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Manufacturing Change Management – a Process-Based Approach for the Management of Manufacturing Changes

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Abstract

Coping with change in manufacturing is one of the everlasting challenges of manufacturing companies. Among others, an increasing complexity of engineered systems like products and factories, more and more strict legislative and quality requirements, and a progressive digitalization of factories impede an effective and efficient management of manufacturing changes.

In product development, the approach of Engineering Change Management (ECM), which addresses the management of product changes, has gained remarkable popularity in both engineering science and industrial practice. In manufacturing, especially approaches for factory planning and continuous factory planning have been emphasized. Also, first concepts dedicated to a Manufacturing Change Management (MCM) emerged during the last years. However, current approaches for MCM are still in their infancy as these barely consider MCM to actually represent a network of activities with numerous dependencies as well as the need for a change-specific adaptability of MCM in industrial practice.

The research at hand is intended to address this deficiency with the development of a process-based approach for the management of manufacturing changes. Guided by the Design Research Methodology, the development of the MCM approach is based on extensive literature reviews, several in-depth case studies, a web-based survey as well as numerous interviews and workshops with practitioners. Main results include a holistic MCM context model, a Manufacturing Change (MC) model covering the multitude of different MCs, a detailed MCM process with proactive, reactive, and retrospective activities, relevant roles, and an MC-specific process adaptation approach. The MCM process design includes relevant activities and their dependencies, i.e., the detailed process architecture. The MCM approach is applied and evaluated with three different manufacturing companies. Overall, this thesis contributes to industrial practice, to engineering science, and to a theory on MCM.

Glossary

Engineering Change (EC)
An alteration made to parts, drawings, or software that have already been released during the product design process. An EC can be of any size or type, can involve any number of people, and take any length of time.

Engineering Change Management (ECM)
Refers to organizing and controlling the process of making alterations to a product. This includes the totality of measures to avoid and specifically front-load as well as efficiently plan, select, process, and control ECs.

ECM process
The network of activities performed with the goal of managing ECs.

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.

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 MCs.

MCM process
The network of activities performed with the goal of managing MCs.

Contents

1 Introduction

"Nothing endures but change." (HERACLITUS 535-475 BC)
"Only change remains"[1] (REINHART & HOFFMANN 2000)
"Change is the law of life." (KENNEDY 1963)
"Everything remains different"[2] (GRÖNEMEYER 2000)

1.1 Change in manufacturing becomes the rule

Change is ubiquitous in the often cited dynamic or turbulent environment (e.g., WIENDAHL et al. 2007, YUSUF et al. 1999). Among others, changes occur on economic, social, and structural levels, in societies, in companies, as well as in engineered systems such as product or factory systems. For industrial enterprises, managing turbulence has no prospect on success, but coping with it – which means coping with change – does (CHAKRAVARTHY 1997, p. 77, FRICKE et al. 2000).

During the last decades, the complexity of these engineered systems increased significantly, hampering any attempts to deal with change in industrial enterprises. From an economic perspective, this fact also manifests in the rule-of-ten, stating costs of change to exponentially increase the later the change occurs during the life cycle of such a system (CLARK & FUJIMOTO 1991). At the same time, legislative and quality requirements increasingly encourage the application of structured approaches to address the everlasting challenge of handling changes effectively and efficiently (e.g., DIN EN ISO 10007, DIN EN ISO 9000). In addition, the progressive digitalization enables the creation and utilization of ever more extensive models of engineered systems (factories

[1] Translated by the author. Original text in German: "Nur der Wandel bleibt" (REINHART & HOFFMANN 2000)
[2] Translated by the author. Original text in German: "Bleibt alles anders" (GRÖNEMEYER 2000)

and products), which in turn leads to the challenge of harmonizing both changing digital models and changing real-world systems (e.g., PROSTEP IVIP E.V. 2015). The importance of the challenge of coping with change cannot be overestimated, as results from a recent survey among more than 80 manufacturing companies (KOCH et al. 2015b; see figure 1.1) and the following real-world examples of changes in different factory systems demonstrate.

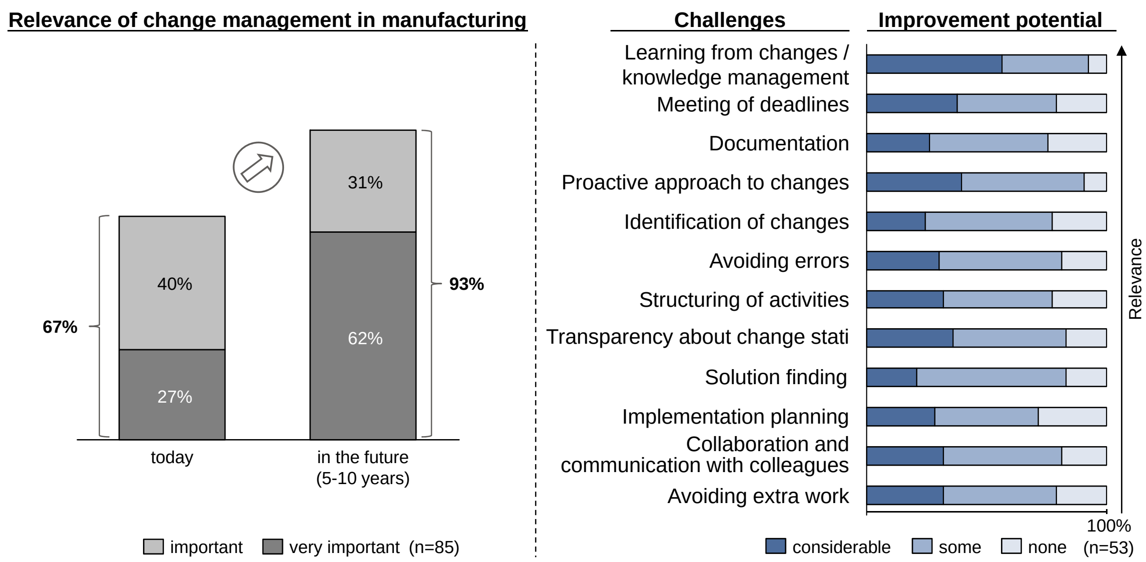

Figure 1.1: Importance of change management in manufacturing; related challenges and improvement potential (KOCH et al. 2015b)

Company Alpha[3] intended to replace an aged, but well-functioning manufacturing resource with one of the latest models available to increase productivity and cut down energy consumption. As usual with these projects, the necessary invest has been proposed to and approved by production management after assuring technical feasibility. Once the new machine was installed, severe problems with the produced product component arose due to some specific configuration requirements the factory planners had not been aware of. After identifying these together with engineers responsible for the development of the affected product component, the machine had to be extensively reconfigured. In the meantime, hundreds of thousands of dollars of

[3] Name of company (and other companies mentioned in this thesis) changed by the author for reasons of confidentiality.

additional costs accumulated for acquiring replacement parts for the products, as well as for identifying and solving the technical issues with the new manufacturing resource. In total, costs of change had almost doubled compared to initial cost estimations.

Company Beta acquired a new paint-spray line for a specific product component to improve painting quality and productivity. At the same time, the product engineering was able to implement some small specification changes to the product, so that painting the product component was no longer necessary. Both changes were implemented almost at the same time without prior information exchange during planning, leading to a high investment in a "soon-to-be-obsolete" machine.

These examples represent two rather large changes in manufacturing with severe consequences, but in practice actually a lot more changes occur – different in terms of, for example, scope, costs, or impact – but every now and then with similar, unexpected effects. The magnitude of manufacturing changes often reaches upper three-digit numbers per year for most manufacturing companies (KOCH et al. 2015b). In order to support companies to better cope with such changes, two major aspects have been in focus of engineering science: changeability and agility.

Innumerable publications investigated the phenomenon of changeability and closely related subsets such as flexibility, transformability[4], adaptability, or reconfigurability (e.g., FRICKE & SCHULZ 2005, WIENDAHL & HERNÁNDEZ MORALES 2006, EL-MARAGHY 2009, RYAN et al. 2013). Together, these are sometimes referred to as "ilities" (ROSS et al. 2008, DE WECK et al. 2011), which describe "an inherent system property" (BERNARDES & HANNA 2009). In this context, multiple approaches have been developed to analyze, evaluate, or plan and design these system properties.[5]

In contrast, agility has been proposed as "an approach to organizing the system" (BERNARDES & HANNA 2009) – i.e., the ability to quickly respond to anticipated or unexpected changes, exploiting and considering them as opportunities (DOVE 1994, KIDD 1994, SHARIFI & ZHANG 2001). Considered as an overarching approach for a whole company, agility comprises changeability (and its subsets) as one capability (e.g.,

[4] In German publications the term "Wandlungsfähigkeit" is usually emphasized in this context.

[5] For manufacturing: e.g., , CHRYSSOLOURIS (1996), HERNÁNDEZ MORALES (2002), ABELE et al. (2006), or MOURTZIS et al. (2012); for product development: e.g., GU et al. (2004), FRICKE & SCHULZ (2005), KASARDA et al. (2007), or ENGEL & BROWNING (2008).

WIENDAHL et al. 2007). Further relevant capabilities like proactiveness, competency, or quickness have been proposed by ZHANG & SHARIFI (2007).[6]

In product development, the concept of Engineering Change Management (ECM) has been investigated for several decades as the enabler to manage changes of and within the product system (Engineering Change (EC); HAMRAZ et al. 2013). From a product development perspective, this ability of managing ECs reflects the agility of a company (TAVČAR & DUHOVNIK 2005, p. 205). Several approaches on general ECM concepts, ECM processes, and ECs are available in scientific and practitioners literature (e.g., LINDEMANN & REICHWALD 1998, JARRATT et al. 2011, VDA 2010a).

In manufacturing, different concepts have been proposed to contribute to the agility of a company. While approaches for factory planning can be utilized to plan changes (e.g., VDI 5200), especially the concept of continuous factory planning has been suggested as a control loop-based application of factory planning to monitor factories and identify required adaptations within the factory (e.g., CISEK 2005, DASHCHENKO 2006, NYHUIS et al. 2010). At the same time, approaches to actually manage changes in manufacturing have only been sporadically developed based on the direct application of ECM in manufacturing (e.g., AURICH et al. 2004, RÖSSING 2007, PROSTEP IVIP E.V. 2015). Among the first to actually introduce the concept of Manufacturing Change Management (MCM) as the enabler to manage Manufacturing Changes (MCs) of and within the factory are PROSTEP IVIP E.V. (2014). Overall, only basic, purely ECM-based approaches are available for MCM, including simple concepts to describe MCs and rudimentary MCM processes. In industrial practice, this leads to heterogeneous approaches to deal with MCs, which often mainly focus on planning and implementing rather than actually managing MCs. Moreover, the variety of MCs leads to potential mismatches between available approaches and MCs causing, for example, additional work, deviations from standards, and long lead times. In consequence, this hinders the potential contribution to a company's agility from a manufacturing perspective.

[6] Note, that in contrast to most cited publications and also the understanding within this thesis, FRICKE & SCHULZ (2005) consider agility as a subset of changeability.

1.2 Objectives of this thesis

The success of ECM in product development and repeated calls for agility in manufacturing on the one hand, and the perpetual challenge to cope with change and scattered contributions to an approach for MCM on the other hand substantiate the motivation for research on MCM. The overall objective of this research is *to support practitioners in managing MCs effectively and efficiently – i.e., to contribute to agility and add to a company's overall value*. Effectiveness relates to conducting appropriate, beneficial activities and measures in a meaningful sequence to manage MCs with respect to agility and the company's value[7]. Efficiency relates to conducting these activities and measures with appropriate initial and especially continuous efforts for the respective MC (cf. also section 1.4).[8] Therefore, this thesis seeks to contribute to engineering science, a theory on MCM, and industrial practice in four ways (sub-objectives):

O1 Proposing a company-independent concept for MCM.
In order to systematically develop any support for the management of MCs, which is applicable to a multitude of companies, first, an overall concept of MCM and its context is required.

O2 Developing an approach to describe MCs.
In order to be able to manage any MC occurring in a company, a general approach to describe any MC covering its relevant characteristics is required.

O3 Designing a precise, detailed process for the management of MCs.
In order to achieve a more effective and efficient management of MCs a process is required to manage relevant activities and related resources (cf. DIN EN ISO 9000, p. 5). This includes not only a precise and detailed process design including process content and architecture, but also an approach to account for different MCs.

[7] A company's value describes its monetary worth as a whole.

[8] Note, that in the field of ECM effectiveness and efficiency are often addressed in terms of change strategies. These include, for example, to avoid unnecessary changes, front-load changes, select the best alternative for a change, communicate necessary changes early (JARRATT et al. 2005, p. 281). For this research, the focus is on the effectiveness and effectivity of management activities necessary to process any MC.

O4 Estimating the benefits achieved by the MCM approach.
In order to evaluate the developed MCM approach, an estimation of the benefits achieved by its application in industrial practice is required.

Regarding the practitioners intended to use the research results on MCM, especially change managers, production planners, work planners, production staff, quality management, manufacturing strategy, and management of production/manufacturing shall be mentioned. In addition, also employees from related functions like, for example, product development, purchasing, or laws and regulations might have points of contact with MCM.

1.3 Research methods and environment

This sections outlines the type of research described in this thesis and elaborates on available theories on research methods and their selection and application for this research on MCM. Based on the objectives (cf. section 1.2), the guiding research questions are derived, before closing with a brief description of the research environment.

1.3.1 Research questions

Based on the overarching objective, the main research question is formulated drawing attention to the "how" rather than the "what", i.e., the intended result of this research:

How does an MCM have to be designed that enables practitioners to manage MCs efficiently and effectively?

To provide further guidance to the intended research activities, the main research question is further detailed into four sub-questions. These address both potential data sources providing input for this research: science as well as industrial practice. The four sub-questions allocate to the four sub-objectives of this research (see section 1.2) and are formulated as follows:

Q1 How could a company-independent concept for MCM be designed in order to guide a subsequent, system-oriented development of a more detailed MCM?
MCM is considered to have company-specific characteristics and peculiarities (i.e.,

instances of a general MCM), but what is the basic scheme common to any MCM? And how can it be utilized to support a system-oriented design of a more detailed MCM approach (e.g., an MCM process)?

Q2 How could a Manufacturing Change generally be described to support MCM?
MCs can be characterized by different attributes (e.g., costs, impact, duration) – but which are these? And how can they be generalized and structured?

Q3 How could a process to efficiently and effectively manage different MCs be designed?
An MCM process is considered to support an effective and efficient MCM – but which activities are relevant? How should the process architecture be designed? And how can the different MCs be accounted for in the process design?

Q4 What are the benefits achieved by applying the MCM approach?
MCM is considered to contribute to the companies' efforts to manage MCs efficiently and effectively – but which benefits can be achieved by its application? And what are potential trade-offs?

1.3.2 Research methodology

Creating the base for a science of manufacturing, HOPP & SPEARMAN (1995, p. 4) described the partial overlap of the field of manufacturing and the field of Operations Management (OM), the so-called field of "manufacturing operations" or "intersection between OM and manufacturing". The research topic of MCM is located right in the center of this intersection and has a focus on building and extending theory on MCM, which includes the understanding of utilized concepts of and current issues with MCM in the real world. To conduct such research, empirical research methods such as qualitative case studies (BARRATT et al. 2011, p. 329) have been proposed by multiple authors in both fields, OM as well as manufacturing. From an OM perspective, "case study research" (e.g., EISENHARDT 1989, YIN 1984), and the "Grounded Theory Method (GTM)" (GLASER & STRAUSS 1967) are common approaches, while from a manufacturing perspective the concept of applied science (e.g., P. ULRICH & HILL

1976a, P. ULRICH & HILL 1976b, H. ULRICH 1984)[9] is often propagated to build and extend theory.

In OM, GLASER & STRAUSS (1967) created the scientific basis for iterative theory building based on data collection in the field – the GTM. Among others, YIN (1984), EISENHARDT (1989), J. MEREDITH (1998), and EISENHARDT & GRAEBNER (2007) added an approach to build theory from case study research, which is generally seen to be in line with GTM. Authors like HANDFIELD & MELNYK (1998), STUART et al. (2002), and VOSS et al. (2002) provide further guidance on the research process for case-based research in OM and, like EISENHARDT (1989), encourage the application of triangulation, i.e., applying different methods of data collection in case studies to increase validity of results. Summarizing, the authors share the general idea of iteratively building theories based on qualitative data from case studies, mirrored to existing theories if available.

In the field of engineering and design, and therefore also for manufacturing and manufacturing operations, the Design Research Methodology (DRM) as suggested by BLESSING & CHAKRABARTI (2009) is one of the most comprehensive and highly detailed research methods available today. The core of DRM is the so-called DRM framework, a four-stage research approach comprising a research clarification, a descriptive study I, a prescriptive study, and a descriptive study II (cf. figure 1.2). BLESSING & CHAKRABARTI (2009) state DRM to overlap with OM research methods especially in the first two stages, i.e., the creation of understanding or building of theory. However, from an engineering perspective, building theory includes understanding, but also improvement of existing models, theory, knowledge, or support. According to GREGOR (2006) and URQUHART et al. (2010), theory can manifest as a "theory for design and action", which would provide theories with a greater scope and, if possible, even "formal concepts".

From an OM perspective, this could also contribute to the call by SCHMENNER et al. (2009) for clever experiments and case studies with a stronger focus on "creativity, insight, and understanding". This understanding of building theory can also be mapped

[9] Note, that the research methodology proposed by the authors originally focuses on business studies, but is often referred to by research conducted on manufacturing and especially manufacturing operations in German scientific literature (cf., e.g., NAU 2012, p. 37, WEMHÖNER 2005, pp. 6-13)

to the general ideas of applied sciences by P. ULRICH & HILL (1976a) and H. ULRICH (1984), which are repeatedly referred to by German publications on manufacturing operations. However, DRM provides a more comprehensive perspective on this topic, considers especially the relation to research methods from, for example, OM, and encourages the integrative application of other methods such as systems thinking[10] and systems engineering[11] (cf., e.g., CHECKLAND 1981, PAHL et al. 2007) or the Soft Systems Methodology (SSM)[12] (e.g., CHECKLAND & SCHOLES 1990). Therefore, DRM has been chosen as the leading research method for this research on MCM. The details on the approach, the consideration of the others (e.g., case study research), and the application for this research are provided in the following section.

1.3.3 Application of DRM and structure of thesis

Guided by DRM, the structure of this research is based on the proposed four iterative stages: research clarification, descriptive study I, prescriptive study, and descriptive study II. Relevant means (e.g., literature, assumptions, empirical data), desired results of each stage (general and MCM-specific), and cross-references to the structure of this thesis, which is organized accordingly, are provided in figure 1.2. The main points for each DRM stage are briefly summarized below.

Research clarification. Based on an extensive literature review, several expert interviews, and a web-based study the motivation and objectives for this research on MCM are specified, the research method is described, research questions are formulated, and requirements towards MCM are derived. The literature study is performed applying a structured keyword sieve as proposed by WEBSTER & WATSON (2002) in

[10] "The discipline for seeing wholes [...] Today we need systems thinking more than ever because we are being overwhelmed by complexity [...] Systems thinking is a discipline for seeing the structures that underlie complex situations." (SENGE 1990, pp. 68-69).

[11] Definition by the International Council on Systems Engineering: Systems engineering is "an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem" (INCOSE 2016)

[12] A method similar to DRM, but as action research focused on on-site evaluation resulting in local solutions. In contrast, DRM focuses on the generation of more generic solutions and evaluation of an initial support in realistic, but not necessarily real situations (BLESSING & CHAKRABARTI 2009, pp. 40-41).

their literature review guideline. The expert interviews are based on semi-structured questionnaires (e.g., FLICK 2010), the web-based study on approaches for the creation of questionnaires and surveys (e.g., BÜHNER 2011, PORST 2011). The derivation of objectives and requirements is guided by methods to analyze and establish these (BLESSING & CHAKRABARTI 2009, p. 278).

Descriptive study I. This stage comprises both a review and meta-analysis of scientific literature on MCM and MCM-related topics (e.g., ECM, factory planning) as well as several case studies on the application of MCM in industrial practice. The results of these analyses create the basis for the development of MCM in the next stage. The review and analysis of literature is guided again by WEBSTER & WATSON (2002) and the concept of research meta-analysis by GLASS (1976). The selection, preparation, and conduction of case studies is based on approaches by YIN (1984), EISENHARDT (1989), VOSS et al. (2002), and EISENHARDT & GRAEBNER (2007).

Prescriptive study. This stage covers the development of the intended MCM support and comprises an MCM context model to generally describe the concept of MCM, an approach to model MCs, and an MCM process including a procedure for the consideration of different MCs. These research activities are guided by methods of systems thinking and systems engineering (e.g, CHECKLAND 1981, PAHL et al. 2007).

Descriptive study II. In the last stage, the MCM support developed is evaluated in industrial practice. Based on the application in three different companies and for exemplary MCs, the developed solutions are assessed and evaluated regarding the effectiveness and efficiency of MCM – i.e., their contribution to companies' agility and overall value. For this purpose, the same case-study approaches as for the descriptive study I are applied.

Where necessary, further details on the applied research methods and approaches are provided in the following chapters and sections of this thesis.

1.3.4 Research environment

In order to substantiate the research environment for this thesis, this section describes the scope, limitations, and adjacent topics of this research and concludes with a brief introduction to the superior research project.

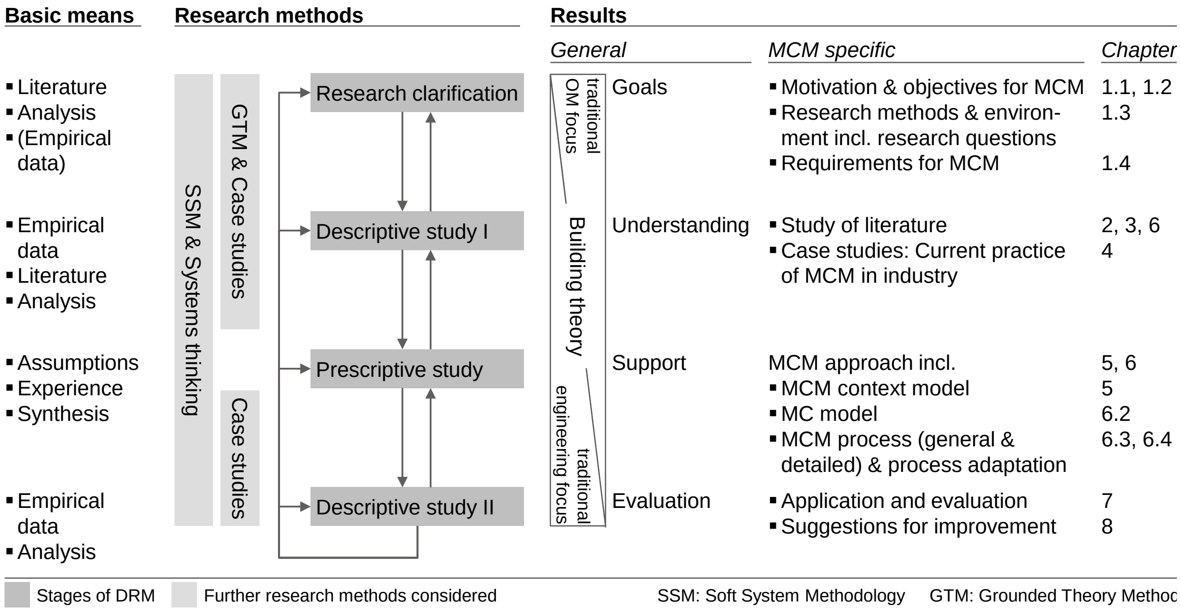

Figure 1.2: DRM framework and related research methods for this research

Scope of research

Given the vast literature and the sheer amount of different topics, concepts, methods, and approaches for change management, manufacturing and factory planning, or changes in manufacturing, just to name a few terms related to the topic of this thesis, the scope of research is limited to facilitate a thorough but focused contribution to a theory of MCM. This includes a general understanding of the concept of MCM, an approach to describe MCs, an MCM process, and a procedure to account for different MCs in MCM. Therefore, the following fields of research and data sources are considered relevant.

Fields of research. First, the focus is on the main subject of this research – MCM – and especially the topics of MCM concepts, processes, and approaches to model MCs. Second, the field of ECM with its various contributions to similar topics in the domain of product development is in focus. Third, approaches for manufacturing and factory planning are addressed, in particular processes or process-oriented ones. This includes contributions to the fields of continuous factory planning and factory planning. In addition, approaches for adaptations of processes as well as suitable methods for modeling, analyzing, and improving MCM are considered relevant for this research. Finally, the concept of agile manufacturing and ideas from concurrent engineering are taken into consideration.

Scientific literature. From a literature perspective, major journals in the fields of manufacturing and production planning, factory or manufacturing systems, OM, change management, engineering design, and systems engineering are in focus. Among others, these include CIRP Annals, CIRP Journal of Manufacturing Science and Technology, Journal of Operations Management, International Journal of Production and Operations Management, International Journal of Production Economics, International Journal or Production Research, Production Engineering – Research and Development, Management Science, Production and Operations Management, Research in Engineering Design, Journal of Engineering Design, Computers in Industry, Systems Engineering, and IEEE Transactions on Engineering Management. Also, proceedings of CIRP, International Conference on Engineering Design (ICED), DESIGN, International DSM Conference, and textbooks are considered. In addition, the widespread German-speaking literature on these topics is in focus, especially wt Werkstattstechnik, Zeitschrift für wirtschaftlichen Fabrikbetrieb, dissertations, and textbooks. Major databases and search engines used include Web of Science™, Scopus®, IEEE Xplore, EBSCOhost™, and Google Scholar™.

Industrial practice. From a practitioners perspective, the following sources of data are in scope of this research: companies from manufacturing industry[13], practitioners / experts in the field of MCM, ECM, factory planning, manufacturing operations, and general managers. Please refer to chapter 4 for a more detailed description of the data sources from industrial practice.

Limitations of research and adjacent topics

This section outlines, which related topics are not in scope of this research and why they are not considered. First, approaches and concepts dealing with changeability, flexibility or related "ilities" are not in focus, as these address (factory) system properties, not "approaches to organizing the system" (BERNARDES & HANNA 2009). However, a short discussion and reference to major publications is provided in section 2.3.3. Second, methods and approaches for change prediction or to model and

[13] These companies can be of any size ranging from a Small and Medium-sized Enterprise (SME) to an international corporation, manufacture products in small, medium or large series, or as projects, and have a location in Germany or within driving distance from TUM to allow for on-site visits.

analyze change propagation are out of scope. These can provide valuable support for users of MCM while processing MCs, but do not influence the development of MCM. Readers interested in change propagation and related topics might refer to, for example, CLARKSON et al. (2004) or PLEHN (2016). Third, the field of Organizational Change Management (OCM) (cf. section 2.2.3) provides tremendous information how to deal with changes affecting the organization and / or culture of a company (e.g., a reorganization, introduction of lean management). As MCM addresses the management of MCs to, for example, the factory system or documentation (cf. section 2.1.3), OCM represents an adjacent topic to this research. Nevertheless, it could provide valuable input to answer the question of how to accompany an MC that is severe enough to also impact teams or even the whole organization. In that case, OCM can add to and accompany MCM. Fourth, the topic of concurrent engineering (cf. section 2.3.5) focuses on accelerating new product development (and manufacturing planning) by parallelizing of activities in the product development process, but does not specifically address the management of changes in manufacturing or engineering. Indeed, certain concepts of concurrent engineering such as parallelization or interdisciplinary exchange of information could be valuable input for developing a theory on MCM. Fifth, project management represents a generalized, broadly practiced approach to manage any type of project. The approach comprises an integrated change control to account for changes occurring to the project. Generally, it can be applied to large MCs, but the project management concept does not consider specific activities dedicated to MCM (cf. section 2.3.5). Sixth, the field of ramp-up management is out of scope for this research, as it rather focuses on production readiness for new product developments, but not on approaches to manage occurring MCs. The same applies for the field of configuration management, relevant in the field of product development and especially software development. Configuration management is related to ECM, as ECM contributes to achieve proper configurations of product versions, but it does not support the development of MCM. Finally, approaches focusing on the digital factory and related, software-oriented methods can provide support for different MCM activities (cf. section 6.3.4; e.g., WESTKÄMPER & BRIEL 2001), but do not contribute to an actual MCM approach.

Superior research project

The research on MCM has been conducted at the Institute for Machine Tools and Industrial Management (iwb), Technische Universität München (TUM), in the context of the Collaborative Research Center (CRC) 768 “Cycle management of innovation processes” and the sub-project “Cycle-oriented planning of changeable production resources”. Several chairs and institutes from TUM and Ludwig-Maximilians-Universität München (LMU) with a focus on engineering, economics, IT, psychology, and sociology make this CRC a highly transdisciplinary research project with more than 15 sub-projects. In engineering, especially the close collaboration with the Chair of Product Development and other sub-projects at the Institute for Machine Tools and Industrial Management (iwb) have been an important contribution to the research at hand.

Further, this research benefited from an international collaboration with Professor Browning from the Neeley School of Business, Texas Christian University, USA, with his experience on Operations Management, methods of structural complexity management, and process design.

Finally, intense cooperations with selected companies from different industries and innumerable practitioners from MCM, ECM, as well as factory and manufacturing planning significantly contributed to this research on MCM.

1.4 Requirements for Manufacturing Change Management

Main objective of this research is to contribute to a company’s agility and overall efficiency by aiding the effectiveness and efficiency of MCM with specific concepts and approaches (see also section 1.2). Both MCM effectiveness and MCM efficiency are further substantiated to provide profound guidance to the intended development of MCM based on proposed methods to analyze objectives and establish requirements (BLESSING & CHAKRABARTI 2009, p. 278).

In a first step during research clarification (cf. section 1.3.3), requirements and main aspects for agility as well as similar or related concepts of MCM proposed in scientific literature (cf. sections 1.3.4 and 3) have been gathered, compared by a meta-analysis, clustered, and consolidated. In total, more than 80 different requirements and aspects have been identified, which were grouped to general MCM requirements. Again, these were further consolidated to categories, which describe different aspects of MCM effectiveness. In the next step during the descriptive study I (cf. section 1.3.3), these categories and requirements have been supplemented and updated with MCM requirements identified in several expert interviews and a web-based survey on MCM (KOCH et al. 2015b).

Overall, six categories related to MCM effectiveness have been identified comprising fourteen general requirements for MCM. In addition, MCM efficiency has been mentioned frequently and is considered as a seventh, additional category for MCM.[14] Table 1.1 shows the results; a list of publications considered is provided in the appendix, table A.2.

The six categories of MCM effectiveness cover general aspects such as *holistic view* and *applicability*, but also more MCM specific topics such as *process orientation*, *proactivity*, *problem solving & analytic capabilities*, and *knowledge management*. Compared to the main capabilities for agility (cf. section 2.3.4), the similarity and general fit of MCM to agility becomes apparent also from a requirements perspective.

Regarding efficiency, two types have to be distinguished: first, an MCM efficiency describing the ability for efficient processing, i.e., to conduct MCM without wasting, for example, resources or time (cf. MERRIAM-WEBSTER 2016); second, an overall company's efficiency in terms of, for example, designing, manufacturing, and selling goods and products – which could also be considered a kind of value of a company. However, situations may arise where a local decrease in efficiency for MCM (e.g., due to more extensive analyses, more alignments and approvals) actually increases a company's overall efficiency and value by avoiding unforeseen changes or change propagation. In this context, efficiency is always related to situations that will actually have never occurred (but could have without applying MCM; cf. also REPENNING & STERMAN 2001). Realizing that, MCM (and also ECM) can be considered as a type of risk insurance for changes – and the efforts to be made strongly depend on the company's business environment and overall situation. In consequence, for this

[14] MCM efficiency has been added as a seventh category, but rather than contributing to MCM effectiveness it constitutes an additional aspect of MCM comparable to MCM effectiveness. Note, that the all requirements also relate to MCM efficiency once implemented in a company.

Table 1.1: Derived categories and general requirements for MCM

Categories: MCM effectiveness	General requirements	Details
Holistic view	Systemic perspective	Modeling of MCM as a holistic system with elements and dependencies, i.e., its content and architecture / hierarchical structure
	Stakeholder involvement & interfaces	Consideration of relevant stakeholders and interfaces for MCM
Applicability	Enterprise-independent applicability	Consideration of characteristics of different industries, approaches, and widespread vocabulary
	Transparency & simplicity	Illustrating and describing the MCM approach in a simple, unambiguous, and intelligible manner
	Clear roles & responsibilities	Provision of relevant roles and their responsibilities for MCM
Process orientation	Defined process architecture	Description and visualization of a general and detailed process architecture
	Coordination & information flow	Description and visualization of information flows and the coordination and responsive behavior of MCM
	Process adaptation	Description and visualization of an MC-specific approach for the adaption of the MCM process
Proactivity	Change identification	Support the early identification of change causes and potential MCs
	Early change evaluation	Foster detailed knowledge about MCs early in the MCM process
Problem solving & analytic capabilities	Cause & impact analysis	Support the analysis of an MC, its change cause, and impact
	Solution finding & implementation	Support the identification, evaluation, and detailed planning of solutions for MCs
Knowledge management	Archiving & tracing of information	Support the archiving and tracing of information on MCM and any MC
	Control of success & lessons learned	Support the evaluation of MCM and any processed MC, lessons learned, and the utilization of information for MCM
MCM efficiency	Efficient processing	Support an efficient application of MCM and an MC-specific process adaptation

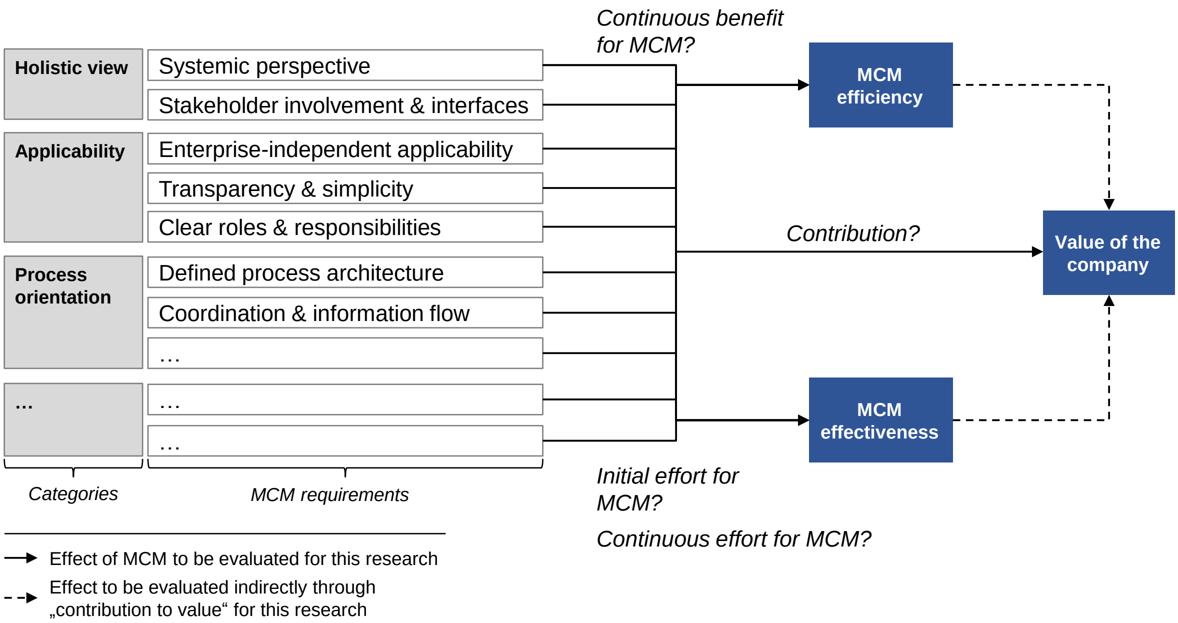

Figure 1.3: Assumed dependencies of MCM requirements to MCM effectiveness, efficiency and a company's overall value

research efficiency of MCM is considered in terms of a best[15] risk insurance. Therefore, a holistic approach and a precise, detailed process for MCM will be developed, which can be adapted to specific changes and business requirements.

The MCM requirements create the basis for the research on MCM. First, they are used to evaluate the state of the art in scientific literature and the current practice of MCM in industry. Second, they guide the development of the MCM approach including, for example, the MCM process design. For this purpose, the requirements are further specified for the MCM approach (see appendix, table A.1) and briefly discussed at the beginning of the respective section of this thesis. Finally, the requirements frame the application and evaluation of the developed MCM approach in three industrial case studies. To evaluate the effect of the MCM approach on MCM effectiveness, efficiency, and the general value of a company, the contribution of the MCM approach to each requirement and category will be estimated in terms of initial efforts, continued efforts, continued benefit, and the contribution to the company's overall value. Figure 1.3 illustrates the assumed dependencies, further details on the MCM evaluation are provided in section 7.1.

[15] I.e., most extensive, but adaptable to the requirements and needs of a company.

2 Fundamentals and Modeling Approaches

This chapter covers the fundamentals and discussion of basic definitions for changes in industrial enterprises, the management of these changes, and related approaches (cf. section 1.3.4) as well as systems, processes, and their modeling. In accordance with the historical emergence of change-related terms and approaches, changes in engineering are introduced prior to changes in manufacturing, followed by organizational changes.

2.1 Changes in industrial enterprises

Fundamentally, change is defined as *"an act or process through which something becomes different"* (OXFORD DICTIONARIES 2016). In industrial enterprises, changes occur on very different levels of observation and are referred to with different terms such as change, modification, adaptation, reconfiguration, or design change of an object. In general, three change objects can be distinguished: product, production (comprising technological or logistical processes and parts of the manufacturing facilities), and business organization (WIENDAHL et al. 2007).[1] The underlying causes for changes of these company-internal change objects can be of very different types (e.g., varying market requirements, introduction of new technologies).[2] This section provides the fundamentals for the relevant types of change and the underlying change causes.

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[1] Within this thesis, the terms production and manufacturing are used interchangeably. The same applies for the related terms factory system, production system, and manufacturing system. Note, that the latter term is also used to describe a single manufacturing resource (cf. C.I.R.P. 2012). A factory system represents "the spatial arrangement, relations, and properties of a 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. 2015).

[2] Note, that in literature these change causes are often also termed as changes companies have to cope with (KOREN et al. 1999, ELMARAGHY 2009, p. v, WESTKÄMPER & ZAHN 2009, p. 9). For this research, terms for the relevant changes and change causes are clearly defined in this chapter.

2.1.1 Causes of change

During the last decades, causes of change received much attention, especially in the context of the complex and dynamically changing environment of industrial enterprises, for which the term "turbulent environment" has been coined (e.g., EMERY & TRIST 1965, WARNECKE 1992, p. 4, CHAKRAVARTHY 1997). Different terms like influencing factors, change drivers, or transformation drivers have been applied to phenomena like increasing product variance, new production technologies, or changing legislative requirements (HERNÁNDEZ MORALES 2002, pp. 157-163, WIENDAHL et al. 2005, p. 9, WULF 2011, pp. 23-36, KLEMKE 2014, pp. 63-66). The impact of the influencing factors and change drivers is considered to manifest in so-called receptors (time, cost, quality, number of units, product, technology; CISEK et al. 2002, MÖLLER 2008, pp. 21-25). These have been described as "change dimensions" by KLEMKE (2014, pp. 35-37), while REINHART et al. (2009a) and REINHART et al. (2009b) describe the latter three as dynamic, cyclic triggers for change and the former three as control variables for management. Overall, the understanding of the different, cause-related terms is rather ambiguous in scientific literature.

In the context of product changes, mainly the two terms – cause and reason – are mentioned (e.g., DALE 1982, PIKOSZ & MALMQVIST 1998, FRICKE et al. 2000). Even though CONRAT (1997, pp. 50-55) argues on a slight difference between these terms, in literature they are most often used interchangeably.

In contrast to the heterogeneous utilization of several terms for causes of change in literature, for this research one distinct term – the change cause – is defined based on the general understanding of a cause as a "[. . .] thing that gives rise to an action, phenomenon, or condition" (OXFORD DICTIONARIES 2016) and the description of change drivers as triggers of impulses for change (ELMARAGHY 2009, p. 8).

A change cause is a fundamental fact / condition that gives rise to a need for change.

2.1.2 Engineering Change (EC)

Changes of products have become an increasingly important topic for industry and consequently gained strong relevance in research within the last decade (JARRATT et al. 2011). Today, Engineering Change (EC) has become the established term for the phenomenon of product changes.

More than thirty years ago, DIN 199 Part 4 described changes of drawings and part lists[3], while other early definitions of ECs included also related "[...] changes of tangible and intangible production factors [...]"[4] (PFLICHT 1989, p. 9) or to production processes (CONRAT 1997, p. 47). A rather general definition of ECs as an "agreed definition of a new instead of the previous state and the associated transformation [of a released configuration]"[5] has been provided by LINDEMANN & REICHWALD (1998, p. 325). More recently, JARRATT et al. (2011) proposed a comprehensive and broadly acknowledged definition, which is based on several, only slightly differing definitions of an EC published by, for example, WRIGHT (1997), TERWIESCH & LOCH (1999), and HUANG & MAK (1999):[6]

An Engineering Change (EC) is an alteration made to parts, drawings, or software that have already been released during the product design process. An EC can be of any size or type, can involve any number of people, and take any length of time.

2.1.3 Manufacturing Change (MC)

Despite the undisputed relevance of change in manufacturing, up to date there is no common understanding or definition of the term Manufacturing Change available in literature or industry. However, change is ubiquitous in manufacturing and referred to with the general term change (e.g., WIENDAHL et al. 2007, AZAB et al. 2013) as well as in form of various synonyms or closely related terms (e.g., modification,

[3] Translated by the author. Original wording: "Zeichnungs- und Stücklistenwesen" DIN 199 Part 4.

[4] Translated by the author. Original wording: "Technische Änderungen sind Veränderungen an den materiellen und immateriellen Produktionsfaktoren [...]" (PFLICHT 1989, p. 9).

[5] Translated by the author. Original wording: "[...] vereinbarte Festlegung eines neuen Zustands anstelle des bisherigen Zustands und die zugehörige Transformation [an einer freigegebenen Konfiguration]." (LINDEMANN & REICHWALD 1998, p. 325).

[6] Note, that HAMRAZ et al. (2013) generalized this definition to account for the broad range of research and publications on ECM. "ECs are changes and / or modifications to released structure (fits, forms and dimensions, surfaces, materials, etc.), behavior (stability, strength, corrosion, etc.), function (speed, performance, efficiency, etc.) or the relations between functions and behavior (design principles), or behavior and structure (physical laws) of a technical artefact". For this research, the more precise EC definition by JARRATT et al. (2011) is referred to.

adaptation, alteration, transformation, reconfiguration; e.g., KLEMKE 2014, pp. 37-39, HERNÁNDEZ MORALES 2002, pp. 43-47, NOFEN 2006, pp. 55-57, DASHCHENKO 2006, pp. 371-373).

HOPFMANN (1989) and REISS et al. (1997) further specify a change by means of three dimensions: effects, potential, and time (HOPFMANN 1989) and width, depth, and duration (REISS et al. 1997) respectively. Based on this, HERNÁNDEZ MORALES (2002, pp. 43-47) developed a differentiation of changes based on system theory: “structure coupling”, describing the change of relations between system elements, and “transformation”, comprising profound changes including new designs of system relations and elements. WIENDAHL et al. (2007) describe changes on different levels of production as a result of proactive and reactive decisions based on model-based change prediction or target-performance comparisons of factory operations. In contrast, AZAB et al. (2013) distinguishes three levels of change depending on the “depth of change”[7]. Furthermore, WESTKÄMPER et al. (2000, p. 23) describe a change as an “alternation of a characteristic of a change object at a specific change location compared to its previous state”[8]. Similarly, KLEMKE (2014, p. 39) defines an adaptation as a “required change of elements in a factory and / or their relations in order to implement an alternative action”[9].

In contrast, RÖSSING (2007, p. 9) uses the term EC for changes in manufacturing and describes an “engineering change in the production” as the “requirements-based modification of design parameters and elements of the production system to changing conditions”[10]. According to this and REINHART et al. (2009a), MALAK et al. (2011) define ECs in manufacturing as the reconfiguration, addition, substitution, and removal of production objects as well as changes to the structure of interrelationships between

[7] The depth of change relates to the necessity of using a system’s flexibility or reconfigurability, or of restructuring the system.

[8] Translated by the author. Original wording: “Allgemein kann eine Veränderung als der Wechsel einer Merkmalsausprägung eines Veränderungsobjekts an einem definierten Veränderungsort im Vergleich zu einem vorherigen Zustand beschrieben werden.” (WESTKÄMPER et al. 2000, p. 23).

