selected, covering different manufacturing industries and different types of manufacturing changes. Application experiences and expert feedback gained have been discussed and used to improve the method continuously.

9.2 Future research

This thesis concludes with a discussion of suggestions for further research that have been identified in the course of theory development or based on the application experiences gained from the case studies. These recommendations for future research activities are structured in four categories: *Method application*, *Data gathering*, *Algorithm extensions*, and *Promising analogies* of propagation phenomena.

Method application

1. *Alignment with Manufacturing Change Management (MCM).* The primary intended use case scenario of the developed approach is providing decision support for MCM (KOCH 2016). Future research needs to investigate the integration of the method into this concept, designing an efficient exchange of information. Often, engineering changes ultimately cause manufacturing changes. Thus, the question of how Engineering Change Management (ECM) and MCM could be combined in order to create a consistent, pervasive, and more effective approach for the management of technical change in manufacturing companies is crucial.

2. *Generalization of the method.* Beyond the assessment of change impact in manufacturing systems, the developed approach may be useful for alternative use cases. Examples are the proliferation of uncertainty due to fuzzy information in factory planning projects (HAWER et al. 2016) and the design of changeable manufacturing system architectures. In addition, the modeling of process interdependencies is a potential research path for the prioritization of value-adding activities of supporting manufacturing functions (LOCK & REINHART 2016). Generally, the approach could be applied to any system that can be represented by entities, relations, edge weights, and impact measures—which can be other than money and time.

Data gathering

3. *Model generation and data acquisition.* At present, model building and model parameterization rely on the elicited expert knowledge and available documentations of a system. A challenging topic for future research could be the automatic transformation of existing models (e.g., manufacturing layouts, plant simulation models, digital models of the factory etc.) in order to lower the effort of model building. Furthermore, the increasing digitalization of manufacturing companies is accompanied by an enhanced availability, and probably also quality, of change management data. That means, opportunities arise for an automated computation—or at least scrutiny—of change likelihoods and impact predictions using data analytics or machine learning to reduce subjectivity. Better

availability and quality of data would also allow to assess the validity of the developed approach with respect to a better prediction of change impact by means of longitudinal studies of change management performance ratios as described in section 8.4 (e.g., predicted cost compared to actual cost).

4. *Expert elicitation.* Basically, the elicitation procedure suggested in this thesis is designed to support constructive discourse and a consensus of the expert group during the formalization phase. Further research could investigate alternatives for weighting conflicting expert judgment. For instance, BABUSCIA (2014) suggests a methodology that generates an expert score, which is employed to aggregate multiple-expert assessments to mitigate subjective biases in engineering design risk analysis and WESTERMEIER et al. (2014) apply confidence levels for weighting expert judgment in the context of quality parameter classification in lithium-ion cell production. Beside the aggregation of expert opinion, also the selection of suitable experts for change assessment may be scrutinized.

Algorithm extensions

5. *Propagation behavior & learning curve effects.* Within this thesis, three priority rules have been suggested to provide configurations that reflect different change management policies with regard to work prioritization. Whether these policies reflect the actual behavior of change managers should be further investigated by means of interview studies. The CISGA allows for cyclic structures of the system and revisiting of nodes. However, these rework cycles could require less effort than for the first execution due to learning curve effects as described by J. F. MAIER et al. (cf. 2014, p. 286). Beyond that, node revisiting (i.e., rework or redesign) may only be permissible for selected entities of the system model. At present, no case differentiation is possible as the revisiting rules are applied for the whole model. Finally, the magnitude of a change may depend on "upstream" changes or activities (CHUA & HOSSAIN 2012, p. 484). Adding this path dependency information to the simulation model can further increase the quality of impact predictions.

6. *Conditional probabilities.* A major assumption of the approach is that changes, activities, and events are stochastically independent. Nevertheless, situations

where conditional probabilities are required to reflect the real-world change scenario more realistically may occur—an extreme example would be an exclusive-OR, e.g., if one activity is performed another becomes invalid. Currently, conditional probabilities cannot be processed by the algorithm. Like the Change Prediction Method (CPM), the CISGA is based on direct change transition probabilities between each pair of nodes of the reduced graph model $G(V,E,p_{ij})$. For undirected cyclic graphs, Markov random networks may be an interesting approach. For directed but acyclic graphs, Bayesian belief networks may be used as a graphical representation of conditional dependencies.

7. *Waiting time*. During the second case study, the question arose whether waiting time could also be included to the impact prediction. Beside the effective implementation time, waiting time is an inevitable consequence of changes if, e.g., external parties are involved in a change process. For instance, lead times of suppliers may cause severe delays of projects and are thus important information for project scheduling. In contrast to effective working hours, however, total waiting time is not necessarily additive when it is caused apart from the critical path—it can be parallelized. Hence, the assessment of cost incurred due to waiting time requires further research.

Promising analogies

Multiple analogies of network-based propagation analysis do exist in diverse non-engineering research disciplines such as the sciences, economics, epidemology, political science, sociology, and social psychology. These approaches partly share a common theoretical background and make use of similar modeling techniques—i.e., graphs and matrices—to model the underlying system structure and propagation phenomena. Some of the most prominent analogies and ideas are listed in the following. On the one hand, to provide thought-provoking starting points for further interdisciplinary research activities and, on the other hand, to indicate areas for potentially beneficial method transfer.

8. *Traceability, contagion, and diffusion.* In software engineering, *requirements traceability* is defined as “the ability to describe and follow the life of a requirement, in both a forwards and backwards direction (i.e., from its origins, through its development and specification, to its subsequent deployment and use, and

> through all periods of on-going refinement and iteration in any of these phases)" (GOTEL & FINKELSTEIN 1993). Beyond the traceability of requirements, also *software change impact* has been analyzed using structural modeling techniques (cf. e.g., BOHNER 2003). More recently, *requirements changes* have also been studied in an engineering design context (cf. e.g., MORKOS & SUMMERS 2010). VESPIGNANI (2012, p. 32) states that "the emergence of macro-level collective behavior in complex systems follows a conceptual route essentially similar to the statistical physics approach to non-equilibrium phase transitions." In particular, *contagion phenomena* rely on "very similar spreading models" used to model the diffusion of knowledge and innovations as well as the spread of virus epidemics (VESPIGNANI 2012). The analysis of complex social and socio-technical systems has evolved as a promising field of study with various applications of structural models. Social network analysis has come to the fore during the last decade using network-based approaches for the investigation of the empirical structures of social relations to understand social behavior. Exemplary phenomena in this area, which have been approached by means of networks, are e.g., *information propagation* (cf. e.g., RODRIGUEZ et al. 2014) as well as *knowledge* (cf. e.g., COWAN & JONARD 2004), *technology* (GEROSKI 2000, cf. e.g.,), and *innovation diffusion* (cf. e.g., VALENTE 1995; ABRAHAMSON & ROSENKOPF 1997). Furthermore, the progression of *epidemics* (cf. e.g., LLOYD & MAY 2001; PIONTTI et al. 2014) and the spread of *computer viruses* in the Word Wide Web (cf. e.g., BARRAT et al. 2008) have been studied based on graph models, substantiating their versatility.

In manufacturing systems, changes are the rule rather than the exception (K. B. CLARK & FUJIMOTO 1991). An efficient management of these changes is still a major challenge, but also a potential competitive edge for today's manufacturing companies. The method for change impact assessment developed in this thesis, contributes to resolve this challenge.

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Appendix

A.1 Literature review

A.1.1 Journals and conference proceedings

Table A.1: List of screened academic journals and conference proceedings

Manufacturing Systems & Technology	
Manufacturing Technology (CIRP Annals)	Int. J. of Flexible Manufacturing Systems
Manufacturing Science and Technology (CIRP Journal)	Manufacturing Science and Engineering (ASME Journal)
Procedia CIRP	Manufacturing Systems
Production Engineering (WGP)	Manufacturing Letters (SME)
Engineering and Technology Management	Int. C. on Manufacturing Research (ICMR)
C. on Manufacturing Systems (CIRP CMS)	Int. J. of Engineering Science
Int. J. of Machine Tools and Manufacture	
Engineering Design	
Engineering Design	Int. C. on Engineering Design (ICED)
Research in Engineering Design	Int. C. on Research into Design (ICoRD)
Int. J. of Design Engineering	International Design Conference (DESIGN)
Int. Dependency and Structure Modelling Conference (DSM)	Int. Design & Engineering Technical Conferences (DETC)
Product Innovation Management	Systems Engineering
Operations & Engineering Management	
Int. J. of Production Economics	Production and Operations Management
Operations Management	European J. of Operational Research
Manufacturing & Service Operations Mgmt.	IEEE Transcations on Engineering Mgmt.
Int. J. of Operations and Production Mgmt.	Int. J. of Production Research
Zeitschrift für wirtsch. Fabrikbetrieb (ZWF)	wt Werkstattstechnik
Management & Operations Research	
Management Science	Academy of Management Review
Int. J. of Management Science (Omega)	Operations Research
Academy of Management Journal	
Computers in Industry	
Computers & Industrial Engineering	
Computers in Industry	
Computer Integrated Manufacturing Systems	

A.1.2 Changeability assessment

A.1.2.1 Degree of changeability

In general, enabler-based methods for the assessment of changeability build on the assumption that an engineering system can be characterized by certain properties that enable or inhibit the implementation of specific changes. Hence, the degree of changeability depends on the underlying change enablers' degree of fulfillment.

What level of changeability is reasonable?

HERNÁNDEZ (2002) presents a method to identify the required amount of transformability of manufacturing systems based on a comparison of current (system-inherent) and target (market-driven) transformability. A similar approach is proposed by DRABOW (2006), who builds on the work of HERNÁNDEZ (2002). To assess current transformability of a manufacturing system, the degrees of freedom of all factory objects that constitute the system have to be determined. These are derived from specifying properties that are assumed to enable a certain object to change (the enablers) through respective change supporting attributes. In order to derive the target transformability, scenario management techniques are employed. The environment of a factory is examined to identify key change drivers. Potential future scenarios of these influences are developed by means of projection. The resulting vision forms a starting point to determine the target transformability required in the future. While comparing both current and target transformability, depth (as the difference between status quo and target) and breadth (number of affected objects) of change have to be analyzed to classify the objects according to how strongly they will be influenced by expected changes.

Building on the framework of transformability proposed by HERNÁNDEZ (2002) a three-step approach for the evaluation of factories' transformability is developed by HEGER (2007). The approach is applicable on all manufacturing system layers from workstation up to manufacturing site except the network level. The application is supposed to take place during plant design in order to quantify the required changeability of factory objects.

The method comprises a monetary and non-monetary evaluation of transformability and integrates these perspectives within the "integrative evaluation of transformability" as a process model for evaluation and decision making. The transformability potential is evaluated in eight categories—mobility, universality, neutrality, scalability, standardization, modularity, compatibility, and the object-specific changeability potential—of which six have been adapted from the transformability enablers of HERNÁNDEZ (2002, p. 54). On the whole, HEGER identifies 232 transformability characteristics in the areas of technology, organization, and space, which are weighted and assigned to the transformability potential categories. Each manufacturing system layer is finally, albeit mostly qualitatively, assessed in the aforementioned areas using the identified characteristics.

With regard to the economic analysis of transformability, a net present value calculation is proposed. Doing so, all transformability-related cash flows over the factory's life cycle are discounted to their present value.[1] To account for the associated uncertainty of future cash flows' frequency and amount, their expected value, based on estimated probability distributions, is used for the net present value calculation. Transformability potential and profitability analysis are used during the integrative evaluation of transformability to calculate the overall monetary and non-monetary scores of alternative plant designs. The process model allows the user to skip individual steps of the approach if the respective data is unavailable.

HEGER presents a comprehensive approach to evaluate the transformability of factory objects. Because of the large span of manufacturing system hierarchies covered, most transformability characteristics can only be assessed qualitatively, making the result highly dependent on the user's experiences. The incorporation of uncertainties is only performed generic. A scenario analysis considering the probability of occurrence of change drivers as well as their specific impact on the factory is not included. Amount and frequency of transformability-related cash flows are solely based on expert estimations (HEGER 2007, p. 123).

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[1] However, HEGER notes that the timespan to be considered must be set depending on the ability to predict future events (HEGER 2007, pp. 117, 124).

Component adaptability factor

In the context of modular engineering systems, ENGEL & BROWNING (2008) propose an approach to assess the value of architecture adaptability. The authors argue that system modules can be thought of as real options, providing the right but not the obligation to upgrade the system in the future depending on the functions desired by stakeholders in the future. Because of the method's focus on real options, it is presented in section A.1.2.2. As the method also includes the calculation of the Component Adaptability Factor (CAF), which is basically an enabler-based metric for architecture adaptability, this feature is discussed in this section.

Adaptability is defined as "a characteristic of a system amenable to change to fit altered circumstances" including both "the context of a system's use and its stakeholders' desires" (ENGEL & BROWNING 2008, p. 126). Six categories, originally used for the assessment of software quality, are adopted as "System Adaptability Metrics". Between two and five sub-metrics constitute each of the six major categories, which are Functionality (F), Reliability (R), Usability (U), Efficiency (E), Maintainability (M), and Portability (P). Depending on the context and type of the system, experts need to assign weights w_i in order to reflect each category's perceived importance for the overall adaptability. All metrics and sub-metrics can take values $\in [0;1]$.

$$CAF = w_F F + w_R R + w_U U + w_E E + w_M M + w_P P \tag{A.1}$$

$$\sum_{i=\{F,R,U,E,M,P\}} w_i = 1 \tag{A.2}$$

As in a conventional qualitative utility analysis, the sum of weights for both hierarchy's of metrics equals 1, hence, $CAF \in [0;1]$ as well.[2] ENGEL & BROWNING (2008, p. 133) state that this is because of the standard's narrower view and focus on software quality. However, not every metric can be meaningfully transfered to the domain of manufacturing systems, its "hardware", and organizational aspects.

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[2] Note, that "Adaptability" and "Changeability" are included as sub-metrics by ISO/IEC 9126-1 (see figure A.1).

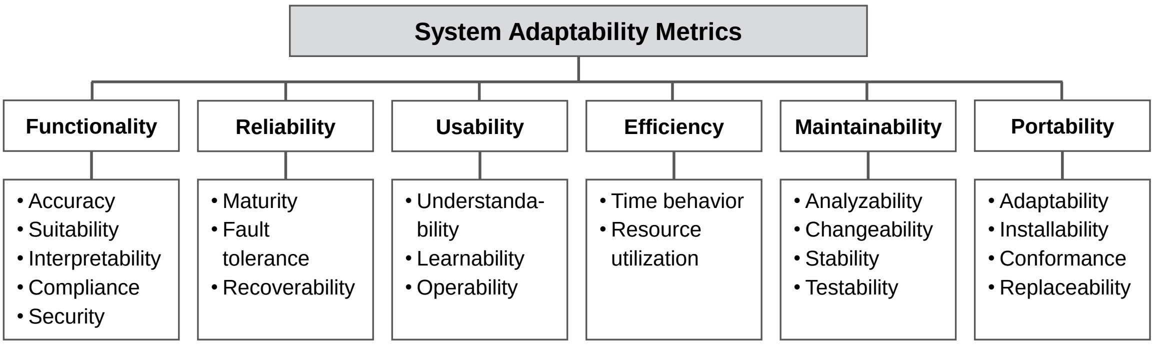

*Figure A.1: System Adaptability Metrics (*ISO/IEC 9126-1:2001 *Software engineering—Product quality—Part 1: Quality model)*

A.1.2.2 Value of changeability

Real options

In academia, real options are an established approach for the valuation of changeability (FITZGERALD et al. 2012, p. 2). These methods draw from the well grounded theory of option pricing for financial assets, commonly referred to as “the underlying”. Real options, which have been introduced by MYERS (1984) in the context of strategic decision-making, denote the right but not the obligation to buy or sell tangible assets (i.e., “real” things). Essentially, real options in a changeable design aim to prevent downside risks or to gain from upside opportunities due to future uncertainties.

Valuation of modular system architectures

With a strong focus on modular system architectures, ENGEL & BROWNING (2008) present an approach for designing adaptability into system architectures to increase their lifetime value. The authors introduce “architecture options” to determine the optimal degree of adaptability maximizing the lifetime value of a system. Two models are discussed: a static modeling approach to measure adaptability of a given system architecture and a dynamic modeling approach to assess its value fluctuation over time. The first model shall be outlined in the following.

According to ENGEL & BROWNING (2008, p. 129) “the more modules in a system, the more options there are”. Hence, the modules represent the “options value” of a system architecture. However, with the number of modules in a system also the number of module-to-module interfaces is increasing, which represents the “options price” of adaptability. Three major steps are required to identify optimal architectures with respect to maximized lifetime value:

1. *Options value calculation.* Determine the components of a system which are associated to functions potentially desired by system stakeholders in the future.
2. *Options price calculation.* Identify each module-to-module and module-to-environment interface in the architecture.[3]
3. *Architecture optimization.* Combined application of analytical and meta-heuristic optimization techniques to determine value maximizing architectures.

As a special case of the real "in" options concept by DE NEUFVILLE (2003)[4], architecture options interpret "the modules constituting a system as options in an economic sense" (ENGEL & BROWNING 2008, p. 130). To calculate the option value of each module, the Black-Scholes formula for options pricing is used (cf. BLACK & SCHOLES 1973). However, note that all input parameters heavily depend on the quality of subjective expert estimations and that the assumptions of the Black-Scholes model are fairly restrictive.[5] By means of DSMs, modules and the number of interfaces are derived to calculate the Component Adaptability Factor (CAF), the Component Option Value (COV), and Interface Cost Factors[6] for module-to-module ($I_{i_{n,k}}$) and module-to-environment ($I_{e_{n,l}}$) interfaces (where n, k, l are component indices). With the expected option value COV_n, and the corresponding adaptability factors CAF_n, the expected economic value of the j^{th} module X_j in architecture variant (1) is

$$X_j^{(1)} = \sqrt{\sum_n \left(COV_n \cdot CAF_n\right)^2} - \sum_n \left(\sum_k I_{i_{n,k}} + \sum_l I_{e_{n,l}}\right). \tag{A.3}$$

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[3] ENGEL & BROWNING (2008, p. 137) state that intra-module interfaces do not affect cost calculations and are thus neglected.

[4] Real options "in" projects are options which involve a change in design of a system.

[5] For a discussion of alternative models and the assumptions, cf. e.g., LAUTERBACH & SCHULTZ (1990) or CLARKSN & BANK (1995).

[6] Interface Cost Factors specify importance and intensity of each interaction between modules, measured on a $[0;1]$ scale. Four types of interactions—i.e., Material, Spatial, Energy, and Information—are measured and aggregated. Hence, $I_{i_{n,k}}$ and $I_{e_{n,l}}$ are $\in [0;4]$.

It is assumed that the economic value $V^{(1)}$ of the entire architecture is additive, i.e.

$$V^{(1)} = \sum_j X_j^{(1)} \tag{A.4}$$

for the first architecture variant. Since $CAF_n \in [0;1]$ and $I_{i_{n,k}}, I_{e_{n,l}} \in [0;4]$ are subjective metrics, the architecture value is a relative economic measure.

Valuation of changeable manufacturing systems

MÖLLER (2008) develops an approach for the valuation of changeable manufacturing systems. According to MÖLLER, the changeability of manufacturing systems can be interpreted as the opportunity to exercise real options, to hedge against future uncertainties or to capitalize on growth opportunities. The objective of the method is to enable a relative economical *comparison* of alternative manufacturing system designs. However, an absolute calculation of the financial value of changeability is not provided (MÖLLER 2008, p. 160).

The approach is strongly inspired by the hybrid real options method introduced by NEELY (1998) to combine the features of both decision and options analysis. This way, it is possible to separately consider different sources of risk. To model project risk, a decision tree is used, while the market risk is represented by a market model (NEELY & DE NEUFVILLE 2001). MÖLLER (2008) adopts this idea to distinguish "primary" and "secondary" uncertainties for manufacturing systems, which are related to project and market risk. Primary uncertainties are explicitly modeled using binomial trees representing only those uncertainties, which have the potential to influence manufacturing change decisions. Secondary uncertainties, in contrast, have a lower impact on the profitability of manufacturing systems and do not induce investment decisions directly (MÖLLER 2008, pp. 133-138). Secondary uncertainties are modeled by Monte-Carlo Simulation. For the final comparison of production system alternatives, their "extended" NPV (NPV_E) is calculated as a sum of the static NPV at risk without real options (NPV_R) and the additional NPVs generated by allowing for k real options of each alternative A_j (NPV_k).

$$NPV_E(A_j) = NPV_R(A_j) + \sum_k NPV_k(A_j) \tag{A.5}$$

Real options are derived by a complex procedure starting with the analysis of the production system and the market environment identifying the most relevant influences for economic performance. To encounter these uncertainties, generic measures for adaptation are selected from a catalog and ranked by their strike price and their impact with respect to cost and profit structure MÖLLER (2008, p. 129). Finally, "option profiles" are constructed as sets of possible adaptations for each alternative. A brief, albeit not complete, overview of the method is also given in MILBERG & MÖLLER (2008). [7]

Valuation of product adaptability

For the valuation of product adaptability, SCHRIEVERHOFF et al. (2014) propose a four-step approach based on an Expected Net Present Value (ENPV) calculation, where expected revenues and costs in each period of time, which are associated to adaptability, are discounted to the present. Firstly, key parameters determining the future performance of the system are identified by expert interviews to specify sources of value. Secondly, experts need to propose different rigid and adaptable designs, which not only lead to differing option and upgrade costs in terms of magnitude, but also in terms of their occurrence over time. The third step deals with the prediction of future developments taking uncertain boundary conditions of relevant markets and technologies into account. Using Monte-Carlo Simulation the proposed designs are compared based on the distributions of their ENPV in the final step. Hence, associated risk of the design is also considered in the valuation process. A drawback of the approach is its strong dependence on detailed data for option costs, expected revenues and the selection of key parameters at the very start. (SCHRIEVERHOFF et al. 2014)

Trade space exploration

The trade space exploration approach has been developed in the Space Systems, Policy, and Architecture Research Consortium (SSPARC) at the MIT as a process for a value-focused development of space systems. It was refined until today particularly by

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[7] Another application of real options for the valuation of flexibility in investment decisions in the context of manufacturing systems is presented by ABELE et al. (2006).

researchers in the Engineering Systems Division (ESD) (ROSS & HASTINGS 2005; ROSS et al. 2014). The major purpose of trade space exploration is to "broaden the perspective of designers in conceptual design" and to provide "a framework for communicating and quantifying concepts such as the impact of changing requirements, uncertainty, flexibility, and policy robustness" (ROSS & HASTINGS 2005).