[9] Translated by the author. Original wording: “Erforderliche Veränderung der Elemente einer Fabrik und / oder deren Verbindungen zur Umsetzung einer Handlungsalternative.” (KLEMKE 2014, p. 39).

[10] Translated by the author. Original wording: “Technische Änderung in der Produktion”; “[...] anforderungsgerechte Modifikation der Gestaltungsparameter und Elemente des Produktionssystems an sich ändernde Rahmenbedingungen [...]” (RÖSSING 2007, p. 9).

these objects. STANEV et al. (2008) are among the first to explicitly use the term Manufacturing Change, which is also referred to by PROSTEP IVIP E.V. (2015).

Regarding the increasing relevance of changes in manufacturing together with the different prevailing understanding of this term, a definition of the term Manufacturing Change is required. Based on the definitions given above and closely following the definition of an EC, an Manufacturing Change[11] is defined as follows:

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.

2.1.4 Organizational Change (OC)

Besides ECs and MCs, changes of the organization represent the third major type of change occurring in industrial enterprises. According to BURNES (2009), change is an ubiquitous feature of organizations at an operational as well as a strategic level. It can be described as a difference "in how an organization functions, who its members and leaders are, what form it takes, or how it allocates its resources" (G. P. HUBER & GLICK 1993, p. 216). More crisp, QUATTRONE & HOPPER (2001, p. 408) describe an Organizational Change (OC) as when organizations "transform their structure and operations". The general idea of an OC can be further categorized into subsets regarding, for example, planned and emergent changes (BURNES 2005). MORAN & BRIGHTMAN (2001) outline several observations on OCs such as their non-linearity or the importance of a personal dimension. For further details on OCs and more detailed theories please refer to, for example, ARMENAKIS & BEDEIAN (1999), TODNEM BY (2005), or HAYES (2014). It shall be noted that in literature the term Organizational Change is often substituted by the more general term change. For this research, change is considered an umbrella term for the described sub-sets EC, MC, and OC; hence, an OC shall be defined in accordance with the aforementioned definitions.

[11] Note, that in the field of maintenance, DIN EN 13306 and C.I.R.P. (2012, p. 483) define a change (or modification) as the "combination of all technical and administrative measures for changing the function of a unit". In contrast to an Manufacturing Change, a change in maintenance usually describes the re-establishment of a unit's function, not an alteration in general.

An Organizational Change (OC) is an alteration made to the overall structure or the operations of a company. An OC can be of any size or type, it can involve any number of people, and take any length of time.

2.2 Change Management

For industrial enterprises, coping with change demands the management of changes. This includes all types of changes with their different characteristics as described in section 2.1 – and the different approaches available to manage them. In scientific literature, the term change management has been established to describe "an iterative process of assessment, formulation, and implementation of strategic and operational changes [...]" (PETTIGREW & WHIPP 1993), as "the process of continually renewing an organization's direction, structure, and capabilities to see the ever-changing needs of external and internal customers." (MORAN & BRIGHTMAN 2001, p. 111), or similarly as "all measures, which are required to initiate and implement new strategies, structures, systems, and behaviors" (GATTERMEYER & AL-ANI 2001, p. 14). Following this understanding, change management is used as the collective term for more specific change management approaches, i.e., especially Engineering Change Management, Manufacturing Change Management, and Organizational Change Management.[12]

2.2.1 Engineering Change Management (ECM)

For the term Engineering Change Management (ECM), various but similar definitions can be found in literature. LINDEMANN & REICHWALD (1998) define ECM as the "totality of measures to avoid and specifically frontload as well as efficiently plan, select, process and control product changes"[13]. Following HUANG & MAK (1999), "ECM usually includes four stages, namely, identifying, evaluating, implementing, and

[12] Note, that most publications available in the field of management science do not consider the management of changes in technical system and therefore use "change management" synonymously for the more specific approach of Organizational Change Management (cf., e.g., TODNEM BY 2005, BURNES 2009, AL-HADDAD & KOTNOUR 2015).

[13] Translated by the author. Original wording: "Gesamtheit aller Maßnahmen zur Vermeidung sowie zur gezielten Vorverlagerung und effizienten Planung, Auswahl, Bearbeitung und Regelung von Produktänderungen." (LINDEMANN & REICHWALD 1998, p. 327).

auditing ECs", while ROUIBAH & CASKEY (2003) define ECM as "[...] the process of making ECs to a product in a planned or systematic fashion." Besides further definitions, more recently JARRATT et al. (2011) stated that "Engineering Change refers to making alterations to a product and Engineering Change Management to the organising and controlling of this process".

Generally, the definitions share the following foci, which create the core of ECM: ECs, process-orientation, and measures / activities like planning or controlling. Based on this and closely following LINDEMANN & REICHWALD (1998) as well as JARRATT et al. (2011), for this thesis ECM is defined as follows:

Engineering Change Management (ECM) refers to organizing and controlling the process of making alterations to a product. This includes the totality of measures to avoid and specifically front-load as well as efficiently plan, select, process, and control Engineering Changes.

2.2.2 Manufacturing Change Management (MCM)

Up to date, no distinct term for the management of changes in manufacturing has been defined in literature. The few authors dealing with this research topic usually refer to the ECM terminology and transfer it to the domain of manufacturing. For example, AURICH et al. (2004, p. 381) describe a "[...] structured approach to identify, realize and revise changes of production processes"[14], which is based on ECM. Building up on this, RÖSSING (2007, p. 38) proposes a procedure to support "the initiation, realization and post-processing of engineering change in production"[15]. Other authors like MALAK (2013) or AURICH & CICHOS (2014) follow up on this understanding. As one of the first, PROSTEP IVIP E.V. (2014) introduce the term Manufacturing Change Management (MCM) based on the example of ECM, but do not provide a definition of the term or a comparison to related terms in scientific literature. In

[14] Translated by the author. Original wording: "[...] strukturiertes Vorgehen, um gezielt Änderungen an Produktionsprozessen zu identifizieren, umzusetzen und nachzubereiten" (AURICH et al. 2004, p. 381).

[15] Translated by the author. Original wording: "[...] Initialisierung, Durchführung und Nachbereitung technischer Änderungen in der Produktion [...]" (RÖSSING 2007, p. 38).

their subsequent publication, ProSTEP iViP e.V. (2015) describe MCM as the "information management between planning and production".

Recognizing a general similarity between MCM and ECM, the proposed definition of MCM closely follows the understanding of ECM, but accounts for the different object of observation (factory instead of product). In general, the focus of MCM is rather on a factory in operation than on new factory planning; nevertheless, it may be applied to both scenarios.

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.

2.2.3 Organizational Change Management (OCM)

Taking the synonymous usage of the term change management and OCM in literature into account, the aforementioned definition by Gattermeyer & Al-Ani (2001) is further substantiated based on, for example, Todnem By (2005), Burnes (2009), Lauer (2014), and Al-Haddad & Kotnour (2015). The proposed definition of OCM is now differentiated from the collective term change management and comparable to the definitions of ECM and MCM.[16]

Organizational Change Management (OCM) comprises all measures, which are required to initiate, adapt, and implement new strategies, structures, organizational systems, behaviors and capabilities in a company.

2.3 Related concepts and terms

Beyond the management of changes in manufacturing, planning of factories is one of the major fields of research in engineering science. Two main terms have to be distinguished: Factory planning denotes the basic activities to "decide on and make

[16] Note, that also sequences of actions have been developed to guide companies and managers on how to cope with OCs (e.g., Kotter 1995, Luecke 2003).

arrangements for in advance" (OXFORD DICTIONARIES 2016) regarding a factory, while continuous factory planning describes factory planning activities concurrent to factory operations. In addition, further relevant terms like changeability together with its sub-sets such as flexibility or reconfigurability are briefly explained.

2.3.1 Factory planning

VDI 5200 defines the term factory planning as a *"Systematic, objective-oriented process for planning a factory, structured into a sequence of phases, each of which is dependent on the preceding phase, and makes use of particular methods and tools, and extending from the setting of objectives to the start of production."*. Further definitions are provided by, for example, KETTNER et al. (1984, p. 3), AGGTELEKY (1987, p. 26), or SCHMIGALLA (1995, p. 71), sharing the understanding of the concept of an objective-oriented, structured, and methodological planning and designing of factories. According to this, factory planning is a process-oriented approach with the same object of observation as MCM (i.e., the factory), but focuses on the planning of factories (and changes) rather than the management of MCs. For this thesis, the broadly acknowledged definition of factory planning in the VDI 5200 is referred to.

2.3.2 Continuous factory planning

The term continuous factory planning (or synonymously continuous planning, continuous production planning, or continuous manufacturing planning) denotes the idea of applying the control loop concept in factory planning. While FELIX (1998) describes factory planning as a control loop, DASHCHENKO (2006, pp. 376-377) further specify that "the adoption of structures can be seen as a permanent configuration process [...] thus, continuous planning is not only necessary in production planning and control at commission level, but also in the planning of new and adapted production systems, in performance units and in the factories and networks themselves". The other publications on continuous factory planning share this understanding of the application of the control loop concept to factory planning, but do neither provide further detailed definitions nor consider activities for the management of MCs (cf., for example, CISEK 2005, NOFEN 2006; cf. also section 3.3.4). Based on this, the following definition is proposed for this thesis:

Continuous factory planning describes the concurrent, control loop-based application of factory planning approaches during factory operations.

2.3.3 Changeability

Nowadays, changeability is broadly recognized as an umbrella term for more specific system properties often referred to as "ilities": for example, flexibility, transformability, adaptability, or reconfigurability (e.g., FRICKE & SCHULZ 2005, WIENDAHL et al. 2007, ROSS et al. 2008, RYAN et al. 2013). Among these, especially the concept of manufacturing flexibility has been extensively investigated by, for example, UPTON (1995) and TONI & TONCHIA (1998). In German-speaking literature, the term "Wandlungsfähigkeit" (transformability) has been emphasized in addition to flexibility (e.g., REINHART & HOFFMANN 2000, HERNÁNDEZ MORALES 2002, ZÄH et al. 2005, WIENDAHL et al. 2007). Appropriate sources for the other properties mentioned are, among others, BORDOLOI et al. (1999) and KATAYAMA & BENNETT (1999) for the term adaptability, KOREN et al. (1999), DASHCHENKO (2006), and ELMARAGHY (2009) for the term reconfigurability.

In line with BERNARDES & HANNA (2009), who defined flexibility as "an inherent system property", changeability also describes an inherent system property, which differentiates it from the term agility, an "approach to organizing a system" (BERNARDES & HANNA 2009, cf. also section 2.3.4). Hence, changeability can be considered an enabler for MCM, but not an alternative. For this research, the definition proposed by PLEHN et al. (2016b) is followed, who conducted an extensive literature review on this topic:

"*Changeability. 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).*"

2.3.4 Agility and agile manufacturing

In 1995, HOPP & SPEARMAN (1995) published the famous and ground-breaking book "Factory physics", where the authors proposed the "science of manufacturing". As part of this evolving theory, they described agility (or agile manufacturing) as "the plant's ability to rapidly reconfigure a manufacturing system for efficient production of new products as they are introduced". In the following years, agility has been subject to extensive scientific discussions (cf., for example, GOLDMAN et al. 1995, GUNASEKARAN 1999, S. MEREDITH & FRANCIS 2000). Following DOVE (1994) and KIDD (1994), SHARIFI & ZHANG (2001) state agility to comprise two factors:

– "Responding to changes (anticipated or unexpected) in proper ways and due time."

– "Exploiting changes and taking advantage of changes as opportunities."

Further concretizing the concept of agility, ZHANG & SHARIFI (2007) propose main capabilities for agility based on a broad literature review. In addition to responsiveness and flexibility (as a subset of changeability, see section 2.3.3), these comprise proactiveness, competency, quickness, focusing the customer, and partnership; all of them addressing a companies' competitiveness.

Years later, BERNARDES & HANNA (2009) published a broadly acknowledged review of available definitions of agility and the relation to flexibility and responsiveness. Summarizing the scientific discourse, they define agility as the "*ability of the system to rapidly reconfigure (with a new parameter set)*" and propose agility to be "*the ready ability to fundamentally change states to accommodate unforeseen circumstances in a timely manner*", i.e., an "*approach to organizing the system*". In contrast, flexibility states an "inherent system property" (cf. also section 2.3.3), while responsiveness describes a "system behavior or outcome". For this thesis, the understanding of agility proposed by BERNARDES & HANNA (2009) is referred to.

2.3.5 Further related concepts and terms

The following concepts and terms represent topics adjacent to MCM, which contribute to a further clarification of the overall concept of MCM.

Concurrent engineering. According to WINNER et al. (1988), "*Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacturing and support. [...]*". In line with this definition, subsequent publications on concurrent engineering also emphasized the early integration of relevant functions, the creation of interdisciplinary teams, the exchange and simultaneous consideration of required knowledge and information, and the parallelization of activities during product development (cf. the extensive literature review on concurrent engineering by TENKORANG 2011). Note, that the term simultaneous engineering is often used synonymously for the concept of concurrent engineering (cf. e.g., SOHLENIUS 1992).

Project management. Project management has always been applied and practiced, but became a distinct, well-understood and standardized profession (e.g., PMI 2000, DIN 69901-5, ISO 21500:2012). It is defined as "*the application of knowledge, skills, tools, and techniques to project activities to meet the project requirements*" (PMI 2000, p. 205).[17] The project management reference process comprises the phases initiating, planning, executing, monitoring and controlling, and closing. Changes are considered a relevant part of projects and to be accounted for during project management. Vice versa, project management can also be applied to manage large changes, which are supposed to be handled as a project (e.g., section 4.2.1).(PMI 2000, pp. 4-36)

2.4 Systems and processes

This section provides an introduction to systems, their contexts, and processes.

2.4.1 Systems

The term system is broadly used in common parlance and literature. A system is ...

– ... *"a regularly interacting or interdependent group of items forming a unified whole" or "an organized or established procedure"* (MERRIAM-WEBSTER 2016)

– ... *"the model of an entirety with a) relationships between attributes (inputs, outputs, states, etc.), b) interlinked parts or subsystems, and c) delimited by its surroundings or a super system."*[18] (ROPOHL 2009, p. 77).

[17] In German, project management is defined in line with this definition as "Gesamtheit von Führungsaufgaben, -organisation, -techniken und -mitteln für die Initiierung, Definition, Planung, Steuerung und den Abschluss von Projekten" (DIN 69901-5, p. 14).

[18] Translated by the author. Original wording: "Ein System ist das Modell einer Ganzheit, die (a) Beziehungen zwischen Attributen (Inputs, Outputs, Zustände etc.) aufweist, die (b) aus miteinander verknüpften Teilen bzw. Subsystemen besteht, und die (c) von ihrer Umgebung bzw. von einem Supersystem abgegrenzt wird." (ROPOHL 2009, p. 77).

In line with these general definitions, comprehensive explanations of systems in engineering science have been proposed by, for example, PATZAK (1982), SHISHKO & ASTER (1995), DAENZER & F. HUBER (1997), PAHL et al. (2007), and LINDEMANN (2009). Briefly summarizing, the authors describe systems to consist of interrelated elements, which again can be systems themselves (i.e., sub-systems). The relations determine the structure of the overall system, which is demarcated to its environment (the super-system) by a system boundary.

In engineering, nowadays most systems can be considered complex systems (LINDEMANN et al. 2009, p. 3). Following the definition by SAGE & ROUSE (2009, p. 388), complex systems are characterized by "system architectures that cannot be resolved into combinations of parallel and series configurations." According to BROWNING (2009, p. 70), complex systems are systems, "which are impossible to describe and understand completely from a single point of view." The complexity of these systems generally arises from the number of elements, dependencies, and variants (LINDEMANN et al. 2009, p. 29). Further detailed descriptions and definitions of complexity as an attribute of systems have been proposed by, for example, C. WEBER (2005) and LINDEMANN et al. (2009).

In the domain of manufacturing, KOREN et al. (1999), HERNÁNDEZ MORALES (2002), WIENDAHL et al. (2007), MANNS et al. (2008), and many others follow up on systems thinking investigating, for example, factory systems, manufacturing systems, and assembly systems. Taking a more general perspective on manufacturing, for example WESTKÄMPER & ZAHN (2009) and VDI 2870 focus on so-called lean or holistic production systems. Besides these technical systems, also organizations and processes can be considered systems or even complex systems (BROWNING et al. 2006); in combination with technical systems those create socio-technical systems (ROPOHL 2009).

2.4.2 Context

The environment any system operates or shall operate in can be called the context of this particular system (OLIVER et al. 1997, pp. 44-49). In general, this term can also be described as "the interrelated conditions in which something exists or occurs" (MERRIAM-WEBSTER 2016), or similarly as "the circumstances that form the setting for an event, statement, or idea, and in terms of which it can be fully understood”[19] (OXFORD DICTIONARIES 2016). From an IT perspective, a context model can be described as a common formal environment with a semantic foundation, which supports a better understanding and comparison of models and theories (GEBHARDT & KRUSE 1993). Even though being highly formal, this description is also seen to be in accordance with the aforementioned definitions.

2.4.3 Processes

The term process describes “a series of actions or steps taken in order to achieve a particular end” (OXFORD DICTIONARIES 2016). In accordance with this understanding, DIN EN ISO 9000 defines that “*Any activity, or set of activities, that uses resources to transform inputs to outputs can be considered as a process*”. Similarly, DAVENPORT (1993) defines a process as “*a specific ordering of work activities across time and place, with a beginning, an end, and clearly identified inputs and outputs*”. In line with these, other available definitions emphasize the set of relations of activities that form a process: A process is “*an organized group of related activities that work together to create a result of value*” (HAMMER 2001) or “*a network of customer-supplier activities to produce results of value*” (PALL 1999).

For any process, usually different versions exist or tend to be created depending on a given situation (HAMMER & CHAMPY 1993, p. 55). In this context, good processes are characterized by their capability of being tailorable (DAVENPORT 1993, p. 77). Beyond the very similar definitions of a process, subsets of this term have been proposed. One often emphasized is the term business process, which will be elaborated on in the following.

Business process

Very similar to the definitions of the term process, a business process is defined as “*a collection of activities whose final aim is the production of a specific output*

[19] While this description does not explicitly mention the term system, however, from a more abstract perspective an event or idea can also be a system or object.

that is of value to the customer. A business process has a goal and is affected by events occurring in the external world or in other processes" (HAMMER & CHAMPY 1993, p. 85), or "*as a set of logically related tasks performed to achieve a defined business outcome*" (DAVENPORT & SHORT 1990). Further similar definitions have been proposed by different authors, which ALDIN & DE CESARE (2011) summarize in their comprehensive literature review on business process modeling. Even though some authors seem to take the terms process and business process synonymously, AGUILAR-SAVEN (2004) proposes a precise distinction, which is followed by the research at hand: "*a business process is related to enterprises, as they define the way in which the goals of the enterprise are achieved and thus they are a subset of the set of processes*". HAMMER & CHAMPY (1993, p. 2) also note that a "business process only works if it generates added value, not internal activity", which relates to the proposed evaluation of the effect of MCM as described in section 1.4.

In addition to the distinction between a general process and a business process, the latter can be further distinguished into a set of rather sequential, more rigid business processes and a set of rather network-like, iterative business processes (BROWNING et al. 2006). For the latter, well-known examples are the product development process and the subordinate design process; examples for the former can be order processing, purchasing, or manufacturing processes. In this context, CLARKSON & ECKERT (2005, p. 64) point out that "design processes seek to do something novel, once, whereas many other business processes seek to do the same thing repetitively". In the following, the specifics of network-like, iterative business processes will be further elaborated on based on the exemplary product development process and change processes, which are of particular importance for this research.

Product development process

A product development process is "*the sequence of steps or activities which an enterprise employs to conceive, design, and commercialize a product*" (K. T. ULRICH & EPPINGER 2003, p. 12). It can be thought of in three ways: the creation of product concepts including the narrowing of alternative solutions until actual production of the product, an information processing system (cf. also CLARK et al. 1987), and a risk management system (K. T. ULRICH & EPPINGER 2003, p. 13). Typically, product development involves creativity and innovation, is nonlinear and iterative (KLINE

1985). That causes product development processes to rather form an activity network than a linear process (BROWNING & RAMASESH 2007). These are highly iterative (e.g., ULLMAN 2010, p. 117, UNGER & EPPINGER 2009) and "seek to do something new, once" (BROWNING et al. 2006, p. 114).[20]

A main part of each product development process is the (engineering) design process for the "organization and management of people and the information they develop in the evolution of a product" (ULLMAN 2010, p. 8). It represents a network of highly complex, socio-technical activities performed with the goal of producing design (CLARKSON & ECKERT 2005, pp. 46,62). A detailed version of a design process is provided by VDI 2221 (see figure 2.1); the interaction with the product development process has been visualized by, for example, HALES & GOOCH (2004, p. 28). Overall, both processes are very similar in terms of process characteristics and can be understood as complex, highly iterative activity networks seeking to create something novel.

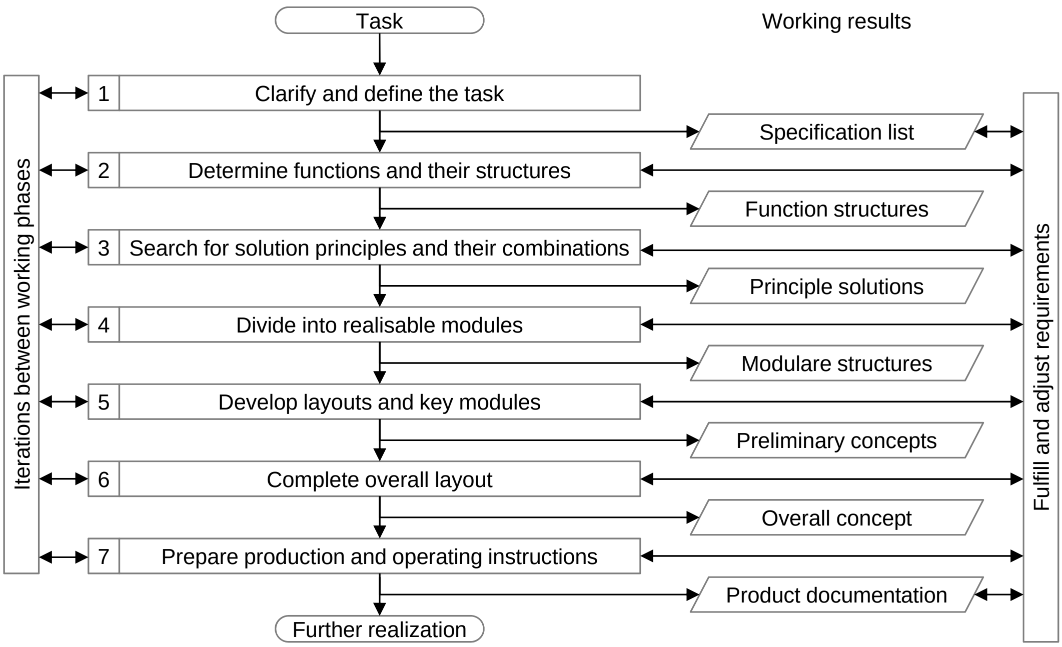

Figure 2.1: Design process (VDI 2221, p. 9)

[20] For a representative example of a product development process please refer to PAHL et al. (2007).

ECM process

Despite the amount of scientific literature available on ECM, only few distinct descriptions of the ECM process have been proposed. One of the most concise descriptions has been suggested by LEECH & TURNER (1985), who state a change process to be "a mini, highly constrained design process or project" (CLARKSON & ECKERT 2005, p. 270); and according to DIN EN ISO 9000, a project is in turn "a unique process". Vice versa, FRICKE et al. (2000) argue that "the entire product development process can be described as a continuous change management process". According to BROWNING et al. (2006) and BROWNING & RAMASESH (2007), such processes are typically modeled as activity networks. Following JARRATT et al. (2011), the terms EC and interchangeably ECM refer to the organizing and controlling of the process of conducting ECs. Similarly, but rather general, VDA (2010a, p. 5) defines an ECM reference process as "the overall reference process as it relates to ECM. The ECM process comprises several ECM Reference Sub-Processes". Based on these and aforementioned definitions and descriptions of processes and product development processes, the term ECM process is defined as follows. Examples for ECM processes are provided in section 3.3.1.

An ECM process is the network of activities performed with the goal of managing Engineering Changes.

MCM process

Up to date, the term MCM process has been seldomly referred to in scientific literature. Closely following process models for ECs, AURICH et al. (2004, p. 382) and RÖSSING (2007, pp. IV-V) interpret an MCM process as being separated into three phases – initialization, realization, and post processing – each covering specific activities. This creates the basis for a systematic processing of MCs (RÖSSING 2007, p. 14). More recently, PROSTEP IVIP E.V. (2015, p. 2) describe a reference process for MCM as "a reference sequence of steps for managing the changes between planning and the shop floor".

Regarding the general similarity between MCM and ECM described before (cf. section 2.2.2), the proposed definition of the term MCM process is based on the ECM process definition and accounts for the available descriptions of this process. The MCM processes available in literature are discussed in section 3.3.2.

An MCM process is the network of activities performed with the goal of managing Manufacturing Changes.

2.5 Modeling of systems and processes

A model is "an abstract representation of reality that is build, verified, analyzed, and manipulated to increase understanding of that reality" (BROWNING et al. 2006, p. 105). It can be either a mental or a codified model, and it can be a descriptive or a prescriptive model (HAZELRIGG 1999, BROWNING et al. 2006). Also, models can be distinguished in explanation and simulation models (for experiments; VDI 3633). However, "all models are wrong, but some are useful", as any system existing in the real world cannot be exactly represented by any simple model (BOX 1979, p. 2). Hence, modeling of systems, processes, and also their respective context aims at creating useful models, for example in terms of describing complex phenomena in industrial practice, testing assumptions and measures, or guiding activities and procedures.

2.5.1 Modeling of systems and their context

Different approaches have been developed to model systems. In general, a system can be modeled using, for example, a block diagram, spreadsheets, deterministic approaches, or different languages (e.g., mathematical, software, or graphical languages) (RECHTIN 1991, pp. 78-80). According to DAENZER & F. HUBER (1997) and DE WECK et al. (2011), especially matrix- and graph-based approaches have been recognized being beneficial for modeling especially the structure or architecture[21] of a system. Also, structured modeling frameworks (or languages) such as the Unified Modeling Language (UML), Systems Modeling Language (and other related, object-oriented languages) are commonly used to model systems. Despite their general capability of modeling also process systems (AGUILAR-SAVEN 2004),

[21] Architecture usually refers to a hierarchical structure, hence a specific type of structure (cf. also LINDEMANN et al. 2009, p. 8).

they are almost exclusively used to model, for example, software systems or product system functionality and behavior (BROWNING et al. 2006).

In contrast, matrix- and graph-based approaches are considered highly beneficial for process systems, as these are very likely to be complex systems (BROWNING 2001). Regarding matrix-based approaches, in recent years, Design Structure Matrix (DSM), Domain Mapping Matrix (DMM), and Multiple-Domain Matrix (MDM) became broadly used modeling frameworks for systems in various research areas (BROWNING 2015). Regarding graph-based approaches, many different languages and approaches such as IDEF[22] or Colored Petri-net (CPN) are available with differing characteristics and advantages. For comprehensive reviews and compilations of relevant modeling approaches, the interested reader may refer to, for example, AGUILAR-SAVEN (2004) or BROWNING et al. (2006).

OLIVER et al. (1997, pp. 11-49) emphasize the benefit of carefully considering and modeling also the context of any system in focus to account for relevant influences and interactions between the system and its context. In line with this, BROWNING et al. (2006) and NEGELE & WENZEL (2000) discuss the advantage of modeling systems together with related systems – i.e., its context – to aid their design, verification, and management. The modeling approaches are generally congruent with the aforementioned approaches for system modeling.

2.5.2 Modeling of processes

Process models provide the basis not only for planning and managing of activities or projects, but also for codifying and communicating organizational knowledge about required work and related procedures. In addition, process models support companies to comply with internal and external standards such as the DIN EN ISO 9000 series regarding process documentation.(BROWNING et al. 2006)

For this purpose, a tremendous variety of approaches to create process models – so-called modeling frameworks – have been developed (BROWNING et al. 2006). Among others, Supplier-Input-Process-Output-Customer (SIPOC), phase / stage-based

[22] ICAM Definition for Function Modeling, where ICAM is an acronym for Integrated Computer Aided Manufacturing.

models, activity networks, IDEF, extended Event-driven Process Chain (eEPC), and also DSM shall be mentioned. Several comprehensive reviews of those modeling frameworks are available by, for example, SMITH & MORROW (1999), AGUILAR-SAVEN (2004), O'DONOVAN et al. (2005), BROWNING et al. (2006), and ALDIN & DE CESARE (2011). Another, rather novel but already prevalent modeling approach is the Business Process Model and Notation (BPMN), which is promoted, maintained, and improved by the independent Object Management Group (OMG) since 2006 and is freely accessible (CHINOSI & TROMBETTA 2012, ALLWEYER 2015).

BROWNING et al. (2006) further distinguish between, for example, descriptive[23] and prescriptive[24] process models. According to BROWNING et al. (2006) and BROWNING (2009), many different and partially overlapping "views" on a process are created by these process models, which in turn leads to data inconsistency and missing synchronicity. For this reason, the Process Architecture Framework (PAF) has been developed to create a single, rich process model as a basis for the derivation of different process views (cf. BROWNING 2009, BROWNING 2014). For further details and the reasoned selection of the modeling approaches for this research please refer to the following sections.

2.5.3 Selection of modeling approaches

Following the approach of systems thinking and systems engineering (cf. section 1.3.3), appropriate approaches are required to design an MCM with respect to the derived requirements (see section 1.4). According to the main objective of this research – designing an MCM concept with an MCM process, which enables practitioners to manage MCs efficiently and effectively – and the derived definitions of ECM, MCM, and related concepts a potential complexity of both MCM in general and an MCM process in particular is to be accounted for. To model these, matrix- and graph-based approaches have been chosen, as they proofed their suitability to model

[23] "A descriptive process model attempts to capture tacit knowledge about how work is really done. It tries to describe key features of the 'as is' reality. It is built inductively." (BROWNING et al. 2006).

[24] "a prescriptive process model tells people what work to do and perhaps also how to do it. It is built deductively, perhaps drawing from an external standard and/or documentation from other projects. A prescriptive process is a standard process or procedure accompanied by a mandate to follow it exactly." (BROWNING et al. 2006, p. 115).

complex systems and processes in a flexible, precise, and illustrative manner (cf., e.g., EPPINGER & BROWNING 2012, BROWNING 2015).[25] Regarding matrix-based approaches, especially DSM, DMM, and MDM – sometimes also referred to as methods of structural complexity management (cf. LINDEMANN et al. 2009) – enable a uniform and consistent modeling of different domains (e.g., process, factory, MC) with varying levels of abstraction (e.g., a detailed MCM process vs. a general MCM concept).

Graph-based approaches create models of systems equivalent to the matrix-based approaches (DE WECK et al. 2011), but can provide additional value, for example, in terms of visualization or architectural properties (PEKTAS 2010). Among others, AGUILAR-SAVEN (2004), BROWNING (2009), and BROWNING (2010) conduct comprehensive reviews of the numerous approaches available.[26] As BPMN has been released afterwards, for this research the modeling framework has been evaluated with the approach conducted by BROWNING (2010) and compared with their results. It was found to rank among the top five approaches offering several advantages compared to the other four: (a) it is a standardized approach (in contrast to, e.g., eEPC); (b) it includes also roles, organization, and data elements (in contrast to, e.g., SIPOC); (c) it visualizes not only the relations, but also sequences of activities (in contrast to, e.g., IDEF0). Both the evaluation and its high prevalence for modeling processes make BPMN the preferred graph-based modeling approach for this research.

Another important aspect for modeling an MCM process – and processes in general – is the need to generate different views on a process depending on the user and purpose (BROWNING 2009). As most process modeling approaches mainly create specific views only[27], the PAF has been selected to create an extensive model of the MCM process.

In addition to these approaches, also the stage-gate approach by COOPER (1990) has been selected for this research. In contrast to DSM or PAF enabling highly detailed

[25] Note, that object-oriented approaches have been optimized to model, for example, software or product systems, but not processes.

[26] Note: These comprise mostly, but not exclusively, graph-based approaches. BROWNING et al. (2006) describe them as “process modeling frameworks”.

[27] For example, a DSM creates a specific view on the process architecture, BPMN on the process sequence.

models, it is considered to support a high-level structuring and visualization of complex processes. Finally, non-formalized graphical and textual approaches are supplemented where needed.

2.5.4 Modeling approaches for MCM

The four main modeling approaches selected for this research are described in the following sections. If required, these generally powerful approaches are configured for the application on MCM. Non-formalized graphical and textual approaches are considered common knowledge and not further described.

Stage-Gate

The concept of a stage-gate system has been proposed by COOPER (1990) to support the management of the innovation process in industrial practice. This approach divides a process in several stages and gates. Stages comprise the activities relevant to the process, i.e., "where the work is done" (COOPER 1990, p. 46), gates comprise a set of deliverables, the outcomes or results of the activities. The gates fulfill a review function and ensure a sufficient level of quality by typically involving a team or committee of senior managers ("gatekeepers", COOPER 1990, p. 46). The stage-gate approach fosters process structure and quality of results in processes; however, ROSENTHAL (1992), TATIKONDA & ROSENTHAL (2000), and others note the risk of over-formality, inefficiency by the focus on reviews, and hampered flexibility. In more recent versions of the stage-gate approach, these concerns have been addressed by encouraging, for example, iterative and parallel activities in stages, optional reviews, and increased cross-functionality at gates (e.g., COOPER 1994, COOPER 2008).

Process Architecture Framework (PAF)

The PAF is a comprehensive framework to model processes, which are subdivided into activities and deliverables (BROWNING et al. 2006, BROWNING 2009, BROWNING 2014). It can be considered as a matrix-based approach with large textual components. These components capture the numerous attributes to describe activities and deliverables – for example "name", "brief description", "input", "output", "format", or "medium". In total, about 26 attributes for deliverables and 32 for activities have been identified by the authors and described in BROWNING (2009). For this research, eight attributes for deliverables and twelve for activities have been identified most relevant to model the MCM process. The remaining attributes have been excluded because they are considered either company-specific, focused on the development of an IT-tool supporting the process, or unnecessary for an initial process design. Details about the attributes and reasons for their selection / exclusion are provided in the appendix, tables A.4 and A.5. Table 2.1 illustrates an excerpt of the PAF as applied within this research to model the MCM process.

Table 2.1: Illustration of an excerpt of a PAF model – activities and deliverables

Name	**Description**	**Parent**	**Mode**	**Deployment**	**...**
a1.1 "Activity x"	"Content of activity"	Stage s1	standard	tailorable	...
a1.2 "..."	...	Stage s1	...	...	...
...	...	...	...	...	...
d1.1 "Deliverable y"	"Content of deliverable"	Gate g1	standard	...	...
...	...	...	...	...	...

Design Structure Matrix (DSM), Domain Mapping Matrix (DMM), and Multiple-Domain Matrix (MDM)

The three matrix-based approaches DSM, DMM, and MDM have become very common methods in science and practice providing simplicity, conciseness, accuracy, and enabling specific analyses (BROWNING 2015). For DSM, three types of matrices are most common: product DSMs modeling the relations between components, organization DSMs visualizing, for example, dependencies between persons and functions, and process DSMs describing, for example, dependencies between activities or the information flow (BROWNING 2001, EPPINGER & BROWNING 2012). A DSM always represents the subset of one single domain (e.g., process activities). To model two domains in one matrix, a DMM is used (e.g., process activities vs. roles), while an MDM is applied to model at least two domains as well as the associated subsets of

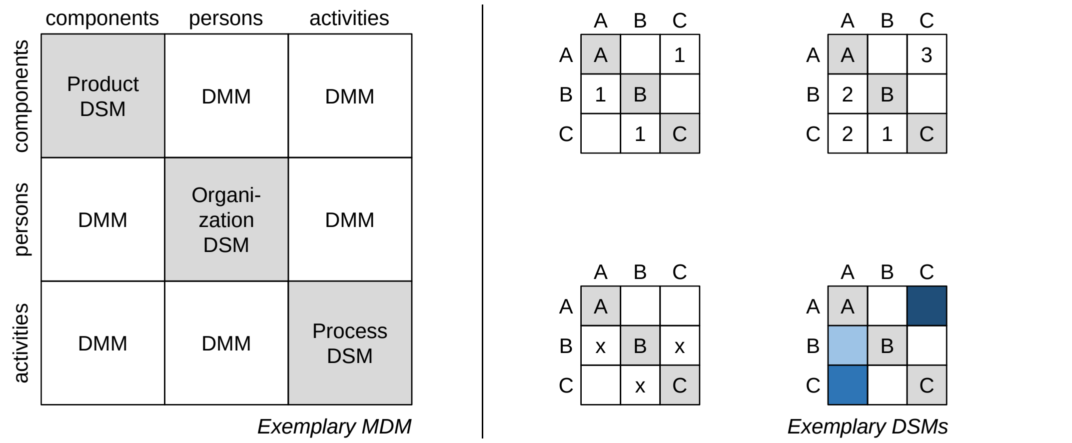

Figure 2.2: Exemplary MDM with its subsets of DMMs and DSMs (left side); exemplary DSM with different codings (right side) (based on EPPINGER & BROWNING *2012, p. 5)*

DSMs and DMMs (LINDEMANN 2009; see figure 2.2). Regardless of the type of matrix used, two main conventions on how to read them have to be distinguished:

IR / FAD: Input in Rows / Feedback Above Diagonal
IC / FBD: Input in Columns / Feedback Below Diagonal

For this research, the convention IC / FBD is used, as it is assumed to provide a more convenient orientation while reading the matrices. Also, it shows similarity to common Gantt charts and IDEF models.

DSM. Created by *n x n* corresponding entries (*n* columns *x n* rows), a DSM is always a square matrix. It is usually coded using numbers, symbols, color shading, or a combination of these to model relations between the entries, which are either static or time-based dependencies (see figure 2.2; BROWNING 2001). For this research, all three types of coding are applied depending on the respective relations (cf. section 6.3.3).

Any DSM can be transformed into a graph-based representation and vice-versa. Therefore, five basic transformation rules are available, which are briefly described in figure 2.3. Beyond, DSM is a highly beneficial method when it comes to process design and analysis. For example, it can be used to minimize iterations and feedback loops in processes, to develop in-depth know-how about input-output relations, or visualize the detailed process structure (cf. EPPINGER & BROWNING 2012, p. 136). There are two main methods necessary: sequencing and clustering.

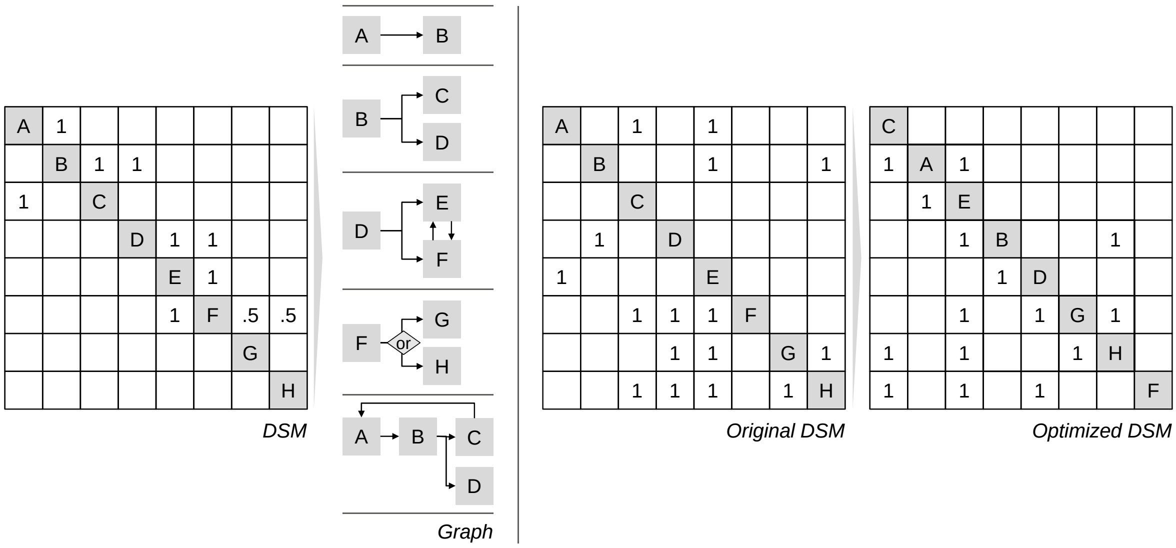

Figure 2.3: Exemplary transformation of a DSM to a graph-based representation (left side); effect of sequencing and clustering on a DSM (right side; both based on EPPINGER & BROWNING *2012, pp. 134, 142)*

To sequence a DSM, columns and rows are swapped to minimize the distance of dependencies to the matrix diagonal, as well as the number of iterations and feedback loops (dependencies below the diagonal[28]). To cluster a DSM, relations are intended to be consolidated in blocks (or clusters) close to the matrix diagonal, while minimizing inter-cluster relations. Based on early publications on DSM by, for example, STEWARD (1981) and GEBALA & EPPINGER (1991), several optimization algorithms have been offered that are useful especially for large and complex matrices. However, for the matrices and amount of dependencies dealt with in this research, visual inspection and manipulation is considered sufficient. In addition, further activities such as subdividing, aggregation, or adding single elements to a DSM can be advantageous, but have to be applied prudently (BROWNING 2001). Figure 2.3 shows an exemplarily sequenced and clustered DSM.

Further, there are multiple analyses applicable to DSMs, of which activity, criticality, and cyclicality are most frequently used – and also applied within this research. The activity of an element describes its tendency to impact or be affected by other elements

[28] Note: This applies to the IC / FBD convention used for this research; for IR / FAD, iterations and feedback loops are found above the matrix diagonal.

and is determined by the quotient of its active and passive sum.[29] The criticality of an element denotes the connectivity to other elements and is the product of its active and passive sum.[30] Cyclicality represents the extend to which an element depends on itself via other elements and is determined by multiplying the DSM with itself (SOSA et al. 2013, p. 476, LINDEMANN et al. 2009, pp. 125-126).

DMM. To relate and compare two DSMs to each other, a DMM is used. This is a rectangular *m x n* matrix that extends the analytical possibilities offered by each DSM by creating transparency about inter-domain dependencies. These dependencies are coded similarly to those in DSMs. Also, the same analytical approaches used for DSMs can be applied to DMMs, if reasonable. (DANILOVIC & BROWNING 2007)

MDM. An MDM represents an even more generalized matrix comprising both DSMs and DMMs, and is used to model systems and networks with different domains and types of dependencies. Similar to DSMs and DMMs, these relations can be coded with numbers or symbols, but also qualitatively by terming the type of dependency (cf., e.g., MAURER 2007, LINDEMANN et al. 2009). Within this thesis, especially the latter type of MDMs is utilized.

In order to model and analyze systems with DSMs / DMMs / MDMs, the approach suggested by EPPINGER & BROWNING (2012, p. 10) has found broad application (cf., e.g., BROWNING 2015). Consequently, the main steps[31] described in table 2.2 are applied for this research.

Business Process Model and Notation (BPMN)

Published in version 2.0 in 2011, today BPMN is a widespread and highly popular notation for modeling business processes (FREUND & RÜCKER 2014, ALLWEYER 2015). Developed, maintained, and further enhanced by the OMG, it aims to provide a standardized notation readily understandable by all users supporting both business process design and implementation in practice (OMG 2011, p. 1). The graph-based

[29] Active sum is the sum of all entries in a row, passive sum the sum of all entries in a column (for DSMs with IC / FBD notation).
[30] Please refer to LINDEMANN et al. (2009, pp. 201-236) for further details on these analyses.
[31] Based on EPPINGER & BROWNING (2012, p. 10); slightly adapted by the author.

Table 2.2: Main steps to model and analyze systems with DSMs, DMMs, or MDMs

Decomposition	Break down of the system into its elements.
Identification	Description of the relationships of the elements.
Analysis	Application of methods for analysis, such as sequencing or clustering.
Visualization	Visual representation of the matrix and their specific features.
Application and improvement	Implementation of potential system improvements identified by previous analysis.

visualization of processes is based on numerous standard symbols and icons, of which those relevant for this research are listed in figure 2.4 (OMG 2011, pp. 29-41).

To model processes with BPMN, several IT-tools like Adonis Community Edition (Adonis:CE), Bizagi Modeler, Semtalk, or Signavio have been developed. For this research, Adonis:CE is selected, as it available free of charge, provides a conceived high usability (e.g., drag and drop), and allows for the export of graphs in editable file formats like Comma-Separated Values (CSV).

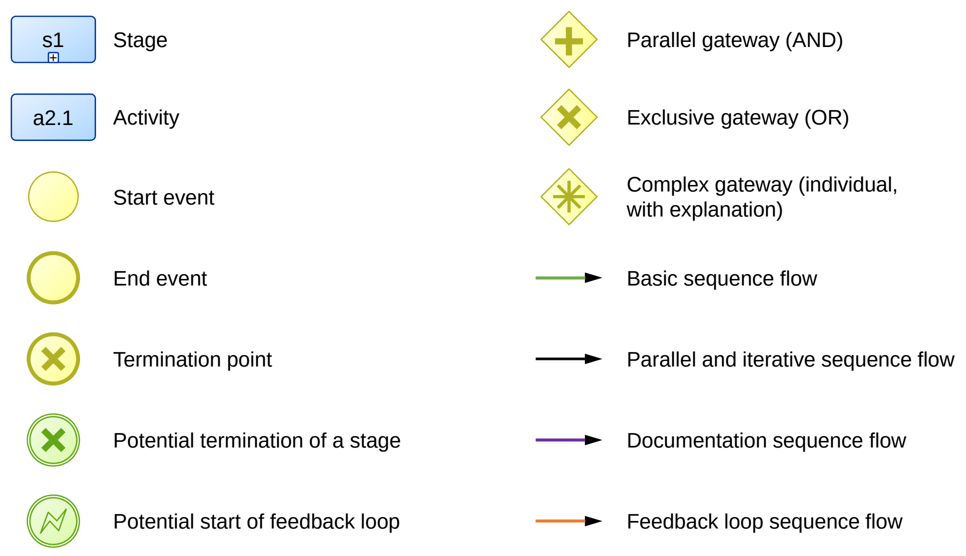

Figure 2.4: BPMN notation relevant to this research (based on OMG *2011, pp. 29-41 and Adonis:CE)*

3 State of the Art

This chapter covers the relevant publications on Engineering and Manufacturing Change Management as well as related topics as specified in section 1.3.4. While ECM has been subject of research for many years, MCM arose as a rather new topic that builds upon concepts and ideas from ECM. For this reason, the state of the art is presented according to the historical emergence of these topics in scientific research and covers publications dating back up to 35 years. Each section introduces and briefly discusses the major publications and research results, followed by a short assessment and evaluation based on the MCM requirements derived in section 1.4. Based on the four research questions (cf. section 1.3.1), this chapter concludes with a discussion of the findings from the state of the art.

3.1 System and context models

Modeling systems and their context is considered advantageous in order to account for relevant influences, dependencies, and interactions within and between systems and their context (cf. also section 2.5). In the following, relevant models for ECM, MCM, and other system and context models are briefly discussed.

3.1.1 System and context models for ECM

In scientific literature, different context models are available addressing ECM, of which three representative models are briefly outlined.

PIKOSZ & MALMQVIST (1998) focus on the ECM process in the context of a system, information, and roles and propose an “entity-relationship diagram over the models”[1], providing a comprehensive, formalized view on specific elements and their relations in the ECM context.

ROUIBAH & CASKEY (2003) address the concept of ECM in the context of supporting IT-systems and model the four elements process, person (role), product, and documents with different sub-elements and their relations on a schematic level. Based on this model, the authors identify and allocate improvement potentials and measures for ECM.

In contrast, LANGER et al. (2011) focus explicitly on system and context modeling of changes in product development processes. Taking up the preliminary work on system-oriented modeling of development projects (cf. BROWNING et al. 2006), the authors propose an “exploratory model” for ECs integrating a system and a context perspective. While the system perspective accounts for elements (or sub-systems) such as process system and goal system, the context perspective yields elements such as environment, market, or company. Relevant dependencies of the different elements are also part of the model.

3.1.2 System and context models for MCM

Among the few authors dealing with MCM, RÖSSING (2007, pp. 45-53) was one of the first to propose a “reference object model”[2] to describe a general approach for the implementation of changes in manufacturing on “the highest level of abstraction”[3]. It comprises relevant objects for an implementation of changes in manufacturing as generalized classes (e.g., Engineering Changes, change project, production object), their interrelations (e.g., Engineering Change generates change project), and selected attributes (for the production object: e.g., name, responsible, status). The different classes again comprise sub-classes (production object contains, e.g., production unit,

[1] I.e., process, system, role, and information models.
[2] Translated by the author. Original wording: “Referenzobjektmodell” (RÖSSING 2007, pp. 45-53).
[3] Translated by the author. Original wording: “auf höchster Abstraktionsebene” (RÖSSING 2007, p. 44).

assembly unit) with specific attributes. The same model is also described in AURICH & RÖSSING (2007).

Very similar, MALAK (2013, pp. 45-51) propose a conceptional model for a software-based planning method for ECs in manufacturing, comprising relevant elements and their interrelations. The model describes the chosen field of observation and represents a type of context model (see figure 3.1).

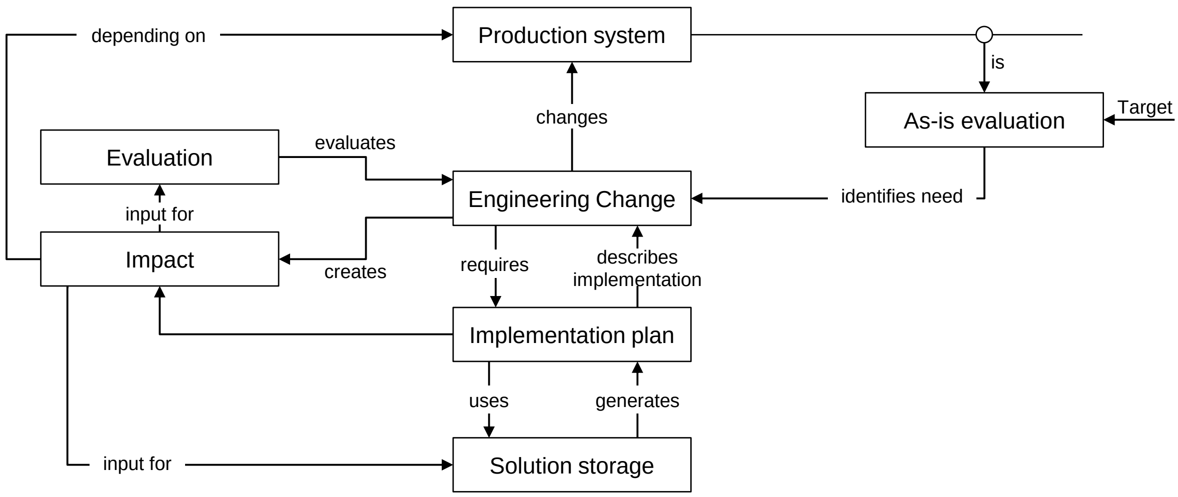

Figure 3.1: Context model of ECs in production (based on MALAK *2013, p. 45)*

Limiting the field of observation from general changes in manufacturing to reconfigurations of manufacturing resources as one specific example of an MC, KOCH et al. (2014) propose a system-based view on the concept of reconfiguration planning. The suggested model of the so-called "Extended Manufacturing System" comprises relevant elements (e.g., manufacturing resource, influencing factors) and their relations (e.g., influencing factors influence manufacturing resource). In contrast to RÖSSING (2007) and MALAK (2013), the authors emphasize partly different elements, for example, a continuous reconfiguration planning process or influencing factors. This accounts for their focus on a system-based analysis of continuous planning processes rather than the application of ECM in manufacturing.

In contrast, PROSTEP IVIP E.V. (2015, pp. 15-17) proposes a data model for an MCM concept as a basis for the development of an IT support (see figure 3.2). The model also represents a type of context model and comprises different elements, detailed attributes, and the relations of the elements. However, elements like change cause or EC are not considered.

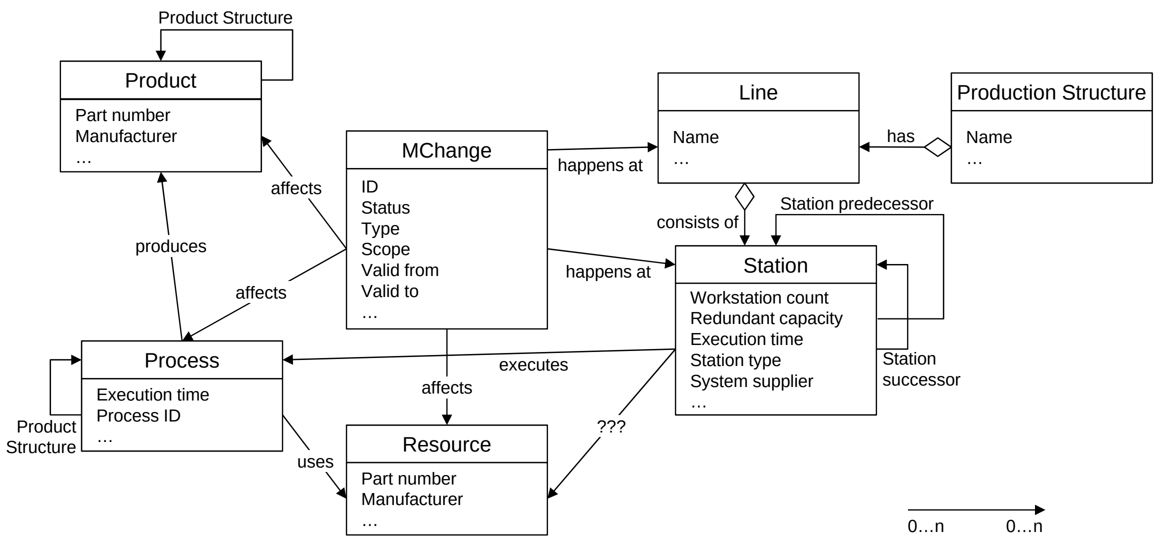

Figure 3.2: Context data model of MCM (based on PROSTEP IVIP E.V. *2015, p. 16)*

3.1.3 Other system and context models

In other fields of research like manufacturing planning, integrated design and process planning, or design process development, different system and context models have been developed. A representative selection of such models is described in the following.

SCHMIGALLA (1995, pp. 72-76) proposes several models of factory planning and its context focusing on the relations between factory planning and, for example, factory functions, or long-term enterprise planning. NOFEN et al. (2003) suggest a schematic model of control loop-based transformation processes and their context, which has been slightly modified in NOFEN (2006, p. 63). Addressing a control loop-based concept for changeability, AZAB et al. (2013) introduce an extended control loop model considering elements such as “changeable manufacturing system”, “required configuration”, “change drivers”, and their general relations.

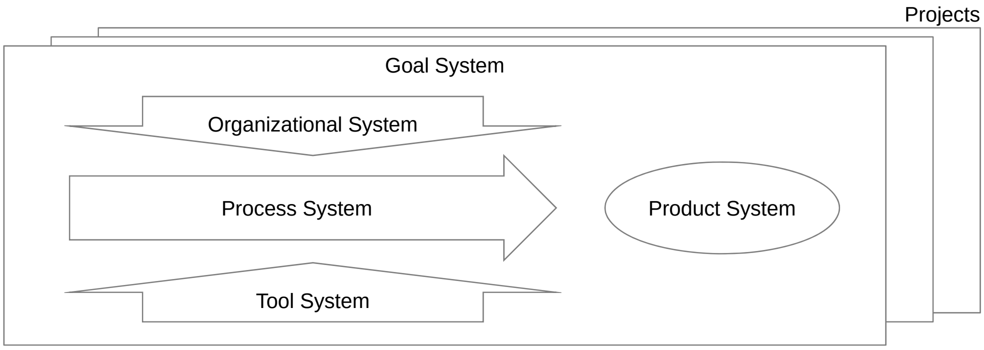

Figure 3.3: Abstract system model of the product development process in a project context (based on BROWNING *et al. 2006)*

GRABOWSKI et al. (1995, pp. 32-38) propose an integrated product and production model with relevant objects for the development and manufacturing of a product. EVERSHEIM et al. (1997) suggest a "reference model for integrated design and process planning" as a basis for the development of a simultaneous engineering approach. It includes elements such as activity, technical system, and information. Also, relevant relations as well as partial models of the elements are considered. JONAS (2000, p. 103) describe a holistic, context-like data model for an integrated assembly planning. The model comprises the classes product, process, dependency information, and resource as well as their sub-classes.

NEGELE & WENZEL (2000) develop the ZOPH[4] model as a system-based model of a product development project. Based on this, BROWNING et al. (2006) propose a similar model comprising five systems (product, organization, tool, product, and goal system) and their relations (see figure 3.3).

Other authors such as HALES & GOOCH (2004, p. 28) also developed a context model for the engineering design process in an industrial context, considering not only business functions (e.g., engineering, finance), activities (e.g., conceptual design, process planning), and outputs (e.g., production documents), but also other (context) fields (e.g., management, market), and external influences (e.g., social, economic). CLARKSON & ECKERT (2005, p. 26) finally model the design process on a more abstract level visualizing the interplay between the elements process, product, user,

[4] German acronym for "Zielsystem" (goal system), "Objektsystem" (product system), "Prozess-System" (process system), and "Handlungssystem" (agent system).

designer, and contextual aspects (e.g., design practice, design management).

3.1.4 Conclusion

Modeling of systems and contexts has been conducted for both ECM and MCM. Despite a rather close relation between these two concepts, available models mainly comprise elements (or classes, objects respectively) and dependencies from one domain only. Also, context models for MCM do barely include the element change cause and only sometimes elements like roles or a process. However, for a holistic MCM approach these elements will be identified relevant in subsequent sections (cf. sections 4.3 and 5.1). The general structure of the models is visualized with non-formalized or formalized graphical illustrations, but details on the actual system architecture, for example in form of DSMs or MDMs, are rarely provided.

Besides ECM and MCM, numerous system and context models are available for integrated design and process planning, assembly planning, or product development projects. These models are generally similar to context models for MCM, as they also consider very different elements in form of a system with a context. Furthermore, most models demonstrate a basic process orientation considering a process (system) as a major part of the respective model. Again, details about the detailed system architectures are seldomly provided.

As the publications on ECM and MCM are considered most beneficial for this research, the results of the evaluation against the MCM requirements applicable and hence relevant for the development of an MCM context model are provided in table 3.1. Further details on the different requirements are provided in section 1.4 and in the appendix, table A.1.

3.2 Modeling of changes in engineering and manufacturing

Understanding and describing the nature of changes in engineering and manufacturing can be considered as a basis to actually become able to manage them. For both types of changes several basic models have been developed. In this section, these are discussed and exemplarily detailed. In depth analyses of relevant change models are provided in section 6.2.2 as part of the development of the MC model.

Table 3.1: Evaluation of the system and context models for ECM and MCM

		ECM			MCM			
Category	**Requirement**	PIKOSZ & MALMQVIST (1998)	ROUIBAH & CASKEY (2003)	LANGER et al. (2011)	RÖSSING (2007)	MALAK (2013)	KOCH et al. (2014)	PROSTEP IVIP E. V. (2015)
Holistic view	Systemic perspective	◑	◑	◑	◑	◑	◑	◑
	Stakeholder involvement & interfaces	◑	◑	◑	○	○	○	◑
Applicability	Enterprise-independent applicability	●	●	●	●	●	●	●
	Transparency & simplicity	●	◑	◑	●	●	◑	◑
	Clear roles & responsibilities	◑	◑	○	○	○	○	◑
Process orientation	Defined process architecture	◑	◑	◑	○	○	◑	◑
	Coordination & information flow	◑	●	●	◑	◑	◑	◑
Proactivity	Change identification	○	○	◑	○	○	●	◑

● Fully addressed ◑ Partly addressed ○ Not addressed

3.2.1 Modeling of ECs

In ECM literature, numerous publications on ECs and their attributes are available. It was found that all change models comprise lists or collections of attributes considered relevant to describe ECs (e.g., DALE 1982, PFLICHT 1989, pp. 30-32, DIN EN ISO 10007, BELENER 2008, pp. 35-37). Some authors use their change model also to classify the change (e.g., CONRAT 1997, p. 97, LINDEMANN & REICHWALD 1998, pp. 302-311, ASSMANN 2000, pp. 92-101) or utilize them as a basis to conduct change analyses (e.g., GEMMERICH 1995, GIFFIN et al. 2009, SHARAFI 2012). The amount and type of change attributes differ between publications, however, several attributes like change object, change cause, impact on product, or impact on production are agreed upon by most authors.

As a representative example, the change model proposed by ASSMANN (2000, p. 101) comprises several attributes, which can be used to classify ECs (see figure 3.4). The

Checklist for the classification of changes		Creator	Date
Change number		Affected component	Project
Due date		Affected suppliers	End of project
Change type	**A**	**B**	**C**
Example	New requirement Malefunction	Cost reduction Dysfunction	Correction of drawing
Critical part	Yes	No	Not relevant
Duration	>4 months	1 to 4 months	< 1 month
Capacity	> 1 month manpower	Up to 1 month manpower	< 1 week manpower
Costs	Change of product price > x	Change of product price < x	No change of product price
Complexity	More than 5 components	2 to 5 components	1 or less components
Novelty	Objective and solution	Objective and solution	Objective and solution

Figure 3.4: Exemplary change model for an ECs (based on ASSMANN *2000, p. 101)*

attributes cover aspects like change number, duration, costs, or novelty. Also, the model generally accounts for different values of the attributes.[5]

3.2.2 Modeling of MCs

In manufacturing, several attributes for MCs but only few actual MC models have been proposed. Among others, HERNÁNDEZ MORALES (2002, pp. 43-47) and MALAK (2013, pp. 55-58) focus on technical aspects of MCs and required measures (for example, in terms of changing relations between factory elements or creating partly new factory systems), while KLEMKE (2014, pp. 167-175) provides a comprehensive list of potential change measures for MCs. Other authors such as NOFEN (2006, pp. 72-79) or AZAB et al. (2013) address indicators to identify needs for change and describe different levels of change, for example, restructuring of a factory or the utilization of flexibility. Change models or the identification of specific change attributes are not addressed.

In contrast, AURICH et al. (2004), WIENDAHL et al. (2007), and AURICH & CICHOS (2014) suggest actual attributes relevant to describe MCs (e.g., change cause, purpose, time frame). RÖSSING (2007, p. 48) proposes several similar change attributes and embeds them in a basic change model. Also, the author suggests a basic change

[5] According to (ASSMANN 2000, pp. 99-101), the values of attributes depend on the company using them.

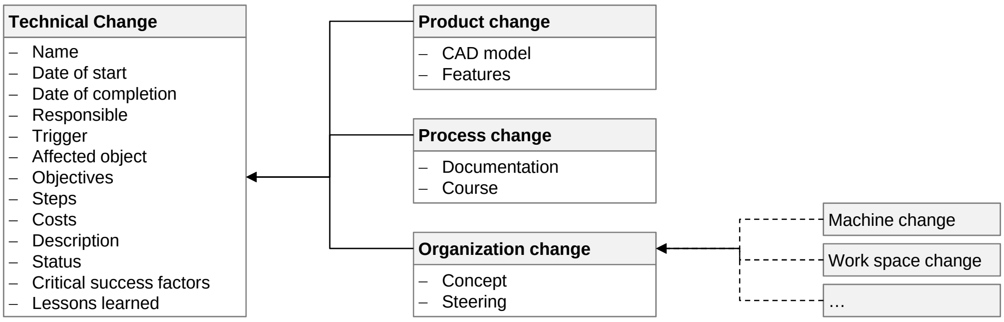

Figure 3.5: Exemplary change model for a technical change (based on RÖSSING *2007, p. 48)*

classification based on the attribute "change object" – i.e., a product, process, or an organization change. This model is found to be a simple, but still one of the most advanced MC models proposed in scientific literature so far (see figure 3.5).[6]

3.2.3 Conclusion

For both ECs and MCs numerous attributes have been identified to describe these changes. Also, several change models have been proposed, especially for ECs. These models include partially different change attributes to capture the various facets of a change. Most extensive change models have been developed for ECs by, for example, ASSMANN (2000), CONRAT (1997), or LINDEMANN & REICHWALD (1998). For MCs, one similar, but less extensive model has been suggested by RÖSSING (2007). The other publications available provide even more simple change models or just describe different change attributes. Despite any given evidence for each of these change models and attributes, the publications available do not exploit detailed case studies or cross-case analyses of literature to provide further substantiation of relevant change attributes in order to create a holistic, attribute-based MC model. For the most extensive and relevant publications the detailed evaluation results against the MCM requirements are provided in table 3.2. For further information about the requirements please refer to the appendix, table A.1.

[6] Note, that the author uses the term technical change instead of MC, as the proposed model is based on the application of ECM in manufacturing.

Table 3.2: Evaluation of the change models for ECs and MCs

		EC										MC			
Category	**Requirement**	Dale (1982)	Pflicht (1989)	Gemmerich (1995)	DIN EN ISO 10007	Conrat (1997)	Lindemann & Reichwald (1998)	Assmann (2000)	Belener (2008)	Giffin et al. (2009)	Sharafi (2012)	Aurich et al. (2004)	Rössing (2007)	Wiendahl et al. (2007)	Aurich & Cichos (2014)
Holistic view	Systemic perspective	◑	●	○	○	●	●	●	○	◑	◑	○	●	○	○
	Stakeholder involvement & interfaces	●	●	●	●	●	●	●	●	●	●	◑	●	○	◑
Applicability	Enterprise-independent applicability	◑	●	◑	●	●	●	●	◑	●	●	◑	◑	◑	◑
	Transparency & simplicity	●	●	◑	◑	●	●	●	◑	●	◑	○	○	○	○
	Clear roles & responsibilities	◑	○	○	◑	○	◑	○	○	◑	◑	○	●	○	○
Process orientation	Defined process architecture	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Coordination & information flow	◑	●	○	○	◑	◑	●	◑	◑	○	○	◑	○	○
	Process adaptation	○	○	○	○	◑	◑	●	○	○	○	○	○	○	○
Proactivity	Change identification	●	●	●	●	●	●	◑	●	◑	◑	○	●	◑	◑
	Early change evaluation	◑	◑	◑	◑	●	◑	◑	●	◑	◑	○	◑	◑	○
Problem solving & analytic capabilities	Cause & impact analysis	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	○	◑	◑
	Solution finding & implementation	◑	◑	◑	◑	●	◑	●	◑	◑	◑	○	◑	○	○
Knowledge management	Archiving & tracing of information	●	●	◑	○	◑	●	◑	◑	◑	○	○	◑	○	○
	Control of success & lessons learned	○	○	○	○	●	●	○	◑	○	○	○	◑	○	○
MCM efficiency	Efficient processing	◑	●	○	○	◑	◑	◑	◑	○	○	○	◑	○	○

● Fully addressed ◑ Partly addressed ○ Not addressed n/a: not applicable

3.3 Processes for the management and planning of changes

Processes provide support and guidance for the management of changes, regardless of the respective domain the change occurs in. To understand, model, and improve such processes, previous work addressed especially ECM processes, while some publications also focused on MCM. In contrast, processes for the planning of changes in manufacturing have been in focus of engineering science since decades – and are usually referred to by the terms factory planning and continuous factory planning. This section discusses the relevant processes for these research fields. The complete list of processes investigated as well as detailed results from process analyses are provided in section 6.3 as part of the design of the MCM process.

3.3.1 ECM

Covering the last thirty years, this research field yields more than 400 publications (cf. HAMRAZ et al. 2013), of which multiple deal with ECM processes. These publications share a focus on the process-oriented management of ECs providing profound insights into the ECM process design.

In the early 80s, DIN 199 Part 4 and DALE (1982) were among the first to investigate basic approaches for ECM. Building up on these, HILLER (1997) also considered interdisciplinary teams and change impacts relevant, while CONRAT (1997) added the identification of changes to ECM. LINDEMANN & REICHWALD (1998), KLEEDÖRFER (1998), and ASSMANN (2000) advanced the available concepts with an integrated view on ECM processes – the so-called "integrated change management"[7]. In this context, the authors took not only the organization and management as well as methods and tools, but also people and experienced-based knowledge about ECs into account.

At the same time and also during the following years, many other authors developed similar processes for ECM based on industrial case studies (e.g., TERWIESCH & LOCH 1999, TAVČAR & DUHOVNIK 2005) or literature studies (e.g., JARRATT et al. 2005). Combining these two approaches, more recently WICKEL et al. (2014) proposed an

[7] Translated by the author. Original wording: "Integriertes Änderungsmanagement" (LINDEMANN & REICHWALD 1998, p. 1).

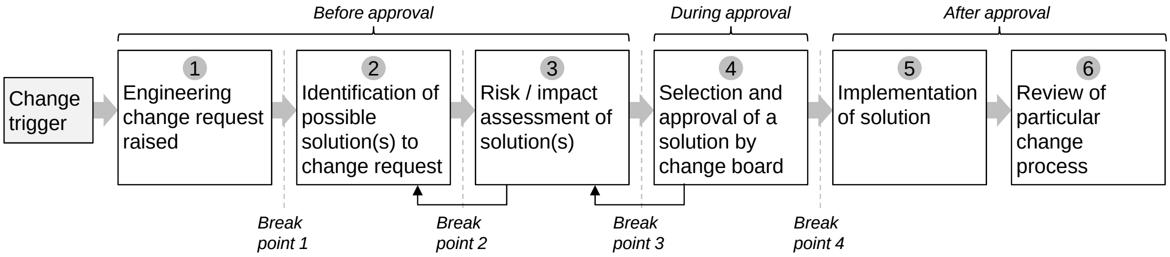

Figure 3.6: Generic ECM process (based on JARRATT *et al. 2005)*

ECM reference process and discussed the utilization of the different ECM process phases in industrial practice. The most detailed ECM process available has been published by VDA (2010b) as part of an industrial recommendation for ECM. Here, the generic MCM process suggested by JARRATT et al. (2005) is visualized exemplarily (see figure 3.6).

3.3.2 MCM

In contrast to the large literature body available on ECM, only few scientific publications deal with the management of changes in manufacturing. Basic process-oriented procedures for MCM have been proposed by AURICH et al. (2004), RÖSSING (2007), PROSTEP IVIP E.V. (2014), AURICH & CICHOS (2014), and PROSTEP IVIP E.V. (2015). The publication by STANEV et al. (2008) focuses on the integration of manufacturing flexibility in industrial approaches for MCM, while MALAK et al. (2011) and MALAK (2013) investigate a software-based approach for the planning of MCs.

The first two publications directly transfer the concept of ECM to the manufacturing domain and suggest a purely ECM-based, high-level process for the management of changes in manufacturing. AURICH et al. (2004) describe a change process with three phases: “Initialization of change”, “Implementation of change”, and “Follow-up of change”, of which each covers several activities. Based on this, RÖSSING (2007) proposed a very similar, linear process[8] with the identical three phases and only slightly different, but more detailed activities (see figure 3.7). Besides the general, unformalized process description, both provide only few information about the process

[8] Denoted as “application model” (Translated by the author. Original wording: “Anwendungsmodell”) (RÖSSING 2007, p. 54).

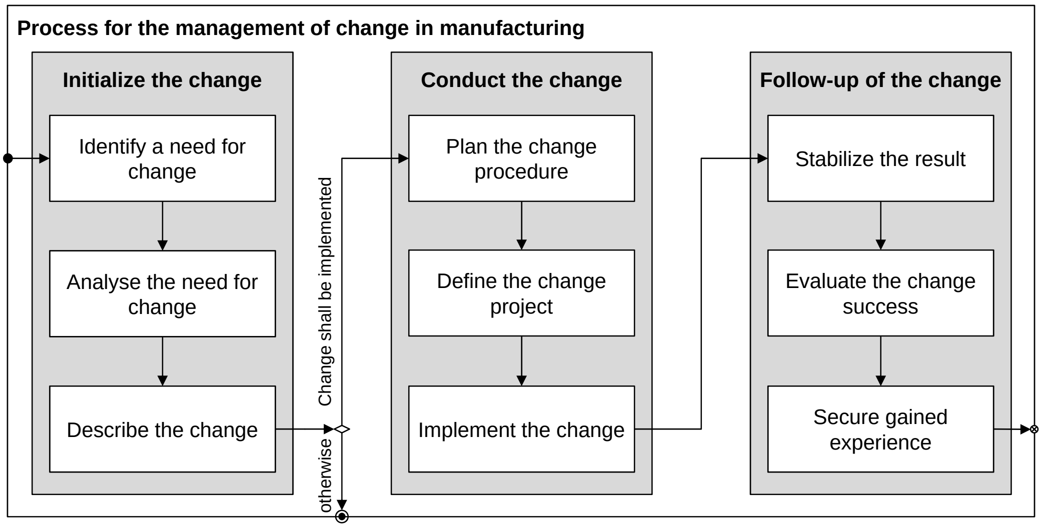

Figure 3.7: Process for the management of changes in manufacturing (based on RÖSSING *2007, p. 54)*

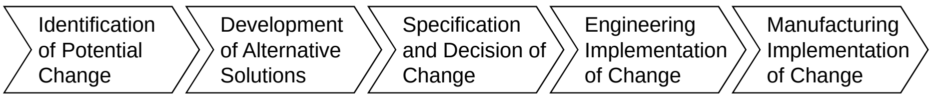

*Figure 3.8: General, cross-organizational MCM process (*STANEV *et al. 2008)*

design and architecture. Also, available processes from, for example, ECM or factory planning are not described to have been taken into consideration for the process development.

STANEV et al. (2008) derive a high-level, cross-organizational MCM process[9] based on industrial business scenarios in two companies (see figure 3.8) and elaborate on the consideration of information about the production system's flexibility within this process. Again, details about the process design are not provided; other processes from scientific literature have not been considered.

Extending the software-based approach for the analysis and planning of MCs and their impact on factory systems (MALAK et al. 2011), MALAK (2013, pp. 51-55) suggest a method for the planning of MCs with four general phases: evaluation, planning, implementation, and review. These are detailed with few activities and their sequence. The focus of the approach is on the planning of required measures to implement an

[9] Referred to as "production change management process" (STANEV et al. 2008).

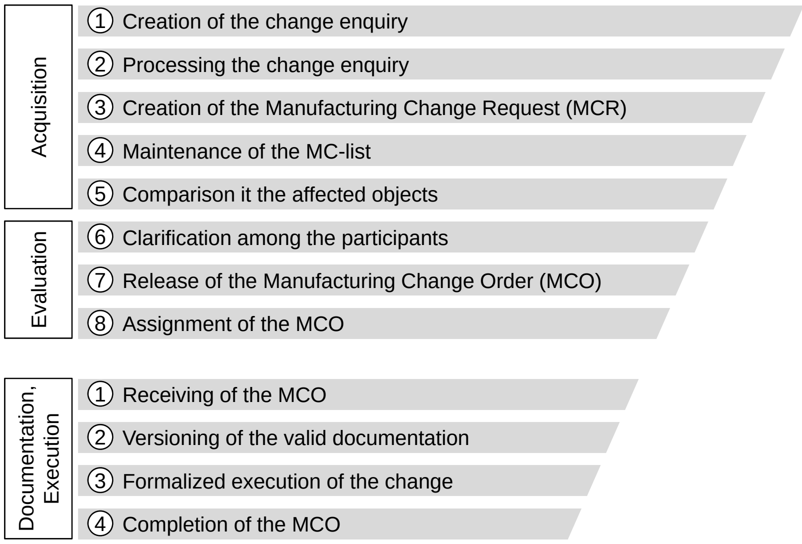

Figure 3.9: Reference process for MCM (based on PROSTEP IVIP E.V. *2015)*

MC in a production system. An actual MCM process with activities, deliverables, and a detailed process architecture is not provided.

Based on interviews with practitioners, PROSTEP IVIP E.V. (2014) suggest a two-staged approach for MCM comprising a Manufacturing Change Request (MCR) and a Manufacturing Change Order (MCO) with a total of twelve process-steps. This approach has been further enhanced to a reference process with details on implementation tasks for each process-step, and an analysis of potential use cases (PROSTEP IVIP E.V. 2015, see figure 3.9). These include other approaches in industrial practice like ECM or the continuous improvement process, which have been mapped to the proposed MCM process. Finally, a first IT prototype is introduced to support MCM. Overall, both publications mainly address practitioners with information about a general, linear MCM process, but neither elaborate on the actual process design and architecture, nor provide formalized process models. Also, available research on MCM and related approaches are not described to have been taken into consideration for the process development.

Furthermore, DECKER (2009) propose an approach for restructuring and continuously controlling a production system based on a comparative analysis of the socio-technical production system as well as product and market characteristics. POHL (2013) developed an approach for the adaptation of production structures with a focus on the identification, scheduling, and evaluation of required adaptations. Focusing on specific elements of the production structure, KARL & REINHART (2015) suggest a method to identify and plan reconfigurations of manufacturing resources. These publications contribute especially to the identification and planning of specific changes in manufacturing and the production structure, but do not address approaches for the management of MCs in particular.

Finally, AURICH & MALAK (2010) investigate mechanisms of change impacts in manufacturing, while AURICH & CICHOS (2014), CICHOS & AURICH (2015), and CICHOS et al. (2016) introduce a high-level approach for planning and controlling several parallel changes in manufacturing, but do not provide additional information regarding a change management process for MCM.

3.3.3 Factory planning

While the scientific basis for this research field has already been set in the 1960s and 1970s (VDI 5200), the past thirty years yielded an abundance of new, process-oriented factory planning approaches. Among others, KETTNER et al. (1984), BULLINGER & AMMER (1986), AGGTELEKY (1987), REFA (1991), WIENDAHL (1996), DOHMS (2001), SCHENK & WIRTH (2004)[10], BERGHOLZ (2005), VDI 5200, and SCHULZE (2013) introduced factory planning processes (or assembly planning processes, cf. BULLINGER & AMMER 1986), which have been chosen exemplarily for this research.

All approaches deal with the factory as the object of observation and propose specific process descriptions for factory planning. These address the approach for planning a factory (or parts of the factory), but differ regarding the level of detail and specific process content provided (see sections 6.3.2 and 6.3.3). Thereof, VDI 5200 is the latest German norm on factory planning available and an illustrative example for a comprehensive factory planning process.

Defining terms and procedures for a contemporary factory planning, VDI 5200 suggests an approach comprising seven consecutive (and partly iterative) planning phases (see figure 3.10) and an additional project management for organizational tasks. Starting with the setting of objectives through the concept and detailed planning to the

[10] Note: the new issue SCHENK (2014) reveals the same factory planning process.

Figure 3.10: Factory planning process (based on VDI 5200)

final ramp-up support, the process enables factory planning throughout the factory life cycle[11] and for various planning levels[12]. Despite the generally broad range of application, the main focus of this and all other factory planning approaches is on an initial factory planning.

3.3.4 Continuous factory planning

In the late 1990s, FELIX (1998) was one of the first to develop a factory planning approach based on AGGTELEKY (1987) that is no longer a linear planning process, but a planning cycle similar to a control loop. Consisting of 10 phases and 25 sub-phases, the planning cycle starts and ends with an analysis and KPI-based evaluation. This final phase contains a target-performance comparison serving as both a conclusion for the past factory planning and a potential trigger for a new factory planning.

A few years later, CISEK (2005) developed a methodology to plan and evaluate continuous reconfiguration processes. This approach focuses on a dedicated monitoring module to identify the need for structural factory adaptations based on performance-, cost-, and utilization-oriented KPIs. In the same period of time, NOFEN (2006) introduced a concept integrating a control loop into a factory planning process. Similarly to CISEK (2005), this approach also contains a so-called “change monitor” to identify the need for adaptations in a factory.

NYHUIS et al. (2010) also developed a control loop-based concept for continuous factory planning. The control loop describes the production system as well as the analysis and evaluation regarding the system’s flexibility and adaptability. However, the concept has not been combined with or integrated into a factory planning process

[11] The factory life cycle comprises phases like, for example, development planning, re-planning, or clearance / demolition.

[12] Planning levels represent, for example, a work center, a segment, or a plant.

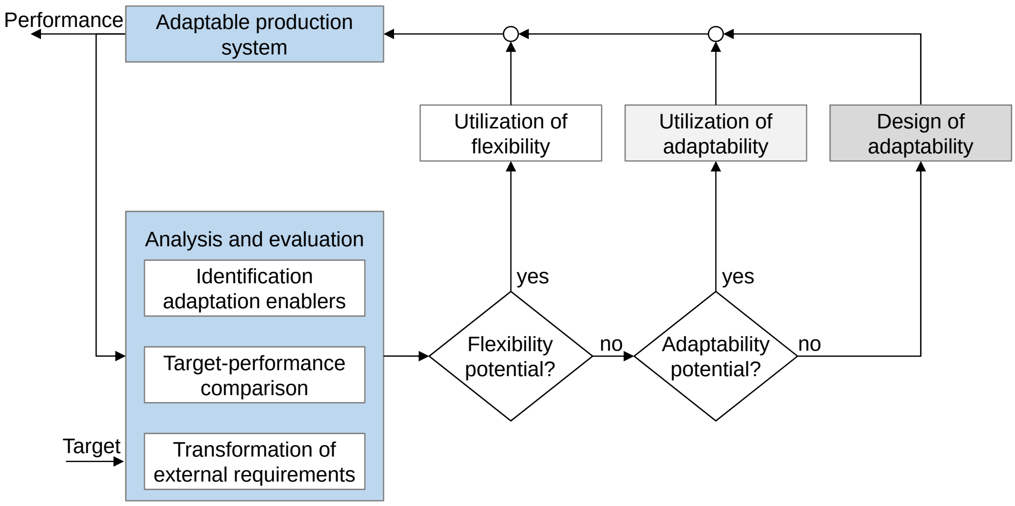

Figure 3.11: Concept of continuous factory planning applying a control loop (based on NYHUIS *et al. 2010, p. 6)*

(see figure 3.11). In the following years, authors like WAGNER (2012), PACHOW-FRAUENHOFER (2012), AZAB et al. (2013), and KLEMKE (2014) modified and further enhanced the control loop concept. The advanced concepts address, for example, the planning of changeability (PACHOW-FRAUENHOFER 2012) or the identification and valuation of needs for change in the context of planning the changeability of factories (KLEMKE 2014).

Overall, the publications on continuous factory planning address the control loop concept and its utilization for the monitoring of factories and the identification of required adaptations or changes within a factory.

3.3.5 Conclusion

During the last decades, multiple, process-based approaches have been developed for the management and planning of changes. While only few publications address processes dedicated to MCM, the fields of ECM, factory planning, and continuous factory planning provide a broad basis of approaches potentially relevant for this research. However, most publications propose rather general approaches with few information on the detailed process design and architecture only. Also, formalized process models are rarely found. Up to date, the most detailed process descriptions for MCM can be found in RÖSSING (2007) and PROSTEP IVIP E.V. (2015), for ECM in JARRATT et al. (2005), VDA (2010b), and WICKEL et al. (2014).

Despite the extensive amount of literature especially for ECM, factory planning, and continuous factory planning, most processes are found to be developed based on interviews with practitioners from industry or on insights from available publications and logical reasoning. Evidence for detailed case studies or an analysis of MCM and MCM-related processes in literature regarding a process design and architecture could not be found. Nevertheless, the available publications represent an extensive basis for a comparative meta-analysis of the processes and provide valuable insights regarding the design of an MCM process.

Due to the large amount of available processes, all publications on MCM and selected, exemplary contributions from the three other fields of research are evaluated against the relevant MCM requirements (see table 3.3). The detailed results of the comparative meta-analysis of the processes are provided in section 6.3.

3.4 Process support for the management of changes

Roles as well as methods and tools represent supportive elements for any process – and so they do for MCM and other change processes. In the following, relevant publications on these topics are discussed.[13]

3.4.1 Roles for ECM and MCM

Available publications rarely address the development and description of roles for ECM and for MCM. Most authors discuss the situation in industrial practice based on findings from expert interviews or case studies.

Among others, especially CONRAT (1997, p. 106) and LINDEMANN & REICHWALD (1998, pp. 70-74) describe the responsibility for ECs to be often assigned as an additional task to the head of the engineering department or the head of work planning. According to LINDEMANN & REICHWALD (1998, pp. 70-74), HUANG & MAK (1999), and BELENER (2008, p. 83), also the formation of committees for the coordination of

[13] Note, that other elements like, for example, IT-based workflow systems also represent a process support. These are intended to reflect the process, the roles, etc. – for this reason, they are not considered here.

Table 3.3: Evaluation of the processes for the management and planning of changes

		ECM			MCM					FP			CFP		
Category	**Requirements**	Jarratt et al. (2005)	VDA (2010b)	Wickel et al. (2014)	Aurich et al. (2004)	Rössing (2007)	Stanev et al. (2008)	Malak (2013)	ProSTEP iViP e. V. (2015)	Aggteleky (1987)	Schenk & Wirth (2004)	VDI 5200	Cisek (2005)	Nyhuis et al. (2010)	Azab et al. (2013)
Holistic view	Systemic perspective	◑	●	●	◑	●	◑	●	●	●	●	●	●	●	●
	Stakeholder involvement & interfaces	◑	●	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑
Applicability	Enterprise-indep. applicability	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Transparency & simplicity	◑	◑	●	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑
	Clear roles & responsibilities	◑	●	○	○	○	○	○	◑	◑	◑	○	○	○	○
Process orientation	Defined process architecture	○	◑	◑	○	○	○	○	○	○	◑	◑	○	○	○
	Coordination & information flow	◑	●	◑	◑	◑	○	◑	◑	◑	◑	◑	◑	○	◑
	Process adaptation	○	◑	○	○	○	○	○	○	○	○	○	○	○	○
Proactivity	Change identification	○	○	◑	●	●	●	●	●	○	○	○	●	◑	●
	Early change evaluation	◑	●	●	●	●	○	●	◑	○	○	○	●	◑	●
Problem solving & analytic capabilities	Cause & impact analysis	●	●	●	●	◑	○	●	◑	◑	◑	◑	●	◑	●
	Solution finding & implementation	●	◑	◑	●	●	◑	●	◑	●	●	●	◑	◑	◑
Knowledge management	Archiving & tracing of information	◑	◑	●	●	●	○	◑	○	○	◑	◑	○	○	○
	Control of success & lessons learned	◑	◑	●	●	●	○	◑	○	○	◑	◑	○	○	○
MCM efficiency	Efficient processing	◑	●	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑

● Fully addressed ◑ Partly addressed ○ Not addressed
FP: Factory planning CFP: Continuous factory planning

and decision on ECs – so-called “change control boards”[14] – is very common in practice. As part of the “Integrated ECM”[15], LINDEMANN & REICHWALD (1998, p. 229) proposed the creation of interdisciplinary teams for the alignment and development of solution concepts for ECs. However, detailed role descriptions or an assignment of roles to activities of the ECM process are not provided.

In contrast, VDA (2010b, pp. 12-15) define a detailed set of roles for ECM. The roles described include, for example, a change requester, a change request receiver, an ECR creator, and an EC manager. Further, a change team, a decision team, and a coordinator contact group[16] are introduced. Also, the roles are assigned to the proposed, detailed ECM process (cf. also section 3.3.1).

For MCM, less information on relevant roles is available. AURICH et al. (2004) briefly states that the responsibility for MCs is usually with the manager of a manufacturing department or assigned to the employee responsible for the manufacturing resource or location affected by the MC.

PROSTEP IVIP E.V. (2015, p. 4) propose two roles for MCM. One is responsible for the change request, the other for the implementation of the change. The specific responsibilities are described to be very similar to the regular planning activities in manufacturing. In contrast to VDA (2010b, p. 14), the authors propose to prefer the integration of MCM into existing organizational structures for planning and production rather than the creation of an additional department or function. However, a critical discussion or comparison with ECM roles is not provided.

3.4.2 Compilation of methods and tools for MCM

Within the field of ECM, for example, LINDEMANN & REICHWALD (1998, pp. 143-147) and HUANG & MAK (1999) describe exemplary methods like Quality Function

[14] Note, that this term is similarly used in project management, where it is defined as a “formally constituted group of stakeholders responsible for approving or rejecting changes to the project baseline.” (PMI 2000).

[15] Translated by the author. Original wording: “Integriertes Änderungsmanagement” (LINDEMANN & REICHWALD 1998, p. 229).

[16] This group comprises persons who serve as a contact for other employees regarding EC-related topics (VDA 2010b, p. 14).

Deployment (QFD) or Failure Mode and Effect Analysis (FMEA) for the identification of ECs, while ASSMANN (2000, pp. 104-108) proposes only a structure for the categorization of methods, but no actual methods.

For MCM, CICHOS & AURICH (2015) discuss the introduction of Production Planning and Scheduling (PPS) methods to MCM. The other few publications available on MCM mostly deal with single methods dedicated to, for example, impact analysis or evaluation of changes (e.g., AURICH & MALAK 2010, MALAK 2013). These are discussed in the context of the application during an MCM process. Indeed, actual compilations of methods are neither provided for ECM nor MCM.