A trade or design space is spanned by completely enumerating design variables, which are defined as "designer-controlled quantitative parameters that reflect an aspect" of a system (e.g., size, performance, weight), forming a design vector (ROSS & HASTINGS 2005). By complete enumeration of valid parameter combinations a space of possible design options is created—the *trade space*. For a simple manufacturing system, design variables could be represented by target volume [*units*] and volume flexibility, which, for instance, can either be 5% or 10%. Assuming that the volume can only be increased in 10 unit increments and a realistic range for demand be [80; 100], the resulting trade space $\mathbf{T}_D$ is

$$\mathbf{T}_D = \big((80,5\%);(90,5\%);(100,5\%);(80,10\%);(90,10\%);(100,10\%)\big) \tag{A.6}$$

$$\text{with} \quad (x_1,x_2) = (\text{target volume}, \text{volume flexibility}). \tag{A.7}$$

Usually, the utility-cost plot of the trade space is referred to as the trade space as well, where utility is a parameter reflecting the value under uncertainty perceived and defined by system stakeholders (ROSS & HASTINGS 2005). The points of such a plot are members of the cost-utility vector $\mathbf{T}_{C,U}$. Given the illustrative example above, this vector could be

$$\mathbf{T}_{C,U} = \big((0.7,50);(0.8,55);(0.85,60);(0.75,60);(0.85,70);(0.9,90)\big) \tag{A.8}$$

$$\text{with} \quad (x_3,x_4) = (\text{utility}, \text{cost}). \tag{A.9}$$

Within the plot, a Pareto Front can be drawn to visualize the options that provide the best possible utility for a given cost (see figure A.2). All design options below that frontier are dominated solutions [like (0.75, 60); (0.85, 70) in the example], which should be dropped unless they outperform designs on the Pareto Front "in an uncaptured metric" (ROSS & HASTINGS 2005). Note that for each design option cost and utility models are required to derive the respective utiliy and cost values based on the design variables representing the option. However, once this effort has been made, ROSS & HASTINGS (2005) argue that trade-offs can be quantitatively analyzed and that the effect of changes, e.g., in the utility function of decision makers can be easily computed.

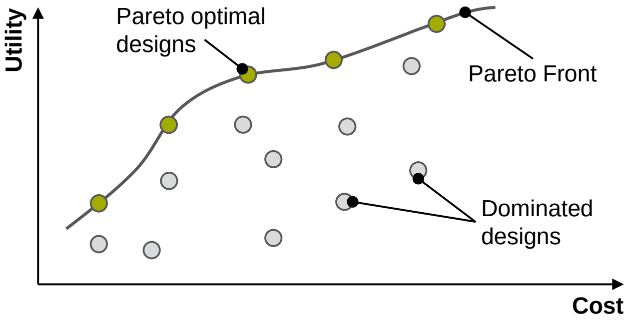

Figure A.2: Illustrative trade space in conceptual design

For the quantitative assessment of changeability and other related concepts, different approaches have been developed in the past 15 years, mostly by researchers of MIT's ESD. As an example, the work of ROSS et al. (2008) shall be presented here.

Changeability quantification using trade space exploration

ROSS et al. (2008) propose a "value-centric" approach for changeability quantification using parametrization of systems and Multi-Attribute Tradespace Exploration (MATE). Similar to NILCHIANI & HASTINGS (2007), system designs are compared with respect to cost and value to decision-makers. With N design variables, the technical degrees of freedom for designers are represented by the design variable set $\left\{DV^N\right\}$. To capture the M types of value perceived by decision-makers, the attribute set $\left\{X^M\right\}$ is constructed. Now, two scalar functions for the mapping of design variable sets to cost, i.e.,

$$f_C : \left\{DV^N\right\} \to C \tag{A.10}$$

and for the mapping of value attributes to an aggregate utility measure, i.e.,

$$f_U : \left\{X^M\right\} \to U \tag{A.11}$$

are introduced. The authors state that these functions could be instanced either by *cost models* or through multi-attribute *utility functions*, respectively (ROSS et al. 2008,

p. 252).[8] In order to derive the specific attribute values $\left\{X^M\right\}$ for a design alternative, the mapping

$$F_{XM} : \left\{DV^N\right\} \rightarrow \left\{X^M\right\} \tag{A.12}$$

also has to be instanced by system designers, which can be achieved through "models and simulations in the analysis phase" according to Ross et al. (2008, p. 252). As in traditional MATE, system designs are plotted on a cost-utility trade space for quantitative comparison.[9]

Changeability is not defined with respect to the position of a design in the trade space, but rather dependent on the number of available change opportunities—so-called *transition paths* represented by arcs between design alternatives within the trade space plot. That way, a *trade space network* arises (cf. figure A.3). Limited by *transition rules* defined by allowed changes to the design variable set $\{DV^N\}$, system designers have to conceive transitions paths for each design. The more transition paths available with a design, the more changeable it is considered, where the *acceptability tensor* $\mathbf{T}_{ijk}$ contains the cost for a transition of design $\{DV_i^N\}$ to design $\{DV_j^N\}$, following transition rule k. (Ross et al. 2008, p. 253).

As a subjective metric for changeability, the *filtered outdegree* has been introduced by Ross (2006), counting the number of all transition paths for a design i whose transition costs are below the *acceptability threshold* $\hat{C}$ of decision-makers, i.e.

$$\textit{filtered outdegree} = \left|\left\{\{DV_i^N\} \rightarrow \{DV_j^N\} \mid t_{ijk} < \hat{C} \;\forall j,k\right\}\right| \tag{A.13}$$

$$\text{with} \quad t_{ijk} \in \mathbf{T}_{ijk}. \tag{A.14}$$

What is acceptable cost in terms of time and money to decision-maker A might be rejected by a more conservative decision-maker B, inevitably bringing subjectivity into changeability evaluation.

In this context, Ross (2006) refers to *path-enablers* like modularity, integrability, and decentralization strategies to increase changeability. According to Ross et al. (2008, p. 258), real options and path enablers are similar concepts that "both allow for a

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[8] Ross et al. (2008) recommend the use of Keeney-Raiffa utility functions (Keeney & Raiffa 1993).

[9] Multi-Attribute Tradespace Exploration (MATE) has been introduced by (Ross et al. 2003). For recent applications see also (Ross et al. 2010, 2014).

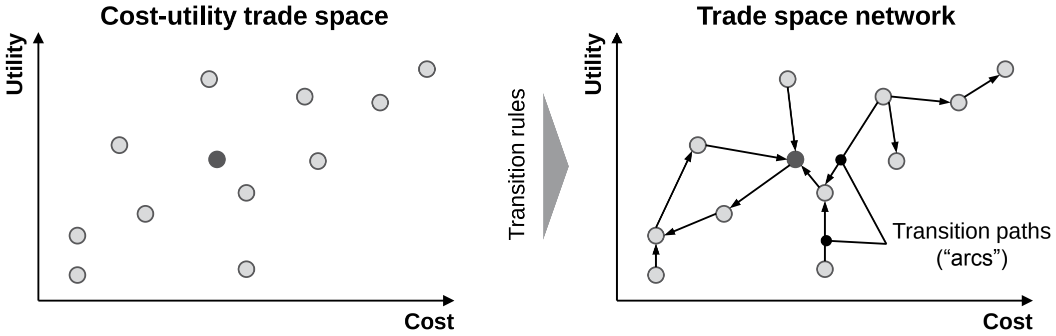


*Figure A.3: Transforming a trade space into a trade space network applying transition rules (*Ross *et al. 2008, p. 253)*

system change, and may not contribute to system value if left unused". The approach provides a rigorous quantification of changeability—its applicability in industrial practice, however, depends on the availability of appropriate data for populating the trade space with suitable system design alternatives.

Epoch-era analysis

Based on the Epoch-Era Analysis (EEA) first introduced by Ross (2006) the Valuation Approach for Strategic Changeability (VASC) is proposed by Fitzgerald et al. (2012) to analyze the value of changeability under uncertainty. The effort for estimating the benefits of incorporating changeability into systems is generally higher than doing so for the required cost and results are usually less reliable because changeability is activated in the future. Five steps constitute the VASC, starting with data gathering (e.g., design variables, change mechanisms) for all epochs, which are a means for "piecewise consideration of time sequences in constant-context sections" (Fitzgerald et al. 2012, p. 6). In a second step, screening metrics (and other design identification techniques) are used to select suitable alternatives, reducing the available design space. Applying so-called rule usage strategies, a multi-epoch changeability analysis is performed in the fourth step to determine end states and transition costs for each combination of design, epoch, and rule usage strategy. In the final step, randomly generated eras are simulated to calculate a comprehensive set of changeability metrics for the most promising design alternatives. With the "Going Rate" a new concept for computing the trade-off between cost and value for including a change mechanism is introduced. (Fitzgerald et al. 2012)

A.1.2.3 Summary

In this section, different approaches for the assessment of changeability have been discussed. Application examples included a variety of system types ranging from manufacturing plants to space systems. To determine the degree of changeability different enablers have been identified for a hierarchical break down of this strategic system property to more detailed supporting principles. With regard to the valuation of changeable systems, real options analysis, trade space exploration, and the epoch-era analysis have been presented. Apparently, the impact of changes is, above all, assessed in terms of cost and utility to system stakeholders. While methods for changeability evaluation generally consider change from the perspective of the *changeable system*, change impact assessments (cf. §§ 3.2 and 3.3) scrutinize the change *affecting* the system.

A.2 Deterministic Change Impact Simulation Graph Algorithm

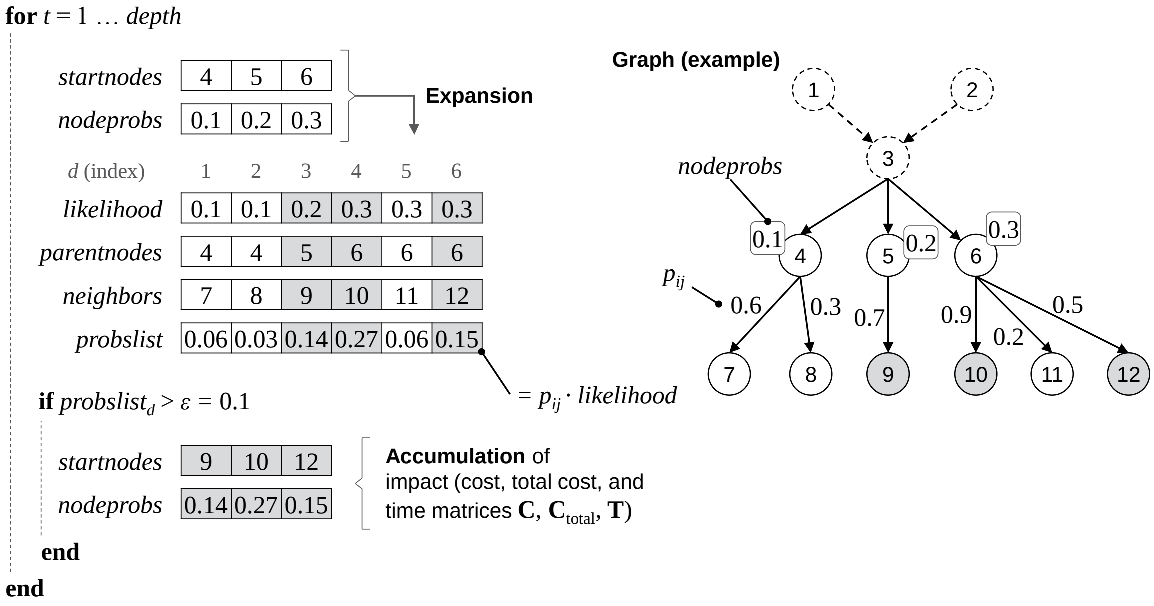


Figure A.4: Illustration of the deterministic CISGA

Basically, the deterministic algorithm is an expected value calculation of change impact. It is similar to the combined risk computation of the CPM by CLARKSON et al. (2004). Table A.2 provides a description of the additional variables required for the procedure `ChangeImpactExp`.