In other fields of research like factory planning, authors like SCHENK & WIRTH (2004, pp. 182-217) propose a compilation of methods and tools, which are allocated to the phases of the factory life cycle based on the assumed suitability for the respective phase. In OCM, lists of methods structured according to an OCM process have been proposed by, for example, VAHS & WEIAND (2010) or ROEHL et al. (2012). Further extensive compilations of methods are available for product development and the product development process (e.g., VDI 2221, pp. 33-38, PAHL et al. 2007, pp. 77-124, LINDEMANN et al. 2009, pp. 57-62, EHRLENSPIEL & MEERKAMM 2013, pp. 344-529). Similarly, literature on project management also provides several compilations of methods and tools to support the activities of the project management process (cf. also section 2.3.5; e.g., DREWS & HILLEBRAND 2007, ANDLER 2012, HABERFELLNER 2012, pp. 365-370, or DIN 69901-2, pp. 18-51).

3.4.3 Conclusion

Both roles and methods have been described and discussed in literature in the context of ECM and MCM. While the most detailed set of relevant roles and their allocation to an ECM process has been proposed by VDA (2010b), among the very few publications on MCM only PROSTEP IVIP E.V. (2015) briefly introduces two roles for MCM. Further detailed descriptions of roles are currently not available.

Regarding methods and tools, extensive compilations are available for factory planning, OCM, product development, and project management. These are usually structured according to the accompanied process and the specific process phases. In contrast, for ECM and MCM only selected methods have been described and allocated to the respective change process. Up to date, an extensive compilation of methods has not been proposed. For this reason, an evaluation of the publications discussed before against the MCM requirements will not provide further insights and has been omitted for this thesis.

3.5 Adaptation of change processes

While each change is unique to some extent, the processes to manage these changes are often defined as a determined set of activities a priori. According to the practitioners interviewed (cf. also section 1.4), this leads to delays, the creation of workarounds, or deviations from the standard process to meet certain deadlines or to accelerate the process. In engineering science, only few authors addressed this aspect by investigating approaches to adapt change processes.

For ECM, ASSMANN (2000) propose an EC-specific selection of methods, which is to be applied during the ECM process. The selection is based on a categorization of ECs depending on their specific attributes (e.g., impact, costs). Also, a more advanced selection of methods based directly on the EC attributes is briefly mentioned, but not further elaborated on (ASSMANN 2000, p. 107). A similar approach for an adaptive ECM process has been proposed by ABRAMOVICI et al. (2010), who relate the goals for an EC (e.g., targeted processing time) to the ECM process. However, both concepts remain in a rather conceptional status, specific adaptation rules are not provided.

For MCM, no contributions to an adaptation of MCM processes could be found in literature.

Focusing on an integrated product development and manufacturing, MURR (1999) and GRUNWALD (2001) developed an approach to model and configure integrated development and planning processes based on "process building blocks"[17]. Similarly, but focusing on adaptive product development processes, LÉVÁRDY & BROWNING (2009) propose a general set of process activities and activity modes to be selected depending on the respective situation.

[17] Translated by the author. Original wording: "Prozessbausteine" (cf. MURR 1999); furthermore, GRUNWALD (2001, pp. 191-201) provides an extensive, generalized set of process building blocks.

Further examples for an adaptation of processes including also a selection of roles are available for, for example, software development processes (e.g., PEDREIRA et al. 2007, XU & RAMESH 2007, HÖHN & HÖPPNER 2008, XU & RAMESH 2008). Proposing also a project- or situation-specific adaptation of the process, these approaches are comparable to those described before. Very similar, research on adaptive process management investigates process-aware information systems to enable IT to better support a situation- and case-based adaptation of processes (e.g., B. WEBER et al. 2008, HALLERBACH 2009).

Overall, the adaptation of change processes has rarely been in focus of research on ECM and product development, and has not been addressed for MCM at all. However, the few concepts available discuss a situation- or change specific adaptation of the respective processes. Very similar, publications on software development processes or adaptive process management investigate project- and situation-based approaches for the adaptation of processes. This resemblance of available concepts indicates a general suitability and meaningfulness of a situation – i.e., change specific – adaptation of processes also for MCM.

3.6 Evaluation of benefits for ECM and MCM

Several surveys, reviews, and case studies have been conducted to estimate the costs of ECs (e.g., GEMMERICH 1995, p. 105, HUANG & MAK 1999, WILDEMANN 2014, p. 9). The authors indicate minimal costs for processing an EC to range between €1,000 and €2,000, while actual costs of an EC may reach up to several million EUR (e.g., CONRAT 1997, pp. 165-167). In product development about 25% and up to 65% of employees' capacities are used for ECs, in manufacturing about 15 to 40% (cf. DEUBZER et al. 2005, p. 5, LANGER et al. 2012, p. 7). Overall, these figures indicate a significant potential to reduce costs of change by improving ECM.

Up to date, mainly qualitative information are available on challenges in ECM and hence expected benefits of an improved ECM. Among others, an applicable and adaptable ECM process design and an early change identification and evaluation are agreed upon (e.g., CONRAT 1997, pp. 170-243, DEUBZER et al. 2005, pp. 7-11, LANGER et al. 2012, p. 22; cf. also section 1.4). Despite the authors' general agreement on the benefits of ECM and its application, quantitative evaluations of the ECM approaches are barely provided: DEUBZER et al. (2005) and LANGER et al. (2012) indicate about 20 to 30% of ECs to be preventable; WILDEMANN (2014, pp. 242-246) state the application of ECM to reduce costs for ECs by about 25% and decrease the number of approved EC requests by about 75%.[18] However, further details on specific effects and benefits are not provided.

For MCM, the survey by KOCH et al. (2015b) revealed an increasing relevance of MCM in industrial practice (cf. also section 1.1). About 40% of the companies indicated to deal with at least 500 and up to several thousand MCs per year (cf. also section 4.2). As detailed information about costs of MCs is hardly available in literature, average costs per MC have been estimated by companies' experts during the three case studies conducted for this research (cf. section 4.2).[19] Ranging between €1,000 and €1,600, these are similar to the costs for processing an EC and also indicate significant potential to reduce costs of MCs by applying and improving MCM.

The few MCM approaches available have been tested in case studies regarding their applicability – and the authors agree on the fundamental benefit of MCM (similar to ECM; cf., e.g., RÖSSING 2007, MALAK 2013, PROSTEP IVIP E.V. 2015). However, a detailed evaluation of benefits (qualitative or quantitative) of MCM or an estimation of potential cost reductions due to an application of MCM could not be found.

3.7 Conclusion

Based upon the scope of research (cf. section 1.3.4) and the four research questions (Q1 to Q4, cf. section 1.3.1), relevant publications have been identified, reviewed, and evaluated against the MCM requirements (cf. section 1.4). In order to provide a broad and thorough perspective on the state of the art, the publications selected for this research cover about 35 years of research on MCM, ECM, and related topics.

Up to date, the development of a company-independent, system-oriented concept for MCM (cf. research question Q1) has not been accomplished. Although a few system and context models for MCM and ECM have been described, detailed system

[18] These results are based on one exemplary case study.
[19] These costs account for processing an MC, but do not include material costs, engineering hours, etc.

architectures enabling a detailed design of MCM (e.g., MC model, MCM process) are not available. Also, available models neglect certain aspects (e.g., process architecture, roles, interfaces) considered relevant for a holistic perspective on MCM.

In order to describe MCs, only one basic MC model has been proposed – a detailed MC model supporting MCM is not available (cf. research question Q2). In contrast, several EC models and numerous attributes describing ECs are available. Despite any given evidence, most publications do not further substantiate the respective change model (e.g., via case studies). Nevertheless, the available change models provide a sound literature basis for the development of a dedicated MC model.

The process-based management of MCs has rarely been addressed in literature, only few basic MCM processes have been suggested. A detailed process to efficiently and effectively manage MCs is not available (cf. research question Q3). For ECM, factory planning, and continuous factory planning numerous processes have been developed. Most approaches remain rather general providing few information regarding the detailed process design and architecture. Also, evidence for a process design based on detailed case studies and an analysis of related processes in literature can rarely be found. Despite these shortcomings, the available publications represent an extensive literature basis for the design of an MCM process.

Furthermore, there is hardly any literature on dedicated roles for MCM, methods and tools to be used, or approaches for a change-specific adaptation of an MCM process. However, for other processes (e.g., ECM, product development) first adaptation approaches have been discussed by different authors providing guidance for the development of an MCM process adaptation.

A detailed evaluation of benefits (qualitative and quantitative) of an MCM approach could not be found in literature (cf. research question Q4). Available surveys, reviews, and case studies on ECM and MCM correspond regarding a general benefit of change management activities, costs of ECs, and bound capacities due to changes. These indicate a significant potential of reducing costs of changes by ECM (and correspondingly MCM for manufacturing). However, available publications on MCM procedures address their applicability only.

Overall, the state of the art does not provide a process-based approach for the management of MCs fulfilling the MCM requirements and hence supporting practitioners in managing MCs effectively and efficiently (cf. section 1.2). Nevertheless, it creates a broad data basis to be utilized for the development of the desired MCM approach.

4 Current Practice of MCM in Industry

In order to create a profound data base to develop the MCM approach and build theory on MCM, three in-depth case studies have been conducted in addition to the literature review (cf. section 3), a web-based survey (KOCH et al. 2015b), and several expert interviews with practitioners (cf. section 1.4). Within this chapter, first the approach for the three case studies is outlined, followed by the description of the current practice of MCM in industry regarding the overall MCM set-up, utilized MC models, and MCM processes. Then, the findings from a cross-case analysis are discussed based on the MCM requirements and mirrored to the four research questions.

4.1 Introduction and approach

According to the concept of theoretical sampling (EISENHARDT 1989, MCCUTCHEON & J. R. MEREDITH 1993, EISENHARDT & GRAEBNER 2007), the companies observed represent various industry sectors (i.e., mechanical engineering, aerospace, and medical technology), face diverse legislative restrictions and regulations, and have a different background of experience in MCM according to initial interviews with company representatives (cf. also section 1.1). This leverages the validity of the MCM concept developed in this thesis. Within this chapter, the three case studies are ordered according to the level of legislative restrictions and regulations (from low to high).

For each case study, three to four workshops have been conducted together with change managers, production planners, and production managers over a period of several months in 2014 and 2015. After a first alignment meeting, each workshop has been carefully prepared providing templates, structured questionnaires, as well as results from previous analysis work. The duration of the workshops was between a half and a full working day each.

Building upon the expert interviews (cf. also section 1.4), the case studies focus on a detailed understanding of the current practice of MCM in different industries. This includes the overall MCM set-up, utilized models for MCs, and the MCM process in terms of content and architecture. Available MC descriptions are captured using a semi-formal model for visualization, MCM processes are described and modeled with a DSM to determine the process architecture (cf. also section 2.5.4). In addition, roles, supportive methods, and approaches for process adaptation are considered.

The DSM of each MCM process visualizes the relevant phases, activities, and their dependencies. All matrices are modeled according to the convention IC / FBD. The activities are listed chronologically on the two axes of the matrix, the dependencies within the matrix. Two types of dependencies are distinguished: input from one to another activity (modeled by a “1”) and feedback loops describing a return from one to a previous activity (modeled by an “x”). In addition, termination points are marked on the diagonal (dashed fields). These allow for an early stop of the process, for example, if a change is canceled.

All results have been carefully documented and analyzed based on the derived MCM requirements (cf. section 1.4), followed by an extensive review with the respective company. Finally, the findings from the three case studies have been cross-analyzed and consolidated. The results of this analysis are provided in table 4.1.

4.2 Case studies

Starting with a brief introduction to the respective company, the applied MCM concept is described, followed by an analysis of the MC model or similar documentation used. Next, the process (or processes) for MCM are described and analyzed. Finally, each case study comprises a brief description of relevant roles, proposed methods for MCM, if applicable, and approaches for the MC-specific adaptation of the MCM concept.

4.2.1 Initial case study with company A

Company A is an Original Equipment Manufacturer (OEM) in the mechanical, system, and plant engineering industry with more than 9,000 employees in Germany. Looking back on a strong growth in recent years, the portfolio today comprises low volume production as well as small to large scale projects; manufacturing activities cover production, assembly, and service. The industrial sector of company A is subject to only some rules and regulations regarding processes and documentation (e.g., DIN EN ISO 9000). The company has several years of experience in ECM and Order Change Management[1]. For MCM, selected processes are applied. Most MCM activities are based on a project management process, supplemented by few other processes[2], or the invest process in case of smaller changes. These processes are documented with textual descriptions, partly with simplified flowcharts. In total, about 70 large MCs (e.g., new manufacturing resources, manufacturing process change) as well as about 14,500 ECs and 3,000 order changes causing smaller MCs (e.g., mainly alterations of documents) are processed per annum by company A. The resulting costs for processing large MCs are estimated at an average of about €1,300, for small MCs at about €125.[3]

At company A, MCM activities usually start with the identification of a need for change, an MC analysis and evaluation, followed by a concept, detailed change, and implementation planning. The activities conclude with the implementation and closure of the MC. Change causes are not tracked and evaluated. In general, any MC is managed and documented by one dedicated project manager, whereas a change board coordinates the different MCs. Further roles relevant for MCM are only described within the process descriptions. Distinct activities for knowledge management or lessons learned are not considered for the MCM of company A.

To describe MCs, different attributes are utilized by company A. These are described in several standard documents, like a change request or the monthly change report. Even though a dedicated change profile or list of change attributes is not used, the available documents cover MC attributes like change name, description, efforts, or risk evaluation. Figure 4.1 provides a consolidated and structured overview of the attributes identified.

In order to achieve a holistic perspective on the applied MCM approach, the most relevant processes have been analyzed and combined to a joint MCM process with several phases. These range from the creation of change ideas, a concept creation and

[1] Approach to conduct changes in customer orders during production.
[2] For example, a supplier management process.
[3] Note, that the costs for smaller MCs may not account for the total processing costs, as they are based on an average duration for an MC only; efforts for the identification and alignment might add.

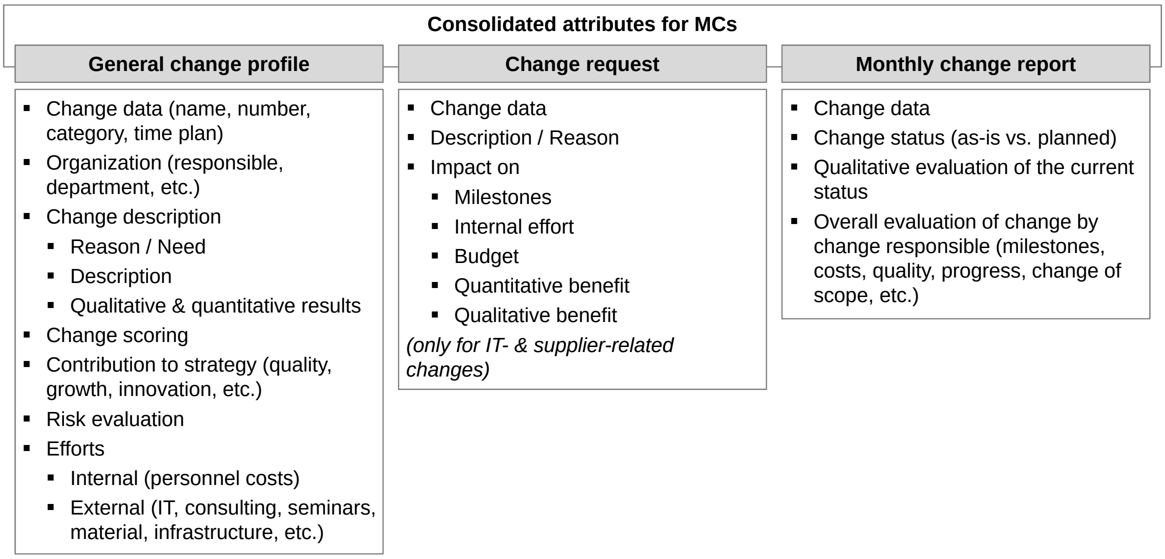

Figure 4.1: Illustration of the attributes for an MC utilized by company A

change specification, to the approval, roll-out, and closure. The phases are detailed by numerous activities described in the process documentation.

The MCM process of company A is structured as a highly linear sequence of activities with some feedback loops (“x” within the DSM) and termination points at the end of most phases (“T” on the diagonal of the DSM), while only few iterations and parallelized activities are considered (see figure 4.2). Within the process, almost no intra- or inter-phase clusters[4] of activities can be identified.[5] The feedback loops are spread throughout the MCM process, but all are described as intra-phase feedback loops. The same applies for the few parallelized activities and iterations. The adaptation of the MCM process is conducted by the change responsible, who plans and coordinates the activities. A distinct approach for process adaptation is sought, but currently not available at company A. According to the practitioners, such an approach should include two aspects, a tailoring of the process and a selection of roles to enable an extensive adaptation of the overall process.

[4] Clusters describe an accumulation of dependencies of activities. Intra-phase clusters are located within one process phase, inter-phase clusters extend over two or more process phases.
[5] Only during the concept creation, at the beginning of the change specification, and the implementation vague signs of clustering can be identified.

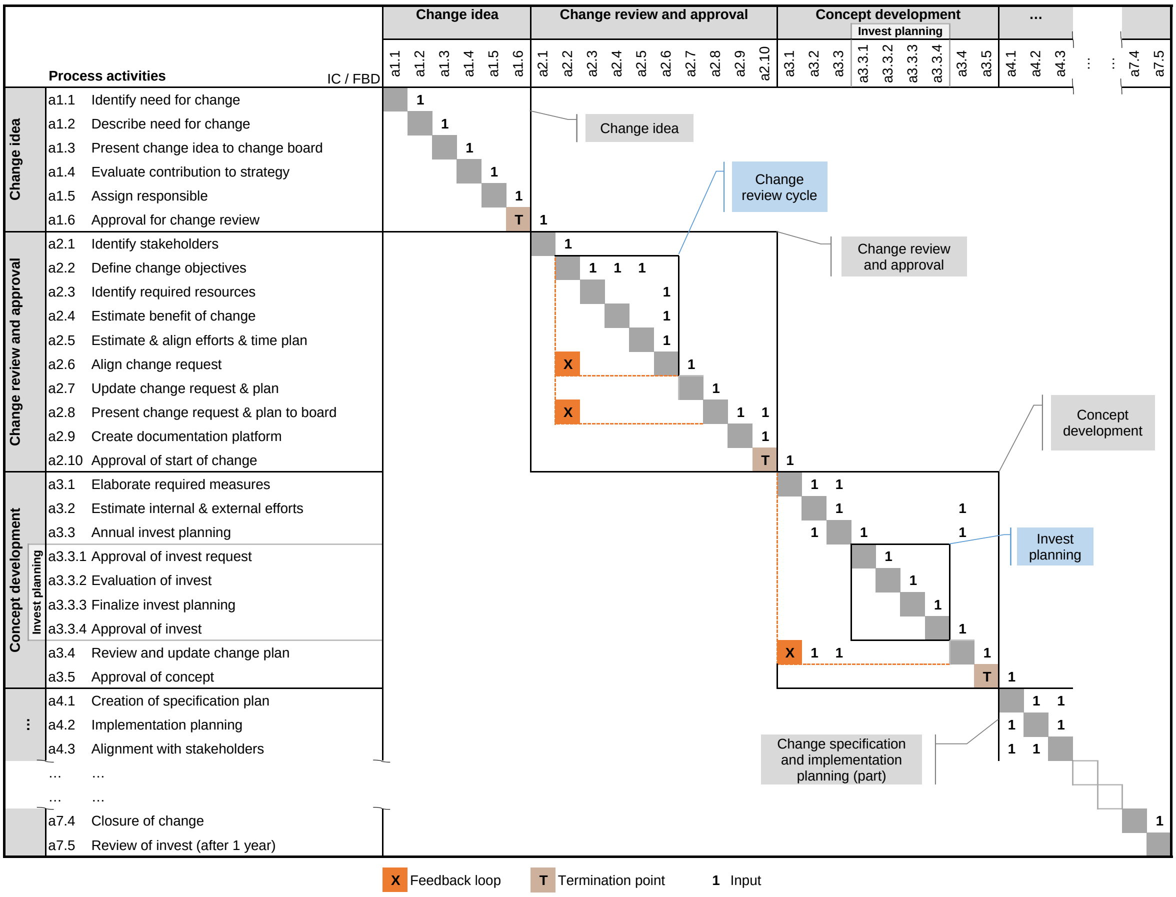

Figure 4.2: *DSM model of the MCM process of company A (excerpt)*

4.2.2 Initial case study with company B

Company B is a system supplier in the aerospace industry with more than 2,000 employees in Germany. The portfolio comprises small and regular series, the manufacturing activities include production and assembly. Being subject to rather strict rules and regulations regarding processes and documentation, the company has multiple years of experience with ECM and utilizes an IT-based workflow system to process ECs. In order to deal with MCs, different manufacturing specific processes are applied for MCM, of which most have been updated during the last two years. All of these processes are centrally documented and interlinked interactively in an IT-based system. Overall, they are utilized for several thousands of MCs per annum. Just for processing these MCs, costs are estimated at an average of about €1,000.

Main reasons for MCs are the annual investment planning, production improvements, and updates of the documentation; however, the change causes are not further specified or monitored at company B. Depending on the cause and type of change (e.g., update

Consolidated attributes for MCs			
General information	**Change impact**	**Classification**	**Checklists for**
▪ Requester	▪ Airworthiness	▪ Major change	▪ Purchase of a manufacturing resource
▪ Short description	▪ Form, weight, function	▪ Minor change	▪ Creation of a work plan
▪ Date of request	▪ Environmental	*(depending on the impact)*	▪ Approval of a work plan
▪ Work plan number	▪ Reliability / Safety		
▪ Time plan	▪ Drawing		
▪ Affected object in factory	▪ Manufacturability		
▪ Cause (error, rationalization)	▪ Tests		
▪ Responsible	▪ Customer		
▪ Specification of component (if product is affected)	▪ Supplier		
▪ Specification of work plan (if work plan is affected)	▪ Authorities		
▪ Costs			

Figure 4.3: Illustration of the attributes for an MC utilized by company B

of documentation, new technology, EC), the relevant change processes are chosen and applied by the person in charge of the respective change. In general, a production planner is responsible for most activities during the processes. However, the process descriptions provide distinct assignments of further roles and responsibilities. All documentation of an MC (e.g., relevant documents, presentations) is consolidated in one folder after the closure of the MC. A central tracking and coordination of MCs, an evaluation and / or documentation of gained knowledge during an MC, or lessons learned are not performed.

At company B, MCs are described with different attributes, which are provided as part of the process descriptions and as a list of questions describing several attributes. A specific change profile or list of attributes is not used. The proposed attributes can be used to specify an MC regarding, for example, the affected object, the impact on suppliers, costs, or the required time (see figure 4.3 for a consolidated list of attributes).

To gain a holistic perspective on the MCM approach applied by company B, a total of ten processes relevant for MCM had to be analyzed and merged to one extensive MCM process with different sub-processes. The resulting MCM process represents the entirety of MCM-relevant processes and structures all activities in three phases: strategic planning, change planning, and implementation. The activities start with a need for change, a first impact analysis and evaluation, and a change concept, followed by a very detailed change planning and implementation. Any MC is closed with the

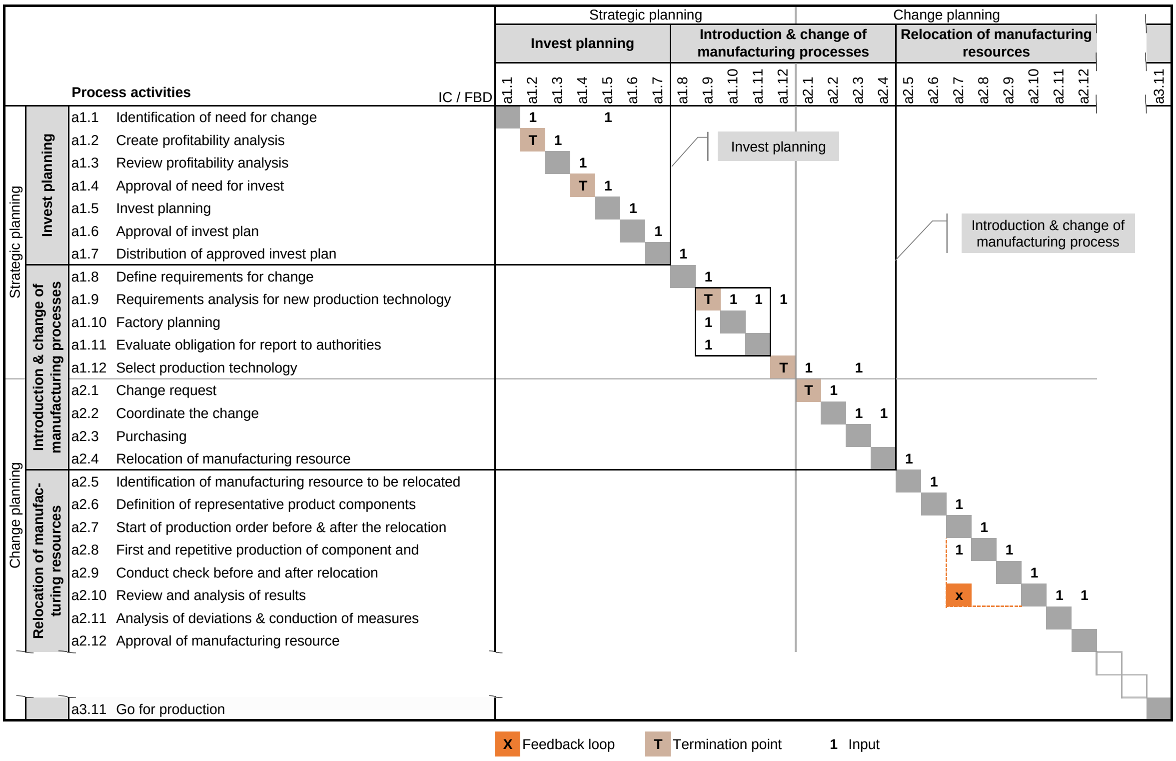

Figure 4.4: DSM model of the MCM process of company B (excerpt)

final documentation and a go for production. A review of the MC or lessons learned are not considered.

The MCM process of company B is structured as a highly linear sequence of activities with only one feedback loop, few termination points, and few parallel or iterative activities. All activities are allocated to specific sub-processes and phases, but only very few clusters of activities can be identified, which do barely reflect the overall process structure. The single feedback loop represents an intra-phase feedback at the beginning of the change planning, while some parallelizations of activities span across phases. The termination points are only available for the first phase (strategic planning) and at the very beginning of the second phase (change planning).

The adaptation of the process is mainly conducted by the change responsible through selecting relevant activities or sub-processes from the MCM process. In addition, some activities of the last phase can be adapted based on the necessity of detailed work plans and change documentation. An MC-specific adaptation of the process is not applied at company B.

4.2.3 Initial case study with company C

Company C is an OEM for medical technology with about 600 employees worldwide, thereof 450 working in Germany. Its portfolio covers several products in low and medium volume production. The company has multiple years of experience in ECM and utilizes an IT-based workflow system to support the ECM activities. Due to increasingly strict requirements regarding conformity with rules and regulations by authorities as well as the pharma industry, company C further developed its ECM and started to use it also for MCM recently. For the upcoming years, their MCM is expected to process at least 150 MCs per annum. In addition, about 250 ECs causing only small MCs (e.g., adaptations of documents) are to be managed each year. Costs for processing any MC are estimated at about €1,600.

The main element of the MCM concept applied by company C is the MCM process. It is triggered by different change causes, which have not been further specified so far. MCM responsibility is with a change coordinator and the management, while change measures for eachMC are defined and conducted by different departments. Knowledge gained during the MCM process manifests in increased experience of involved stakeholders, but is not captured and evaluated systematically within the MCM process.

Any MC occurring in company C can be described with numerous attributes, clustered in four categories. The attributes are documented in a dedicated "change profile" and cover aspects like "general information", "checklists", "change classification", and "distribution". Most attributes address the general information of an MC, providing a high level of detail regarding involved stakeholders, tool information, and change description. In contrast, the change classification only comprises four attributes, of which one is actually used to characterize the MC ("obligatory vs. non-obligatory"). The remaining attributes are distributed across the other two categories. Figure 4.5 visualizes the change profile for MCs of company C.

Starting with a change request, the MCM process of company C structures all activities in a sequence covering six general process phases: "change request", "change analysis & decision", "change planning", "approval", "change implementation & approval", and "closure". From a content perspective, the focus of the MCM process is on processing a distinct change request until its final completion; a proactive change

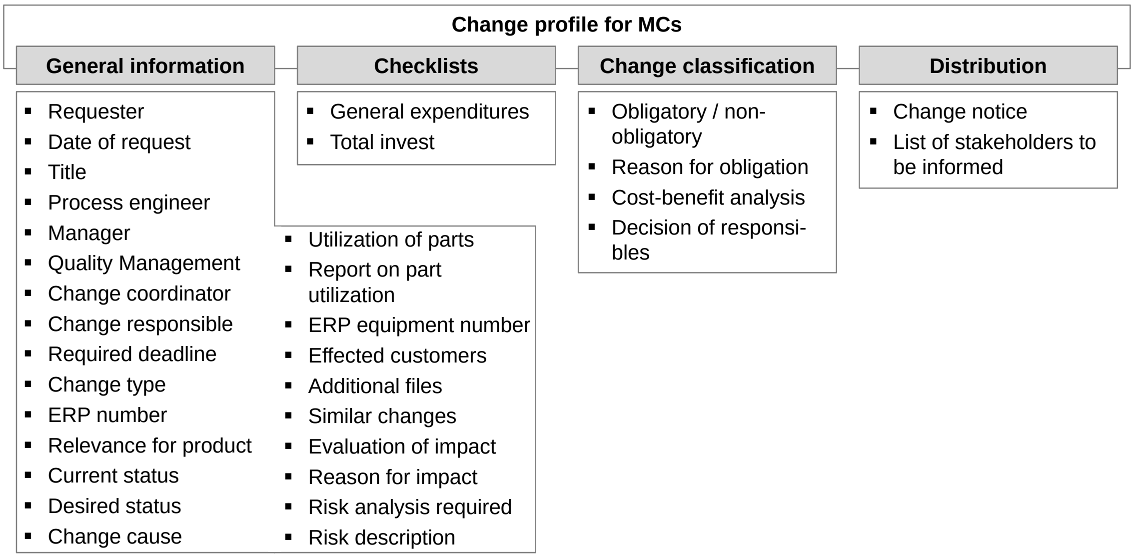

Figure 4.5: Illustration of the change profile for MCs of company C

identification and analysis as well as retrospective activities such as lessons learned are not considered.

The DSM of the MCM process reveals a uniform, highly linear sequence of activities with few iterations and feedback loops (see figure 4.6). The overall process architecture is created by the different phases and allocated activities, but is rarely reflected in the activity network as there is no difference between the relation of activities within or across phases (i.e., there are no clusters of activities for specific phases). In total, the MCM process comprises three iterations: one during phase two, one during phase three, and the third one across phases three to five (the planning of action items cycle). Parallel activities are not considered in the process documentation, but a few inter-phase and intra-phase feedback loops to re-entry the process in case of rework are described. Also, several termination points are provided in the first and second phase to be able to cancel the process in case of, for example, a rejection of a change request.

Finally, there are two possibilities for process adaptations considered in phase two, which depend on the potential obligation of the change and the result of the cost-benefit analysis (see the "forks" in figure 4.6). Besides these two possible adaptations, the MCM process is not adapted to different MCs. However, the stakeholders to be involved for a specific MC are determined and selected by the change coordinator based on a checklist.

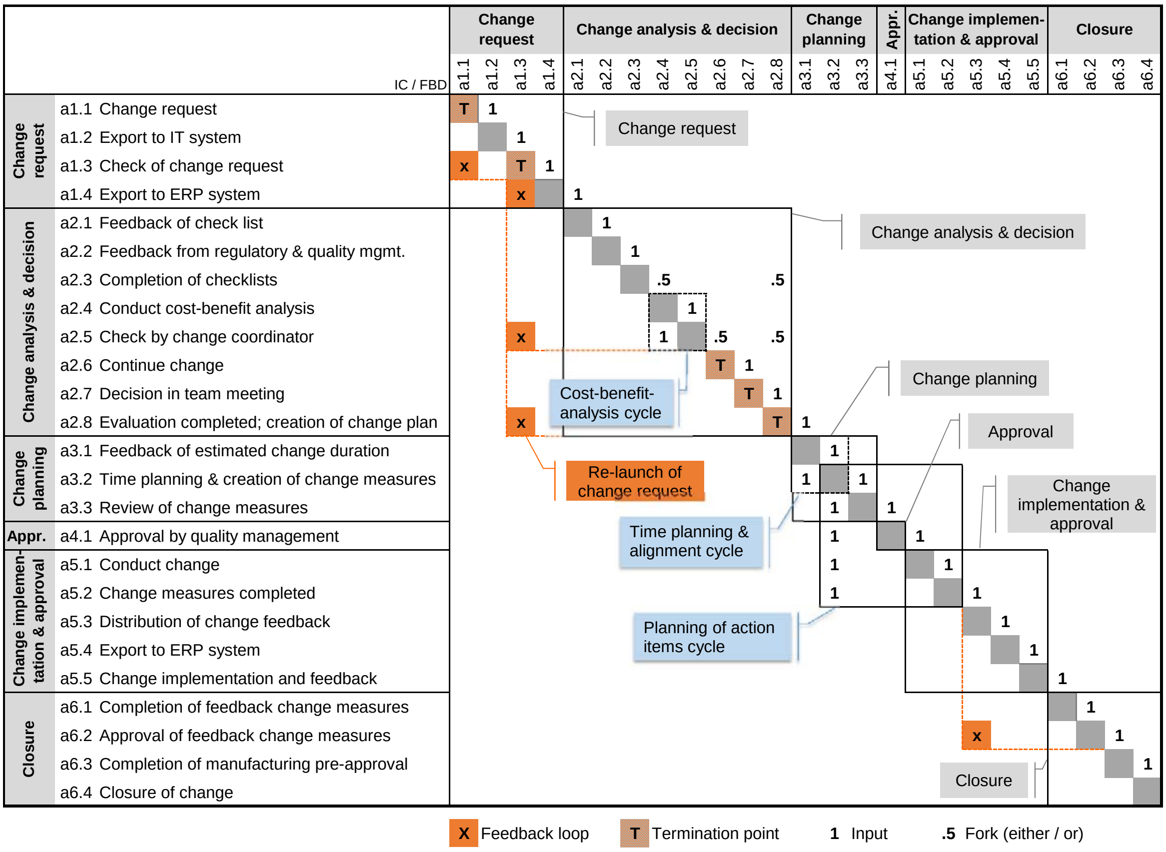

Figure 4.6: DSM model of the MCM process of company C

4.3 Cross-case analysis – findings

Based on the requirements for MCM effectiveness and efficiency (cf. section 1.4), the three case studies are cross-analyzed qualitatively and quantitatively if determinable with accessible data (e.g., for the process structure). Overall, two different MCM approaches have been identified. Company A and B utilize several processes for MCM, while company C applies one single, ECM-based process. MCs are described with various attributes in different documents, for the processes basic descriptions of process content and often rudimentary process architectures are available.

From a content perspective, especially reactive and partly proactive activities are considered for the identification and planning of changes. The adaptation of processes includes two aspects – the tailoring of the processes and the selection of relevant roles. Both are mainly based on experience or checklists (for the role selection). Different roles are described and mostly allocated to the processes, for example, a change manager, a change committee, or a work planner. Despite central coordination functions, MCs are only occasionally aligned and coordinated; reviews and lessons learned are not conducted. In addition to this brief summary, for each MCM requirement the detailed results are described in table 4.1.

Table 4.1: Current practice of MCM in industry: findings from the cross-case analysis

Requirement: **Systemic perspective (Holistic view)**

- **Decentralized MCM approach** with a focus on manufacturing planning (A,B) or **adapted ECM process** with a focus on the description and alignment of MCs (C)
- **Attribute-based MC description**, various documents (e.g., change profile, proposal)
- **One** (C) or **several processes** (A,B) for MCM with **mostly reactive, partly proactive activities**; few deliverables defined; **basic process structure** available and described (C)

Requirement: **Stakeholder involvement & interfaces (Holistic view)**

- Usually **early identification and involvement of relevant stakeholders**, but **no repeated review and update** during the MCM process; involvement of customers not considered

Requirement: **Enterprise-independent applicability (Applicability)**

- **Company-specific concepts** applied for MCM

Requirement: **Transparency & simplicity (Applicability)**

- **Basic process descriptions available** (textual and flow charts), but **few information about process details** like deliverables, in- and outputs, dependencies, etc.
- One (C) or various (A,B) **documents with attributes** available to describe MCs

Requirement: **Clear roles & responsibilities (Applicability)**

- **Different roles for MCM**, allocated to the process (e.g., change requester, project manager, work planner, change committee); usually one main responsible

Requirement: **Defined process structure (Process orientation)**

- Description of **process phases, activities, and their sequence**, but **limited information** on deliverables, in- and outputs, etc.; structure of processes is **highly linear with few dependencies and no activity clusters**
- **Few (planned) iterations** in the MCM process (about 12% to 26% of the activities)
- **Some feedback loops** and **termination points**, few or no reviews and approvals described
- Different degree of **parallelization of activities** (from no to almost 39%)

Requirement: **Coordination & information flow (Process orientation)**

- Limited consideration of **synchronization points** during the process
- **Centralized coordination** established (A,C) or planned (B); conducted by a **change committee** or sometimes by a **change manager**
- **No differentiation of activities** regarding, e.g., required quality of output, thoroughness

Requirement: **Process adaptation (Process orientation)**

- **MC- and experienced-based selection** of processes (A,B), **standardized MCM process with minor tailoring** to account for (non-)obligatory MCs (C)
- **Experienced-based** (A,B) or **checklist-based** (C) **selection of roles** and stakeholders

Requirement: **Change identification (Proactivity)**

- Individual, **decentralized identification** of need for change, partly with planned activities; **early process phases** address the change identification (A,B) or the change request (C)

Requirement: **Early change evaluation (Proactivity)**

- **Rough estimation** of expected costs, required resources, and efforts during the initiation of an MC; **impact analysis** sometimes conducted (C) or not considered (A,B)
- MCs often **processed as separate changes**; except (C), **almost no cross-MC review, alignment, and coordination** applied (A,B)

Requirement: **Cause & impact analysis (Problem solving & analytic capabilities)**

- **Heterogeneous approaches for cause and impact analysis** (e.g., detailed analysis, analysis after detailed change planning, impact analysis with stakeholders)
- **Detailed cost or cost-benefit analysis** during change planning

Requirement: **Solution finding & implementation (Problem solving & analytic capabil.)**

- **Concept development** as part of the MCM process (A,B); concept required as part of the change request to start the MCM process (C)
- **Detailed change planning** as part of the MCM process; **implementation planning** not or only partly considered; **implementation** partly or fully considered

Requirement: **Archiving & tracing of information (Knowledge management)**

- **Individual MC documentation** with subsequent digital documentation (A,B), **continuous digital MC documentation** during the MCM process (C)

Requirement: **Control of success & lessons learned (Knowledge management)**

- **Process ends with successful implementation** of MC, most often **no evaluation of the change**, no documentation of learnings
- Archiving of all information / final report, but **no selection and consolidation of documents / data / information** with closure of MC

Requirement: **Efficient processing (MCM efficiency)**

- No specific measures identified; **costs for processing MCs** range between €1,000 and €1,600; amounts of up to several thousand MCs per year

4.4 Conclusion

These findings contribute to answering the four research questions Q1 to Q4 (cf. section 1.3.1) complementing the state of the art (cf. section 3.7).

The companies utilize company-specific MCM approaches neglecting a holistic, system-oriented perspective on MCM (cf. research question Q1). Although certain aspects from the state of the art (e.g., process-orientation, description of MCs) could be identified, an MCM-specific system and context model is not available.

The description of MCs (cf. research question Q2) is based on different change attributes and documents (such as a change profile). However, a consistent, detailed MC model holistically describing any MC is not available at any of the three companies.

Also, a detailed MCM process to efficiently and effectively manage MCs is not available (cf. research question Q3). The companies use one or more processes mainly addressing the reactive identification and planning of changes. Proactivity and knowledge management are barely reflected within the processes. In addition, the processes are documented as highly linear sequences only, iterations, parallelization, and feedbacks are scarcely considered.

In contrast, different roles for MCM are described providing a valuable supplement to the scarce state of the art for this aspect. Regarding the adaptation of processes, the companies mainly apply an experienced-based selection of processes and roles, a change-specific adaptation approach is not available.

By the time of the case studies, an evaluation of the benefits of MCM (cf. research question Q4) has not been conducted by the three companies. Although the practitioners agreed upon the fundamental benefit of a process-based management of MCs, only estimations of costs for processing MCs and the amount of MCs could be provided. These are generally in line with findings from the state of the art for ECs.

Overall, these case study findings corroborate the need to support practitioners in managing MCs effectively and efficiently (cf. section 1.2), i.e., to develop a process-based MCM approach. Complementing the state of the art, the case studies and the findings from literature together provide a broad data basis for the subsequent development of the MCM approach.

5 Conceptual Design of MCM

As a first major part of the prescriptive study (cf. 1.3.3), this section comprises the conceptual design of the MCM approach – the MCM context model. As expressed by its very name, this context model seeks to not only represent MCM as a separate, independent object, but together with its accompanying setting / circumstances and "in terms of which it can be fully understood" (OXFORD DICTIONARIES 2016). The MCM context model is developed based on the MCM requirements, findings from the literature review (cf. section 3.1) and current practice in industry. Starting with the concept development, the overall composition and structure of the model is defined, followed by the design of the general and the specific MCM system architecture. The results have been carefully reviewed with the case study partners and other researchers and are critically discussed in the conclusion of this section.[1]

5.1 Concept development for the MCM context model

The MCM context model is intended to support an enterprise-independent, detailed development of MCM while also supporting clarity and intelligibility of the overall approach. By this, the MCM context model specifically contributes to the first two categories of MCM effectiveness – "holistic view" and "applicability" – but shall as well reflect and substantiate the remaining categories and allocated requirements (see section 1.4 and the appendix, table A.1 for further details).

Accounting for the concept of systems thinking and systems engineering (cf. section 1.3.3), different but complementary approaches are applied: a non-formalized graphical and textual approach to create and visualize the overall MCM context model, and a matrix-based approach (MDM) to capture the detailed architecture of the model and create a structured conceptual basis for the development of the MCM approach.

[1] Note, that a prior version of the models presented in this chapter has been published in KOCH et al. (2015a) and KOCH et al. (2016a).

The formal MCM context model consists of nodes and edges, modeling elements as nodes and their relations as edges. Each element may be a sub-system itself and contain hierarchically arranged elements and their relations if necessary. The elements considered relevant are either physically tangible or intangible and are clearly termed based on the definitions provided in chapter 2, if not stated otherwise. Together, the elements determine the composition and structure of the overall system, the MCM context model. Accounting for the general purpose of the MCM context model, the MCM requirements, and findings from literature and industrial practice, the following elements are considered relevant (see table 5.1). For each, a brief explanation regarding the selection is provided.

Table 5.1: Elements considered for the MCM context model

Element	**Details regarding the selection**
Change cause	Fundamental origin of any Manufacturing Change or Engineering Change, comprises relevant events or triggers leading to changes
Manufacturing Change	Object of observation of any change management activity in the field of manufacturing
Factory	Subject to any occurring Manufacturing Change, might also create causes for further changes
MCM process	Main design element for a process-oriented MCM concept
Engineering Change	Object of observation of any change management activity in the field of engineering
Product	Subject to any occurring Engineering Change, might also create causes for further changes
ECM process	Main design element for a process-oriented ECM concept
Process support	Relevant objects supporting the implementation and operation of MCM, for example, roles or methods

Besides these, the following elements have not been considered for the context model, but might be incorporated in a further evolved version of the model (see table 5.2). If needed, additional elements and dependencies might be added to adjust the model to company-specific requirements.[2]

Accounting for both the fundamental similarities and dependencies of ECM and MCM as well as the various differences (cf. sections 2.1 and 2.2), the context model is symmetrically

[2] Generally, other processes like the product development process or technology planning represent potential sources of change causes. For the MCM context model, change causes are considered as a distinct element. In case other processes are considered relevant and do not represent potential change causes, those might be added to the model.