Table A.2: Nomenclature of the CISGA (Part 2)

Variable	Type	Description
nodeprobs	vector	Contains path probabilities of the startnodes, i.e., the total probabilities of startnodes to be affected by change
likelihood	vector	Expansion of *nodeprobs*, has the size of *neighbors*, assigns current probabilities to all neighbors
probslist	vector	Contains path probabilities of neighbors, computed as *nodeprobs* multiplied with direct transition likelihoods between current nodes and neighbors

```
Input  : Graph $G(V,E,p_{ij})$ with direct transition probabilities $p_{ij} \in \mathbf{P}$, cost
         estimates $c_{a,ij} \in \mathbf{C}_a$, $c_{m,ij} \in \mathbf{C}_m$, and $c_{b,ij} \in \mathbf{C}_b$, working time estimates
         $t_{a,ij} \in \mathbf{T}_a$, $t_{m,ij} \in \mathbf{T}_m$, and $t_{b,ij} \in \mathbf{T}_b$, hourly rate $c_t$, propagation depth,
         min. req. path probability $\epsilon$, and the initial change vector $\mathbf{s}$ with $s_k \in V$
Output : Aggregated cost $c_{ij}$, working time $t_{ij}$, and total cost $c_{total,ij}$ incurred $\forall$
         edges $e_{ij} \in E$ stored in matrices $\mathbf{C}$, $\mathbf{T}$, and $\mathbf{C}_{total}$
ChangeImpactExp ($\mathbf{P},\mathbf{C}_a,\mathbf{C}_m,\mathbf{C}_b,\mathbf{T}_a,\mathbf{T}_m,\mathbf{T}_b,\mathbf{s},depth,c_t$)
begin
    $\mathbf{C},\mathbf{C}_{total},\mathbf{T} \leftarrow [\,]$
    $\forall k \in I_s : nodeprobs_k = 1$
    $startnodes \leftarrow \mathbf{s}$
    for $t \leftarrow 1 \ldots depth$ do
        $\{likelihood_i \in \mathbb{R} \mid i \in I_{neighbors}\} \leftarrow$
            GenerateParentLikelihoods ($\mathbf{P}, startnodes, nodeprobs$)
        $\{parentnodes_i \in V \mid i \in I_{neighbors}\} \leftarrow$
            GenerateParentNodes ($\mathbf{P}, startnodes$)
        $\{neighbors_i \in V \mid i \in I_{neighbors}\} \leftarrow$
            GenerateNeighbors ($\mathbf{P}, startnodes$)
        $\{probslist_i \in \mathbb{R} \mid i \in I_{neighbors}\} \leftarrow$
            $\{(\mathbf{P}_{u_i,v_i} \cdot likelihood_i)_i \mid u_i \in parentnodes, v_i \in neighbors, i \in I_{neighbors}\}$
        $nodeprobs \leftarrow [\,]$
        $startnodes \leftarrow [\,]$
        for $n_d \in neighbors, d \in I_{neighbors}$ do
            if $probslist_d > \varepsilon$ then
                $cost \leftarrow$ ExpectedCost ($parentnodes_d, n_d, \mathbf{C}_m$)
                $time \leftarrow$ ExpectedTime ($parentnodes_d, n_d, \mathbf{T}_m$)
                $total \leftarrow cost + time \cdot c_t$
                $\mathbf{C}_{parentnodes_d,n_d} += probslist_d \cdot cost$
                $\mathbf{T}_{parentnodes_d,n_d} += probslist_d \cdot time$
                $\mathbf{C}_{total,parentnodes_d,n_d} += probslist_d \cdot total$
                if $startnodes.contains(n_d)$ then
                    $nodeprobs_{startnodes.find(n_d)} +=$
                        $probslist_d - nodeprobs_{startnodes.find(n_d)} \cdot probslist_d$
                else
                    $startnodes.append(n_d)$
                    $nodeprobs.append(probslist_d)$
                end
            end
        end
    end
end
```

Algorithm 3: Change Impact Simulation (deterministic)

In contrast to the `ChangeImpactMCS` procedure, the routine is run only once and, thus, outperforms it in terms of time complexity. However, no insights with respect to the spread of the impact distributions can be gained as `ChangeImpactExp` only yields the expected value, which is computed using the functions `ExpectedCost` and `ExpectedTime`. Another major difference of the algorithms is the termination condition. Instead of the repeated "coin toss" ($u < p_{ij}$) in `ChangeImpactMCS` a minimum path probability ϵ can be specified to an arbitrary value (e.g. $\epsilon = 0.001$) in `ChangeImpactExp`. For $\epsilon = 0$ every node that is reachable by $t = 1 \ldots depth$ steps is definitely visited.

The expansion of *startnodes* and *nodeprobs* depending on the amount of neighbors is implemented analogously by means of the functions `GenerateNeighbors`, `GenerateParentNodes`, and `GenerateParentLikelihoods` in algorithm 3, lines 7 to 10. The current change probability of a node is computed by multiplication with the direct change likelihood between parent and respective neighbor.

As stated in section 4.4, events, changes, and activities are assumed stochastically independent, however, not necessarily mutually exclusive. Hence, the addition law of probability following from Kolmogorov's probability axioms must be applied when computing the probability $P(A \cup B)$ of two crossing paths (e.g., two sequences of events) A and B, i.e.

$$P(A \cup B) = P(A) + P(B) - P(A \cap B) = p_a + p_b - p_a \cdot p_b, \tag{A.15}$$

where $P(A \cap B)$ is the intersection of A and B. The general addition law of probability for two events can be extended to n events using the Principle of Inclusion and Exclusion (PIE) (CAMERON 1994, p. 76) of elementary combinatorics. Accounting for the pair-wise, triple-wise, ..., n-tuple-wise intersections of the events $E_1, E_2, \ldots, E_n$, the probability of the union is (GRIMMETT & WELSH 2014, p. 46)

$$P\left(\bigcup_{i=1}^{n} E_i\right) = \sum_{i=1}^{n} P(E_i) - \sum_{i<j} P(E_i \cap E_j) + \sum_{i<j<k} P(E_i \cap E_j \cap E_k) - \cdots + (-1)^{n+1} P\left(\bigcap_{i=1}^{n} E_i\right). \quad \text{(A.16)}$$

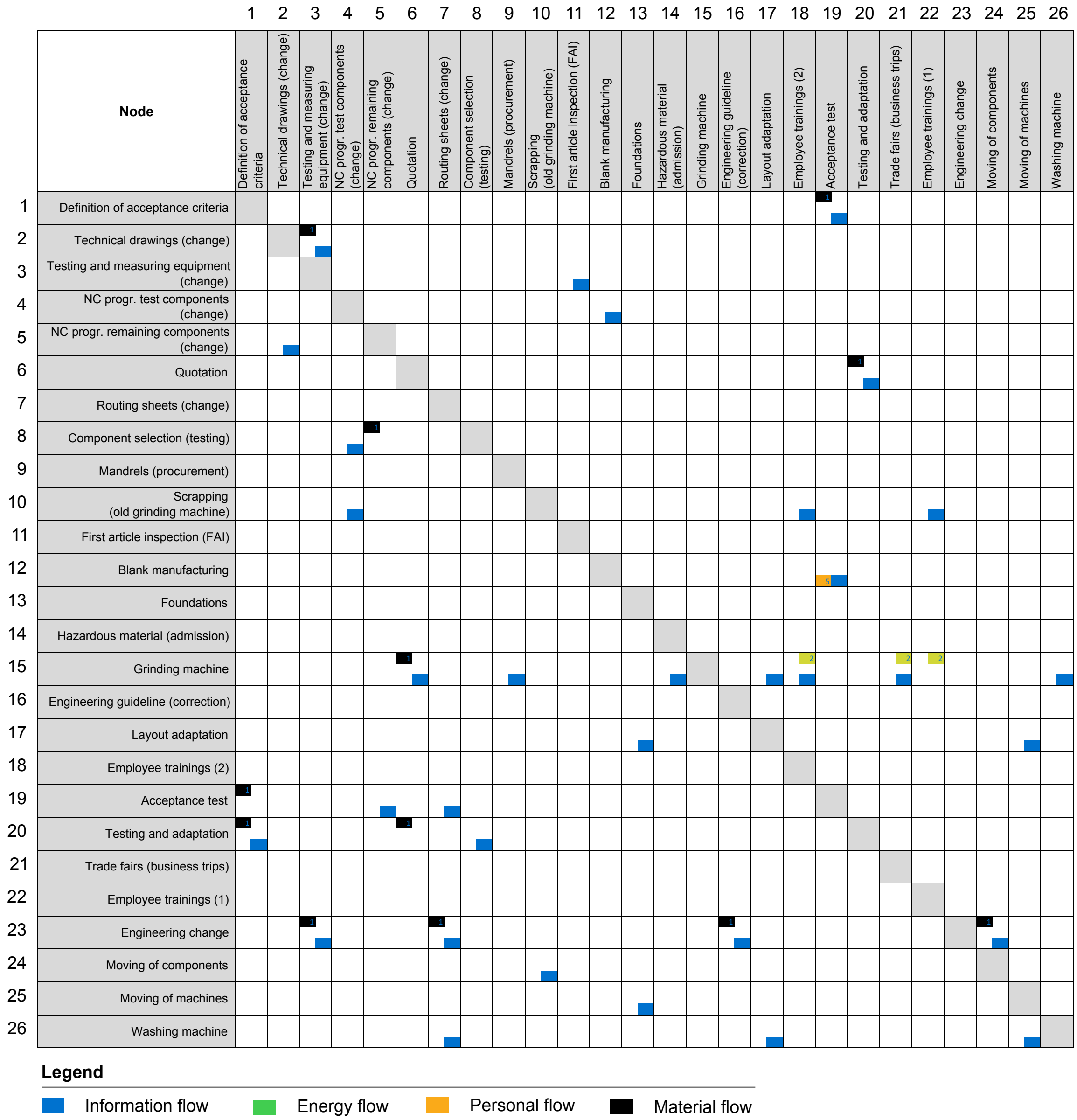
Experiments with a variety of system models have shown that the error of omitting the intersection is $< 5\%$ in most cases because the path probabilities decrease considerably with every depth iteration. However, the general addition rule is applied in line 22 of algorithm 3 to avoid a systematic overestimation of change impact.