Table 5.2: Elements not considered for the MCM context model

Element	Details regarding the non-selection
Factory planning process	MCM mainly addresses factories in operation
Product development process	Mainly relevant for ECM
Additional processes	For example, purchasing or technology planning; mainly serve as potential sources of change causes
Organization	Application- and company-specific
IT	Application- and company-specific

separated into two sections: one for MCM and one for ECM (see figure 5.1). They are closely interrelated, but also able to operate independently. In other words, MCM constitutes the counterpart of ECM in the manufacturing domain.[3] Both sections comprise the same type of elements: a change management process, the change itself, and the object of the change. In addition to their direct interrelations, the two sections are linked by two elements: the change cause and the process support. Together, the context model represents a system with eight elements, of which some also represent systems.

The change processes are located in the very center of the context model reflecting their relevance for the intended process-oriented MCM design. The other elements of the MCM section (change cause, MC, and factory) are arranged from left to right according to their causal relationship (change cause leads to MC, which impacts the factory). The same applies for their counterparts in the ECM section. The process support is located beneath all other elements accounting for its assisting character for MCM (and ECM).

5.2 General MCM system architecture

To capture the system architecture of the MCM context model with a matrix-based modeling approach, its elements are considered different domains, which can comprise several sub-domains. Together with their dependencies, these eight domains form the general system

[3] In principle, a merger of MCM and ECM is conceivable combining both change processes to a joint Engineering and Manufacturing Change Management. Thus, the increasingly strong link between product and factory system could be reflected on a process level leveraging potential synergies of both Engineering and Manufacturing Changes. In the years 2016 to 2019, two sub-projects of the CRC 768 address this topic with the development of a so-called Systemic Change Management.

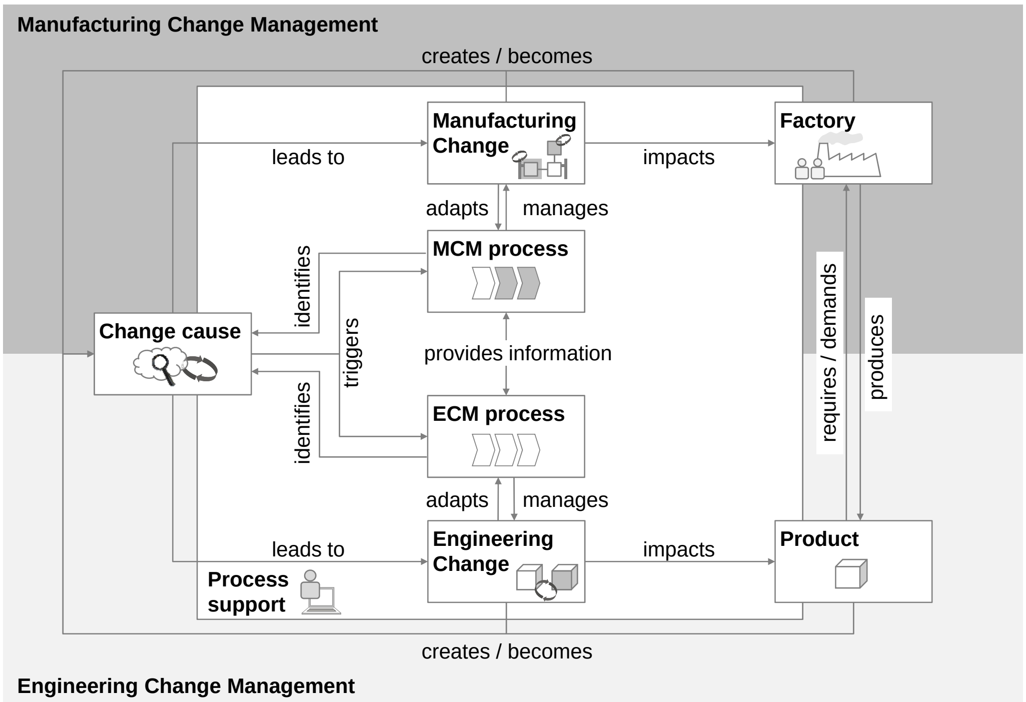

Figure 5.1: Graphical illustration of the MCM context model

architecture and are modeled with an MDM (cf. section 2.5.4). Subsequently, the sub-domains are considered in more specific MDM models of the MCM context model (see section 5.3).

The resulting, non-modified 8 *x* 8 MDM visualizes the general system architecture of the context model (see figure 5.2). Starting with the domain change cause, two main sections (MCM and ECM) can be distinguished having the domain process support in between. Compared to the graphic illustration of the context model, the MDM depicts the specific dependencies between the eight domains more clearly. Also, it provides first insights into the sub-structure of the eight domains[4] and fosters the systemic understanding of MCM.

Based on the definitions derived in sections 2.1 to 2.4 and findings from literature and industry, the eight domains are described as domain models including their scope, their dependencies, and their relevance for the intended MCM approach.

[4] On the diagonal, empty fields indicate a domain consisting of different sub-domains, while fields containing a dependency indicate a domain to consist of associated elements only.

	IC / FBD	Change cause	MCM process	Manufacturing Change	Factory	Process support	ECM process	Engineering Change	Product
	Change cause	relates to	triggers	leads to			triggers	leads to	
MCM	**MCM process**	identifies		manages			provides information		
MCM	**Manufacturing Change**	create / becomes	tailors	affects	impacts	selects			
MCM	**Factory**	create / becomes							produces
	Process support		assists				assists		
ECM	**ECM process**	identifies	provides information					manages	
ECM	**Engineering Change**	creates / becomes				selects	tailors	affects	impacts
ECM	**Product**				requires / demands				

Figure 5.2: MDM of the general system architecture of the MCM context model

Change cause

This domain includes the relevant areas, where events or triggers for either an EC or an MC potentially occur (cf. section 2.1.1). It triggers the MCM process (or the ECM process respectively). As the origin of any change, this domain is considered to have a fundamental relevance for MCM (and ECM) – i.e., it is considered a core element of MCM; its numerous dependencies to the other domains further add to this.

Manufacturing Change

This domain describes any change that occurs within a factory (cf. section 2.1.3) and comprises relevant attributes to specify an MC (cf. 3.2). These attributes are not necessarily independent and might affect each other (e.g., the duration of a change might influence the costs). MCs are subject of any MCM activity, impact the factory, and might create or become change causes themselves (this phenomenon is generally referred to as “change propagation” (cf., e.g., CLARKSON et al. 2004, PLEHN et al. 2016a). Also, MCs could be used to tailor the MCM process and select relevant roles based on their attributes (cf. section 4.2). Overall, this domain is highly interrelated to the other domains, especially to the MCM process. Hence, it represents one of the core elements of MCM.

MCM process

This domain substantiates the process-orientation of MCM and describes a reference procedure to manage changes in manufacturing (cf. section 2.4.3). According to the modeling approaches selected for the MCM process design (cf. section 2.5.4), the domain comprises stages and gates for a high-level understanding and controlling, and activities and deliverables for a homogeneous, detailed understanding and description through PAF.

- *Stage*: Section or phase that comprises a set of activities
- *Gate*: Closure of the previous stage and "entrance" to the subsequent stage; comprises a set of deliverables
- *Activity*: "Constituent element of a process system. [...] packages of work to be done to produce results [...]" (BROWNING et al. 2006, p. 117; cf. section 2.5.4)
- *Deliverable*: "[...] represent any information, data, result, material, etc. produced or required by an activity" (BROWNING et al. 2006, p. 117; cf. section 2.5.4)

The MCM process is applied to identify change causes and to manage MCs. Also, it can be triggered by a change cause, tailored by an MC, and provides information to the ECM process if required. Due to these numerous dependencies and its inherent importance for the process-orientation of MCM, this domain represents the core of MCM.

Factory

This domain describes the grouped production factors fulfilling a defined part of the value stream to produce a tangible item – the product. For MCM, four different sub-domains are considered relevant to be subject to an MC.

- *Factory system*: Comprises "the spatial arrangement, relations, and properties of a 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. 2015)

– *Manufacturing processes*: Especially production and assembly procedures, but potentially also other processes in a factory, for example, maintenance activities[5]

– *Documentation*: Documents, for example, for order control or machine documentation

– *Factory organization*: For example, composition of assembly teams, job assignments, or job shop and order control[6]

These four sub-domains proposed indicate the broad range of potential change objects within a factory and provide valuable input for detailing the attributes of the domain MC (cf. section 6.2). In addition, modeling the domain factory with its various facets promises great potential for further research on, for example, the changeability of a factory or the analysis of change impacts and change propagation in manufacturing.[7] For further information about this field of research please refer to, for example, PLEHN et al. (2015).

The domain factory is impacted by MCs, produces products and can become or create a change cause due to, for example, aging equipment (which could require the exchange of manufacturing resources) or complications in manufacturing (e.g., quality issues leading to an adaptation of the manufacturing process or the equipment). It supplements information for the detailed development of the domains change cause and MC, but is not considered one of the relevant elements for the MCM process design having no relation to this domain.

Process support

This domain covers the supporting elements for the other domains of the MCM context model, especially the processes. It comprises two sub-domains considered relevant for MCM (cf. section 1.4 and 4.2):

– *Role*: Comprises relevant roles to conduct MCM

– *Method & tool*: Comprises relevant methods & tools to support the different activities of the MCM process and the roles

5 The range of relevant processes might vary from company to company depending on the organizational setup of the factory and the MCM.

6 This sub-domain relates to the listed organizational aspects in a factory, but not to changes of the whole or parts of the general organization. Those changes are addressed by Organizational Change Management (cf. section 2.2.3).

7 For this case or even other applications additional sub-domains might be supplemented or exchanged, if desired.

The sub-domain role is especially relevant to guide and simplify an implementation of MCM in industrial practice and to assign responsibilities. Method & tool is not necessarily required to develop an MCM approach, but is assumed to provide valuable information to practitioners to conduct MCM. Due to this supportive characteristic, this domain is also considered a core element for MCM (as well as for ECM).

Domains of the ECM section

The remaining domains of the context model – ECM process, EC, and product – are counterparts of the respective elements within the MCM section and can be modeled similarly with the level of abstraction chosen for this research. The EC comprises relevant attributes and has dependencies to all other domains within the ECM section (cf. section 2.1.2). It impacts the product and can become a change cause leading to further Engineering or Manufacturing Changes. The ECM process (cf. section 2.2.1) can be modeled like the MCM process with the same sub-domains and similar relations. The product is a tangible item produced by the factory, which is a simple but sufficient definition for the purpose of this research. This domain comprises sub-domains such as components and documentation (e.g., drawings, part lists) and has similar relations like the domain factory. Overall, these domains have to be considered for developing MCM, especially regarding their dependencies to the domains change cause, MCM process and process support. Beyond this, an equally detailed design (as for the other domains) is neither intended nor required for the development of MCM.[8]

5.3 Specific MCM system architecture

Based on the MCM context model, its general system architecture, and the more detailed domain models, the specific MCM system architecture can be designed. Embedding all domain models including sub-domains into the MDM of the MCM context model, the model would expand up to a 19 *x* 19 matrix, significantly increasing its complexity. Taking this and the differing relevance of the domains into account, the domains change cause, MC, MCM process, and process support, which represent the core elements for MCM (cf. section 5.2), are selected for the development of the specific MCM system architecture.

[8] Nevertheless, a potential integration of ECM and MCM to a joint, systemic change management might require more detailed ECM models. In this case, comprehensive literature is available in this field (e.g., JARRATT et al. 2011, HAMRAZ et al. 2013).

	IC / FBD	Change cause	Stage	Gate	Activity	Delive-rable	Manufac-turing Change	Role	Method & tool
	Change cause	relates to			triggers		leads to		
MCM process	**Stage**		relates to	generates	includes				
MCM process	**Gate**		starts	relates to		includes			
MCM process	**Activity**	identifies	adds up to		relates to	generates	manages		
MCM process	**Delive-rable**	describes		adds up to	is input for	relates to			
	Manufac-turing Change	creates / becomes				tailors	affects	selects	
Process support	**Role**				conducts	approves		relates to	
Process support	**Method & tool**				supports				relates to

Figure 5.3: MDM of the specific MCM system architecture

Mapping these four core domains to each other, so-called Domain Mapping Matrices (DMM) are created. Each DMM contains the information about the dependencies of one domain to all other domains (e.g., domain change cause and its dependencies to the domains MC, MCM process, and process support). Together, the DMMs create the resulting MDM of the specific MCM system architecture (see figure 5.3), which represents a focused and more detailed version than the MDM of the general MCM system architecture (cf. figure 5.2). Especially, additional insights regarding dependencies of the MCM process' sub-domains to each other as well as to the other MCM core domains are provided. Note that these more detailed dependencies are not depicted in the graphical illustration of the MCM context model for reasons of clarity of the overall context model (cf. figure 5.1).

5.4 Conclusion

In total, eight elements (domains) are considered relevant for this research: change cause, MC, MCM process, factory, EC, ECM process, product, and process support. Together with their dependencies, these form the MCM context model. The selection and modeling of these elements accounts for both findings from the literature review and insights from industrial practice. Also, careful reviews of the results have been accomplished together with practitioners from industry and other researchers from the field of engineering.

Based on the system architecture models, the number of domains and dependencies to be considered for the intended detailed MCM design could be restricted to change cause, MC, MCM process, and process support. Some of the remaining domains have been identified relevant for adjacent research topics like process interfaces (ECM process) or change analyses (factory, product).

Overall, the developed MCM context model addresses the MCM requirements described in section 5.1 and in detail in the appendix, table A.1. Examples are the holistic setup, the consideration of interfaces between elements, a process orientation, and transparency and simplicity. However, the model is limited to manufacturing companies in its current version.

Furthermore, the developed context model allows for exchanges or supplements of domains as well as for further enhancements in future research activities: for example, it could be extended by additional domains (e.g., factory planning process or IT) and dependencies depending on the respective requirements or use cases; the domains ECM process and MCM process could be merged; a formalized graphical representation of the context model could be developed.

For this research, the results described in this chapter provide a thorough basis for the subsequent, detailed MCM design.

6 Detailed Design of MCM

As the second major part of the prescriptive study (cf. section 1.3.3), this chapter comprises the development of the MCM elements (domains) change cause, MC, and the design of the MCM process including the process support. In addition, the dependencies of these elements are described and modeled in detail to subsequently develop an approach for an MC-specific adaptation of the MCM process. For each of the elements as well as the adaptation approach, first a general concept is created based on the MCM requirements (cf. section 1.4) and the MCM context model (cf. section 5.1). Then, the design activities, analyses, and detailed results are described. Finally, each section concludes with a critical review and discussion of the results.

6.1 Change causes

Being one of the main elements of the specific MCM system architecture and the origin of any MC, this element is intended to comprise the relevant areas of change causes and to provide input for the detailed description of an MC as well as the later adaptation approach for the MCM process. In order to provide a generally applicable set of change causes, an extensive literature review is conducted, supplemented with insights from industrial case studies, expert interviews, and a web-based survey on MCM. Regarding the MCM requirements the company-independent applicability, transparency & simplicity, and the change identification are taken into account.[1,2]

6.1.1 Areas of change causes

In order to establish and describe relevant areas of change causes – i.e., where events or triggers for an MC (or an EC) potentially occur (cf. section 2.1.1) – change causes described

[1] In contrast to the other elements, only few requirements are relevant for the change causes.
[2] Note, that an excerpt of this chapter has been published in KOCH et al. (2016a) and KOCH et al. (2016b).

	Manufacturing												*Product development*							
Areas of change causes	Dohms (2001)	Hernandez Morales (2003)	Wemhöner (2005)	Rößing (2007)	Wiendahl et al. (2007)	Nyhuis et al. 2008	Westkämper et al (2009)	Dudic (2010)	Zäh et al. (2010a)	Zäh et al. (2010b)	Wulf (2011)	Klemke (2014)	Pflicht (1989)	Gemmerich (1995)	Wildemann (1995)	Conrat (1997)	…	Ehrlenspiel (2013)	Industrial practice	Σ
Factory life cycle	x	x		x	x	x	x		x	x	x	x	x	x				x	x	23
Manufacturing Change						x								x			…		x	7
Complications			x	x			x	x		x			x	x	x	x		x	x	21
…					…			…				…				…	…		x	…
Errors / Failures				x									x	x	x	x		x	x	20

Figure 6.1: Excerpt of the literature analysis on change cause areas

in literature and considered in industrial practice have been identified, compiled, categorized, and consolidated in utmost accordance with the MCM context model. In total, eleven areas are proposed relevant for MCM either corresponding to manufacturing, to product development, or to general occurrences. Figure 6.1 shows an excerpt of the literature analysis, the complete list of sources reviewed is provided in the appendix, table A.2.

The resulting change cause areas are illustrated in figure 6.2. Each area is further detailed and supplemented with information on exemplary potential information sources, which may be involved in the MCM process for the respective change cause and resulting MC (see table 6.1; cf. also section 6.4.4).

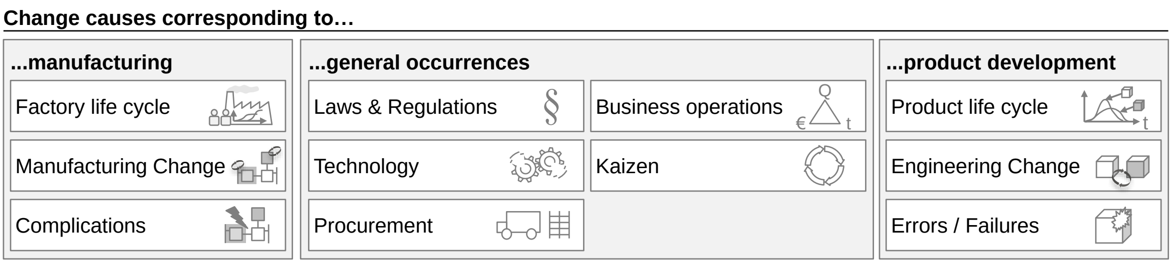

Figure 6.2: Areas of change causes for MCs

Table 6.1: Areas of change causes for MCs

Change cause areas	**Description**	**Potential information sources: Staff from…**
Factory life cycle	Factory-internal change causes such as aging manufacturing resources, an aging factory system, new employees and age structure of workers, production processes, maintenance, and logistics.	Production and factory planning, maintenance, shop floor
Manufacturing Change	Change causes due to other MCs (often referred to with the term “change propagation”).	MCM, production and factory planning, shop floor
Complications	Factory-internal change causes, such as quality issues, disturbances in manufacturing processes, non-fulfillment of requirements, or mistakes in production or factory planning.	Quality management, production or factory planning, shop floor
Laws & Regulations	Company-internal and -external change causes such as new or changed guidelines and norms, governmental laws and regulations regarding, among others, environmental protection, labor time and safety, hazardous materials, or energy consumption.	Legal, workers council, business development, strategy
Technology	Introduction of new product or production technologies.	Technology planning, product development
Procurement	Procurement- and resource-related change causes, for example, changes in the supply chain, quality issues of supplied resources, difficulties in delivery, or availability of new employees.	Purchase departments, supplier management, human resources
Business operations	Company-internal change causes related to operative and strategic goals of a company such as performance and quality targets, improvement measures, or adaptations in business strategy.	Operative and strategic management, business development, strategy
Kaizen	Suggestions for improvement with relation to a product and / or the factory.	Shop floor, factory planning, product development
Product life cycle	Product-related change causes such as changes in the number of units sold, launches of new product variants, or introduction of new products.	Product planning, sales and marketing, business development, strategy
Engineering Change	Very similar to the MC this area covers change causes due to other ECs.	product development, production and factory planning, shop floor
Errors / Failures	Product-related change causes such as quality issues, non-fulfillment of functional requirements, or mistakes in product development.	Quality mgmt., product development, sales, production and factory planning, shop floor

6.1.2 Conclusion

Comprising eleven generalized areas of change causes related to either manufacturing, product development, or general occurrence, the proposed categorization of change causes covers the main events and triggers for MCs and ECs. These provide valuable input for the subsequent development of the MC model and the adaptation approach for the MCM process. Despite the generalized categorization, the relevance of the different change causes might vary depending on the respective industry and company. If needed, additional change causes could be supplemented to further extend the proposed categorization.

6.2 Manufacturing Changes

Being part of the specific MCM system architecture (cf. section 5.3), the element MC represents any change within a factory, thus an alteration made to a production system or its elements (cf. section 2.1.3). Similar to available classification concepts and characterizations proposed in literature (cf. section 3.2) or used in industrial practice (e.g., a change profile; cf. section 4.2), a holistic, generalized model of MCs is developed based on the broad scientific and practical information basis. The MC model is intended to serve as a reference for the description of any MC, the continuous documentation and coordination of MCs during the MCM process (e.g., in form of a change profile), and the MC-specific adaptation of the MCM process. Also, it supports a future development of a formalized MC data model to enable an IT-based recording, analysis, and exchange of MC data.[3]

6.2.1 Concept development for the MC model

Substantiated by the fact of a broad usage of attributes to characterize changes in literature and industry (cf. sections 3.2 and 4.1), for this research attributes are assumed to be suitable to develop a holistic and precise model of an MC. Taking the MCM requirements into account (cf. section 1.4 and the appendix, table A.1), the MC model is consistently structured applying textual and matrix-based approaches.[4]

[3] For an example of an EC data model cf. SHARAFI (2012, p. 157) or VDA (2010a, pp. 63-73).

[4] For the MC model, non-formalized matrices and texts are used to visualize and describe its structure and content. However, also the application of DMM or graph-based approaches is generally possible, but not considered to provide additional benefit regarding the purpose of the MC model.

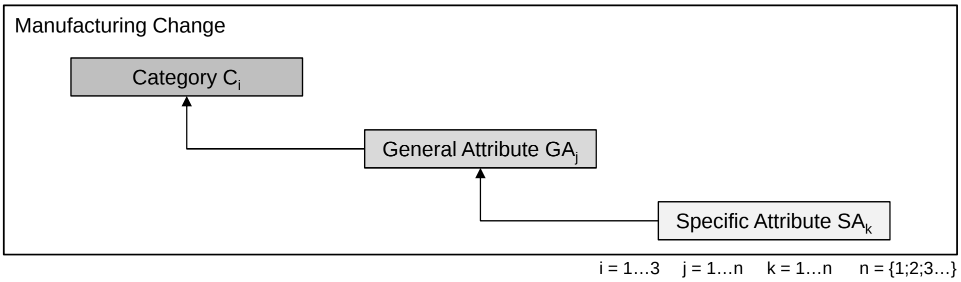

Figure 6.3: Setup of the MC model

The MC attributes are differentiated by general and more detailed, specific attributes describing the characteristics of any MC. All attributes are allocated to categories helping to structure them regarding their subsequent usage during the MCM process (see figure 6.3).

The MC model serves as a holistic, generalized model for any MC, but does not provide predetermined classification schemes for different MCs. As classifications of MCs tend to depend on the respective industry or company (cf., e.g., ASSMANN 2000), the intended MC model is designed to rather represent a thorough basis to derive company-specific classifications. Also, process data (e.g., processing times, number of visits by employees) are not considered for the MC model, as these depend on the potential application of an IT tool, the type of tool, and the rights of information usage in a company. However, these might be supplemented if needed.

For the MC model, the following three categories are proposed based on the findings from the industrial case studies (cf. section 4.2) and the state of the art (cf. section 3.2.3).

– *Specification*: comprises the attributes to clearly and definitely identify any MC

– *Characterization*: comprises the attributes to describe the essentials, the nature of any MC

– *Coordination and evaluation*: comprises the attributes to organize and assess any MC

6.2.2 Detailed MC model

The attributes describing an MC result from a detailed review and analysis of change attributes proposed in scientific literature and / or utilized in industrial practice. In total, 38 publications have been reviewed, of which 4 address MCs and 34 ECs. Regarding the industrial perspective, findings from the three case studies are considered. The change attributes identified have been compiled, clustered, consolidated, and evaluated regarding their description and level of detail provided by the author / documentation.

The evaluation is based on a four-point color scale indicating no consideration of an attribute (white) to specifically considered and described in detail (dark). Figure 6.4 shows an excerpt of the evaluation results covering several publications considered, the three case studies, and the summed total relevance of each attribute. The ordering of attributes results from the combined assessment of the evaluation results, the proposed terms and their meaning, and logical reasoning. The complete list of publications considered is provided in the appendix, table A.2.

General attributes	Specific attributes	MC				EC																		Industry			Total
		Aurich et al. (2004)	Rößing (2007)	Wiendahl et al. (2007)	Aurich et al. (2014)	Diprima (1982)	Dale (1982)	Pflicht (1989)	Balcerak et al. (1992)	Maull et al. (1992)	Kaiser (1993)	Gemmerich (1995)	Inness (1995)	Wildemann (1995)	DIN ISO 10007 (1996)	Reichwald et al. (1996)	Conrat (1997)	Eversheim et al. (1997)	Lindemann & R. (1998)	Kleedörfer (1998)	Assmann (2000)	⋮	⋮	Company A	Company B	Company C	Σ
Specification																											
Change name			4					4							3				3					4	4	4	33
Change description			4				4								4								…	4	4	4	34
Change ID							4	4											4					4	4		36
Responsible	Change owner		4																			…		4	4	4	25
	Requester						4								4				4								24
Timeframe	Start of change		4				4	4			3						4		4					4	3		38
	Deadline / End of change		4				4						2										…	3	3	4	23
Characterization																											
Cause	Cause / Reason / Trigger		4		2		4	4				4			4	4	4	4	4		2			4	4	4	82
Localization	Affected object / level / type	4	4	3			4	4			3	3			3			4						2	4	4	73
Impact on... (internal)	Production / production process	4		3	2						3	2	4	2			2		4	3	2	…			4	4	62
	Product			3				4				4	4						4	3	2					4	44
	Employees				2			3									4			3	2		…	4	4		28
	Factory operations														3										3		6
	Stocks					4	4	3							3									2		4	22
	Organization (e.g., departments)			3					4										3			..		4			17
	Technical documents																			3							3
	Other projects																					..		4	3		10
	Other locations																								3		3
Impact on... (external)	Customer														3			4			2				4	4	17
	Cooperation partner																	4			2		..			4	13
	Supplier														3			4			2				4		26
	…														…								..	…	…		…
...	…		..					..												..							…
Lessons learned	Lessons learned		4														4		4				..				17
	Efficiency of implementation																4										4

Not considered ☐ 2 3 4 Fully considered

Figure 6.4: Results of the analysis of change attributes proposed in literature and industrial practice (excerpt)

In total, more than 80 attributes have been identified relevant, of which single publications refer to at least one and up to 18 of these attributes. Some attributes like cause, affected object, or cost are considered highly relevant to characterize a change; others like impact on customer or change propagation are mentioned only occasionally. The different attributes either correspond to (e.g., cause, change driver, reason) or complement each other (e.g., impact on production,

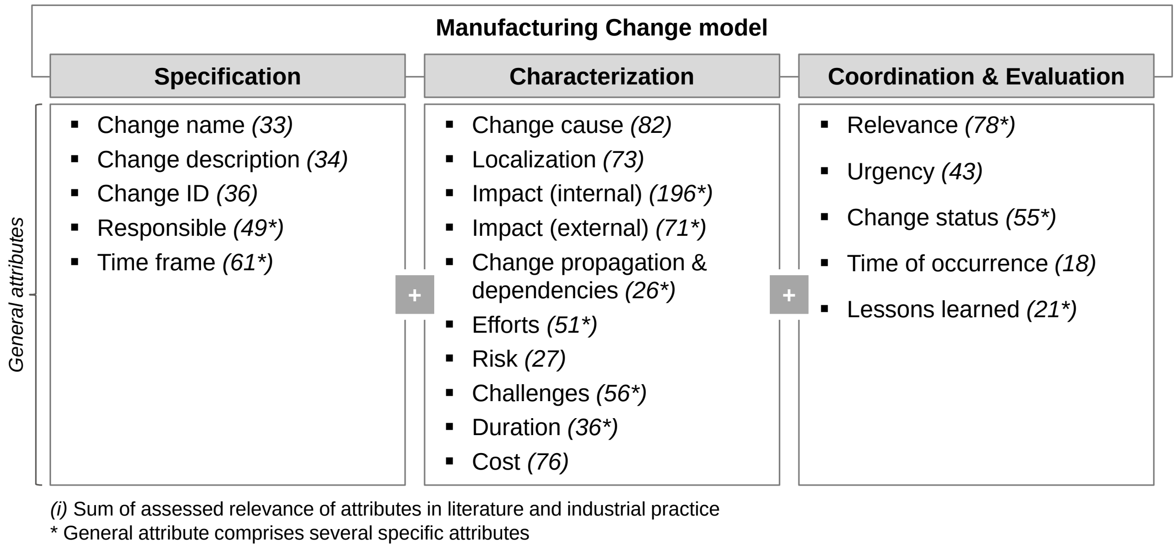

Figure 6.5: Manufacturing Change model with categories and general attributes

impact on product). Thus, the change attributes have been clustered and ordered with respect to their correspondence, i.e., attributes either describe the same characteristic of a change but with a different term or actually different aspects of a change. The resulting 20 clusters represent the general attributes of an MC, which are allocated to the three categories *specification*, *characterization*, and *coordination & evaluation*. The resulting MC model comprises these three categories with 20 general attributes and 35 specific attributes.

Figure 6.5 visualizes the MC model with the categories and general attributes. Also, the varying relevance of the attributes is displayed based on the results of the analysis of the scientific literature and data from industrial practice. Attributes mentioned most frequently tend to describe essential, basic change characteristics (e.g., impact, cause, localization of the change), while attributes mentioned only occasionally tend to express change characteristics, which require, for example, a higher level of information quality or analysis effort (e.g., change propagation & dependencies, risk, urgency). For the complete model including also the specific attributes please refer to the appendix, table A.3.

In order to support also activities like the process adaptation or the coordination, comparison, and evaluation of MCs during the MCM process, not only the relevant attributes but also their possible values are required. For example, an MC can be described by the attribute *cost*, but a process activity or the necessity of involving certain roles depends on its value – for example, low, medium, or high costs. For this reason, the MC model also contains a list of values for each attribute. To achieve a company-independent applicability, these are generalized and rather universal (e.g., no, low, medium, high; or yes, no). The detailed descriptions for each attribute are also provided in the appendix, table A.3.

6.2.3 Conclusion

The proposed model represents a holistic model of any MC with a broad coverage of different change attributes for the specification, characterization, and coordination and evaluation. It can be used to describe and document any MC in a standardized, unambiguous way – for example, in form of a change profile. Also, it provides a basis for an MC-specific adaptation of the MCM process (cf. also section 6.4) as well as for the development of an MC data model.

However, the MC model does not claim final completeness and might be further replenished if needed. For example, additional attributes detailing the localization, the internal and external impact, or the time frame might be added. Also, process data (e.g., processing time, time stamps, approvals) could further enrich the MC model depending on the respective use case.

6.3 MCM Process

The MCM process constitutes the core element of the specific MCM system architecture (cf. section 5.3) and represents a network of activities performed with the goal of managing MCs (cf. section 2.4.3). Its design is intended to serve as a reference base for MCM processes in manufacturing companies and future research activities on MCM processes.

Based on the MCM requirements, the MCM context model, findings from the case studies on the current practice of MCM in industry, and an extensive literature study the concept for an MCM process is specified, followed by a general and a detailed process design. Therein, the process design comprises both the design of the process content as well as the process architecture.

6.3.1 Concept development for the MCM process

In accordance with the MCM requirements (cf. section 1.4) and the four modeling approaches selected and configured in section 2.5, the general MCM process architecture is designed as a stage-gate process with allocated activities and deliverables. The general MCM process design describes the overall architecture of the process based on the stage-gate approach; the specific MCM process design covers the detailed process content and architecture using both DSM and DMM as well as PAF and BPMN. Their application addresses requirements like, for example, systemic perspective, defined process structure, coordination & information flow, and transparency & simplicity. Rather content-related requirements like proactive change identification and evaluation or evaluation & knowledge management are considered especially

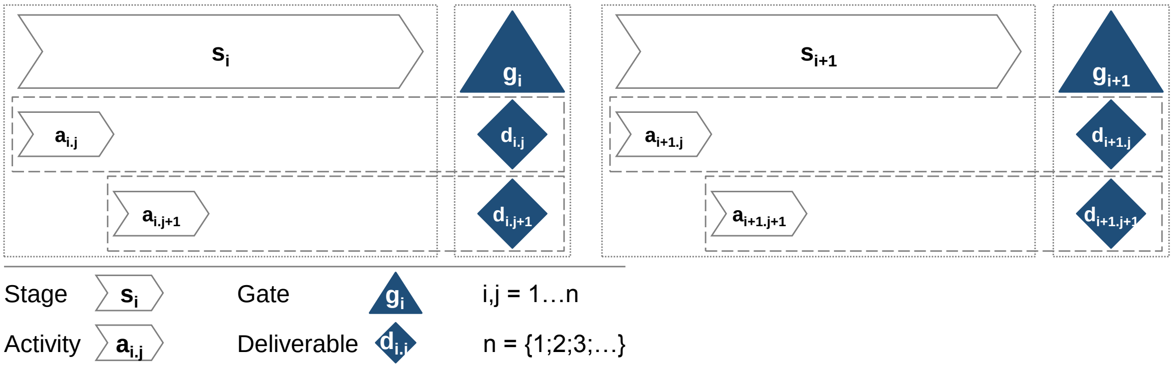

Figure 6.6: Overall architecture of the MCM process

for the development of the process content. An overview of all MCM requirements is provided in the appendix, table A.1.

The general architecture of the MCM process includes stages (s_i), gates (g_i), activities ($a_{i.j}$), and deliverables ($d_{i.j}$) with $i, j = 1 \dots n$ and $n = \{1;2;3;\dots\}$ (see figure 6.6). Stages and gates as well as activities and deliverables form a one-to-one relationship, of which the latter two are described in detail based on the PAF. The dependencies between activities (and deliverables respectively) are modeled and visualized with a DSM as a matrix and with BPMN as a flowchart.

6.3.2 General MCM process design

The general MCM process design creates the structured basis for the subsequent, detailed process design. At the same time, it aims to support the understanding of the process-oriented approach to manage MCs more effectively and efficiently. In order to develop the general MCM process design, for each field of research[5] a reference process is derived based on an analysis and comparison of the available processes proposed in literature (cf. also section 3.3). The phases of all processes are evaluated on a four-point color scale regarding the level of accordance to the respective reference process phase (from “not considered”: white to “fully considered”: dark; e.g., figure 6.7). The level is determined depending on the amount of information provided in the respective publication – i.e., from “not considered in texts or figures” to “description of the process stage and its content in texts and / or figures”. In the next step, the reference processes derived for each field of research and the industrial case

[5] MCM, ECM, factory planning, and continuous factory planning (cf. also section 1.3.4).

studies (cf. section 4.2) are analyzed and the general MCM process is derived.[6] Finally, the resulting process is modeled as a stage-gate process.

Reference process based on MCM literature

Out of the few publications available on MCM only five actually describe an MCM process.[7] All have been published within the last twelve years, the most recent in 2015 (ProSTEP iViP e.V. 2015). The proposed MCM processes comprise four to five mostly overlapping phases. Comparing and matching these processes to each other, a general reference process for MCM can be formulated (see figure 6.7). This reference process comprises seven phases, of which each has been considered relevant by at least three authors (e.g., phase *solution finding*). Two phases are reflected in all MCM processes analyzed (phases *change identification* and *implementation*). From a chronological perspective, the processes proposed by Aurich et al. (2004) and Rössing (2007) represent the oldest, but also the most extensive examples. More recent MCM processes lack at least one and up to three phases of the derived reference process.

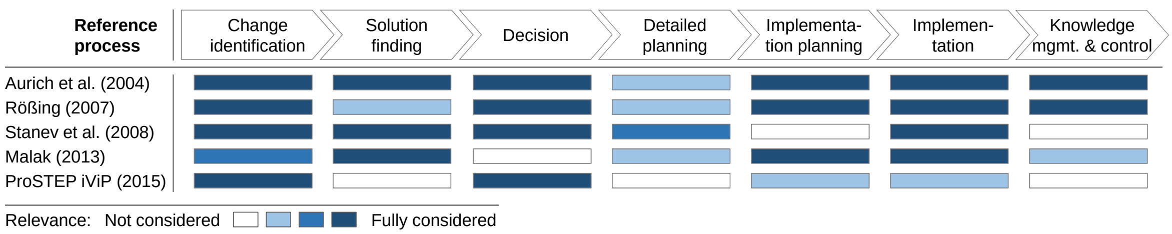

Figure 6.7: Reference process based on MCM literature

Reference process based on ECM literature

The ECM reference process is based on the comparative analysis of twenty ECM processes discussed in scientific literature during the last thirty-five years (see figure 6.8). Besides the reference process, some findings are noteworthy.

[6] Note, that the publications investigated are ordered chronologically in the subsequent figures.
[7] Note, that ProSTEP iViP e.V. (2015) is based on ProSTEP iViP e.V. (2014) and represents an extended, more recent version of the MCM process.

The three oldest publications focus on the evaluation, processing, and implementation of ECs (cf. DIN 199 Part 4, DALE 1982, and MAULL et al. 1992).[8] HILLER (1997) and CONRAT (1997) were among the first to emphasize the identification of ECs and the finding of solutions. Most subsequent publications are in line with these, but complement the ECM process with an additional phase – *knowledge management & control*. In addition, an early ECM phase located at the very beginning of the process has been proposed by some authors, the so-called *latent need for change*. However, this phase has only been mentioned by four out of the twenty publications, but also the most recent one (WICKEL et al. 2014).

The derived ECM reference process comprises seven phases in total. Four of these phases are well covered by most publications, while the phases *change planning* as well as *knowledge management & control* are considered by about 50% only. The very first process phase has only been mentioned occasionally. Overall, these findings reflect the development of ECM from its origin of processing change requests (e.g., DIN 199 Part 4) to a more comprehensive approach for an actual management of Engineering Changes (e.g., WICKEL et al. 2014).

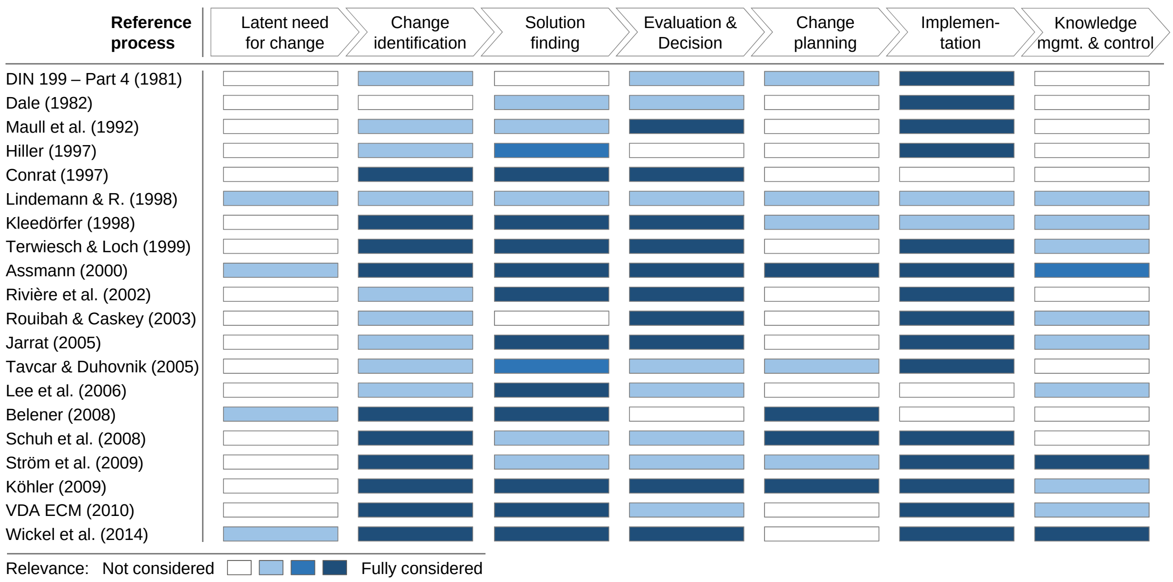

Figure 6.8: Reference process based on ECM literature

[8] Another well-known publication on ECM by PFLICHT (1989, pp. 28-32) does not develop an own approach for ECM, but refers to the process proposed by DIN 199 Part 4. Hence, it is not considered separately.

Reference process based on factory planning literature

In scientific literature, numerous factory planning processes have been proposed during the last decades. For the derivation of a reference process for factory planning, ten broadly acknowledged publications have been chosen covering about the last thirty-five years. Although these represent only a selection that could be further extended, the results of the process analysis already indicate a high conformance of the different processes (see figure 6.9).

In total, the factory reference process comprises six process phases, of which the first four are considered by nine of the ten publications. The fifth phase *implementation* has been described by six authors especially during the last twelve years. The same applies for the final phase, which in contrast has only been mentioned briefly. These findings reflect the general focus of factory planning on rough, detailed, and implementation planning rather than on, for example, knowledge management and control, or the identification and alignment of MCs.

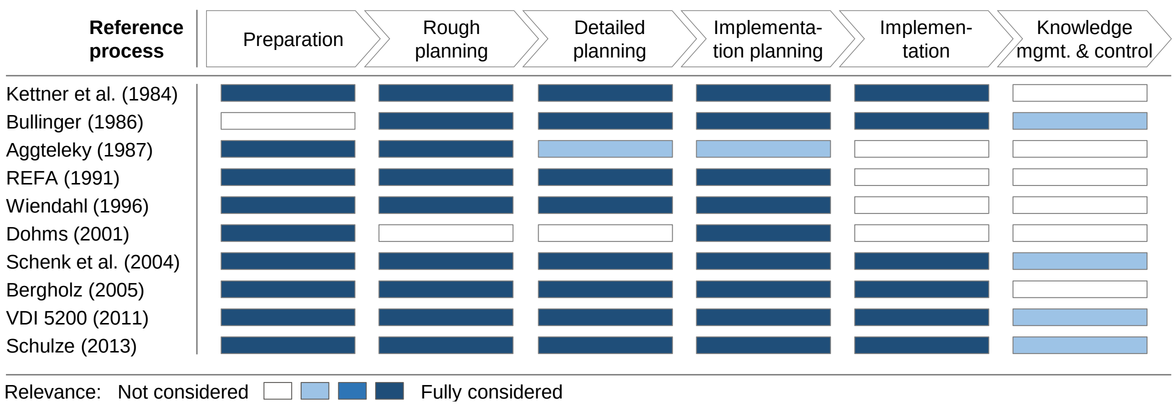

Figure 6.9: Reference process based on factory planning literature

Reference process based on continuous factory planning literature

During the last years, the concept of continuous factory planning has gained increasing attention in manufacturing science. In total, eight approaches have been identified, of which the latest dates back to 1998. All of these are based on a control loop analogy (cf. sections 2.3.2 and 3.3.4).

Analyzing these approaches, a reference process can be derived comprising seven phases (see figure 6.10). The early publications address all process phases, while the more recent approaches, published in 2010 and thereafter, emphasize the first four phases only. This reflects the narrowed focus of continuous factory planning on change identification and rough planning rather than on detailed planning and implementation activities. In contrast, these latter aspects are considered highly relevant for factory planning as described beforehand.

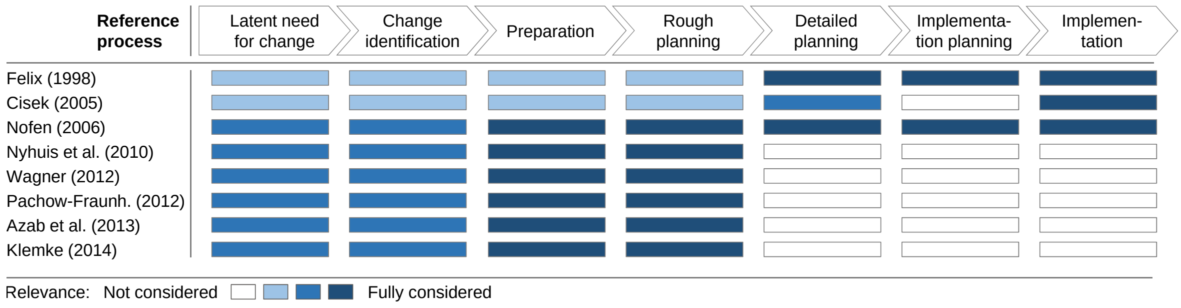

Figure 6.10: Reference process based on continuous factory planning literature

Reference process based on industrial case studies

The industrial case studies (cf. section 4.2) revealed different types of processes utilized for MCM. Two companies apply a set of processes to manage MCs, one company uses a modified ECM process. The results of the comparative analysis and the generalized reference process are visualized in figure 6.11.