A.3 Case study material

A.3.1 Case 1: Substitution of a grinding machine

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1																			0.8							
2			0.7																							
3											0.9															
4												1														
5		1																								
6																				1						
7																										
8				0.8																						
9																										
10				1																		0.9				
11																										
12																			1							
13																										
14																										
15						1			0.9					0.1			1	0.8			1		1			0.5
16																										
17													0.3												0.5	
18																										
19					0.8		1																			
20	1							1																		
21																										
22																										
23			1				1									0.5								0.5		
24										0.9																
25													0.3													
26							1																1		0.5	

Table A.3: Transition probability matrix $\mathbf{P}_{\lambda}$ *of case 1*



	Node	1 Definition of acceptance criteria	2 Technical drawings (change)	3 Testing and measuring equipment (change)	4 NC progr. test components (change)	5 NC progr. remaining components (change)	6 Quotation	7 Routing sheets (change)	8 Component selection (testing)	9 Mandrels (procurement)	10 Scrapping (old grinding machine)	11 First article inspection (FAI)	12 Blank manufacturing	13 Foundations	14 Hazardous material (admission)	15 Grinding machine	16 Engineering guideline (correction)	17 Layout adaptation	18 Employee trainings (2)	19 Acceptance test	20 Testing and adaptation	21 Trade fairs (business trips)	22 Employee trainings (1)	23 Engineering change	24 Moving of components	25 Moving of machines	26 Washing machine
1	Definition of acceptance criteria																			■1 🟦							
2	Technical drawings (change)			■1 🟦																							
3	Testing and measuring equipment (change)											🟦															
4	NC progr. test components (change)												🟦														
5	NC progr. remaining components (change)		🟦																								
6	Quotation																				■1 🟦						
7	Routing sheets (change)																										
8	Component selection (testing)				🟦	■1																					
9	Mandrels (procurement)																										
10	Scrapping (old grinding machine)				🟦														🟦				🟦				
11	First article inspection (FAI)																										
12	Blank manufacturing																			🟧5 🟦							
13	Foundations																										
14	Hazardous material (admission)																										
15	Grinding machine						■1 🟦			🟦					🟦			🟦	🟩2 🟦			🟩2 🟦	🟩2				🟦
16	Engineering guideline (correction)																										
17	Layout adaptation													🟦												🟦	
18	Employee trainings (2)																										
19	Acceptance test	■1				🟦		🟦																			
20	Testing and adaptation	■1 🟦					■1		🟦																		
21	Trade fairs (business trips)																										
22	Employee trainings (1)																										
23	Engineering change			■1 🟦				■1 🟦									■1 🟦								■1 🟦		
24	Moving of components										🟦																
25	Moving of machines													🟦													
26	Washing machine							🟦										🟦								🟦	

Legend

🟦 Information flow 🟩 Energy flow 🟧 Personal flow ■ Material flow

Figure A.5: *ES-MDM of retrospective replacement investment analysis*

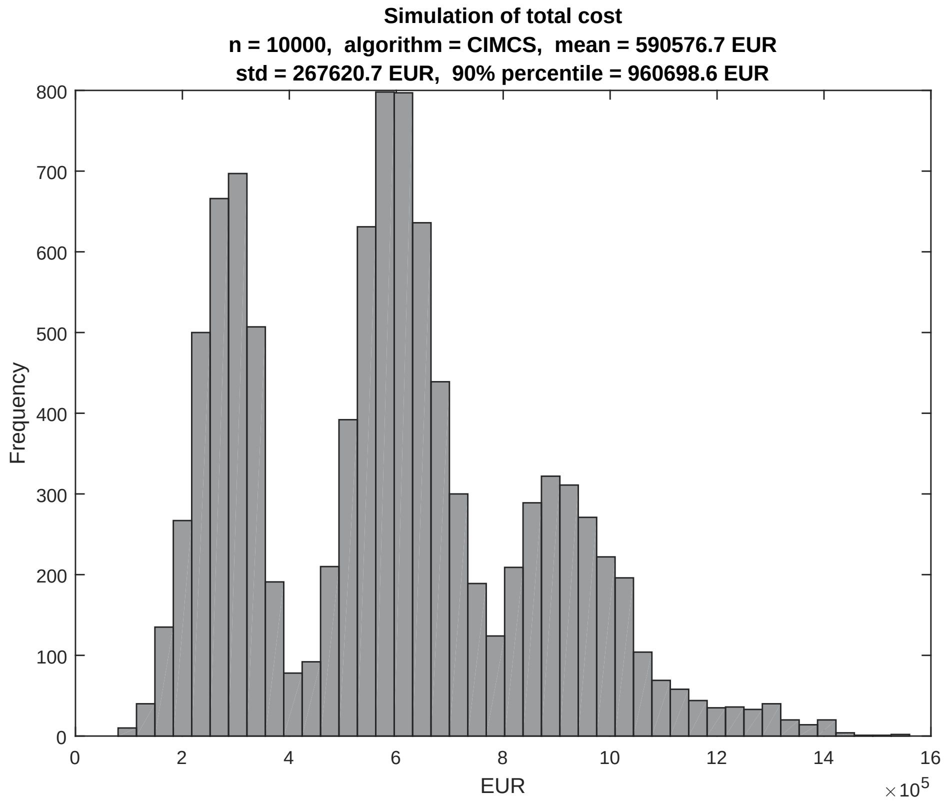


Figure A.6: Total cost distribution for the grinding technology substitution

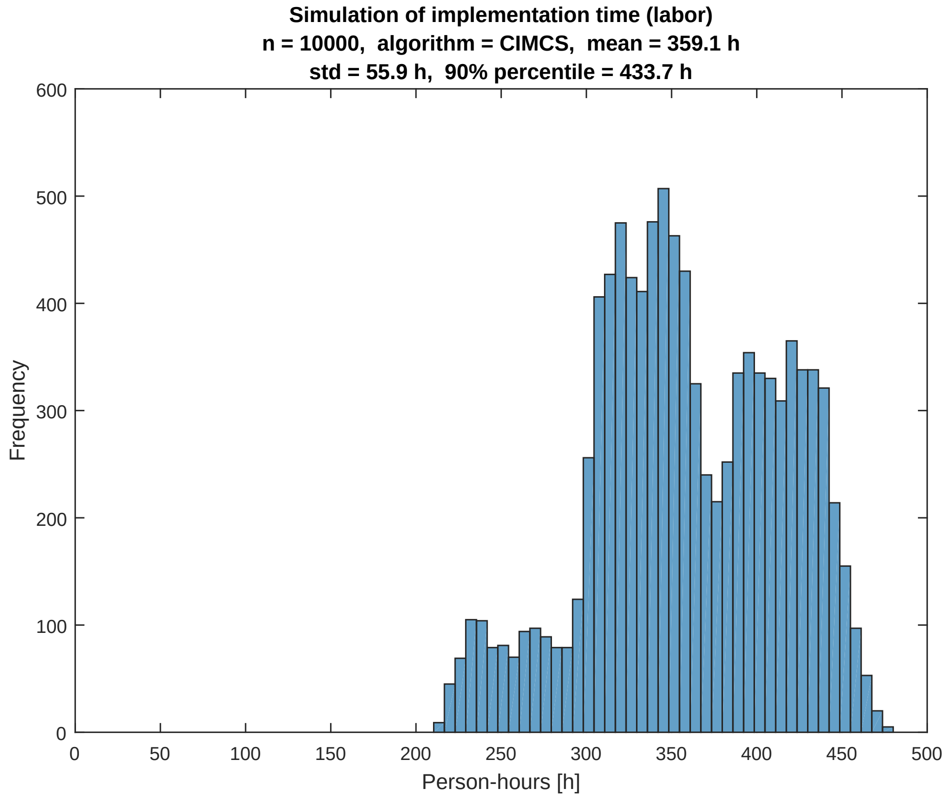


Figure A.7: Implementation time distribution for the grinding technology substitution

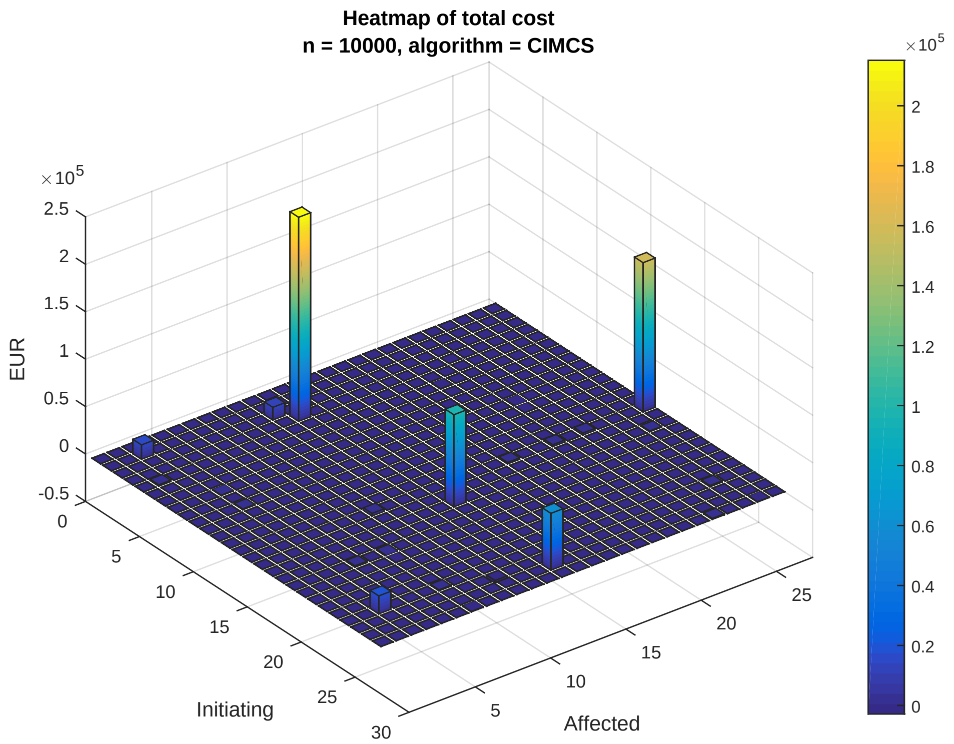


Figure A.8: Change impact heat map of the grinding technology substitution

A.3.2 Case 2: Analysis of a polymer injection molding plant

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1		1									0.8							
2	0.65		0.1		0.5													
3		0.1		0.7		0.7		0.5	0.7				0.7					
4			0.5								0.9	0.9						
5		0.5																
6			0.5								0.9	0.9						
7															0.1			
8			0.5															
9			0.5								0.9	0.9						
10																0.5		
11	0.1			0.1		0.1			0.1				0.1				0.1	
12				0.1		0.1			0.1		0.1		0.1			0.1		
13			0.5								0.9	0.9						
14		0.1													0.6			
15							0.1			0.2						1		
16												0.1			0.1			
17											0.8							
18															1			

Table A.4: Transition probability matrix $\mathbf{P}_\varphi$ *of case 2*

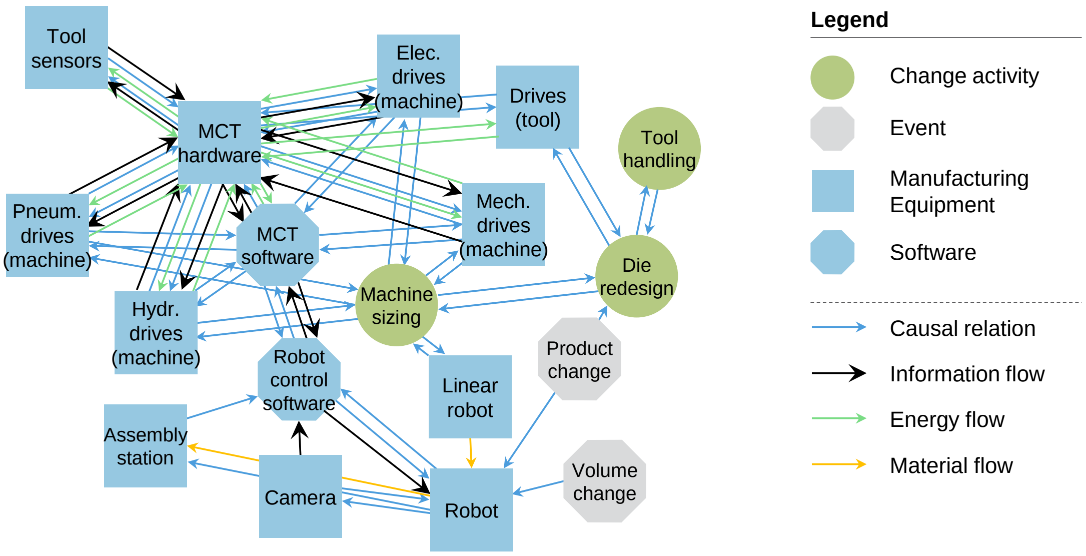


Figure A.9: Multi-graph of the injection molding manufacturing system

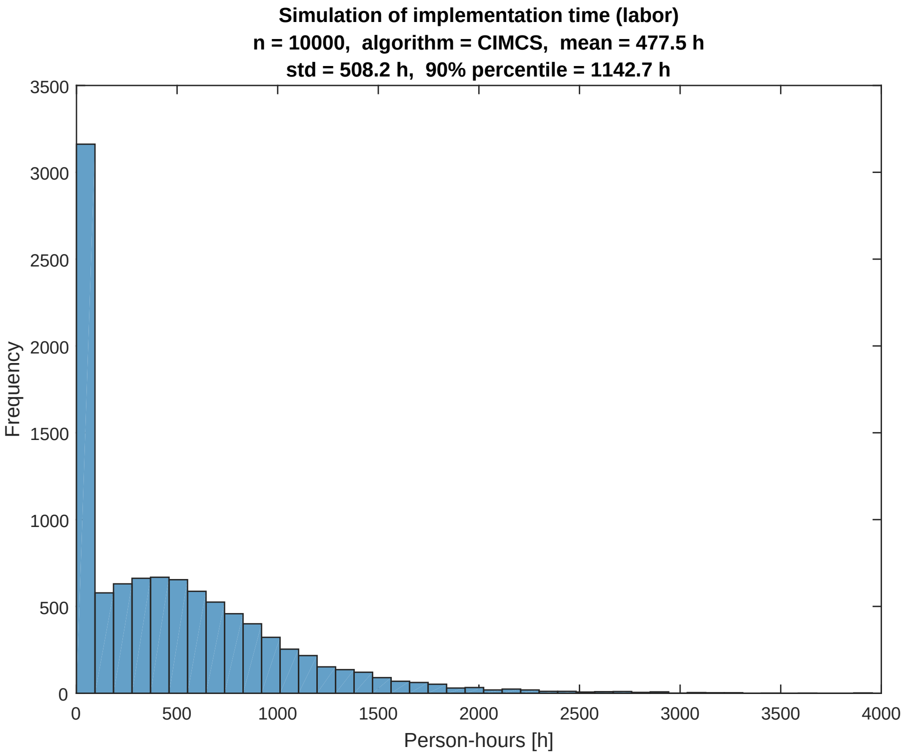


Figure A.10: Implementation time distribution for the impact of the die redesign

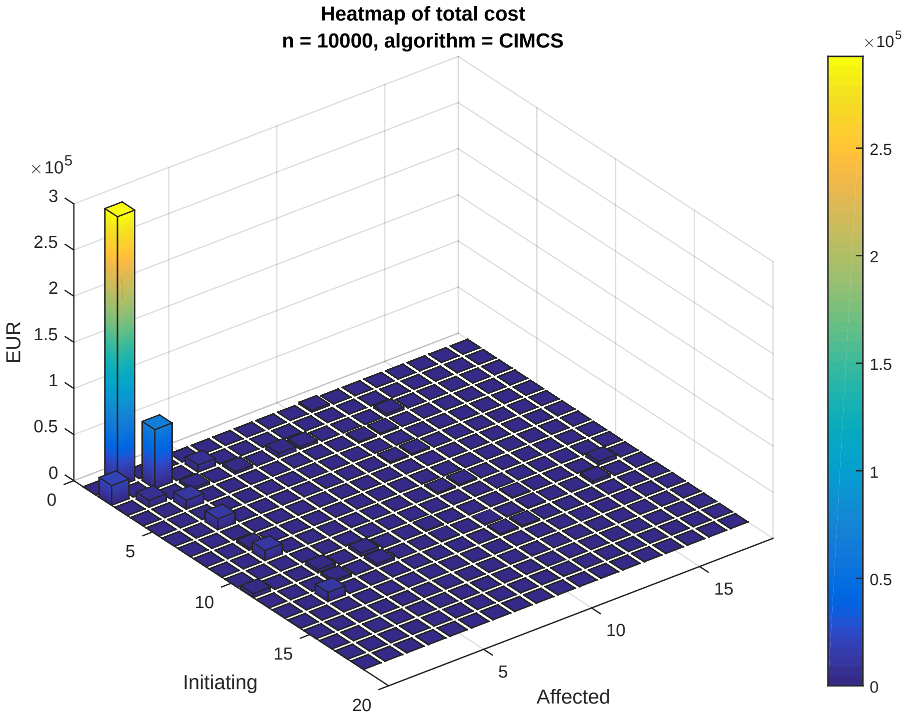
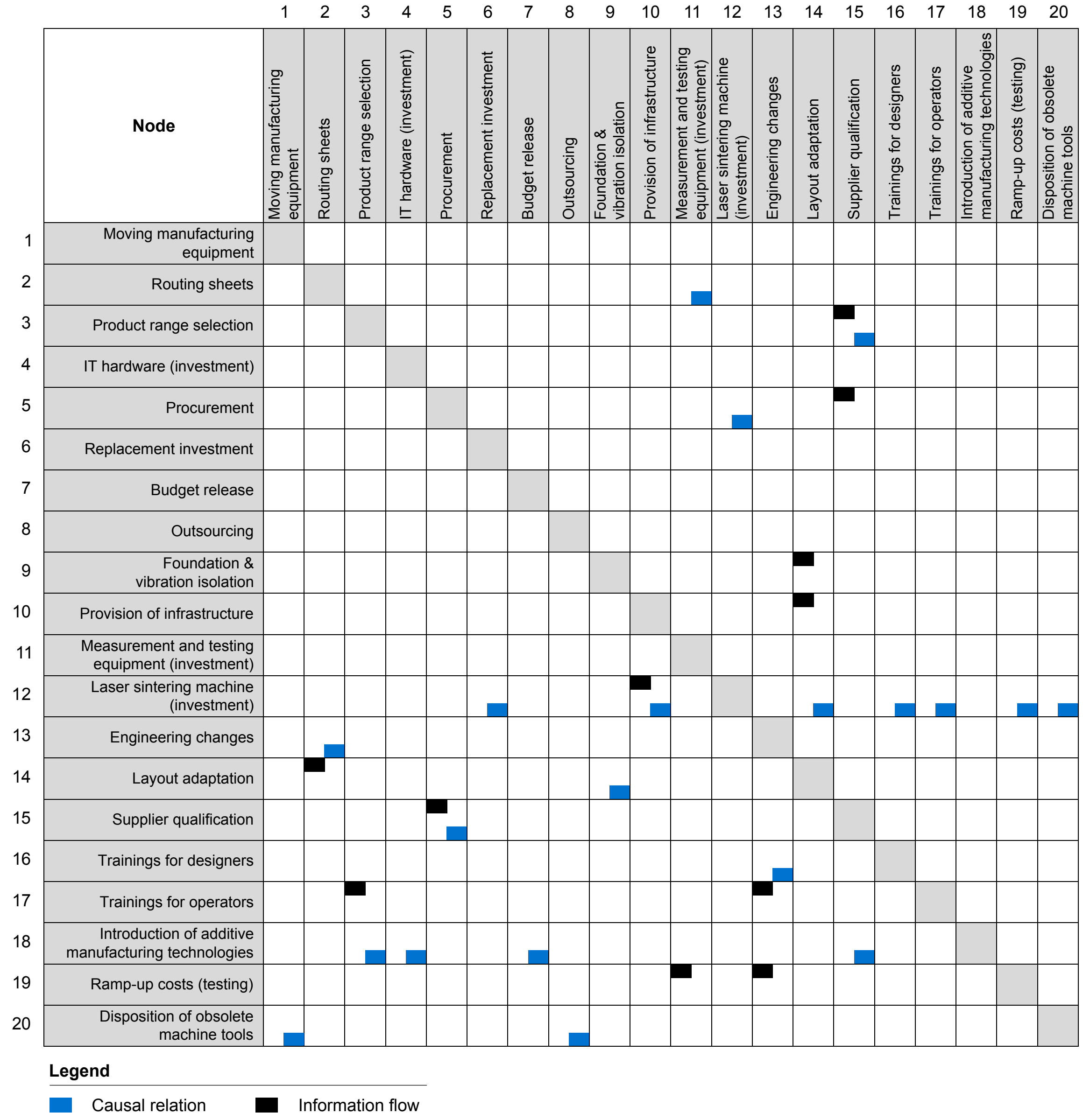


Figure A.11: Change impact heat map of the die redesign

A.3.3 Case 3: Introduction of additive manufacturing

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1											1									
2															0.8					
3																				
4												0.9								
5																				
6																				
7																				
8																				
9																				
10																				
11						0.4			0.5	1				1		1	0.9		0.9	0.6
12		1																		
13									0.5											
14					1															
15													1							
16																				
17			1	0.3			1								1					
18																				
19	0.3							0.7												
20																				

Table A.5: Transition probability matrix $\mathbf{P}_{\kappa}$ *of case 3*



	Node	1 Moving manufacturing equipment	2 Routing sheets	3 Product range selection	4 IT hardware (investment)	5 Procurement	6 Replacement investment	7 Budget release	8 Outsourcing	9 Foundation & vibration isolation	10 Provision of infrastructure	11 Measurement and testing equipment (investment)	12 Laser sintering machine (investment)	13 Engineering changes	14 Layout adaptation	15 Supplier qualification	16 Trainings for designers	17 Trainings for operators	18 Introduction of additive manufacturing technologies	19 Ramp-up costs (testing)	20 Disposition of obsolete machine tools
1	Moving manufacturing equipment																				
2	Routing sheets											🟦									
3	Product range selection															⬛ 🟦					
4	IT hardware (investment)																				
5	Procurement												🟦			⬛					
6	Replacement investment																				
7	Budget release																				
8	Outsourcing																				
9	Foundation & vibration isolation														⬛						
10	Provision of infrastructure														⬛						
11	Measurement and testing equipment (investment)																				
12	Laser sintering machine (investment)						🟦				⬛ 🟦				🟦		🟦	🟦		🟦	🟦
13	Engineering changes		🟦																		
14	Layout adaptation		⬛							🟦											
15	Supplier qualification					⬛ 🟦															
16	Trainings for designers													🟦							
17	Trainings for operators			⬛										⬛							
18	Introduction of additive manufacturing technologies			🟦	🟦			🟦								🟦					
19	Ramp-up costs (testing)											⬛		⬛							
20	Disposition of obsolete machine tools	🟦							🟦												