It becomes apparent that each company-specific process contains activities for the review of change ideas and a change request, the specific planning of the change, and the implementation. These reflect basic activities required to manage changes. The phases for *concept development* and *closure of a change* are considered in two processes, while the creation of change ideas and change analysis are represented in one process only.

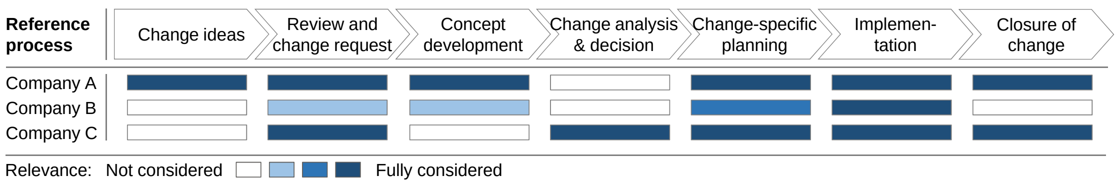

Figure 6.11: Reference process based on industrial case studies

General MCM process

The five reference processes from literature and industrial practice provide the basis to derive the general MCM process. Taking also the MCM requirements (cf. section 1.4 and the appendix, table A.1) into consideration, the reference processes are merged to one general reference process, which is then further specified towards the general MCM process (see figure 6.12).

A comparative analysis of the reference processes reveals multiple overlapping, but also complementary phases. Overall, each phase is represented in at least three, sometimes even four or all of the reference processes. For this reason, each phase is considered relevant for an MCM process.[9] The resulting general MCM process comprises eight phases; their names have been chosen to be as self-explanatory and precise as possible. In consequence, the names account not only for the phases of the five reference processes, but also for the specific activities to be conducted within each phase. These activities are derived and described in the subsequent section 6.3.3.

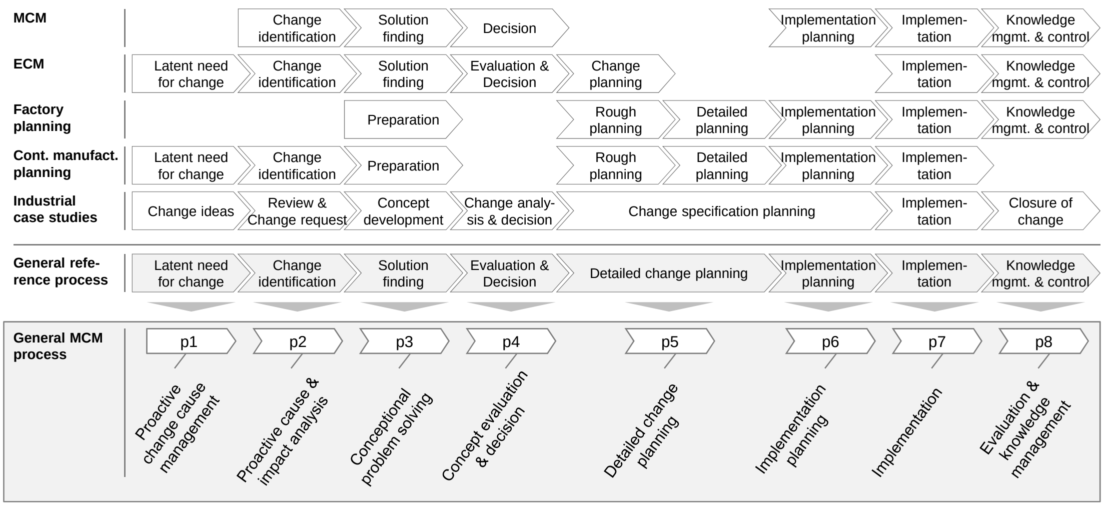

Figure 6.12: Derivation of the general MCM process based on reference processes from literature and industry

[9] While the distinction between rough and detailed planning is found to be specifically relevant for factory planning and partly continuous factory planning, available approaches for MCM and ECM rather account for change planning or change specification planning. Therefore, the phase *detailed change planning* has been chosen for the general MCM process to reflect the aforementioned two phases.

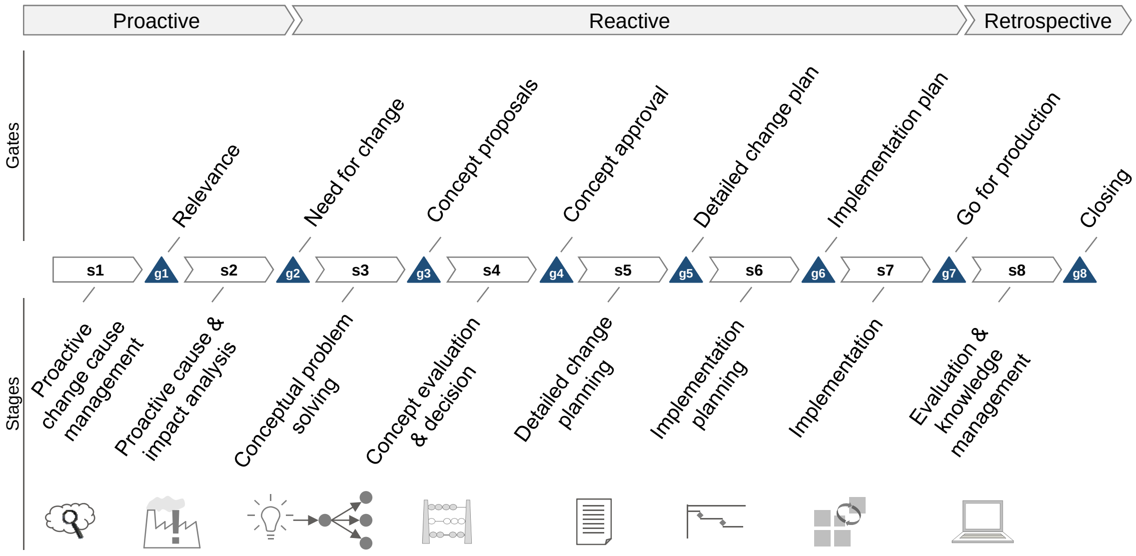

Figure 6.13: Stage-gate model of the general MCM process

Based on this, the stage-gate process model of the general MCM process can be developed. Each of the eight phases represents a stage and is completed with a specific gate. The gates are defined according to the respective stage, the activities, and allocated deliverables (cf. also section 6.3.3). Together, the eight stages and eight gates model the resulting general MCM process (see figure 6.13). Their detailed descriptions are provided in table 6.2.

The MCM process can be separated in three major phases: proactive MCM, reactive MCM, and retrospective MCM. These phases represent the three main foci of MCM and comprehensively capture its essence.

Proactive MCM. This phase comprises all activities to identify, avoid, front-load, create, and / or control a change cause and a potentially resulting MC rather than just respond to it after its occurrence.[10]

Reactive MCM. This phase comprises all activities to prepare, evaluate, plan, process, and implement an MC after a confirmed need for action – i.e., the confirmation of the occurrence of a defined change cause. In other words: "showing a response to a stimulus" (OXFORD DICTIONARIES 2016).

Retrospective MCM. This phase comprises all activities to look back on, review, and learn from a past MC.[11]

[10] Cf. also the definition of the term "proactive" in OXFORD DICTIONARIES (2016): "creating or controlling a situation rather than just responding to it after it has happened".

[11] Cf. also the definition of the term "retrospective" in OXFORD DICTIONARIES (2016): "looking back on or dealing with past events or situations".

Table 6.2: Description of the stages and gates of the MCM process

Code	Stage (s) / Gate (g)	Description
s1	Proactive change cause management	Screen for, identify, and pre-assess change causes and potential changes. Then, create a change profile, assign responsibility, and decide on the relevance of the potential MC.
g1	Relevance	Confirmation of relevance for the potential MC.
s2	Proactive cause & impact analysis	Identify stakeholders, describe and evaluate the potential MC and its impact, create a change proposal, review and update the documentation, and decide on the release of a change request.
g2	Need for change	Release (or rejection) of the change request.
s3	Conceptual problem solving	Develop solution concept proposals, analyze the potential change propagation, estimate the invest and benefit of the MC, and compile the final solution concept proposals.
g3	Concept proposals	Documentation of concept proposals for the change request.
s4	Concept evaluation & decision	Evaluate the concept proposals and pre-select one; if needed, align it with the customer, analyze costs in detail, decide on the most favorable solution concept, review and update the documentation, and prepare the release of a change order.
g4	Concept approval	Approval of the proposed concept and release of the change order.
s5	Detailed change planning	Specify and describe the required measures for the change order in a detailed change plan, prepare a sourcing plan, approve both and prepare a final detailed change plan.
g5	Detailed change plan	Approval and release of the detailed change plan.
s6	Implementation planning	Plan and schedule the implementation of measures for the MC, procure technical equipment, review and update the documentation, and prepare the approval and release of the MC.
g6	Implementation plan	Approval and release of the MC for implementation.
s7	Implementation	Execute the MC according to the detailed change plan and the implementation plan, review and update all relevant documents and information systems, prepare final "go for production" for the change.
g7	Go for production	Approval and release of the changed objects (e.g., manufacturing equipment, work plan) for production.
s8	Evaluation & knowledge management	Review and evaluate the MC, its documentation, and results; conduct and document lessons learned, clear up the documentation and close the MC.
g8	Closing	Completion and final release of documentation (and lessons learned) for the MC.

Figure 6.14: Analysis of the processes based on the derived MCM process

To further increase plausibility of the general MCM process, all 46 processes are analyzed and evaluated regarding their level of accordance with each stage of the MCM process. The results shown in figure 6.14 confirm the suitability of available processes as input for the MCM process design, the correctness of the derived process, and shed light on the various foci of the available processes (cf. also sections 4.3 and 3.3.5).

The following main findings are to be mentioned:

– None of the available processes covers all stages of the MCM process derived.

– Most processes consider the reactive process stages and show great conformity within the respective field of research (e.g., almost all ECM processes consider *conceptual problem solving*, *concept evaluation & decision*, and *implementation* in detail).

- The first stage of the proactive phase of the MCM process is mainly considered by continuous factory planning and few, but recent ECM processes.
- The retrospective phase of the MCM process is considered in detail by some MCM processes, recent ECM processes, and in less detail by some factory planning processes.
- MCM processes consider almost all stages, but describe only selected ones in detail.
- ECM and MCM processes address the same stages on a comparable level of detail (e.g., *change identification*, *implementation*) reflecting the approach of available publications on MCM of directly transferring the concept of ECM to the manufacturing domain (cf. section 3.3.2).
- Factory planning and continuous factory planning processes are mostly complementary: factory planning focuses on planning and implementation, continuous factory planning addresses the early MCM process stages.
- Processes observed in industry consider most stages, but barely account for the very first, the last, and the implementation planning stage.

Conclusion

The general MCM process design aims to support the understanding of a company-independent, process-based approach to manage MCs. It is structured in three phases – proactive, reactive, and retrospective – covering all aspects from an early identification of occurring change causes, planning and processing an MC, to reviewing and learning from a completed MC. These phases are further detailed with a total of eight stages and eight gates. These capture and sequence the relevant aspects for an MCM process. At this level of detail, the proposed sequence of stages and gates tends to be true for generally managing any MC (cf. also section 7). However, in practice the MCM process rather constitutes an activity network than a purely sequenced process (cf. section 2.4.3). For the general stage-gate model of the process this characteristic also applies, but has not been visualized in favor of structure, simplicity, and clarity. In fact, the network characteristic is fully accounted for with the detailed design of the MCM process in the subsequent section.

6.3.3 Detailed MCM process design

Building upon the general MCM process, the detailed MCM process design increases its level of content and details its architecture. Based on the application of PAF, DSM, and the data from the literature review and the case studies, activities, deliverables, and their dependencies are derived and described in detail. In other words, activities and deliverables can be seen as the result of a decomposition of stages and gates (cf. section 6.6). The resulting MCM process finally intends to serve as reference base for an effective and efficient MCM in manufacturing industries.

Activities of the MCM process

The identification and selection of activities relevant to an MCM process are conducted similarly to the derivation of the eight stages. Building upon the general MCM process design, all 46 literature sources and processes applied in industry are reviewed and comparatively analyzed in detail. This includes structuring, consolidating, evaluating, and sequencing of the activities based on the information provided by the different sources.[12] Also, logical reasoning as well as DSM-based process sequencing and clustering are applied in several workshops conducted at TUM with two to four researchers of the superior research project, followed by several interviews with practitioners. In the following, the resulting final MCM process with its content and architecture is elaborated on together with a description of the proposed activities and deliverables.

In total, 53 activities and 53 corresponding deliverables are proposed relevant for the MCM process.[13] Although this compilation of activities and deliverables serves as a comprehensive base for an MCM process, it does not claim for exhaustive completeness: single activities might be left out or added depending on the respective situation and use case.

Figure 6.15 shows an excerpt of the activities and the aggregated evaluation of their relevance in scientific literature and industrial practice – and in consequence for the MCM process. The complete list of publications considered is provided in the appendix, table A.2.

Overall, the distribution of activities pertinent to one of the four research fields and an MCM process stage corresponds with the results from the analysis of the process phases (cf. figure 6.14). However, due to the “higher resolution” of this analysis, foci on specific activities can now be recognized within a process stage. For example, the MCM processes propose a high relevance of the stage *concept evaluation & decision*, but only three out of the eight activities

[12] The same four-color evaluation scheme as for the general MCM process design has been applied for the evaluation of the process activities (cf. section 6.3.2).

[13] Note, that some activities of the compilation are scarcely or even not considered relevant in literature, but required by practitioners in industry (cf., for example, activity a4.6 or a5.6). After careful review and evaluation, these have been included, because they are assumed to contribute to accuracy and sophistication of the MCM process. The same applies for activities that show low relevance in both literature and industry.

are considered in detail. Further, a differing relevance of the activities can be noticed – between the different fields of research, industry, and also between the activities themselves. This is due to the different foci of the processes in terms of content and observed objects (cf. sections 1.3.4 and 3.3). Another reason is the fact that the authors and companies preferably address and emphasize activities being most important from their point of view – but those do not necessarily make up for a holistic MCM process. However, the re-occurrence of similar or even the same activities is assumed to indicate a general importance. This presumption is supported by a further insight non-obvious at first sight: calculating the upper quartile of activities (based on their resulting total relevance in literature and industrial practice), it is found that each stage of the MCM process comprises at least one activity out of this quartile (indicated by the shaded background of the respective activities in figure 6.15). The balanced distribution of these "highly-valued" activities across all stages further contributes to the plausibility of the general MCM process design.

Based on these results and applying the PAF (cf. section 2.5.4 and the appendix, table A.4), all 53 activities have been described in detail regarding the PAF attributes *name*, *brief description*, and *parent* (i.e., the respective stage). Further attributes like *input*, *output*, or *mode* are supplemented in the following sections. For spatial reasons the PAF model of the MCM activities is provided in the appendix, table A.6.

Deliverables of the MCM process

Accompanying the development of the activities, the deliverables are specified accordingly. In contrast to the activities, which describe "what needs to be done", the deliverables concretize "what is the final output of an activity". Due to the one-to-one relationship, their relevance matches the results of the comparative analysis for the activities provided in figure 6.15. The detailed description of each deliverable is based on the PAF. Attributes covered are, for example, *name*, *brief description*, and *parent*. Further attributes are supplemented in the subsequent sections (e.g., *supplier*, *customer*, or *mode*). The full PAF model can be found in the appendix, table A.7.

Design of the detailed MCM process architecture

After decomposing the MCM process into its activities and deliverables, the detailed MCM process architecture is designed applying a DSM. The resulting DSM model concisely captures and visualizes the structure of the MCM process in great detail, i.e., the dependencies between the 53 activities. Similar to the development of the activities and deliverables, the proposed architecture is based on findings from the expert interviews, the literature study, the case studies,

Stage		Activity		MCM	ECM	FP	CFP	Industry	∑
		MCM process		*Literature*					
s1	Proactive change cause management	a1.1	Screen for potential MCs (actively and passively)	3	4		3	2	100
		a1.2	Change coordination: check for siblings and aggregation potential					2	2
		a1.3	Make short impact rating of change cause		4			2	50
		a1.4	Create MC profile for change cause	3	2			3	25
		a1.5	Assign responsible for potential MC	2	2			2	8
		a1.6	Decide on relevance of potential MC		2		2	4	20
s2	Proactive cause & impact analysis	a2.1	Identify and inform stakeholders about potential MC	4	3	2	2	3	30
		a2.2	Review and update risk and impact rating	3	4		3	3	74
		a2.3	Aggregate information and define actual requirements on factory	3	2		4	3	51
		a2.4	Identify deviations between requirements and current	2	4	2	4	2	53
		a2.5	Coordinate the MC	3	3				24
		a2.6	Create a change plan proposal	2	3		4	2	27
		a2.7	(Re-)assign roles and responsibilities	4	4				18
		a2.8	Review MC profile	2	2			2	13
		a2.9	Decide on the release of a change request	3	3		3	4	67
s3	Conceptual problem solving	a3.1	Make a detailed problem and target description		2	3	4	3	52
		a3.2	Develop and describe solution concept proposals	4	3	3	4	3	129
		a3.3	Make change and change propagation analysis	3	3		3	2	47
		a3.4	Make stakeholder review		3				11
		a3.5	Estimate invest and benefit of MC	3		2	3	4	35
		a3.6	Formally approve invest plan	2				4	14
		a3.7	Prepare solution concept proposals for MC		2	2	2	2	26
s4	Concept evaluation & decision	a4.1	Evaluate solution concept proposals and make pre-selection	2	3	3	4	2	85
		a4.2	Align solution concept proposal(s) with customer						0
		a4.3	Make detailed cost analysis	4	4	3	2	3	40
		a4.4	Select and approve solution concept	2	3	3	2	3	44
		a4.5	(Re-)assign roles and responsibilities	2	3				8
		a4.6	Review change plan		2			3	10
		a4.7	Review MC profile		2	2		2	8
		a4.8	Approve solution concept and release change order	3	3	2		4	77
s5	Detailed change planning	a5.1	Select and integrate suppliers		2			3	12
		a5.2	Plan MC in detail	3	3	4	4	4	86
		a5.3	Align detailed change plan with customer		2			2	6
		a5.4	Make sourcing plan proposal		2	4	2	2	25
		a5.5	Approve detailed change plan		4			2	10
		a5.6	Approve sourcing plan					3	8
		a5.7	Compile final detailed change plan	4	3	4	4	2	61
s6	Implementation planning	a6.1	Make implementation plan proposal	3	3	4	4	4	82
		a6.2	Approve implementation plan					2	7
		a6.3	Procure technical equipment					3	8
		a6.4	(Re-)assign roles and responsibilities	4	2				6
		a6.5	Review change plan			4		2	10
		a6.6	Review MC profile			2		2	6
		a6.7	Approve MC to be implemented		4			3	26
s7	Implemen-tation	a7.1	Implement MC	4	4	3	4	3	126
		a7.2	Check implemented MC	3	3	4	4	3	42
		a7.3	Make quality and performance test	3		4	4	3	24
		a7.4	Review and update information systems	2	3	3	2	3	41
		a7.5	Make overall "go for production" check			2		4	16
s8	Evaluat. & knowledge mgmt.	a8.1	Review and evaluate the MC	4	3	3	2	2	50
		a8.2	Describe and highlight lessons learned	3	4		2		40
		a8.3	Clean up	2				2	6
		a8.4	Close MC	3	3			3	28

FP: Factory planning CFP: Continuous factory planning Average relevance: Not considered [ ] 2 3 4 Fully considered

Activities of the third quartile (based on ∑)

Figure 6.15: Activities of the MCM process and the consolidated analysis results from literature and current practice in industry

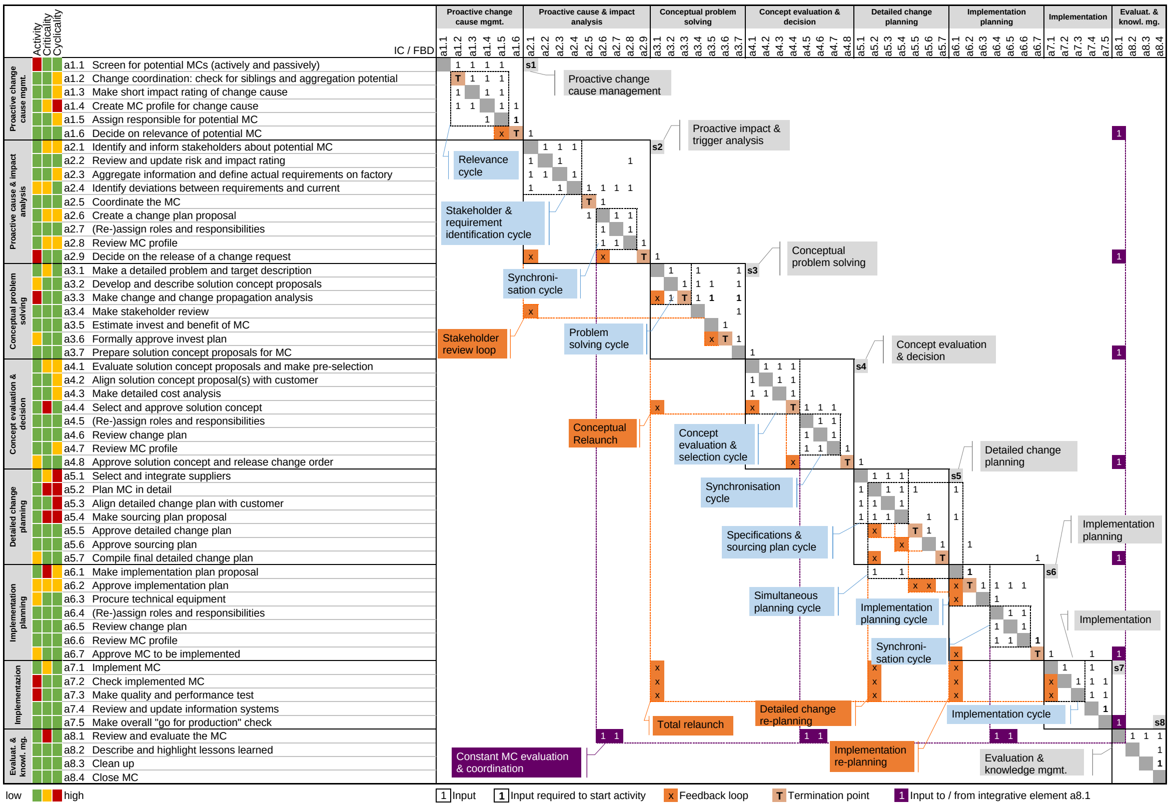

Figure 6.16: DSM model of the MCM process architecture

workshops with two to four researchers from the superior research project, and discussions with several change managers and production planners during workshops of the "working group change management" of the TUM. In addition, logical reasoning and DSM analyses (e.g., sequencing; cf. section 2.5.4) have been applied.

The results are modeled using "1" for an input-output relation and "x" for feedback loops.[14] The final model of the MCM process architecture is visualized in figure 6.16, mapping the activities as row and column headings, and the dependencies within the matrix. A larger, hence more readable version of the DSM is provided in the appendix, figure A.1.

Process sequence. The activities of the MCM process are listed in a chronological order. Upstream activities are placed in the upper rows and left columns of the DSM, downstream activities in the lower rows and right columns. The proposed process sequence arises mainly along the diagonal of the matrix (cf. the stream of "1" along the diagonal), i.e., the process has a precise "direction of flow". However, it is not designed as a purely sequential, hence rather slow and time-consuming process. Instead, it provides multiple parallelizations and feedback

[14] The assumptions and reasons justifying each single dependency could not be included in this thesis due to spacial restrictions.

loops while also considering relevant iterations and termination points (cf. the different "1" and "x" above and below the diagonal, and also the "T" for termination points on the diagonal). These account for the needs to efficiently process any MC, to distribute all required information between the activities in accordance with the process structure, and to allow for rework at specified points in the MCM process. The proposed sequence also reflects the general MCM process design with its eight stages as the respective activities of a stage create coherent activity clusters. These clusters are interlinked by one specific activity – the final activity of any stage completing the stage and the associated gate.[15]

Parallelization. In order to support the efficiency of the MCM process, some activities have been designed to start in parallel. Parallelized activities can be identified in the DSM by "1s" laid out row-wise. Reading from left to right, the first "1" in each column indicates the start of the activity once the related previous activity has been accomplished. For example, activities a2.2 to a2.4 start simultaneously once activity a2.1 has been accomplished. In contrast, solely activity a5.1 starts, when the activity a4.8 has been accomplished.

However, there are some cases to be considered, where an activity gets input from more than one previous activity, but is not supposed to start based on the first "1" in the column. Instead, the activity starts only if the previous activity marked with a bold "1" has been accomplished. Examples for this case are found with, for example, activity a1.6 or a6.2. In total, 23 (about 43%) of the activities remain in consecutive sequence, while 30 (about 57%) of the activities have been parallelized with at least one other activity.

Iterations. Accounting for the iterative nature of change processes, the MCM process architecture incorporates these iterations where required and assumed to be beneficial. These iterations, which model downstream inputs from activities to parallelized or prior activities, are marked by "1s" below the diagonal of the DSM. In order to benefit from these planned iterative activities during process execution, two states of activity completion are to be distinguished: (1) the accomplishment of an activity and (2) the closure of an activity.

(1) The accomplishment of an activity allows to start subsequent activities, but still leaves the opportunity to benefit from (iterative) input of these subsequent activities by further enhancing and updating the output of the activity, i.e., the associated deliverable. This again can then be considered for subsequent activities and their deliverables.

(2) The closure of an activity terminates it and creates the final deliverable of the respective activity. This can only be done after all related iterative activities are in state (1) in order

[15] Stages s6 and s7 are an exception, because these comprise the simultaneous planning cycle, which covers not only the detailed change planning, but also parts of the implementation planning.

to guarantee the consideration of iterative inputs for these activities and their associated deliverables.

These two states apply for all iterative activities of the MCM process and can be exemplarily understood looking at the activities a2.1 to a2.4. The accomplishment of activity a2.1 triggers the activities a2.2 to a2.4, but as a2.1 might get iterative input from these, it can only be closed after their accomplishment. In total, 29 (about 55%) of the activities are considered and designed as iterative within the MCM process.

Activity clusters. Considering parallelization and iterations together, different activity clusters can be identified in the MCM process. These clusters are characterized by a more or less symmetrical conglomeration of “1s” below and above the diagonal. In accordance with the stage-gate design of the general MCM process, the activities of each stage form a cluster named by the respective stage and marked with solid black lines in the DSM. In addition, smaller, even more dense clusters of activities exist. These mainly intra-stage clusters are distributed across the MCM process, occur in almost every stage, and are marked with black dashed lines. They are named based on the respective focus of the activities comprised – for example, “problem solving cycle” in stage s4 or “implementation planning cycle” in stage s6.

Feedback loops. The consideration of specified feedback loops in the MCM process enables the re-entry to the process at previous activities. Such feedback loops are necessary in case of required re-work of activities. This might be due to, for example, the rejection of a change request, of proposed change plans, or an invest plan for an MC. The unexpected and hence unplanned nature of this re-work marks the main difference between a feedback and an iteration. However, a feedback can also be seen as an expensive iteration. In order to prepare the MCM process for those at the time of occurrence unexpected events, the feedback loops have been designed as an integral part of the overall MCM process and are considered throughout the different stages.

All feedback loops are modeled with an “x” in the DSM. In total, 28 potential feedback loops are considered for the MCM process. These can be distinguished into 15 intra-stage and 13 cross-stage feedback loops. In general, the latter cause more severe reversals accompanied by more re-work to be done, while the former also cause re-work, but just for fewer activities being all within the same stage. The distribution of feedback loops across the MCM process stages reflects the increasingly high impact on the MCM process in case of required re-work:

while only five feedback loops originate from the first three stages, three originate from stage s4 and s5 each, five from stage s6, and eleven from stage s7.[16]

Process terminations. Once started, any potential MC might be either implemented or rejected during the MCM process. Within the process, eleven points for process termination have been integrated across the different stages, marked with a “T” on the diagonal of the DSM. Except the last two stages for “implementation” and “evaluation & knowledge management”, each stage has two termination points – one in the middle and one at the end. This regular distribution accounts for the need to be able to terminate an MC in a timely manner and according to the standard MCM process, if required.

Almost all of the termination points correlate with a feedback loop (cf., e.g., activities a5.5, a6.2, or a6.7).[17] Vice versa, not every feedback correlates with a termination point, as there can be reason to do re-work, but most likely no reason to terminate the process at the activity (for example, the rejection of a sourcing plan might require re-work, but would most likely not terminate the MC in general).

Integrative elements. In order to enable a constant evaluation and coordination of an MC being processed, the activity “Review and evaluate the MC” (a8.1) of the final stage s8 is designed as an integrative element. This activity possesses several relations to activities in other stages across the whole MCM process. Firstly, activity a8.1 gets input from the last activity of each stage to consolidate information about the MC. This creates the basis for a comprehensive, process-accompanying review and evaluation of the respective MC. Secondly, this activity also provides input to activities in stages s2, s4, and s6 dealing with roles and responsibilities as well as the overall project plan for the MC – i.e., the main activities relevant for the evaluation and coordination of an MC. The cross-stage dependencies of activity a8.1 are modeled with “1s” and a shaded background to differentiate dependencies with an integrative character from the regular dependencies within the DSM.

Activity, criticality, and cycles. These three key figures of DSM analyses (cf. section 2.5.4) provide insights to the MCM process regarding the relevance of the different activities, which are considered to differ in terms of, for example, intended quality of deliverables, required thoroughness, and necessary teamwork. For each process activity, these three aspects are estimated based on the calculation of the key figures *activity* (for the quality of deliverables), *criticality* (for required thoroughness), and *cyclicality* (for necessary teamwork), followed by

[16] Note, that for activities providing more than one feedback loop, the appropriate one has to be chosen depending on the respective MC and situation.

[17] The single termination point not correlating with a feedback is at activity a1.2, because there is no need for a feedback loop during this early stage.

a plausibility check. The results are classified into three categories and marked with a color code in the DSM model (see figure 6.16; low (green), medium (yellow), and high (red)). The top 10% of the activities are marked red, the remaining 15% of the upper quartile are marked yellow.

Some of the information modeled with the DSM can be supplemented to the PAF model of the MCM process. The "1s" determine the attributes *input* and *output* for the process activities, the "**1**" the attribute *entry criteria* (cf. also table A.4 in the appendix).

BPMN model of the MCM process

Based on the stage-gate model and the DSM model of the MCM process as well as the proposed roles (cf. section 6.3.4), a flowchart model of the MCM process is developed applying BPMN (cf. section 2.5.4). Both the general and the detailed MCM process are modeled. The models are intended to add another, formalized view on the MCM process design in order to support practitioners and researchers in understanding and applying the MCM process.

The flowchart of the general MCM process visualizes the stages and their sequence, inter-stage feedback loops, and the dependencies for the integrative elements (see figure 6.17). According to the notation for the DSM, dependencies are marked with black arrows, feedback loops with orange arrows, and the "basis path" with green arrows (cf. section 2.5.4, figure 2.4 for the full caption / explanation of the notation). In addition, the main feedback loops are named to describe their purpose.

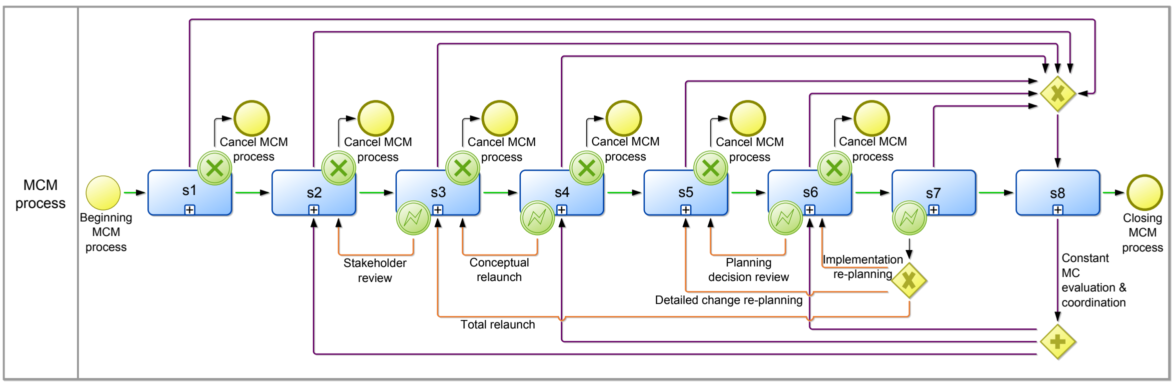

Figure 6.17: BPMN flowchart model of the general MCM process

The detailed MCM process has been modeled similarly taking also roles for MCM into account. Activities are visualized in a chronological order from left to right and allocated in swim lanes

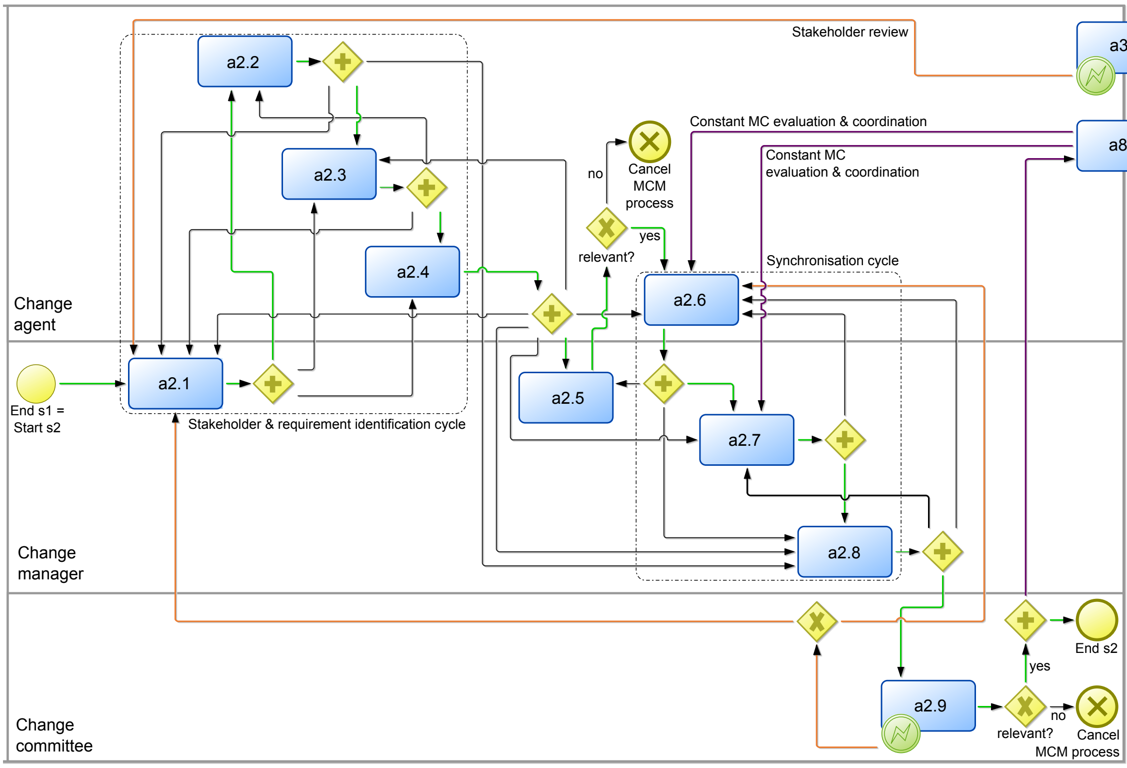

Figure 6.18: BPMN flowchart model of the detailed MCM process, stage s2

to the responsible role (see figure 6.18; the BPMN models of all stages are provided in the appendix, figures A.3 to A.10). The roles and their responsibilities for MCM will be described in detail in the subsequent section 6.3.4.

In contrast to DSM and DMM models (cf. also section 6.3.4), the BPMN models combine information about process sequence and responsibilities in a flowchart representation. Even though the information presented is the same, the appearance and transparency provided differs. DSM and DMM rather emphasize the architecture of the process, BPMN the activities, their sequence, and assigned responsibilities. Also, the former describe even high numbers of dependencies in a clear and unambiguous manner, while the latter tends to become rather confusing as figure 6.18 proves. Exploiting these differences, both together create a supplementary set of models providing a more holistic view on the MCM process.

Conclusion

Intended to serve as a reference base for manufacturing companies regarding an effective and efficient MCM, the detailed MCM process has been developed. Based on the analysis of 43 processes proposed in scientific literature and three applied in industrial practice, the resulting process comprises 53 activities and the associated deliverables. Each activity and each deliverable is modeled with the PAF, their different dependencies are defined applying a DSM. Also, specifics for each activity as well as the overall process structure, for example in terms of activity clusters, feedback loops, or iterations, are derived and discussed.

6.3.4 MCM process support

An enterprise-independent applicability of the MCM concept also requires an "organization-neutral" development of the MCM process support. This support comprises two elements identified most relevant for MCM – *role* and *method & tool*. Specified roles are required for the application of MCM, while the provision of methods and tools usable during the different activities of the MCM process supports practitioners in conducting MCM effectively and efficiently. Within this section, generalized roles and a set of methods and tools supporting the MCM process are specified based on findings from the industrial case studies and a broad literature review. The dependencies of the process support to the MCM process are modeled with DMMs. In addition, the results are incorporated into the PAF (see table A.6 in the appendix).

Roles for MCM

In addition to the findings from scientific literature on ECM and MCM, the industrial case studies and the web-based survey revealed further insights on relevant roles for MCM. Among others, especially production managers, group leaders, change initiators, or change managers have been mentioned as being responsible for MCs and MCM. Companies experienced in dedicated MCM concepts tend to emphasize the role of the change manager and a change committee, while companies more focused on factory planning and project management processes tend to emphasize the relevance of manufacturing / production planners and production management (cf. chapter 4 and Koch et al. 2015b). Taking these observations and the general MCM requirements (cf. section 1.4) into consideration, the following set of roles is proposed for MCM. These are intended as a basic, lean set of roles relevant to conduct MCM; the proposed roles might be adjusted or added to depending on the respective situation and company seeking to introduce MCM or modify its MCM concept. In general, the roles are independent from actual persons, i.e., one person may fill more than one role at a time.

- **Change requester**: Person who proposes a potential MC. This person might also be the one to discover or to identify the need for a potential MC – but does not have to.

- **Change agent**: Person who is responsible to manage and process one specific MC. This person executes activities of the MCM process and creates the actual deliverables for an MC.[18]
- **Change manager**: Person who is responsible to coordinate and generally manage all MCs, to delegate and approve / reject activities and deliverables during the MCM process, and to forward decisions / approvals on to the change committee if needed.
- **Change committee**: The change committee is responsible to generally steer MCs in a company and to approve / reject specific activities and deliverables. Different department functions might be participating in the change committee depending on the respective MC and the values of its attributes (cf. also section 6.4); these should comprise decision-makers and representatives from, for example, factory planning, production management, product development, purchasing, quality management, and general management. Also, the change manager as a key responsible for MCM should be part of the committee. Change agents and change requesters might participate as required.
- **Department functions**: These functions represent, among others, manufacturing and factory planning, product development, quality management, sales, purchasing. They contribute to specific activities of the MCM process and might participate with decision-makers and representatives at the change committee.

These roles are assigned to the MCM process activities applying a DMM and based on the specific MCM system architecture model (cf. section 5.3). The general dependency of any role supporting activities of the MCM process is further detailed into six specific dependencies: a role gets information, executes, and / or approves, or does one of these optionally. An excerpt of the role-activity-DMM is visualized in figure 6.19, for the full DMM please refer to the appendix, figure A.11.

Each activity is primarily executed by one role (specific responsibility, indicated by a “2”); however, other roles might optionally contribute to this activity if helpful (indicated by a “(2)”). This can be the case if, for example, information relevant for the change is highly distributed in the company or an MC impacts different department functions. Some activities of the MCM process require specific approvals, which are mostly assigned to the change committee (indicated by a “3”). Nevertheless, the change manager might also conduct approvals in the process if applicable, for example, in case of simple or non-expensive MCs (indicated by a “(3)”). Finally, some roles should be informed during specific activities to be up to

[18] For larger MCs it can be a project manager, for smaller MCs a regular line function, for example, from production planning.

IC / FBD		Proactive change cause mgmt.						Proactive cause & impact analysis										
		a1.1	a1.2	a1.3	a1.4	a1.5	a1.6	a2.1	a2.2	a2.3	a2.4	a2.5	a2.6	a2.7	a2.8	...	...	a8.4
		Screen for potential MCs (actively and passively)	Change coordination: check for siblings and aggregation potential	Make short impact rating of change cause	Create MC profile for change cause	Assign responsible for potential MC	Decide on relevance of potential MC	Identify and inform stakeholders about potential MC	Review and update risk and impact rating	Aggregate information and define actual requirements on factory	Identify deviations between requirements and current	Coordinate the MC	Create a change plan proposal	(Re-)assign roles and responsibilities	Review MC profile	⋮	⋮	Close MC
Roles	r1 Change requester	2	2	2	2	1	1										...	1
	r2 Change agent							(2)	2	2	2	(2)	2	(2)	(2)	...		1
	r3 Change manager			(2)	(2)	2	2 (3)	2	(2)	(2)	(2)	2	(2)	2	2		...	2 (3)
	r4 Change committee						3						(2)			...		3
	r5 Department functions							1	(2)		(2)						...	1

1	gets information	2	executes	3	approves
(1)	gets information (optional)	(2)	executes (optional)	(3)	approves (optional)

Figure 6.19: DMM of roles and activities (excerpt)

date regarding the MC (indicated by a “1” or “(1)”). This is usually the case at the end of process stages or at activities requiring an approval. In order to provide a clear, unambiguous assignment of roles, the main responsibility for each activity of the MCM process is indicated by the highest number in each column. Note, that the resulting DMM also reflects the necessary information for the PAF attribute *roles* (cf. section 2.5.4).

Methods and tools for the MCM process

Based on the findings from a literature review on methods, compilation of methods and tools for MCM, and related topics (e.g., ECM, product development, project management; cf. section 3.4.2), a set of methods and tools supporting the activities of the MCM process is proposed. Taking the description of each activity, the associated deliverable, and relevant dependencies into account, suitable methods and tools are identified and allocated to the respective activity. Methods and tools considered for this research support at least two activities of the MCM process, i.e., singular methods and tools are not listed, but may be supplemented. Figure 6.20 visualizes an excerpt of the DMM modeling the MCM process and the methods and tools; the full DMM is provided in A.12 reflecting also the information for the PAF attribute *methods & tools* (cf. section 2.5.4). Note, that the actual requirements, efforts, and benefits of each method and tool might differ depending on the company, the MC, and the users’ experience.

	s1						s2									s3					s8		
Methods & Tools IC / FBD	a1.1	a1.2	a1.3	a1.4	a1.5	a1.6	a2.1	a2.2	a2.3	a2.4	a2.5	a2.6	a2.7	a2.8	a2.9	a3.1	a3.2	a3.3	:	:	a8.3	a8.4	Σ
Meeting	x	x		x	x	x	x		x		x		x	x	x								35
Check list		x	x	x		x		x			x			x		x		x				x	20
Survey / Questioning	x		x					x	x	x						x	x	x					19
Effort estimation methods		x		x							x	x		x						…			12
Eisenhower method		x		x		x					x	x		x									11
Cost estimation		x		x							x			x									10
Change profile		x	x	x				x			x			x				x		…			9
KPI systems	x			x						x				x									8
Questionnaire	x	x									x					x	x		…				7
Observation	x																						6
Scenario planning	x		x					x										x					6
FMEA	x		x					x										x					6
Fault tree analysis	x		x					x										x					6
Target-performance comparison										x													6
…																				…			
…																							
Lessons Learned																							2
Keyword list																	x				x		2

x Method / Tool supports activity

Figure 6.20: DMM of methods & tools and activities of the MCM process (excerpt)

6.3.5 Conclusion

The proposed MCM process support comprises a generalized, organization-neutral set of roles and a compilation of methods and tools. Relevant dependencies to the activities of the MCM process are modeled with DMMs. These models include all relevant information for the attributes *roles* and *methods & tools* of the PAF model of the MCM process. Overall, the MCM process support does not claim completeness, but might be further complemented depending on the respective application and company.

6.4 MC-specific adaptation of the MCM process

This section describes the approach for adapting the MCM process based on an MC. This approach comprises two aspects: the tailoring of the MCM process and the selection of roles. Based on the system architecture of the MCM context model (cf. section 5.1), insights from the state of the art on the adaptation of processes (cf. section 3.5), and findings from industrial practice (cf. section 4.2), the dependencies between an MC, process activities and deliverables, and roles are modeled and described. Finally, a set of rules for tailoring the MCM process and selecting roles is proposed.[19]

6.4.1 Concept development for the MC-specific adaptation

The intended MC-specific approach is considered to contribute to MCM effectiveness by supporting the process orientation as well as transparency and traceability, to MCM efficiency by an MC-specific simplification (or extension) of the MCM process while maintaining the general MCM process architecture (cf. also section 1.4 and the appendix, table A.1).

For reasons of clarity and rigorousness, the dependencies between an MC, the MCM process, and the roles are modeled and described with a DMM and the PAF. More specifically, the MC attributes are linked to both the deliverables of the MCM process and to the roles. Based on the MC attributes and their values, the deliverables can be directly tailored to and the roles selected for a specific MC. The deliverables have been chosen for tailoring, because they can be specified and verified more easily than the activities. Nevertheless, the MCM process activities are tailored indirectly by the MC attributes, as any activity is related to a deliverable by an one-to-one dependency (cf. section 6.3.1).

6.4.2 Approach for the MC-specific adaptation

MCM process. The PAF provides three attributes for deliverables dedicated to process tailoring that are described in this section: modes, deployment, and tailoring guidance (cf. section 2.5.4 and the appendix, table A.5). Each deliverable is defined to have up to three modes (available variants of a deliverable) – *standard*, *optional*, and *extended*. Also, any deliverable can be either *independent and fix* or *tailorable*, which is described by the term *deployment*. The tailoring guidance covers instructions regarding tailoring – i.e., the process of selecting a suggested mode of a deliverable with respect to the values of the related MC attributes. For this research, the tailoring approach is designed as being conservative. That is, only simple MCs tailor deliverables to the mode *optional*, more complex MCs tailor them to the mode *extended*.[20] Examples for simple changes are a correction of an assembly documentation,

[19] The focus of the proposed adaptation approach is on an enterprise-independent approach. It might be adjusted to account for company specifics and depending on the respective application scenario if needed.

[20] *Optional*: the deliverable is not required for this MC, but can be created; *extended*: a more detailed version of the deliverable is required for this MC (e.g., a more detailed impact analysis, a more detailed change plan).

or the installation of a new computer monitor for a work-station without further impact on the production. In contrast, more complex MCs like the installation of a new manufacturing resource or a factory layout change might have a high impact on the production process and on logistics.

Note, that the activities possess the same attributes for tailoring (modes, deployment, and tailoring guidance) and the same values of these attributes. Due to the one-to-one relationship of deliverables and activities, activities are considered to always be tailored the same as the deliverables are.

Roles. The roles are distinguished in MCM roles and department functions. MCM roles (e.g., change manager, change agent) are selected by default for any MC, because these represent the basic roles required to conduct MCM and process an MC. The involvement of roles for an MC depends on the tailored MCM process, as the roles are linked to the MCM process activities and deliverables (cf. figure 6.3.4). In contrast, the selection of department functions depends on the values of MC attributes. For example, if an MC is caused by a previous EC, the department functions Product Development, Product Life Cycle Management (PLM), and ECM should be selected to be involved during the MCM process; if an MC has an impact on the customer, the departments Sales and Marketing as well as Legal should be engaged. Similar to the tailoring approach, also the selection of roles is designed as being conservative. Roles are either *standard roles* (the MCM roles), or selectable as *required* or *optional, but recommended* (the department functions).

MC attributes. For both process tailoring and role selection, only selected MC attributes with their different values are required. The relevant attributes are all part of the category *Characterization*. The remaining either specify an MC in terms of a *change ID* or a *change description*, or relate to the MC and cross-MC comparison, coordination, and evaluation (see also section 6.2.2). Most of the characterization attributes are used for process tailoring and role selection; however, the attribute *cause* is linked to the department functions only, because the MCM process is considered independent from the change cause. In contrast, the attribute *localization*, which describes the change object (e.g., a manufacturing resource, a tool, or a document), relates neither to roles nor to the MCM process. However, it is considered to aid the selection of specific employees, teams, or responsibles within the different department functions. For example, an MC to a certain manufacturing resource might require the selection of a specific, but different person within the department function *Production* than an MC to an assembly documentation.

Dependencies within the DMM. The dependencies between the MC attributes, the deliverables, and the roles finally describe the information necessary for process tailoring and role selection. Each dependency is modeled by providing the actual value required for a deliverable

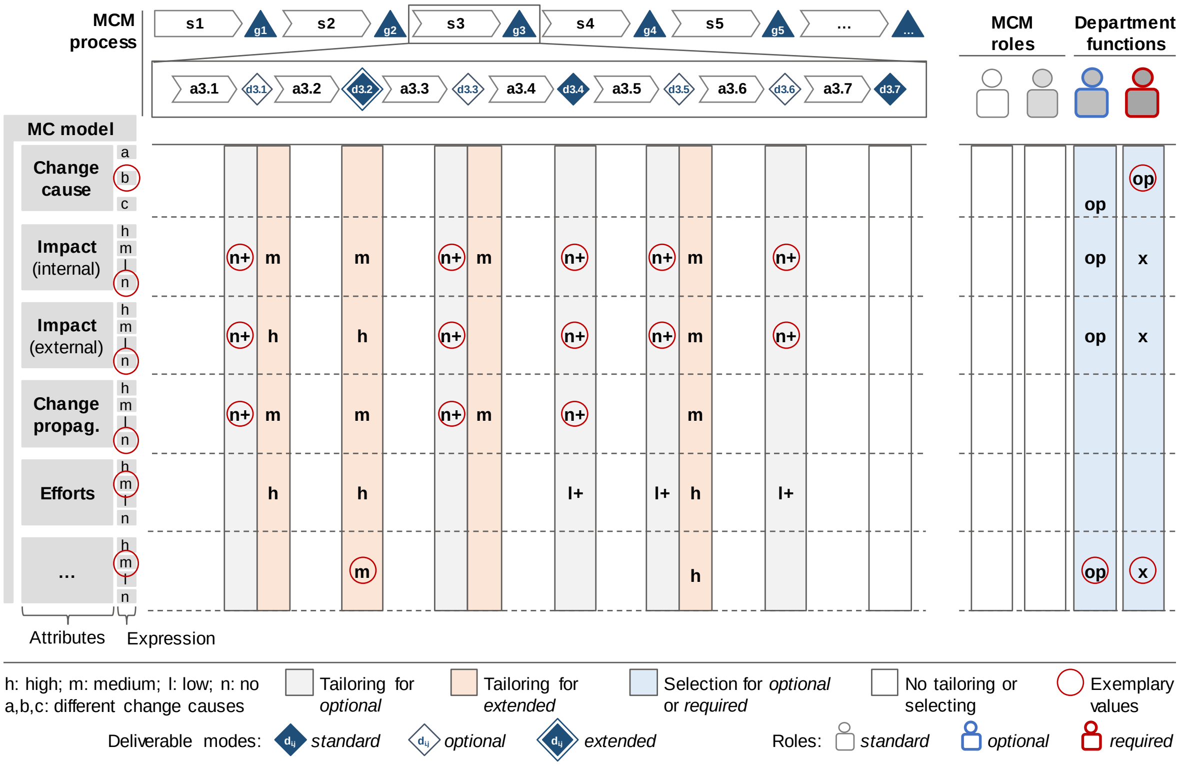

Figure 6.21: Concept for the DMM of an MC and the MCM process deliverables (exemplary)

to be tailored or a role to be selected. A generalized version of the model is visualized in figure 6.21, complemented by the relevant rules and the notation. For the detailed DMM model please refer to the appendix, figure A.13.

The detailed information about the deliverables regarding modes and deployment is supplemented to the PAF (cf. appendix, tables A.7 and A.6).[21] Additional information about the roles can be found in section 6.3.4. The proposed modes, deployment, tailoring guidance, and dependencies between attributes and roles are intended to create a profound basis for a situation- and company-specific adaptation of the concept and might be supplemented or further detailed if required.

Rules and notation for process tailoring

– There is only a dependency considered between an MC attribute and a deliverable if the respective field in the DMM is filled. All deliverables are in mode *standard* as long as

[21] Note, that the relevant information on the tailoring guidance is provided within this chapter with the rules for process tailoring and role selection. If needed, this can be directly supplemented to the respective PAF attribute.

there are no values of MC attributes determined during the MCM process. If no entry exists within the DMM, a deliverable has solely the mode *standard*.

– If a deliverable is tailorable to the mode *optional*, *extended*, or both, the required values of the MC attributes are specified in the column of the deliverable. If both are applicable, there are two columns provided for a deliverable. The left one relates to the mode *optional*, the right one to the mode *extended*.

– Values marked by *n*, *l*, *m*, or *h* (abbreviation for no, low, medium, high) represent a sufficient condition and solely tailor the deliverable. They are applicable and valid for the respective or higher value levels of the attribute for tailoring to *extended* (e.g., *m* is applicable for the attribute and valid in case the actual value of the attribute is either *m* or *h*). For tailoring to *optional*, they are valid for the respective or lower values (e.g., *l* is applicable for the attribute and valid in case the actual value of the attribute is either *l* or *n*).

– Values marked by *n*+, *l*+, *m*+, or *h*+ represent a necessary condition, and only a combination of attributes with these values tailors the deliverable.

– A deliverable remains in mode *standard* as long as the values of the MC attributes do not match the proposed entries within the DMM. Once a value of an attribute (or a combination of them) matches the entry within the DMM, the deliverable is tailored according to the aforementioned rules.

– In case an MC-specific tailoring causes an activity to have no dependencies to subsequent activities anymore, either a temporary dependency to the next non-tailored activity is to be supplemented or the *optional* dependencies apply.

For a detailed DMM model of the tailoring approach please refer to table A.13 in the appendix.

Rules and notation for role selection

– There is only a dependency considered between an MC attribute and a role if the respective field in the DMM is filled. Only in this case, the role is selectable based on a value of an MC attribute; otherwise, the role is always a standard role.

– If a role is selectable as *required* or *optional, but recommended*, the required values of MC attributes are specified in the column of the role.

– Any values of an MC attribute other than *no* – i.e., *l*, *m*, or *h* – represent a sufficient condition for selecting roles. Relevant dependencies are marked by *x* for selecting a role as *required*, or by *op* for selecting it as *optional, but recommended*. In any column, a dependency with *x* overrules other dependencies with *op*.

– More specific values of MC attributes are marked with *xl*, *xm*, or *xh* with the same applicability and validity as regular *x*, but only applicable for values of the same or higher levels (for example, *xm* is only applicable, if the value of the attribute is either *m* or *h*).

6.4.3 MC-specific tailoring of the MCM process

The tailoring concept developed facilitates the adaptation of almost the entire MCM process based on an MC. This includes not only the deliverables and activities, but also the dependencies between these (inputs, iterations, and feedback loops). For each deliverable and each activity, the relevant modes (*optional*, *standard*, and / or *extended*) have been derived according to the descriptions in the PAF. For example, deliverable *MC profile creation* (d1.4) has only one mode (*standard*) as it is required in the same manner for any MC regardless of the value of the MC attributes. The same applies for the related activity *create MC profile for change cause* (a1.4). In contrast, deliverable *detailed cost analysis* (d4.3) comprises all three modes as the scope of the analysis depends on the respective MC. Again, the same applies for the related activity *make detailed cost analysis* (a4.3). Overall, these modes determine the capability for tailoring the MCM process visualized in figure 6.22. The resulting pattern in the DSM process model demonstrates the distribution of modes along the MCM process and provides several insights to the developed tailoring concept.

– The first stage s1 and the second half of the last stage s8 of the MCM process are deployed as *standard* to account for the consistent relevance of these activities (e.g., to coordinate the change, to assign a responsible person for the potential MC, or to finally close the MC).

– The stages in between s1 and s7 show similar patterns: the first deliverables / activities usually comprise all three modes, the later ones mostly have two modes (*standard* and *optional*), the last one concluding a stage has usually the mode *standard* only and can never become optional. Deliverables / activities with all three modes comprise rather work-intensive parts (e.g., *create a change plan proposal* (a2.6) or *plan MC in detail* (a5.2)). Deliverables / activities comprising only the modes *standard* or *standard* and *optional* are allocated to sections of the MCM process with a focus on alignment, review, approval, and coordination (e.g., *review MC profile* (a2.8) or *make stakeholder review* (a3.4)). The alternation between these two types of deliverables / activities within each stage is the reason for the described pattern.

– From a quantitative perspective, 14 of 53 deliverables / activities (about 25%) are independent and fixed to the mode *standard* saving about 75% of the deliverables / activities for process tailoring. This portion further splits into 6 deliverables / activities (about 10%) being either *standard* or *extended*, 16 (30%) being either *standard* or *optional*, and 16 (about 30%)

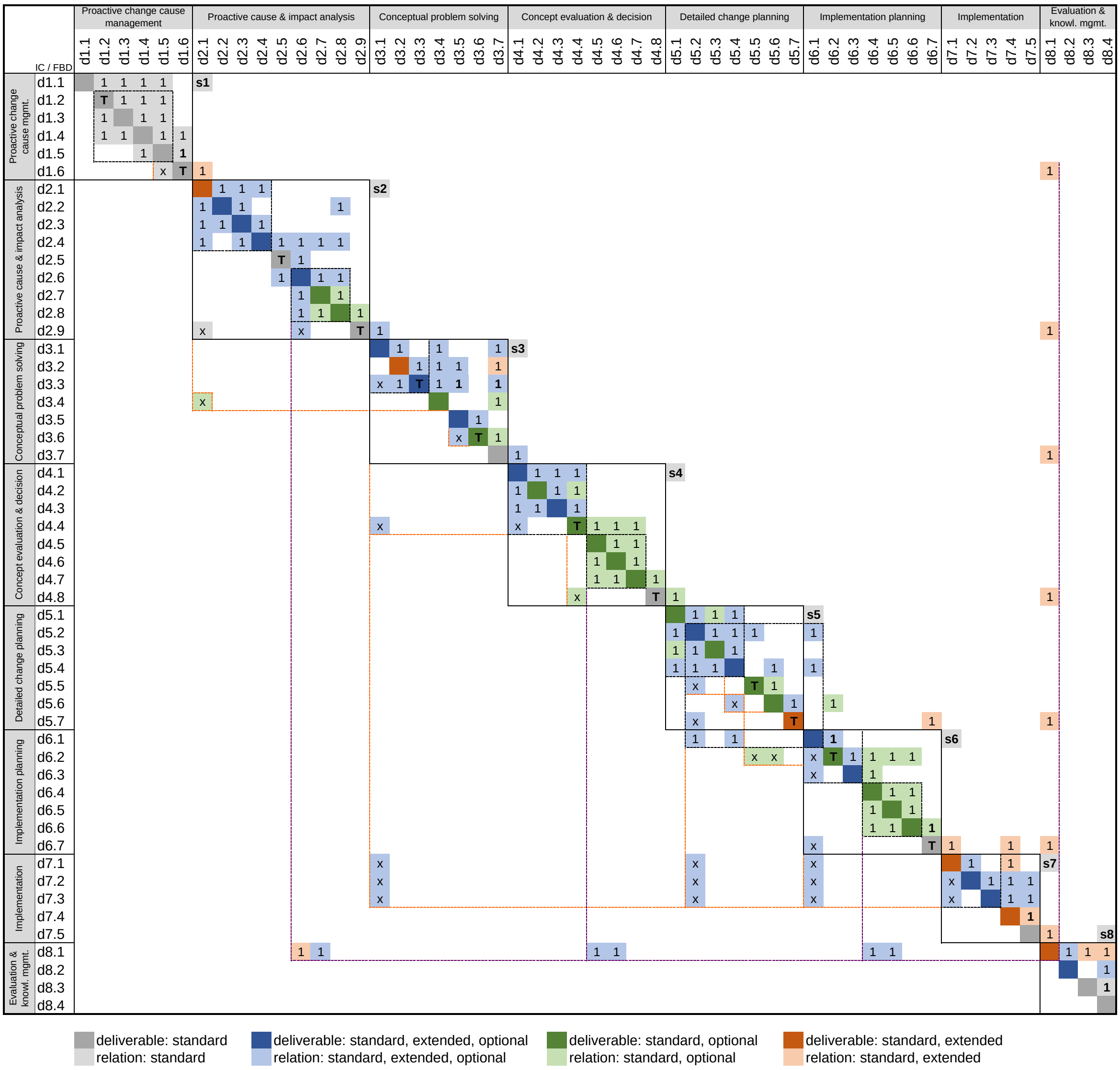

Figure 6.22: Visualization of the tailoring concept with the DSM model of the MCM process

comprising all three modes. The dependencies in the DSM relate to the modes of the two deliverables / activities linked by the respective dependency. Thus, also the dependencies have up to three modes. Overall, these figures reflect the capability of the MCM process for process tailoring based on the developed concept, which accounts for the broad spectrum of potential MCs occurring in industrial practice.

6.4.4 MC-specific selection and involvement of roles

The approach for the selection of roles addresses only the department functions, because the MCM roles are required by default for the MCM process (cf. section 6.4.2). The engagement of the MCM roles for an MC is indirectly determined through the MC-specific tailoring of process deliverables and thus the activities as these have direct dependencies to the MCM roles (cf. section 6.3.4). Hence, the involvement of roles directly reflects the tailoring and deployment of the MCM process (see figure 6.23 and figure A.14 in the appendix for the full DMM model). In consequence, the involvement for the first stage s1, the second half of the last stage s8, and most of the last parts of all remaining stages is set as *standard*. In contrast, for the other activities of the MCM process the involvement scales from *optional* to *extended* depending on the respective activity mode.

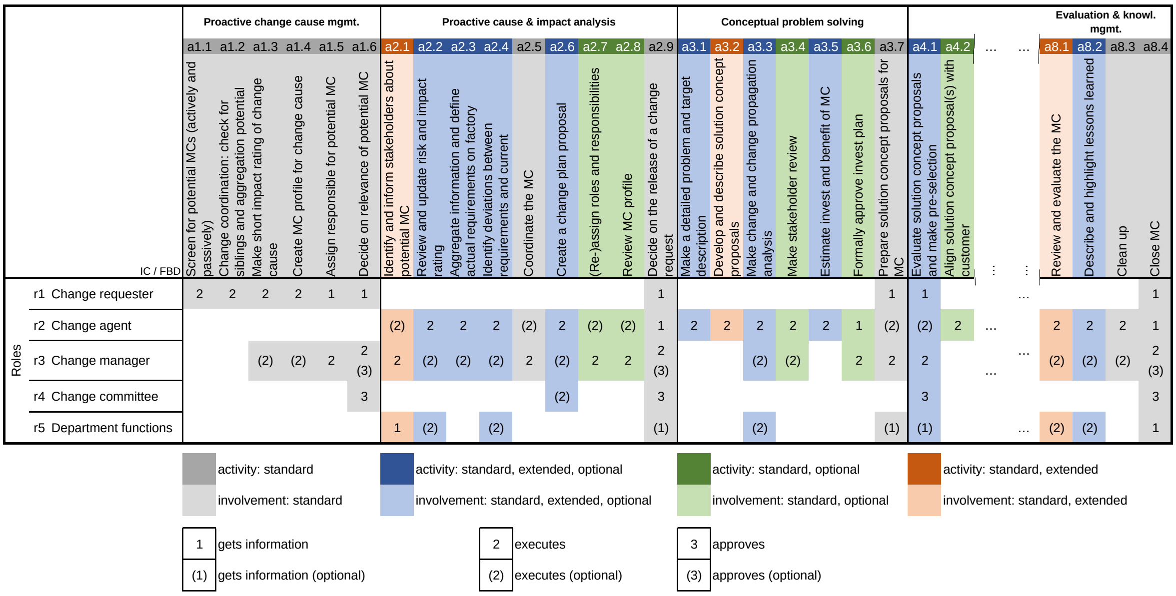

Figure 6.23: DMM with a visualization of the scalable involvement of roles based on the MCM process tailoring (excerpt)

The selection of department roles, whose involvement is scaled the same way as for the MCM roles, is designed MC-specific and mainly depends on three MC attributes: the change cause as well as the internal and the external impact of an MC. Additional attributes related to only few roles are, for example, efforts, risk, and costs. As figure 6.24 shows, department functions closely related to the engineering, planning, and managing of the physical systems (factory and product; cf. section 5.2) are most likely to be selected, whereas other functions like *Legal* or *Sales and Marketing* are only selected for few distinct MC attributes. The attribute *localization* describing the change object of an MC is considered to aid the selection of specific employees or responsibles within a department function – but not the department function in general (cf. figure 6.24 and section 6.4.2). For the complete DMMs for the selection of roles please refer to the appendix, figures A.15.

Attributes of MC model relevant for role selection	IC / FBD	r5.1 Production management / Factory planning	r5.2 Production / Shop floor	r5.3 Quality management	r5.4 Operations excellence / Lean	r5.5 Logistics/Supply chain	r5.6 Technology & product planning	r5.7 Product development	r5.8 PLM & ECM	r5.9 Management / Board	r5.10 HR / Work council	r5.11 Purchasing & Supplier management	r5.12 Sales and Marketing	r5.13 Legal	r5.14 Business development & Strategy	r5.15 External resources
		Department functions														
Cause																
Factory life cycle		x	x		x		x					x				
Manufacturing Change		x	x													
Complications		x	x	x	x											
Product life cycle		x	x				x	x	x	x		x	x		x	
Engineering Change		x	x	x				x	x				x			
Errors / Failures		x	x	x				x	x				x			
Laws & Regulations		x							x	x	x			x	x	
Technology		x		x	x		x	x	x	x						
Procurement		x				x			x		x	x		x		
Business operations		x	x	x	x	x		x		x					x	
Kaizen		x	x		x			x	x							
Localization (affected object)																
Impact on (internal)																
production / production process		x	x	x	op	x		op	op	op						
product		op	op	x		op		x	x	x		op	x			
employees		op	op							x	x			op		
factory operations		x	x	op	op	x			x	x		op	op			
...				...			...			...						
Costs										xh						

l: low m: medium h: high — x required — op optional, but recommended — xl / xm / xh required

Figure 6.24: *Visualization of the MC-specific selection of roles (department functions) with a DMM (excerpt)*

6.4.5 Conclusion

The developed adaptation approach for the MCM process provides a detailed concept and a set of rules for an MC-specific process tailoring and selection of roles. The dependencies between the MC model with its attributes, the activities of the MCM process, and the roles are modeled with DMMs based on generalized values for each MC attribute. The proposed set of rules accounts for the various possible adaptations of the MCM process and provides information for the *tailoring guidance* of the PAF, whereas the required enhancements of the activities and deliverables regarding *modes* and *deployment* are directly documented in the PAF. Overall, the proposed dependencies between the MC attributes, the MCM process, and the roles as well as the set of adaptation rules provide a profound, generalized basis for an MC-specific adaptation of the MCM process. However, these might be further specified or supplemented depending on the respective use case in industrial practice.

6.5 Summary and conclusion

Based on the MCM requirements and the MCM context model, the detailed design of MCM has been developed. The holistic, generalized MCM approach comprises a categorized set of change causes, an MC model, the MCM process with a detailed design of its content and architecture, the process support with roles as well as methods and tools, and an adaptation approach for the MCM process. The development and design of each of these elements account for both the various publications available on MCM, ECM, and related topics, and findings from the current practice of MCM in industry.

Concluding this chapter, a detailed review and assessment of the MCM approach against the MCM requirements is conducted. Table 6.3 provides the structured and consolidated results of this comprehensive examination, which also serve as input for the application and evaluation case studies in the following chapter.

Table 6.3: Review and assessment of the developed MCM approach

Requirement: **Systemic perspective (Holistic view)**

- Consistent, systemic, enterprise-independent **model of MCM and its relevant context**
- Extensive, standardized, **attribute-based MC model** addressing the specification, characterization, and coordination & evaluation for an MC
- Three-phased, **generalized process for MCM** comprising **proactive, reactive**, and **retrospective activities**; detailed design of the **process content and architecture**

Requirement: **Stakeholder involvement & interfaces (Holistic view)**

- **Continuous, MC-specific integration of roles and relevant department functions** already at the very beginning as well as throughout the MCM process

Requirement: **Enterprise-independent applicability (Applicability)**

- Enterprise-independent, **general MCM approach** based on several case studies, an extensive literature review, and a meta-analysis of the data gathered

Requirement: **Transparency & simplicity (Applicability)**

- **Concise, structured model of process content and architecture** (stage-gate, PAF, DSM, and BPMN) including relevant roles and methods & tools
- Holistic **model of an MC with attributes**, their values, and brief explanations

Requirement: **Clear roles & responsibilities (Applicability)**

- **Defined roles for MCM**: dedicated **MCM roles** (e.g., change committee, change manager, change agent) and **department specific roles** (as support for specific process activities)

Requirement: **Defined process architecture (Process orientation)**

- **Stage-gate process** with **activities, deliverables, and their dependencies**; intra-stage clusters of activities and differentiation of dependencies (e.g., feedback loops)
- Consideration of relevant **iterations between activities** (mainly within stages)
- Continuous, defined **approval / rejection and termination points**; several **feedback loops** within and across stages
- **Parallelization of process activities** throughout the MCM process

Requirement: **Coordination & information flow (Process orientation)**

- **Synchronization points throughout the MCM process** for a centralized collection of MC information; **continuous check of progress** through defined deliverables, reviews, and approvals **by an MCM role**; **feedback loops** available in case of deviations
- **Centralized overview and coordination** of all MCs by an MCM role
- **Recommendation of activities** with potentially high demand for diligence / thoroughness vs. quality of results vs. teamwork / alignment

Requirement: **Process adaptation (Process orientation)**

- **Rules for an MC-specific process tailoring** (direct and indirect); same or similar MCs tailor the MCM process the same or similar way
- **Rules for an MC-specific role selection** and scaling of the role involvement through process tailoring ("indirect tailoring")

Requirement: **Change identification (Proactivity)**

- **Early, proactive identification** of (potential) MCs and a **first rough evaluation** are standard activities of the MCM process ("frontloading of activities" and MCs)

Requirement: **Early change evaluation (Proactivity)**

- **Early change and change impact analysis** is a standard activity of the proactive phase
- Early (and repeated) **cross-MC evaluation and coordination** is also a standard activity

Requirement: **Cause & impact analysis (Problem solving & analytic capabilities)**

- **Detailed change cause, impact, and propagation analyses** for the MC solution concepts are standard activities of the reactive stages
- **Cost estimation and detailed cost planning** are also standard activities

Requirement: **Solution finding & implementation (Problem solving & analytic capabil.**

- **Creation and evaluation of solution concepts** are standard activities for an MC
- **Detailed change planning and implementation planning** are standard activities accounting for characteristics of the respective change object and / or factory

Requirement: **Archiving & tracing of information (Knowledge management)**
– **Standardized, continuous MC documentation** throughout the MCM process

Requirement: **Control of success & lessons learned (Knowledge management)**
– **MC evaluation and lessons learned** are standard activities of the retrospective phase
– MC closure and the **selection of information for archiving** are also standard activities

Requirement: **Efficient processing (MCM efficiency)**
– **MC-specific tailoring** of the MCM process and **selection** of roles
– MCM-process-specific **compilation of supportive methods and tools** for each stage
– **Company-specific implementation** of the MCM approach possible

7 Application and Evaluation of MCM

The descriptive study II (cf. section 1.3.3) comprises the application and evaluation of the developed MCM approach in industrial practice. Three case studies have been conducted with three different companies. The approach chosen, the findings from each case study, the results of a cross-case comparison and analysis, and benefits from applying the MCM approach are discussed within this chapter.

7.1 Introduction and approach

Accounting for both the requirements for case sampling (cf. EISENHARDT 1989, MCCUTCHEON & J. R. MEREDITH 1993, EISENHARDT & GRAEBNER 2007) and the data and extensive analysis results available from the initial case studies on the current practice of MCM in industry (cf. section 4.2), the case studies are carried out with the three companies A, B, and C (cf. section 4.2).

In preparation of the case studies, first, the developed MCM approach has been analyzed against the requirements of MCM effectiveness and efficiency (cf. section 6.5). Also, three past MCs from each company have been reviewed and analyzed regarding the MCM requirements. The MCs have been selected to reflect the broad spectrum of occurring MCs from, for example, the replacement of a manufacturing resource to a change in manufacturing documentation. Together with the findings from the initial case study on the current practice of MCM in the respective company, the analysis results of the MCM approach create the data base for the application and evaluation case studies.

All three case studies have been conducted as several workshops together with change managers, production planners, and / or production managers of the respective company. The half-day workshops have been conducted on-site and during a period of several months in 2015 and 2016. Each case study comprises two consecutive parts: (1) the application of the MCM approach, followed by (2) the evaluation of the success.

(1) For each company, the application of the MCM concept in industrial practice has been carried out together with practitioners from MCM and / or manufacturing planning in an extensive

thought experiment. In this context, the MCM concept has been theoretically implemented at the company and applied to the three MCs in an application scenario. Concurrently, the difference between the as-is situation and the developed MCM concept has been determined, cross-checked, and consolidated with the findings from the theoretical application of the MCM concept. The results describe the effect of the application of the developed MCM approach for each company. For the MCs, the effect of the MCM approach for their renewed execution has been assessed similarly. The final results have been documented and cross-reviewed by two researchers and the practitioners, the main findings are described and discussed hereafter.

(2) Based on these results, the effect of the developed MCM concept on the effectiveness and efficiency of MCM as well as the contribution to the overall value of the respective company has been evaluated (cf. section 1.4). More specifically, the initial effort required to introduce the aspect of MCM in the company, the impact on the continuous effort and the continuous benefit for MCM, and the contribution to the overall value[1] has been estimated together with practitioners from the respective company. The evaluation scale ranges from very high ("2") to no ("0") for the initial effort, and from significant increase ("2") to significant decrease ("-2") for the other criteria. The results have been consolidated and reviewed by the involved practitioners.[2]

Due to the large amount of data collected, only the main findings are presented hereafter. The results of the final cross-case comparison of all three case studies are described and discussed in detail to provide a comprehensive perspective on the application and evaluation of the MCM approach in industrial practice (cf. section 7.3.

Finally, the benefits and potential trade-offs of an application of the MCM approach are described. Based on the data collected during the case studies, cost-effects of MCM are estimated quantitatively and discussed in relation to the evaluation results of the MCM requirements.

7.2 Case studies for the application and evaluation of MCM

Recalling the specifics of the three companies, for each case study the effects of the developed MCM approach on the respective company are described. Also, the evaluation results and particularities are briefly discussed.

1 A company's value describes its monetary worth as a whole.
2 The approach has been chosen for this research as both a "real-world" implementation of the MCM approach and an evaluation of potential achievements require at least several months and up to some years to provide feasible and usable data on MCM and necessitate the availability and willingness of companies to participate (cf. also section 7.4).

7.2.1 Case study with company A

Currently, the OEM of the mechanical engineering industry combines several, mostly reactive processes for MCM, which are mainly based on a general project management process and an invest process. These are structured as a highly linear sequence, dependencies between activities are barely considered. Several MC attributes are documented in different documents; only a basic MC analysis, evaluation, and documentation is conducted, retrospective activities are seldomly carried out.

The three MCs selected include the introduction of a new manufacturing resource, the adaptation of the layout of a small manufacturing area, and MCs resulting from continuous improvement activities. Challenges faced include, for example, unexpected change propagation, late or no involvement of relevant stakeholders, poor change descriptions, and delayed "out-of-process" implementation planning, which caused additional costs, raised efforts, rework, and delays.

Applying the MCM approach to company A, favorable effects have been identified regarding the general MCM set-up, the description and analysis of MCs, the utilization of the MCM process, and regarding proactive and retrospective activities. The introduction of the overall MCM approach is considered to strengthen the currently rather decentralized MCM as a pendant to the already available ECM and contribute to the company's agility in terms of processing and executing MCs. The developed MC model enables company A to substitute the different, less specific change documents with a holistic, standardized, attribute-based change profile supporting the evaluation, coordination, and prioritization of MCs throughout the whole MCM process. In this context, the practitioners emphasized the benefit of the MC model also for the three former MCs described beforehand.

The MCM process equips company A with one universal, pertinent process structuring and simplifying their current, multi-process-based approach for the management of MCs. The detailed process architecture (e.g., PAF and DSM models) improves both the quality of the process documentation and the available process know-how. In addition, the clear definition of roles including a change manager and their involvement in the MCM process further fosters the acceptance and applicability of the MCM approach at company A. From a content perspective, especially the proactive and retrospective activities proved to be beneficial as most available activities already address the reactive aspects of MCM. The introduction of the proactive MCM supports especially the early identification of changes, leads to a decrease of unexpected change impacts and change propagation, and strengthens the awareness and capability for MCs and MCM in general. Especially the first two aspects have been stressed to contribute also to the exemplary MCs. The retrospective MCM improves specifically the know-how about

MCs in the medium and long term, but also encourages the process-based evaluation and documentation of MCs.

Finally, the process adaptation represents a significant contribution to the MCM approach applied at company A. The MC-specific tailoring of the MCM process shortens the duration and decreases the required efforts to conduct MCs, which in turn supports the acceptance of MCM in the company.

Most aspects of the MCM approach are considered to provide some or high continuous benefit and to lead to a partial decrease of continuous efforts required (e.g., the adaptation approach or the definition of roles). Also, a contribution to the overall value of company A is emphasized by the practitioners – or, as one stated during a workshop: “The standardized but tailorable process would be a great enhancement to our current project management oriented approach to better deal with changes in manufacturing.” However, some aspects like the detailed MCM process model or the adaptation approach require considerable initial effort for the introduction. For the detailed evaluation result regarding each MCM requirement please refer to the cross-case analysis in section 7.3, table 7.1.

7.2.2 Case study with company B

Up to date, the system supplier in the aerospace industry utilizes a combination of several centrally documented processes for MCM, which form linear sequences with very few dependencies considered between activities. MC descriptions are not standardized; several attributes are described, but a change profile is currently not available. The processes focus on reactive activities, proactive and retrospective ones are barely conducted.

Out of the hundreds of MCs processed each year, the following three MCs have been selected: the integration of a new manufacturing technology into the factory system, a manufacturing process change accompanied by the purchase of a new manufacturing resource, and MCs resulting from continuous improvement activities. Among the main challenges faced by company B are individual or even no initial change descriptions, missing involvement of stakeholders during the MCM process, and a lack of cross-MC and stakeholder alignment hampering the effective and efficient management of MCs.

Compared to company A, the application of the MCM approach reveals mostly similar effects – i.e., regarding the general MCM concept, the attribute-based description and analysis of MCs, the early and continuous involvement of different stakeholders, the implementation of the MCM process, and the introduction of proactive and retrospective activities. The introduction of the MCM concept strengthens the manufacturing perspective for the management of changes in company B while also contributing to its agility. The improved involvement of stakeholders leverages the utilization of available know-how on MCs and fosters the acceptance of MCM across departments and functions.

Introducing the developed MC model, the currently decentralized documentation and determination of MC characteristics is replaced with a holistic and precise, attribute-based description of MCs. This enables not only the analysis and evaluation of a single MC, but also the comparison, prioritization, and coordination across several MCs.

The MCM process substitutes several processes currently applied for MCM in company B. It enhances the MCM approach in terms of process content and process architecture providing a more realistic, representative approach to guide and support MCM activities. Supplemented with the set of roles and a centralized coordination, the current manufacturing planning-oriented set-up at company B is enhanced to a functional, dedicated MCM approach. In addition, the process adaptation is expected to improve the suitability of the MCM process for the different MCs and to support the involvement of roles. Content wise, especially the retrospective activities like lessons learned, knowledge management, and documentation of MCs are considered beneficial. Beyond, the early identification of changes during the proactive MCM as well as the consideration of the implementation planning during the reactive MCM improve the company's capabilities for the management of MCs.

Most of the effects resulting from the application of the MCM concept to company B also manifest for the exemplary MCs. Based on the MC model, the different MCs are described more specifically accounting also for their impact on, for example, the factory or the product. The pertinent, uniform MCM process design simplifies the process-based management of the MCs and supports the users in terms of activities relevant for the respective MC (e.g., analysis of the MC, planning of the implementation, required approvals). Also, the availability of know-how on the MCs and their impacts is improved by the early involvement of relevant stakeholders, the continuous documentation, and retrospective lessons learned.

Due to the partly rather large difference between the current practice of MCM at company B and the developed MCM approach, the initial efforts, but also the expected benefit and contribution to the company's value are repeatedly evaluated as high. For the detailed evaluation result regarding each MCM requirement please refer to the cross-case analysis, table 7.1.

7.2.3 Case study with company C

Recently, the OEM of medical technology started to apply an enhanced version of their ECM process for the management of MCs. It is linearly structured addressing both proactive and reactive activities focused on the description and alignment of MCs. Changes are described based on an attribute-based change profile, stakeholders are identified early in the process. The creation of solution concepts is not part of the MCM process but required for the change request; retrospective activities are seldomly carried out.

The three MCs selected comprise a relocation of a manufacturing resource to improve the material flow, a reconfiguration of a manufacturing resource due to an EC, and the introduction of a new production technology. Challenges faced by company C include the late identification of change causes, unexpected change propagation, and unforeseen or neglected obstacles during MC implementation.

In contrast to companies A and B, several specifics of the developed MCM approach rather than the overall MCM concept create the favorable effects for company C. The MCM concept generally fosters the manufacturing perspective for changes; the developed MC model supplements several MC-relevant attributes to the change profile already available (e.g., impact on factory operations, impact on technical documents). The additional attributes enable a more specific description of MCs – and also for the three exemplary MCs – and simplify the cross-MC comparison, prioritization, and coordination.

The MCM process with its detailed definition of content and architecture provides a more realistic, representative process guiding daily work for MCM compared to the current process of company C. Even though some feedback loops, iterations, and parallelizations are already available, the developed MCM process provides a more extensive and precise approach covering also proactive and retrospective activities. The former are dedicated to the early identification and analysis of change causes and resulting MCs. This applies also for the three MCs resulting in a longer period of time for solution finding and implementation activities. The latter especially add to the quality and usability of information available on MCs in company C. Regarding the reactive phase, the quality and profitability of MCs is improved by the dedicated analysis of change impact, the stage for concept development, and the iterative implementation planning. These aspects are also encountered for the three MCs in terms of a smoothed implementation in the factory.

Finally, the developed process tailoring represents a favorable contribution for the MCM approach at company C. It improves the suitability of the MCM process for different MCs while decreasing the efforts required for their processing. The same applies for the selection of roles, even though a basic, checklist-based approach is already applied.

Most aspects of the MCM approach are considered to provide some and partly even high continuous benefit and contribute to the company's value. This is especially true for the MCM process models, the adaptation approach, and the activities for change identification and solution finding. Nevertheless, the introduction of these aspects of the MCM approach at company C often requires considerable initial efforts and may partly increase continuous efforts. For the detailed evaluation result regarding each MCM requirement please refer to the cross-case analysis, table 7.1.

7.3 Cross-case analysis – results

Comparing and consolidating the results from the three case studies, additional insights on the effects of the developed MCM approach as well as accompanying efforts and benefits are gained. Main findings are briefly discussed hereafter, full results are structured according to the MCM requirements and provided in table 7.1. The quantitative evaluation data is averaged over the three cases for the initial effort, continuous effort, continuous benefit, and the company's value.[3]

Despite the different approaches applied by the companies for MCM (see section 4.2), the utilization of the developed holistic MCM approach is considered beneficial for MCM as well as for the overall company. This comprises not only the MC model and the MCM process, but also the involvement of stakeholders and consideration of interfaces to other departments. MCM provides a pendant to ECM, contributing to a company's agility and strengthening the manufacturing perspective for the management of changes. The MC model provides a standardized, detailed description for any MC, which creates a valuable basis for MC and cross-MC analyses, evaluation, prioritization, and coordination.

Compared to processes currently applied, especially the precise models of content and architecture of the MCM process supply extensive process know-how and aid the transparency and simplicity of the MCM approach. At the same time, the documented process becomes a more realistic representation of and applicable guidance for the MCM activities actually conducted – while also providing a basis for potential process audits.

Regarding the dependencies of activities, especially the potential benefit of iterations has barely been acknowledged by the practitioners. This might be due to an association of rework or delays, but indeed reflects the very nature of any change process (cf. section 2.4.3) and allows for a more realistic process description. In contrast, the identification and highlighting of critical activities of the MCM process to increase process know-how and awareness of employees is considered both highly beneficial and lowering continuous efforts for MCM. However, the

[3] For example, the evaluation results for the continuous benefit of one aspect are A:1, B:1, C:0 the result would be 1; for A:2, B:0, C:1 it would be 1; for A:0, B:2, C:2 it would be 2, for A:-1, B:-1, C:-1 it would be -1, etc.

identification of those activities is based on DSM analyses (e.g., activity, criticality), which require knowledge about the process dependencies – i.e., for example, iterations. Other dependencies like feedback loops and parallelizations tend to be beneficial and require only few additional efforts.

For all three companies, the process adaptation approach represents a highly beneficial aspect of the developed MCM. It improves both the suitability of the MCM process for specific MCs and the selection and involvement of stakeholders. All companies agree on a high initial effort required to implement the developed approach, but also on lowered continuous efforts and a high benefit.

For the proactive and retrospective aspects incorporated into the MCM concept, all three case studies acknowledge a continuous benefit and high contribution to the company's value. Also, all agree on only medium to no initial, and partly even lowered continuous efforts. Regarding proactivity, the main effects comprise a strengthened capability of employees for adaptations and improvements through MCs, an increased risk and impact awareness, and a decrease of unexpected change impacts and hence the overall workload for MCM. Regarding retrospectivity, especially an improved accessibility, re-usability, and consistency of experiences and documentation arises as a contribution to the knowledge management for MCM. Furthermore, the controlling and evaluation of MCs as well as the overall MCM is supported by the retrospective activities.

In the reactive phase, especially the cause and impact analysis for solution concepts is considered beneficial, but also causing initial and continuous efforts. This is in contrast to the early change evaluation during the proactive phase and might be due to the allocation further downstream within the MCM process. The introduction of a dedicated stage for implementation planning to the MCM process further adds to a reduction of unexpected change impacts, accompanied by medium benefits at almost no additional efforts.

Overall, the continuous benefit and the contribution of the MCM approach to the company's value are most often evaluated as medium or high, while initial efforts are non-negligible for the introduction of selected aspects (e.g., the defined process architecture or the adaptation approach). For the continuous efforts both increases and decreases are expected by the practitioners. The figures presented in table 7.1 provide a detailed and valuable estimation of expected effects of the developed MCM approach in industrial practice – and hence on their influence on MC-related costs, which are discussed in the subsequent section 7.4.