Legend

🟦 Causal relation ⬛ Information flow

Figure A.12: ES-MDM of the technology introduction feasibility study

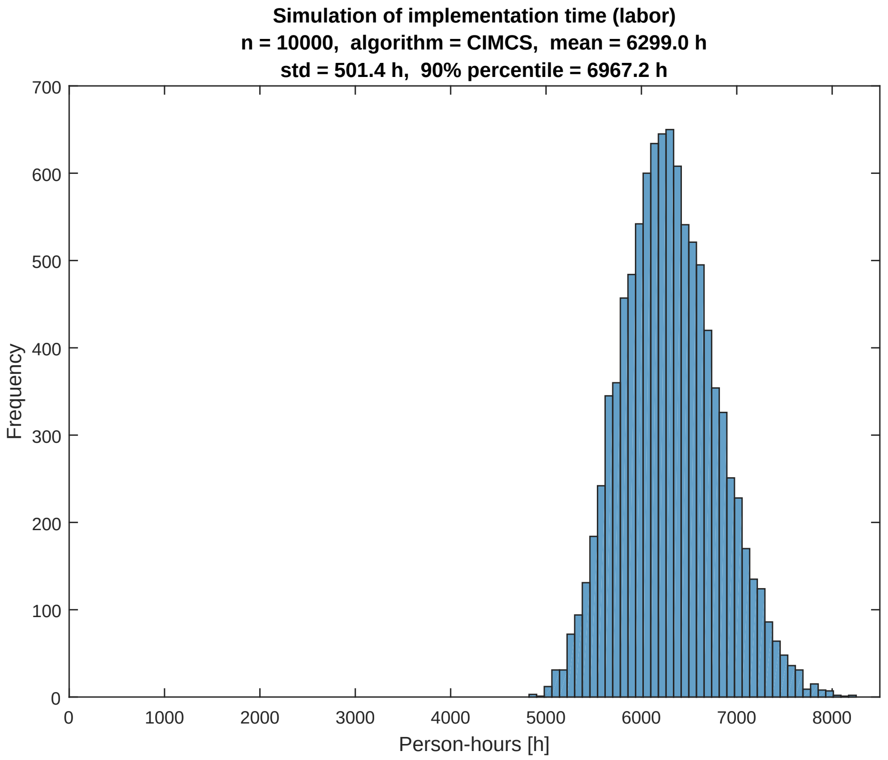


Figure A.13: Implementation time distribution for the technology introduction

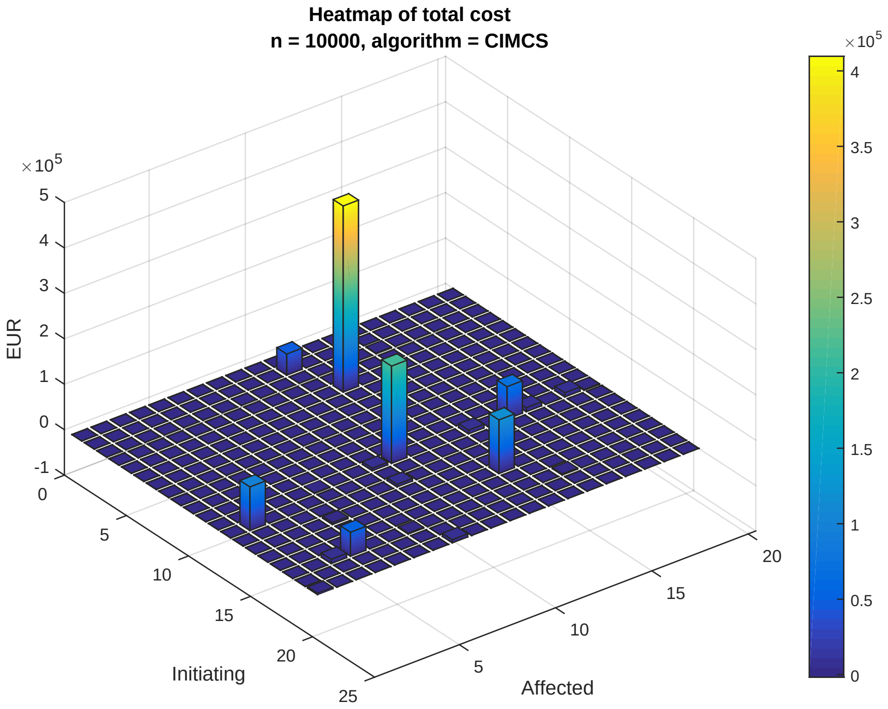


Figure A.14: Change impact heat map of the technology introduction

A.4 Software used

- Citavi™ 5: Reference management program.
- Mathworks MATLAB® 2015a: Numerical computing environment. Used for Change Impact Simulation Graph Algorithm implementation, data analysis, Monte Carlo Simulation, and result statistics (histograms and heat maps).
- Microsoft Excel® 2013: Spreadsheet application. Used for the design of ES-MDM templates for industrial case applications and pay-off method.
- Microsoft PowerPoint® 2013: Slide show presentation program used for all graphical illustrations (except diagrams).
- Soley Studio 2: Graph based domain-specific modeling environment for big data analysis combined with work flow automation. Used for metamodel implementation, multi-graph model illustrations, and data processing.
- TeXstudio 2.8.4: Integrated development environment for LaTeX typesetting.

A.5 Theses supervised

In the context of the research work performed by the author—which is described both in research publications and this dissertation—various master's theses and semester projects have been intensively supervised methodically and with regard to the development of their research clarification, problem statements, objectives, research questions, and content. The supervision took place at the Institute for Machine Tools and Industrial Management (*iwb*) of the Technical University of Munich. Master's theses and seminar papers listed in table A.6 contributed to the author's dissertation (in reverse chronological and alphabetical order).

As the student's theses have been elaborated in close relationship with the author's research activities, their topics are located within the broad fields of changeability in manufacturing and factory system modelling and change impact analysis. Findings and results of these collaborative research projects have partly contributed to this dissertation. The author would like to express his sincere gratitude for the remarkable commitment of all his students and their interesting contributions.

Table A.6: Theses supervised in the course of this research project

Name	Thesis title	Contribution	Type	Year
Graule, D.	Description, Extension and Comparison of the Change Impact Analysis Graph Algorithm	Ch. 7	SP	2016
Stein, F.	Application of a Model-Based Change Impact Assessment Methodology in Industrial Practice	Chs. 4, 8, § 5.3.4	MT	2016
Remmel, F.	Model based Evaluation of Factory System Changeability	§§ 1.2.3, A.1.2	MT	2015
Ostermeier, F.	Changeability of Production Systems. Establishing a Common Understanding and Developing a Holistic Evaluation Method	§§ 1.2.3, A.1.2	MT	2015
Schreiner, D.	Change Impact Analysis in Product Development and Manufacturing - State of the Art and Theoretical Foundation	§ 3.3	SP	2015
Vollmers, O.	Potential of IT-supported Modeling Languages for Visualizing and Analyzing Factory Systems	Ch. 2	SP	2015
Kreuels, S.	Model based Multi-Criteria Analysis of Factory Systems. An Approach to Improve the Identification of Change Measures	§§ 3.2, 2.2	MT	2014
Pinedo, M.	Planning and Evaluation of Flexible Assembly Systems	§ 3.2	MT	2014
Haas, M.	Changeability evaluation of factory and manufacturing structures	A.1.2	SP	2013
Guerrero, P.	Analysis and Evaluation of Existing Planning Methods in Factory and Manufacturing Structure Planning	§ 3.2	SP	2013

MT: Master's thesis SP: Semester project

A.6 Publication list

Preliminary results of this thesis have been used for own conference or journal publications that are listed in the following.

GREITEMANN et al. 2013

Greitemann, J.; Plehn, C.; Koch, J.; Reinhart, G.: Strategic Screening of Manufacturing Technologies. In: *Enabling Manufacturing Competitiveness and Economic Sustainability*. 5th International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV). (München). Ed. by M. F. Zäh. Springer. 2013, pp. 321–326.

KOCH et al. 2013

Koch, J.; Plehn, C.; Reinhart, G.; Zäh, M. F.: Cycle Management for Continuous Manufacturing Planning. In: *Enabling Manufacturing Competitiveness and Economic Sustainability*. 5th International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV). (München). Ed. by M. F. Zäh. Springer. 2013, pp. 9–12.

PLEHN et al. 2015a

Plehn, C.; Koch, J.; Diepold, K.; Stahl, B.; Lohmann, B.; Reinhart, G.; Zäh, M. F.: Modeling and analyzing dynamic cycle networks for manufacturing planning. *Procedia CIRP* 28 (2015), pp. 149–154. ISSN: 22128271.

PLEHN et al. 2015b

Plehn, C.; Stein, F.; Reinhart, G.: Modeling Factory Systems Using Graphs: Ontology-based Design of a Domain Specific Modeling Approach. *International Conference on Engineering Design (ICED 2015)* (2015).

PLEHN et al. 2016a

Plehn, C.; Stein, F.; de Neufville, R.; Reinhart, G.: Assessing the Impact of Changes and their Knock-on Effects in Manufacturing Systems. In: *Factories of the Future in the Digital Environment*. 49th CIRP Conference on Manufacturing Systems. (Stuttgart). Ed. by E. Westkämper; T. Bauernhansl. 2016, in print.

PLEHN et al. 2016b

Plehn, C.; Ostermeier, F.; Remmel, F.; de Neufville, R.; Reinhart, G.: Towards a Uniform Understanding of Changeability Terminology – A Multidisciplinary Review. *CIRP Journal of Manufacturing Science and Technology* (2016), submission in review. ISSN: 17555817.

POHL et al. 2014

Pohl, J.; Stein, F.; Plehn, C.: Adaption von Produktionsstrukturen unter Berücksichtigung von Lebenszyklen. In: *Innovationsprozesse zyklenorientiert managen: Verzahnte Entwicklung von Produkt-Service Systemen*. Ed. by B. Vogel-Heuser; U. Lindemann; G. Reinhart. Berlin Heidelberg: Springer. 2014, pp. 186–205.

STAHL et al. 2013

Stahl, B.; Diepold, K.; Pohl, J.; Greitemann, J.; Plehn, C.; Koch, J.; Lohmann, B.; Reinhart, G.: Modeling Cyclic Interactions within a Production Environment using Transition Adaptive Recurrent Fuzzy Systems. In: *7th IFAC Conference on Manufacturing Modelling, Management, and Control. Manufacturing Modelling, Management, and Control Vol. 7, Part 1*. (St. Petersburg, Russia). Ed. by N. Bakhtadze; K. Chernyshov; A. Dolgui; V. Lototsky. International Federation of Automatic Control. 2013, pp. 1979–1984.

STAHL et al. 2015

Stahl, B.; Zhong, Z.; Plehn, C.; Reinhart, G.; Lohmann, B.: Fuzzy expert system based evaluation framework for management procedure models. *15th IFAC Symposium on Information Control Problems in Manufacturing* (2015).

List of Figures

List of Tables

List of Abbreviations

ADVICE	Active Distributed Virtual Change Environment
AHP	Analytic Hierarchy Process
BFS	Breadth-First Search
CAD	Computer Aided Design
CAF	Component Adaptability Factor
C&CM	Contact & Channel Model
CDF	Cumulative Distribution Function
CECM	Collaborative Environment for Engineering Change Management
C-FAR	Change Favorable Representation
CIRA	Change Impact and Risk Analysis
CIRP	International Academy for Production Engineering
CIS	Change Impact Simulation
CISGA	Change Impact Simulation Graph Algorithm
COV	Component Option Value
CPI	Change Propagation Index
CPM	Change Prediction Method
CPM/PDD	Characteristics-Properties Modeling / Property-Driven Development
CRC	Collaborative Research Center (Sonderforschungsbereich)
CSS	Channel and Support Structures
DDM	Design Dependency Matrix
DEPNET	Dependencies Network
DfC	Design for Changeability
DFG	German Research Foundation (Deutsche Forschungsgemeinschaft)
DIN	Standards Association of German Industry (Deutsches Institut für Normung)
DMM	Domain Mapping Matrix
DRM	Design Research Methodology

DSM	Design Structure Matrix
EC	Engineering Change
ECM	Engineering Change Management
ECR	Engineering Change Request
EEA	Epoch-Era Analysis
ENPV	Expected Net Present Value
ESD	Engineering Systems Division
ES-MDM	Engineering Systems Multiple-Domain Matrix
FBS	Function-Behavior-Structure
FCM	Fuzzy Cognitive Map
FMEA	Failure Modes and Effects Analysis
IDSS	Institute for Data, Systems, and Society
INCOSE	International Council on Systems Engineering
ISF	Information Structure Framework
IT	Information Technology
iwb	Institute for Machine Tools and Industrial Management
JTMS	Justification-based Truth Maintenance System
KPI	Key Performance Indicator
MATE	Multi-Attribute Tradespace Exploration
MBSE	Model-Based Systems Engineering
MC	Manufacturing Change
MCM	Manufacturing Change Management
MCS	Monte Carlo Simulation
MCT	Measurement and Control Technology
MDM	Multiple-Domain Matrix
MIT	Massachusetts Institute of Technology
NPD	New Product Development
NPV	Net Present Value
OMG	Object Management Group
OPM	Object-Process Methodology
OWL	Web Ontology Language
PA	Polyamide
PDF	Probability Density Function
PERT	Program Evaluation and Review Technique
PSS	Product Service System

RAS	Research Process of Applied Sciences
RCI	Relative Change Impact
ROI	Return on Investment
RVI	Relative Value Index
SLS	Selective-Laser-Sintering
SQL	Structured Query Language
SSPARC	Space Systems, Policy, and Architecture Research Consortium
SysML	Systems Modeling Language
TI	Technology Invasiveness
TPE	Three-Point-Estimation
TUM	Technical University of Munich
UML	Unified Modeling Language
VASC	Valuation Approach for Strategic Changeability
VDI	Association of German Engineers (Verein Deutscher Ingenieure)
VR	Virtual Reality
WACC	Weighted Average Cost of Capital
WSP	Working Surface Pairs

List of Symbols

Literature review

$\hat{C}$	Acceptability threshold for design transition costs
CAF	Component Adaptability Factor
COV	Component Option Value
E	Efficiency sub-metric
$ENPV$	Expected Net Present Value
$\left\{DV^N\right\}$	Design variable set representing technical degrees of freedom
F	Functionality sub-metric
f_C, f_U	Scalar functions for the mapping of design variable sets to cost C and aggregate utility U
F_{XM}	$\mathbb{R}^N \longrightarrow \mathbb{R}^M$ mapping of design parameters to specific attribute values
I	Combined change impact
$I_{i_{n,k}}$	Interface cost factor for module-to-module interfaces
$I_{e_{n,k}}$	Interface cost factor for module-to-environment interfaces
L	Combined change likelihood
M	Maintainability sub-metric
M^+, M^-	Order of magnitude and causal direction of influences between parts and components
NPV	Net Present Value
P	Portability sub-metric
R	Combined change risk in CPM / reliability sub-metric of CAF
$\mathbf{T}_{C,U}$	Cost-utility vector in tradespace exploration

$\mathbf{T}_D$	Trade space of possible design options
$\mathbf{T}_{ijk}$	Acceptability tensor describing the cost for a transition from design i to j following transition rule k
U	Usability sub-metric
$V^{(1)}$	Economic value of a system architecture
$w_F, \dots, w_P$	Weights of sub-metrics $F, \dots, P$
$\{X^M\}$	Attribute set capturing M types of value perceived by system stakeholders

Own work

Latin symbols

A, a		Best case / optimistic estimate and corresponding index
B, b		Worst case / pessimistic estimate and corresponding index
c_t	[€/h]	Hourly rate for labor cost
C_t	[€]	Net cash flow in period t
$\hat{C}$	[€]	Cost threshold triggering an application of the method in MCM
$\overline{C}$	[€]	Mean impact over all MCS trials, arithmetic sample mean of $C^{(n)}$
$C^{(n)}$	[€]	Aggregated cost impact of the n-th MCS trial
$c_{a,ij}, c_{m,ij}, c_{b,ij}$	[€]	Best, most likely, and worst case change cost estimate for change transition from node i to j
C_D	[€]	Initial cost for a system design
$C_{F,Method}$	[€]	Fixed expenses required for the method
$C_{F,t}$	[€]	Fixed recurring costs in period t
$\Delta C_{F,t}$	[€]	Difference between original and post-change fixed recurring costs in period t
$c_{ij}^{(n)}$	[€]	Aggregated cost incurred on edge $e_{ij} \in E$ during the n-th MCS trial
$\overline{c}_L$	[€/h]	Average labor cost rate of expert group members

C_{LCC}	[€]	Discounted life cycle cost of a system design
$c^{(n)}_{total,ij}$	[€]	Aggregated total cost incurred on edge $e_{ij} \in E$ during the n-th MCS trial
$\overline{C}_{total}$	[€]	Mean impact over all MCS trials, arithmetic sample mean of $C^{(n)}_{total}$
$C^{(n)}_{total}$	[€]	Aggregated total cost impact of the n-th MCS trial
$\Delta c_{V,t}$	[€]	Difference between original and post-change variable cost per unit in period t
$C_{V,t}$	[€]	Variable recurring costs in period t
$\Delta C_{V,t}$	[€]	Difference between original and post-change variable cost in period t
C_0	[€]	Cash outflow today (at t_0)
d		Index, $d \in I_{neighbors}$
E		Set of edges of the graph $G(V,E)$
e_{ij}		Edge from node i to node j in graph $G(V,E)$
i		Index
$I_{neighbors}$		Index set of adjacent nodes (neighbors)
I_s		Index set of all change initiating system elements s_k with $k \in I_s$
I_0	[€]	Initial investment for the implementation of a system change (equals $\overline{C}_{total}$)
j		Index
k		Index
M, m		Most likely / expected estimate and corresponding index
$\hat{\mu}$		PERT mean
n		Number of trials in MCS
N		Number of nodes, dimension of $\mathbf{P}$ (= cardinality of V)
n_d		Neighbor node d with $d \in I_{neighbors}$
ΔNPV	[€]	Delta NPV due to a system change based on the time horizon τ
p	[€]	Product price
Δp_t	[€]	Difference between original and post-change product price in period t

p_{ij}		Direct change likelihood, $p_{ij} \in \mathbf{P}$
r		Discount rate (e.g. WACC)
s_k		Node representing an initial change in the system model
t		Search depth iteration variable, $t \in \{1, \ldots, depth\}$
t		Payment period in NPV calculation
$\overline{T}$	[h]	Mean impact over all MCS trials, arithmetic sample mean of $T^{(n)}$
$T^{(n)}$	[h]	Aggregated working time impact of the n-th MCS trial
$t_{a,ij}, t_{m,ij}, t_{b,ij}$	[h]	Best, most likely, and worst case working time for change transition from node i to j
t_e	[h]	Elapsed time in PERT
$t_{ij}^{(n)}$	[h]	Aggregated working time incurred on edge $e_{ij} \in E$ during the n-th MCS trial
T_{Method}	[h]	Time required for the method's application
u		Uniformly $U(0,1)$ distributed random variable
v		Node in graph $G(V,E)$
V		Set of nodes of the graph $G(V,E)$
w		Node in graph $G(V,E)$
x		Demand volume per period
Δx_t		Difference between original and post-change demand volume in period t
X		Random variable

Bold Latin symbols

$\overline{\mathbf{C}}$	[€]	Matrix of mean cost impact $\forall$ edges $e_{ij} \in G(V,E,p_{ij})$ of the MCS sample
$\mathbf{C}^{(n)}$	[€]	Cost impact result matrix of the n-th MCS trial, $c_{ij}^{(n)} \in \mathbf{C}^{(n)}$
$\mathbf{C}_a, \mathbf{C}_m, \mathbf{C}_b$	[€]	Best, most likely, and worst case change cost estimate matrices, $c_{\delta,ij} \in \mathbf{C}_\delta$ with $\delta \in \{a,m,b\}$
$\overline{\mathbf{C}}_{total}$	[€]	Matrix of mean total cost impact $\forall$ edges $e_{ij} \in G(V,E,p_{ij})$ of the MCS sample

$\mathbf{C}_{total}^{(n)}$	[€]	Total cost impact result matrix of the n-th MCS trial, $c_{total,ij}^{(n)} \in \mathbf{C}_{total}^{(n)}$
$\mathbf{P}$		Transition probability matrix
$\mathbf{s}$		Vector of initially changed nodes s_k
$\overline{\mathbf{T}}$	[h]	Matrix of mean working time impact $\forall$ edges $e_{ij} \in G(V,E,p_{ij})$ of the MCS sample
$\mathbf{T}^{(n)}$	[h]	Working time impact result matrix of the n-th MCS trial, $t_{ij}^{(n)} \in \mathbf{T}^{(n)}$
$\mathbf{T}_a, \mathbf{T}_m, \mathbf{T}_b$	[h]	Best, most likely, and worst case working time estimate matrices, $t_{\delta,ij} \in \mathbf{T}_\delta$ with $\delta \in \{a,m,b\}$

Greek symbols

α		Form parameter of beta distribution
β		Form parameter of beta distribution
ϵ		Minimum path probability restriction
ρ		Number of people permanently involved during the method's application (cost effective capacity)
$\hat{\sigma}^2$		PERT variance
σ_C	[€]	Standard deviation of aggregated cost $C^{(n)}$ MCS sample
$\sigma_{C_{total}}$	[€]	Standard deviation of aggregated total cost $C_{total}^{(n)}$ MCS sample
$\sigma_{identity}$		Permutation of $I_{neighbors}$: ascending numerical order
$\sigma_{maxprob}$		Permutation of $I_{neighbors}$: most probable neighbor first
σ_T	[h]	Standard deviation of aggregated working time $T^{(n)}$ MCS sample
σ_{rand}		Random permutation of $I_{neighbors}$
τ	[a]	Time horizon of change analysis

Bold Greek symbols

$\boldsymbol{\alpha}^{N\times N}$		Beta distribution form parameter matrix
$\boldsymbol{\beta}^{N\times N}$		Beta distribution form parameter matrix

Variable names

cost	[€]	Random non-recurring cost drawn from a beta distribution
depth		Search / propagation depth
likelihood		Expansion of *nodeprobs*
neighbors		Vector containing all nodes in the neighborhood of current nodes
nodeprobs		Vector containing path probabilities of current nodes
parentnodes		Expansion of *startnodes*
parentpaths		Expansion of *startpaths*
probslist		Vector containing all direct transition likelihoods $\mathbf{P}_{u_i,v_i}$ of current parent nodes u_i to their neighbors v_i with $i \in I_{neighbors}$
startnodes		Vector containing all current nodes in breath-first graph traversal
startpaths		Matrix of search paths corresponding with current nodes
time	[h]	Random implementation time drawn from a beta distribution
total	[€]	Total cost incurred if change propagates from current node to a neighbor
visited		Vector containing all nodes that have been visited

Mathematical operators

$\mathbf{B}(\cdot)$	Beta function
$\mathrm{Beta}(\alpha, \beta)$	Beta distribution
$E[\cdot]$	Expectation operator
$P(\cdot)$	Probability operator
$\sigma(\cdot)$	Permutation operator
$V[\cdot]$	Variance operator