Table 7.1: Application and evaluation of MCM in industrial practice: findings and results

Requirement: **Systemic perspective (Holistic view)**	Initial effort	Cont. effort	Cont. benef.	Value of c.
– Holistic MCM approach as pendant to ECM **contributes to agility** and fosters the **manufacturing perspective for changes**	2	0	1	1
– Extensive, attribute-based MC model (A,B) or supplementation of MC-relevant attributes (C) to **prioritize and coordinate MCs**	1	0	1	1
– **Consideration of proactive, reactive, and retrospective MCM** with a precise definition of process content and architecture	2	-1	1	1
Requirement: **Stakeholder involvement & interfaces (Holistic view)**				
– Early identification and involvement of stakeholders **decrease (unexpected) MC impact** (A,B); continuous involvement to **leverage know-how of disciplines**	1	1	2	2
Requirement: **Enterprise-independent applicability (Applicability)**				
– Simplification of the **cross-company comparison** of MCM and the **alignment with suppliers' and customers MCM**	1	0	1	1
Requirement: **Transparency & simplicity (Applicability)**				
– Supply of **precise process knowledge** to employees, creation of **user-specific views**, and basis for improvement of MCM	2	0	2	2
– Supply of **additional MC knowledge** to employees, basis for **cross-MC analysis and evaluation**, and **process adaptation**	1	0	1	1
Requirement: **Clear roles & responsibilities (Applicability)**				
– Increase the **level of organization** for MCM and the **relevance of MCs** by introducing dedicated roles (A,B); more **detailed, transparent assignment** of responsibilities	1	0	1	1
Requirement: **Defined process structure (Process orientation)**				
– Enhance **process content and architecture** to achieve a **more realistic, representative process** guiding daily work, and to avoid rework, failures, missing alignments, etc.	2	0	1	1
– Achieve a more realistic, representative process with **relevant iterations**, actual practices, and necessary information flows	1	0	0	0
– Achieve a more realistic, representative, and **stable process** with **relevant feedback loops, approvals, and terminations**	0	0	1	1
– **Parallelized activities** to **decrease the process duration** from MC identification to closure and consider actual practices	0	0	1	1

Requirement: **Coordination & information flow (Process orient.)**	Initial effort	Cont. effort	Cont. benef.	Value of c.
– Synchronization points foster the **alignment and knowledge of stakeholders** about MCs, leverage a **cross-MC coordination** (e.g., combination of MCs), and support a **progress control**	1	1	1	1
– Defined roles to support a **centralized, cross-MC coordination** (A,B) as well as an **alignment and controlling** of activities	0	0	1	1
– Identify and suggest **critical activities** to increase **process awareness and knowledge** of employees (e.g., regarding high workload, time planning, or engagement of stakeholders / teamwork)	1	-1	2	1
Requirement: **Process adaptation (Process orientation)**				
– **Process tailoring** increases its **suitability for specific MCs** and **reduces the process duration** and **required capacities**	2	-1	2	1
– **Role selection** improves the **MC-specific selection and involvement of roles** during the MCM process	2	-1	2	1
Requirement: **Change identification (Proactivity)**				
– Strengthens the **capability** as well as **risk and impact awareness** of employees regarding MCs, fosters the **identification and notification of MCs** by all employees	1	1	1	2
Requirement: **Early change evaluation (Proactivity)**				
– **Early change analysis** decreases **likeliness of unexpected change impacts** and potentially the overall workload for an MC	1	-1	1	1
– **Cross-MC evaluation and coordination** leverages the potential of, e.g., **clustering and prioritizing** MCs continuously (A,B)	0	0	1	1
Requirement: **Cause & impact analysis (Problem solving & analytic capabilities)**				
– **Detailed MC analysis** for the solution concept(s) decreases **likeliness of unexpected change impacts and change propagation** and increases risk and impact awareness of employees for MCs	1	1	1	1
– Similar to current practice; **cost analysis** also documented as part of the MCM process (C)	0	0	0	0
Requirement: **Solution finding & implementation (Problem solving & analytic capab.)**				
– **Solution finding** is similar to current practice (A,B); development of **detailed solution concept(s)** creates **solution alternatives** and fosters, e.g., quality, originality, and sustainability of the MC	0	0	0	0

	Initial effort	Cont. effort	Cont. benef.	Value of c.
– **Detailed change planning and implementation** is similar to current practice; **implementation planning** as part of the MCM process decreases **likeliness for unexpected change impacts**	0	0	1	1
Requirement: **Archiving & tracing of information (Knowledge management)**				
– Uniform, process-based **MC documentation** increases **accessibility, usability, continuity, and transparency** of available MC documentation; support the utilization and application of KPIs	1	0	1	1
Requirement: **Control of success & lessons learned (Knowledge management)**				
– MC-review and / or **lessons learned** enable the utilization of experiences and knowledge from MCs for future, similar MCs	1	1	2	2
– **Clean up** of the MC documentation improves its **quality, density of information, and re-usability** for future MCs	0	1	2	1
Requirement: **Efficient processing (MCM efficiency)**				
– **Depends on the implementation** of the MCM approach in the company and is supported by the **process adaptation** approach and the provision of selected **methods and tools**	not applicable here (see section 7.4 for information on costs)			

Initial effort: no 0 / 1 / 2 high benef.: benefit cont.: continuous c.: company
Cont. effort: significant decrease -2 / -1 / 0 / 1 / 2 significant increase
Cont. benefit, Value of c.: significant decrease -2 / -1 / 0 / 1 / 2 significant increase

7.4 Benefits and trade-offs

The three case studies on the application of the MCM approach and the cross-case analysis revealed numerous contributions to an effective and efficient management of MCs in industrial practice. According to the MCM requirements derived in section 1.4, for all three companies most aspects of the developed MCM approach show significant effects with medium to high continuous benefits and contributions to the company's value (cf. section 7.3, table 7.1). Among MCM aspects most valued are the provision of a precise, detailed process model with a proactive, reactive, and retrospective phase, the process-based early change identification and analysis, and the approach for the MC-specific process adaptation. Despite some initial or continuous efforts required to implement the MCM approach with its various aspects, the evaluation results demonstrate the suitability of the developed MCM concept regarding the effective and efficient management of MCs.

Directly cost-effective benefits of the MCM approach are the prevention of MCs, the reduction of processing costs for MCs, and the avoidance of critical changes. According to the surveys by DEUBZER et al. (2005, p. 8) and LANGER et al. (2012, p. 7), about 20 to 30% of changes are preventable in manufacturing companies. Furthermore, WILDEMANN (2014, pp. 242-246) expects a change management to reduce costs of change by about 25%, whereas LANGER et al. (2012, pp. 8-10, 20) delineate the positive effects of an effective change management approach on the occurrence of critical changes. In this context, the companies' experts suggested to assume about 10% reduction of costs per MC and about 10% of MCs to be avoided when applying MCM.[4]

In order to quantify these cost-effects, for each company the overall amount of MCs per year and the occuring costs for processing one MC have been estimated by the practitioners. Those costs are considered to cover all expenses for activities like the identification, description, alignment and approval, or IT-based documentation of an MC. Costs for engineering, implementation activities, materials, or change planning activities are not included. These strongly depend on the respective MC, but can reach up to several hundreds of thousands of EUR, for example, for layout adaptations or the introduction of new manufacturing technologies in a factory as described in one of the very initial examples for MCs (cf. section 1.1). According to the practitioners, especially for critical MCs those costs tend to multiply compared to initial cost estimations and are expected to significantly decrease with an application of MCM.

For all three companies, table 7.2 lists the amount of MCs, the costs for processing an MC[5], and the resulting annual costs for both the current situation without MCM and with an application of MCM.

In total, the costs just for processing MCs sum up to amounts of up to several million EUR per year. With the application of MCM, these costs are expected to decrease by about 19% compared to the current situation, which saves about €0.43 mil. for company A, €1.9 mil. for company B, and €0.12 mil. for company C. These cost reductions result from, for example, an early identification and analysis of potential MCs due to the proactive activities in the MCM process, an early involvement of relevant stakeholders to identify change impacts and to align more economic solution concepts for MCs, an improved process documentation, and a more coordinated information flow avoiding failures and rework (cf. also the continuous benefits for MCM, table 7.1).

[4] Note, that actual cost reductions may be significantly higher, as former industrial surveys revealed about 20 to 30% of changes to be preventable (cf. DEUBZER et al. 2005, LANGER et al. 2012).

[5] Note, that for company A the costs for smaller MCs may not account for the total processing costs, as they are based on an average duration for an MC only; efforts for the identification and alignment might add.

Table 7.2: Directly cost-effective benefits of the MCM approach per year

	Without MCM (today)	Effect of MCM	With MCM
Company A			
Amount of MCs [#]	70 large MCs 17,500 small MCs	-10%	63 large MCs 15,750 small MCs
Average processing cost per MC	€1,300 (large MCs) €125 (small MCs)	-10%	€1,170 (large MCs) €112.5 (small MCs)
Total costs for processing MCs	€2.28 mil.		€1.85 mil.
Total annual cost effect of MCM		- €0.43 mil. (-19%)	
Company B			
Amount of MCs [#]	10,000	-10%	9,000
Average processing cost per MC	€1,000	-10%	€900
Total costs for processing MCs	€10 mil.		€8.1 mil.
Total annual cost effect of MCM		- €1.9 mil. (-19%)	
Company C			
Amount of MCs [#]	150 large MCs 250 small MCs	-10%	135 large MCs 225 small MCs
Average processing cost per MC	€1,600	-10%	€1,440
Total costs for processing MCs	€0.64 mil.		€0.52 mil.
Total annual cost effect of MCM		- €0.12 mil. (-19%)	

In addition, further significant cost reductions may be achieved due to an improved handling or even avoidance of critical changes by applying MCM. As costs for such MCs may unexpectedly reach up to millions of EUR (cf. section 1.1), avoiding just one of those MCs per year could multiply the total cost effect of MCM as listed in table 7.2.

In contrast to these savings, some additional expenses become necessary for the application of MCM (cf. also the initial efforts for MCM, table 7.1). According to the practitioners and the findings from the case studies, personnel costs represent the dominant portion of costs for MCM, investments in hardware or software are not necessary.[6]

In total, one to two persons would be required to initially implement and continuously apply

[6] In general, the application of MCM could be supported by software-based workflow tools, which may require additional expenses. However, the developed MCM approach has been designed to be implementable and applicable also without such IT support.

MCM.[7] Also, capacities from several departments (e.g., production, product development) would be necessary for the implementation of MCM. Additional continuous personnel capacities for meetings, alignments, or documentation are barely required as MCs are currently already planned, implemented, and documented – but based on different processes, procedures, and meetings. Table 7.3 provides an overview on estimated costs for MCM opposed to the expected savings (cf. table 7.2).

Table 7.3: Costs of MCM opposed to cost-effective benefits of MCM

	Unit	Company A	Company B	Company C
Cost-effective benefits	[€/year]	0.43 mil.	1.9 mil.	0.12 mil.
Initial efforts for MCM				
MCM	[person-years]	1.5	1.5	0.75
Production	[person-years]	1.0	1.0	0.5
Quality management	[person-years]	0.5	0.5	0.1
Product development	[person-years]	0.3	0.3	0.1
Management	[person-years]	0.2	0.2	0.1
Total capacity	[person-year]	3.5	3.5	1.55
Total initial costs	[€]	370,000	370,000	165,000
Continuous efforts for MCM				
MCM staff	[# of persons]	2	2	0.5
Total continuous costs	[€/year]	200,000	200,000	50,000
Amortization time	[years]	1-2	<1	2-3

Labor costs per year: €100,000; Labor costs for Management per year: €200,000

In order to implement and continuously conduct MCM, two persons (change managers) would be required at the companies A and B, because their current setup for managing MCs is rather decentralized with different processes and little proactivity and retrospectivity only. At company C the necessary efforts could be accomplished by the change manager currently working on ECs and a part-time support by one engineer from the manufacturing department. Despite the initial and continuous costs for MCM, applying the MCM approach is expected to amortize in about one to three years for companies A and C, and in less than one year for company B.[8] Hence, an implementation and application of the developed MCM approach is

[7] Note, that the actual number of persons required depends on the size of the company, its factories, and the amount of MCs to be covered.

[8] Note, that additional cost savings due to the avoidance of critical changes have not been considered within the MCM cost analysis yet.

justifiable and recommended in each case.

To further detail the costs and cost-effective benefits of MCM, an actual implementation of the MCM approach and its long-term application would have to be accompanied to gather the necessary data. This includes, for example, data on past and current MCs, costs of MCs, and capacities bound for MCM. Accounting for the fact of MCM representing a type of risk-insurance against changes (cf. also section 1.4), also the risks of MCs and the company's risk affinity would have to be determined. Further relevant aspects are the need to comply with norms and regulations, or the utilization of digital models of the factory system. Due to the duration of such a study of several years, this topic is suggested for future research activities on MCM (cf. section 8.3).

Finally, mainly two potential trade-offs are to be considered for an application of MCM. On the one hand, the throughput time for an MC may increase due to, for example, the synchronization points in the MCM process or the intensified involvement of stakeholders. On the other hand, some users of MCM or other employees may consider the process-oriented MCM approach as an increase in bureaucracy and regulations due to the detailed MCM process and the introduction of dedicated roles for MCM. The relevance of these trade-offs depends on the prior availability and utilization of MCM approaches in the company, the actual deployment of the developed approach, and the MCM efficiency achievable (cf. also section 4.3, table 4.1). However, "no complex system can be optimum to all parties concerned nor all functions optimized" (RECHTIN 1991, p. 57).

8 Conclusion

Including a holistic MCM concept, an MC model, the detailed MCM process, and a procedure for an MC-specific process adaptation, the developed MCM approach provides a profound reference basis for both science and industrial practice. The results enable an enterprise-specific deployment of MCM, contribute to a theory on MCM, and may serve as input for the development of an IT-based workflow tool as well as a recommendation or norm for MCM. Within this chapter, the MCM approach is reviewed based on the four research questions, limitations and assumptions are discussed, and future perspectives for MCM are suggested.

8.1 Review and summary

The perpetual challenge of coping with change in manufacturing on the one hand, and the limited availability of dedicated approaches and concepts for MCM on the other hand, the research addresses this discrepancy with the development of a process-based MCM approach. The results are intended to support practitioners in managing MCs more effectively and efficiently, i.e., to conduct appropriate, beneficial activities and measures in a meaningful sequence to manage MCs with respect to agility and the company's value – and with appropriate initial and especially continuous efforts for each MC. Guided by the DRM methodology, the developed MCM approach contributes not only to industrial practice, but also to engineering science and a theory on MCM.

Based on the MCM requirements derived in section 1.4, three detailed case studies, numerous interviews with practitioners, and extensive literature reviews the MCM approach with its different elements has been developed addressing the four research questions and assessed against the MCM requirements (cf. section 6.5).

Q1 How could a company-independent concept for MCM be designed in order to guide a subsequent, system-oriented development of a more detailed MCM?

The MCM context model comprises the elements and their relations considered relevant for MCM. It is modeled as both a non-formalized graphical and a textual representation to support a general understanding. Its general and detailed system architecture is modeled with a matrix-based approach (MDM) creating the basis to guide the subsequent development of the more detailed MCM. For this purpose, the context model with in total 19 elements (domains) and sub-elements (sub-domains) could be reduced to 8 core (sub-)elements, which together form the MCM approach: *change cause*, *MC*, *MCM process* (i.e., *stages*, *gates*, *activities*, and *deliverables*), and *process support* (i.e., *roles* and *methods and tools*).

Q2 How could a Manufacturing Change generally be described to support MCM?

The MC model comprises numerous attributes and their values to describe any MC in detail. In industrial practice, this model can be instantiated, for example, as a change profile, a change request, or a change order. Also, it can be utilized as a reference to develop a data model for an IT-based MCM tool. Within this research, it provides the basis for the development of an MC-specific process adaptation.

In total, the MC model comprises 20 general attributes with 32 specific attributes, which are used for the specification, characterization, or the coordination and evaluation of an MC. The values of each attribute are generalized to capture up to four states of an attribute (e.g., for the attribute *impact*: no, low, medium, high), texts (e.g., for the attribute *name*), or specific, pre-defined objects (e.g., for the attribute *cause*). For the latter attribute, eleven change cause areas are derived describing where relevant MCs might arise from.

Q3 How could a process to efficiently and effectively manage different MCs be designed?

The MCM process defines the detailed process content and architecture. It comprises a proactive, a reactive, and a retrospective phase with in total eight stages and eight gates. Overall, these include 53 activities and 53 deliverables, which are designed to form a one-to-one relationship. In addition, the relevant dependencies between the activities are described. These cover iterations, feedback loops, and parallelizations. Four models capture the MCM in detail: a graphical representation for the general process architecture (stages and gates), a DSM for the detailed architecture (activities and their dependencies), a formalized flowchart based on BPMN (whole MCM process), and a PAF for process content and related information.

The process support describes roles relevant for MCM. These include MCM roles required to manage MCs (e.g., change manager, change committee) and department functions required to, for example, provide information for an MC or to support a concept development (e.g., factory planning, quality management, product development). The roles are allocated to the process activities with regard to their responsibilities (e.g., executes, approves; modeled with a DMM). In addition, the process support comprises a compilation of methods and tools supporting the activities of the MCM process. These are also modeled with a DMM enabling a simplified selection and application of relevant methods and tools.

The adaptation approach finally comprises rules for the MC-specific tailoring of the MCM process and selecting of relevant roles. The attributes of the MC model are linked to the process deliverables and tailor these depending on their values. For this reason, for each deliverable (and activity respectively) up to three modes are defined: *standard*, *extended*, and / or *optional*, which are applied depending on the MC-specific values of the MC attributes. The selection of roles is conducted similarly. However, MC roles are standard, because they are generally required for MCM; department functions are selected as either standard or optional. The involvement of the roles for an MC depends on the tailored MCM process and the modes of the allocated activities. Overall, the adaptation procedure represents a key contribution to the effective and efficient management of MCs.

Q4 What are the benefits achieved by applying the MCM approach?

The implementation and application of the MCM approach offers numerous benefits, but necessitates also some trade-offs. In three industrial case studies the MCM approach has been applied in thought experiments and evaluated regarding the MCM requirements. The application included a theoretical implementation of the MCM concept at the respective company, the processing and execution of exemplary MCs in an application scenario, and the determination of the effects of the applied MCM concept for each MCM requirement. The evaluation included the estimation of the initial efforts, continuous efforts and benefits, and the contribution to the overall company's value – determined for each MCM requirement. Furthermore, cost-effective benefits and costs for MCM have been analyzed.

Based on these case studies, especially the precise MCM process model with its proactive and retrospective aspects, the MC-specific process adaptation approach, and the early selection and involvement of stakeholders are considered beneficial by practitioners. In terms of cost-effective benefits, the application of MCM is expected to decrease processing costs for MCs by at least 10% and to lead to a reduction of MCs by about 10%. In contrast, initial and continuous efforts are required for the implementation and ongoing application of MCM. These mainly manifest in personnel costs and accumulate up to several hundreds of thousands of EUR. Opposed to MCM-related cost savings, however, an amortization of MCM is expected within one to three years for all three companies. Further trade-offs to be considered are a potentially increased throughput time for MCs and raised internal regulations for the MCM process and MCM-related procedures.

8.2 Limitations and assumptions

In addition to the limitations initially described in section 1.3.4, the following aspects are to be supplemented. Firstly, the developed MCM approach addresses companies of the manufacturing industry – for an extension to other industries alterations of the approach might be necessary. Secondly, it is designed as a counterpart to ECM in the manufacturing domain, not as an enhanced substitution. However, ECM and MCM together can provide a profound basis for the management of changes for both product development and manufacturing. The necessary exchange of information between ECM and MCM can be realized by linking ECs causing MCs and vice-versa (documented in the instantiated MC model) and by alignment meetings during the coordination activities in the MCM process. However, additional interfaces might be required depending on the respective company and organizational set-up. Thirdly, the implementation of the MCM approach may substitute other processes within a company, but does not have to (e.g., continuous improvement process). This can require the information and training of employees to ensure the acceptance and utilization of the MCM approach. Also, the necessity to account for company specific aspects and new best practices may arise during or after an implementation of the MCM approach. Fourthly, the MCM approach is based on a process, the MC model on attributes. Both the state of the art as well as industrial practice corroborate this set-up. Nevertheless, other differing but beneficial set-ups and approaches may exists for an MCM. Fifthly, a set of roles relevant for MCM is proposed independent of an organizational set-up – suggestions for organizational set-ups are not included. Sixthly, the adaptation approach represents a generalized procedure for process tailoring and role selection, whose deployment in industrial practice is considered to strongly depend on the respective company and application scenario.

Regarding the research approach chosen, especially the design of the MC model and the MCM process is based on data from extensive literature reviews and case studies. The procedures of data collection, analysis, evaluation, and review with other researchers and practitioners have been carefully conducted according to the research methodology described in 1.4 and reported on in detail within this thesis – still, the results immanently include the author's opinion and judgment.

In order to account for the characteristic of MCM as being a type of risk insurance (cf., e.g., section 1.4), the MCM approach has been designed as being conservative. That is, the MCM process includes all activities, deliverables, and dependencies considered relevant, and the adaptation approach cautiously tailors the MCM process and selects roles based on the specific MC.

Further, the application and evaluation results as well as the analysis of MCM-related costs and cost-effective benefits provide extensive information on the benefits and potential trade-offs of the MCM approach. For a highly detailed cost-benefit analysis of the MCM approach long-term case studies would be required accompanying actual implementations and applications of MCM in industrial practice.

8.3 Future perspectives

Accompanying these achievements in MCM for industrial practice, engineering science, and a theory on MCM, new questions and challenges arise.

a) *Digitalization of manufacturing*

   Often framed with the term *Industry 4.0*, the progressive digitalization of manufacturing may provide numerous possibilities, for example, to enhance the identification and evaluation of potential MCs in the proactive phase of MCM, to enable more detailed analyses of MCs regarding change impact and change propagation in all three phases of MCM, or to develop configurable workflow tools with high usability.

b) *Process adaptation*

   The developed adaptation approach provides a generalized procedure for an MC-specific process tailoring and role selection. Further guidance could be provided by, for example, identifying and describing potentially existing major tailoring patterns for different MCs or industries.

c) *Recommendation for the application of MCM*

   MCM can be considered as a type of risk insurance for manufacturing companies against unexpectedly high costs for MCs. The level and scope of this risk insurance may vary depending on the company and industry. For this purpose, recommendations on the adjusted application of MCM and detailed information on actual cost-effects could be beneficial for industrial practice.

d) *Systemic change management*

   The increasing integration of product and production systems may lead to more interlinked, complex ECs as well as MCs. For this reason, the combination of both ECM and MCM to a joint – systemic – change management could be the logical next step for the management of changes in manufacturing companies.

With respect to these future perspectives for MCM and especially the MCM approach developed and described within this thesis, MCM seems to become a valuable support for managing MCs more effectively and efficiently – thus, a contribution to the agility of a manufacturing company. MCM could, after all, make a difference.

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Appendix

A.1 MCM requirements – further details

Table A.1: Detailed MCM requirements for the MCM approach

MCM context model	MC model	MCM process	Adaptation approach
Systemic perspective (Holistic view)			
Modeling of MCM and the relevant context as a system with elements and dependencies, i.e., the system content and architecture	Modeling of MCs in a holistic, generally applicable manner	Modeling the MCM process as a system with elements and dependencies, i.e, its content and architecture	Consideration of the developed MCM elements (MC model, MCM process, process support) and their dependencies
Stakeholder involvement & interfaces (Holistic view)			
Consideration of relevant interfaces between elements (i.e., focusing dependencies)	Consideration of MC attributes relevant for different stakeholders	Consideration of stakeholders throughout the process and interfaces to related activities	MC-specific selection of roles and tailoring of the process to involve relevant roles
Enterprise-independent applicability (Applicability)			
Defining, detailing, and relating MCM relevant vocabulary	Consideration of characteristics of a broad range of different MCs from practice	Consideration of characteristics of a broad range of industries and different MCs	Consideration of characteristics of a broad range of industries, processes, MCs, and roles
Transparency & simplicity (Applicability)			
Illustrating and describing the concept of MCM in a structured, intelligible manner	Supporting the understanding and simple, unambiguously description of any MC	Illustrating and describing the MCM process simply and unambiguously regarding its content and architecture	Illustrating and describing the adaptation approach in a simple and unambiguous manner
Clear roles & responsibilities (Applicability)			
Provision of relevant roles and their relations to MCM	Consideration of responsibilities for an MC as a descriptive aspect of this MC	Consideration of roles and their responsibilities for the MCM process	Provision of unambiguous rules for the selection of roles for an MC
Defined process structure (Process orientation)			
Description and visualization of a general setup of the process architecture	n/a	Description and visualization of a detailed process architecture	Consideration of relevant process characteristics for a tailoring of the process
Coordination & information flow (Process orientation)			
Description and visualization of the dependencies between MCM elements	Description of MCs in a manner to support the MCM process application, their coordination, and comparison	Description and visualization of the information flow within the process and the coordination of activities	Description and visualization of the selection and involvement of roles in the MCM process

Process adaptation (Process orientation)			
n/a	Provision of information and structure to enable an MC-specific process adaptation	Description of the dependencies between the MCM process, roles, and MCs	Development of an MC-specific approach for process tailoring and role selection
Change identification (Proactivity)			
Consideration of change causes for MCM	Consideration of change cause as a characteristic of MCs	Support the early identification of occurring change causes and potential MCs	Ensure a retention of relevant activities also for a tailored process
Early change evaluation (Proactivity)			
n/a	Consideration of MC characteristics that can be used for its evaluation	Foster detailed knowledge about an MC early in the MCM process	see above
Cause & impact analysis (Problem solving & analytic capabilities)			
n/a	Consideration of the impact of an MC as an MC characteristic	Support the analysis of the MC, the change cause, and the impact	see above
Solution finding & implementation (Problem solving & analytic capabilities)			
n/a	Provide a clear, unambiguous description of any MC	Support the identification, evaluation, and detailed planning of solutions for an MC	see above
Archiving & tracing of information (Knowledge management)			
n/a	Support the archiving of information about an MC and the future tracing	Support the archiving of information about the MCM process, MC, and the future tracing of information	see above
Control of success & lessons learned (Knowledge management)			
n/a	Support the comparison and evaluation of any processed MC, lessons learned, and their utilization for future MCs	Support the evaluation of MCM and processed MC, lessons learned, and the usage of information for future MCs	see above

Efficient processing (MCM efficiency)			
n/a	Support an efficient, detailed, and unambiguous description of MCs in industrial practice	Provide the basis for an efficient implementation and application of the MCM process in industrial practice	Provide an MC-specific simplification (or extension) of the MCM process and a lean selection of roles

A.2 Literature used for the development of MCM

Table A.2: Literature used as input for the development of the MCM approach

Change causes	MC model	MCM process
Manufacturing	*MC*	*MCM*
Dohms (2001)*	Aurich et al. (2004)	Aurich et al. (2004)
Hernández Morales (2002)	Rössing (2007)*	Rössing (2007)*
Wemhöner (2005)	Wiendahl et al. (2007)	Stanev et al. (2008)
Rössing (2007)*	Aurich & Cichos (2014)	Malak (2013)
Wiendahl et al. (2007)		ProSTEP iViP e.V. (2015)*
Nyhuis et al. (2008)	*EC*	
Westkämper & Zahn (2009)	Dale (1982)*	*ECM*
Dudic (2010)	DiPrima (1982)	DIN 199 Part 4
Zäh et al. (2010a)	Pflicht (1989)	Dale (1982)*
Zäh et al. (2010b)	Balcerak & Dale (1992)	Maull et al. (1992)
Wulf (2011)	Maull et al. (1992)	Conrat (1997)
Klemke (2014)*	Kaiser (1993)	Hiller (1997)*
	Gemmerich (1995)	Kleedörfer (1998)*
Product development	Innes (1995)	Lindemann & Reichwald (1998)*
Pflicht (1989)	Wildemann (1995)	Terwiesch & Loch (1999)
Gemmerich (1995)	DIN EN ISO 10007	Assmann (2000)*
Wildemann (1995)	Reichwald & Conrat (1996)	Rivière et al. (2002)
Conrat (1997)	Conrat (1997)	Rouibah & Caskey (2003)*
Wenzel et al. (1997)	Eversheim et al. (1997)	Jarratt et al. (2005)
Fricke (1998)	Lindemann & Reichwald (1998)*	Tavčar & Duhovnik (2005)*
Lindemann & Reichwald (1998)*	Kleedörfer (1998)*	Lee et al. (2006)
Pikosz & Malmqvist (1998)	Assmann (2000)*	Belener (2008)*
Huang & Mak (1999)	Fricke et al. (2000)	Schuh et al. (2008)
Assmann (2000)*	Riedel (2000)	Ström et al. (2009)
Fricke et al. (2000)	Rivière et al. (2002)	Köhler (2009)*
Riedel (2000)	Deubzer et al. (2005)	VDA (2010a)*
Eckert et al. (2003)	Jarratt et al. (2005)	Wickel et al. (2014)
Jarratt et al. (2005)	Scholz-Reiter et al. (2007)	
Conrad et al. (2007)	Belener (2008)*	*Factory planning*
Kolberg et al. (2007)	Giffin et al. (2009)	Kettner et al. (1984)*
Köhler (2009)*	Köhler (2009)*	Bullinger & Ammer (1986)*
Jarratt et al. (2011)	Reddi & Moon (2009)	Aggteleky (1987)*
Ehrlenspiel & Meerkamm (2013)	Kocar & Akgunduz (2010)	REFA (1991)
	Mehta (2010)	Wiendahl (1996)*
	VDA (2010b)	Dohms (2001)*
	Jarratt et al. (2011)	Schenk & Wirth (2004)*
	Reddi & Moon (2011)	Bergholz (2005)*
	Siddiqi et al. (2011)	VDI 5200*
	Sharafi (2012)	Schulze (2013)*
	Wildemann (2014)	
		Continuous factory planning
		Felix (1998)
		Cisek (2005)*
		Nofen (2006)*
		Nyhuis et al. (2010)
		Wagner (2012)*
		Pachow-Frauenhofer (2012)*
		Azab et al. (2013)*
		Klemke (2014)*

* Proposed requirements have been considered for the derivation of the MCM requirements

A.3 MC model

Table A.3: Attribute-based MC model with values and further details

Attributes	Details	Value
Specification		
Change name	Term (one or more words) helping to name and identify the change	Text
Change description	Textual explanation of the MC	Text
Change ID	Identification number of the MC	Number
Responsible	Person(s) responsible for the MC	Selection
Change owner	Person responsible for the MC	Selection
Change requester	Person proposing / initiating the MC	Selection
Timeframe	Dates / Time stamps to specify the MC	Number
Start of change	Date / Time when the change is scheduled to begin	Number
Deadline / End of change	Date / Time when the change is required to be implemented	Number
Characterization		
Cause	Cause / Trigger for the change	Factory life cycle, MC, Complications, Pro-duct life cycle, EC, Errors, Laws & Regulations, Technology, Procurement, Business operations, Kaizen
Localization	Object affected by the MC; determines, where the change will become manifest	Factory system, Manufacturing processes, Documentation, Factory organization
Impact on (internal)	How much is the company affected by the MC?	n / l / m / h
production	How much will the production be affected by the MC?	n / l / m / h
product	How much will the product be affected?	n / l / m / h
employees	How much will employees be affected?	n / l / m / h
factory operations	How much will factory operations be affected by the change? Is a stop of production required?	n / l / m / h
stocks	How much will current stocks / supply be affected?	n / l / m / h

organization (e.g., departments)	How much is the organization affected?	n / l / m / h
technical documents	How much are technical documents affected?	n / l / m / h
other projects	How much are other projects affected?	n / l / m / h
other locations	How much are other locations affected?	n / l / m / h
Impact on (external)	How much are company external partners and elements affected by the change?	n / l / m / h
customer	How much are the customers affected?	n / l / m / h
cooperation partner	How much are cooperation partners affected?	n / l / m / h
supplier	How much are suppliers affected?	n / l / m / h
patents, regulations, certifications	How much are patents, regulations, certifications affected?	n / l / m / h
environment	How much is the environment affected?	n / l / m / h
Change propagation & Dependencies	How much is the MC expected to be interrelated with other MCs or to cause further changes?	n / l / m / h
Change propagation	How much are further MCs / ECs expected to be caused by this MC?	n / l / m / h
Dependencies	To what level are dependencies to past / current changes or projects expected?	n / l / m / h
Efforts	How much effort is required to process this change?	n / l / m / h
Required capacities	How much capacity (e.g., regarding man hours) is required?	n / l / m / h
Required material supplies	How much material supply is required for the MC?	n / l / m / h
Required external resources	How much external capacity (e.g., regarding man hours) is required?	n / l / m / h
Risk	How high is the expected risk for the MC (e.g., regarding economical risk, technical risk)?	n / l / m / h
Challenges	Are there any specific challenges expected? How severe might they be?	n / l / m / h
Novelty	How can the novelty of this MC be rated? Are there already solution concepts available?	n / l / m / h
Difficulties	Are there potential difficulties (e.g., technical feasibility) to be considered? How severe might they be?	n / l / m / h
Special approvals / Certifications	Are special approvals / certifications required for the MC? How likely is it?	n / l / m / h
Duration	How long is the expected duration of the MC?	n / l / m / h
Planning duration	How long is the expected duration of the planning activities?	n / l / m / h

Implementation duration	How long is the expected duration of the implementation activities?	n / l / m / h
Cost	How high are the expected costs of the change?	n / l / m / h

Coordination & Evaluation

Relevance	What is the relevance of the MC?	n / l / m / h
Necessity	What is the considered necessity / need for the MC?	n / l / m / h
Benefit	What is the considered benefit from the MC?	n / l / m / h
Urgency	What is the urgency of the MC?	n / l / m / h
Change status	What is the status of the change?	Text
Change approval	Is the current deliverable already approved?	y / n
Latest status	What is the current status of the change?	Number, Text
Date of implementation	When will the MC be implemented based on the current status?	Number
Time of occurance	When did the MC occur with respect to, for example, the product life cycle, the fiscal year, the release of documents?	Text
Lessons learned	Is the MC relevant for other changes?	y / n
Lessons learned	Is the MC relevant for conducting lessons learned?	y / n
Efficiency of implementation	How can the efficiency of the MC implementation be rated?	l / m / h

n: now l: low m: medium h: high y: yes n: no

A.4 MCM process models

Table A.4: Process Architecture Framework – Selection of attributes for activities (based on BROWNING *2009)*

Attribute	Description	Reasoned selection & details
Name	Descriptive, distinct name and / or code of activity	Identification of an activity
Parent	Link to stage of which this activity is part of	Allocation to the overall process architecture
Brief description	Brief description of activity	Clarification of the content
Mode	Available variants of the activity	Description of activity variants (e.g., optional, extended) for process tailoring
Deployment	Differentiation between standard and tailorable activities	Information on tailorability
Inputs	Link to deliverables providing input for the activity	x-to-one relationship, i.e., deliverables $d_{i.j}$ (produced by activities $a_{i.j}$) provide input for activity $a_{x.y}$; information is provided in the MCM process DSM (cf. figure 6.16)
Output	Link to deliverable produced by the activity	One-to-one relationship, i.e., activity $a_{i.j}$ produces deliverable $d_{i.j}$, which is input for activities $a_{i+n.j+m}$; information is provided in the MCM process DSM (cf. figure 6.16)
Entry criteria	List of events or conditions required to start activity	Input to be available to start the activity; information provided in the MCM process DSM (if available, bold "1" in a column, otherwise first "1" in the column; cf. figure 6.16)
Standard roles	Roles to be filled to execute the process activity	Allocation of roles to the activity; information is provided in the DMM linking roles and activities (cf. figure 6.19)
Methods & Tools	List of methods and tools to support the activity	Compilation of methods and tools; information provided in the DMM of methods & tools and activities (cf. figure 6.3.4)
Tailoring guidance	Instructions regarding, scaling, sizing, tailoring, scoping, etc.	Rules for tailoring and scoping the MCM process; provided in section 6.4

Attributes not considered for this research (application-specific and / or required for an IT tool only): *Exit criteria, Deployed roles, Constituents (Children), Shadowing, Version number, Narrative description, Verifications, Standard process metrics, Deployed process metrics, Basis for requirement, Rules, References, Standard risks, Deployed risks, System identification number, Work breakdown structure element association, Master owner, Standard owner, Deployed owner, Change history, Change notifications*

Table A.5: Process Architecture Framework – Selection of attributes for deliverables (based on BROWNING *2009)*

Attribute	Description	Reasoned selection & details
Name	Descriptive, distinct name and / or code of deliverable	Identification of a deliverable
Parent	Link to gate of which this deliverable is part of	Allocation to the overall process architecture
Brief description	Brief description of deliverable	Clarification of the content
Mode	Available variants of the deliverable	Description of deliverable variants (e.g., optional, extended) for process tailoring
Deployment	Differentiation between standard and tailorable deliverables	Information on tailorability
Suppliers	Link to activity producing input for the deliverable	One-to-one relationship, i.e., activity $a_{i.j}$ is supplier for $d_{i.j}$
Customers	Link to activities using deliverable as input	One-to-x relationship, i.e., activities $a_{i+n.j+m}$ are customers of deliverable $d_{i.j}$; information is provided in the MCM process DSM (cf. figure 6.16)
Tailoring guidance	Instructions regarding, scaling, sizing, tailoring, scoping, etc.	Rules for tailoring and scoping the MCM process; provided in section 6.4

Attributes not considered for this research (application-specific and / or required for an IT tool only): *Format, Medium, Shadowing, Version number, Narrative description, Key criteria and measures of effectiveness, Requirements, Acceptance criteria, Standard process metrics, Deployed process metrics, Artifact, Rules, References, System identification number, Work breakdown structure element association, Change history, Change notifications*

Table A.6: Process Architecture Framework – Activities of the MCM process

Name & Brief description	Parent	Mode	Deployment
a1.1 Screen for potential MCs (actively and passively) Screening of change causes is conducted continuously and "happens in daily business", but should also be organized in order to be conducted in a regular and structured manner, i.e., in small expert team meetings, where several groups / teams discuss their own area / section of responsibility and then report to or meet in a higher-level group / team (e.g., expert circle); (daily) shop floor meeting, discussion of issues / suggestions for improvement, etc.; shop floor manager may create MC profile.	s1	s	i&f
a1.2 Change coordination: check for siblings and aggregation potential Conduct short analysis if change cause has "siblings" (i.e., similar or linked change causes), which have to be considered separately or together ("aggregation potential", i.e., grouping of changes) and document results; conflicts between potential changes or other (change) projects should be detected.	s1	s	i&f
a1.3 Make short impact rating of change cause Determine impacts of the change cause on the factory and its elements; focus on: Where in the factory could the change cause have an impact? What are the consequences of no change? Are there possible adverse effects? Are critical parts of the factory or its elements affected? Are certifications of the factory or manufacturing processes an issue? Are there further impacts on the factory, e.g., on the resource supply for the factory (e.g., power, water, air, surface), production processes, logistics (e.g., risk of obsolete material), customers, suppliers, financials, customer satisfaction, or production schedule?	s1	s	i&f
a1.4 Create MC profile for change cause Create an MC profile (e.g. in an MCM workflow tool), assign a name, brief description, the relevant change cause, an ID, etc. to the MC; MC profile is handled as a potential MC and is the basis to analyze, confirm, and further proceed with the MC.	s1	s	i&f
a1.5 Assign responsible for potential MC Assign a responsible role (e.g., a change agent) to the potential MC: role is responsible to push / promote and proceed the potential MC. The responsibility assigned will be reviewed during the subsequent MCM process stages and be updated if needed; this depends on the specific MC. In case of uncertainties regarding MC attributes, the change manager can take responsibility for the potential MC.	s1	s	i&f
a1.6 Decide on relevance of potential change In dubio pro causa; if the relevance of the MC is not clear, present it to the change committee or the MCM responsible and discuss it; the MC could be automatically confirmed, if it is due to a Kaizen or another direct change request; generally, the change manager confirms the relevance of a potential MC; if the potential MC is currently not relevant, set it as pending (because it might become relevant in the future) or even terminate it.	s1	s	i&f
a2.1 Identify and inform stakeholders about potential MC Identify relevant stakeholders and inform them about the potential MC; stakeholders are roles responsible for sections / areas of the factory, its elements, processes, or organizations (e.g. teams) possibly affected by the potential MC. The better the identification of relevant stakeholders the less efforts, iterations, and unforeseen change impacts will arise. This activity is also an important preparation for the further tailoring of the MCM process and is based on the available information about the potential MC (i.e., the change attributes).	s2	s,e	t

a2.2	**Review and update risk and impact rating**	s2	s,e,o	t
	Review of the MC profile and update, if new information is available; if required: more detailed analysis of risk and impact (e.g., with an FMEA); check of experiences with former (similar) MCs and lessons learned (e.g., of MCs conducted at own or other factory locations).			
a2.3	**Aggregate information and define actual requirements on factory**	s2	s,e,o	t
	Aggregation of information and feedback provided by the relevant stakeholders, the risk and impact rating, own experience, etc.; define actual requirements on affected parts of the factory, its elements, processes, documents, software, etc.			
a2.4	**Identify deviations between requirements and current status**	s2	s,e,o	t
	Identify deviations between the actual requirements on the factory, its elements, processes, etc. and the current status, i.e., identify the delta of as-is vs. to-be / "what has to be changed".			
a2.5	**Coordinate the MC**	s2	s	i&f
	Coordinate the MC, i.e., check for an aggregation potential with other MCs and prioritize the MC (relative to other MCs). Check again for “siblings” to avoid redundancy of MCs; check for conflicts between potential MCs or other projects conducted in the factory. Prioritize the MC based on its attributes and relevant boundary conditions (e.g. available capacity, other MCs).			
a2.6	**Create a change plan proposal**	s2	s,e,o	t
	Create a proposal for the timeline / schedule for the MC based on available information (e.g. MC attributes, other MCs); define required “start of production” / “go live” for the MC, relevant time stamps for the MCM process gates (and deliverables, if required), and check capacities of involved roles and resources. If problems occur, escalate to the change committee or the change manager. The change plan proposal is part of the MC profile and should be communicated to the stakeholders.			
a2.7	**(Re-)assign roles and responsibilities**	s2	s,o	t
	Assign or reassign roles and responsibilities with respect to the MC attributes, the risk and impact rating, and the availability of resources – i.e., one person or a full team might have to be assigned depending on the dimension and impact of the MC.			
a2.8	**Review MC profile**	s2	s,o	t
	Review the MC profile, gather and update all relevant information, formally check all deliverables documented in the MC profile; the reviewed MC profile then serves as a decision basis for the upcoming gate g2.			
a2.9	**Decide on the release of a change request**	s2	s	i&f
	If a need for change is given, release an MC request. With this release, the potential MC passes the gate and enters the next stage. In general, a potential MC can also remain “pending” here (hence, it does not pass the gate at this point in time) and be released when appropriate (e.g., in case of missing resources and / or information).			
a3.1	**Make a detailed problem and target description**	s3	s,e,o	t
	Prepare a detailed description of the need for change based on the MC profile, the stakeholders’ feedback, and the risk and impact analysis; also, prepare a target description, i.e., what is the desired future state, what should be accomplished (after an implementation of the MC).			
a3.2	**Develop and describe solution concept proposals**	s3	s,e	t
	Develop and describe first solution concept proposals for the MC, i.e., which measures (e.g., technical, organizational) are required and which alternative measures would be possible.			

a3.3	**Make change and change propagation analysis**	s3	s,e,o	t
	Analyze the characteristics and effects of the prepared solution concept proposals on the factory; focus especially on potential further MCs and ECs that might occur due to the different solution concepts.			
a3.4	**Make stakeholder review**	s3	s,o	t
	Review stakeholders based on the results of the change and change propagation analysis; update list of stakeholders if needed (in case of further stakeholders to be involved, an iteration of previous activities might be required, e.g., the risk and impact rating).			
a3.5	**Estimate invest and benefit of MC**	s3	s,e,o	t
	Estimate the required invest for the different solution concept proposals for the MC and their potential benefit (e.g., cost efficiency, process improvement, increase in capacity). Note: the benefit might materialize not only at the actual location of the MC, but somewhere in the factory, in related departments, units, or functions. Prepare a preliminary invest plan for the different solution concepts.			
a3.6	**Formally approve invest plan**	s3	s,o	t
	Cross-check the invest plan by a second role and formally approve the invest plan.			
a3.7	**Prepare solution concept proposals for MC**	s3	s	i&f
	Aggregate all information within the different solution concept proposals and conduct a final check of the solution concept proposals for the MC; prepare the solution concept proposals as evaluation and decision basis.			
a4.1	**Evaluate solution concept proposals and make pre-selection**	s4	s,e,o	t
	Evaluate the solution concept proposals regarding different characteristics, e.g., costs, impacts, benefit, change propagation (based on the MC profile); review other MCs for new aggregation potential; pre-select most favorable solution concept proposal(s) for the alignment with customers (if needed) and the change committee.			
a4.2	**Align solution concept proposal(s) with customer**	s4	s,o	t
	Inform the customer about the MC and the solution concept proposal(s) for the MC in case there is an obligation to inform the customer (or another need / desire to inform the customer); align the concept proposal(s) with the customer; Note: the integration of the customer can also already happen very early in the MCM process (e.g., during stakeholder identification and information) depending on the companies strategy and setup, the customer relations, and the specific MC.			
a4.3	**Make detailed cost analysis**	s4	s,e,o	t
	Conduct a detailed cost analysis for the favorable solution concept proposal(s) and substantiate the preliminary invest plan.			
a4.4	**Select and approve solution concept**	s4	s,o	t
	Review the full solution concept proposal(s) and select the most favorable one; approve the proposal for further proceeding in the MCM process.			
a4.5	**(Re-)assign roles and responsibilities**	s4	s,0	t
	Assign or reassign roles and responsibilities with respect to the selected solution concept proposal, the MC attributes, the risk and impact rating, and the availability of resources – i.e., one person or a full team might have to be assigned depending on the dimension and impact of the MC.			

a4.6	**Review change plan**	s4	s,o	t
	Review the change plan for the MC based on the progress for the MC, i.e., the fulfillment of deliverables and gates with respect to the change plan; plan / re-plan timeline for the next deliverables and gates based on the MC profile, the progress, and available capacities.			
a4.7	**Review MC profile**	s4	s,o	t
	Review the MC profile, gather and update all relevant information, formally check all deliverables documented in the MC profile; the reviewed MC profile then serves as a decision basis for the upcoming gate g4.			
a4.8	**Approve solution concept and release change order**	s4	s	i&f
	Review and approve the solution concept proposal for the MC; release the change order based on the approved concept.			
a5.1	**Select and integrate suppliers**	s5	s,o	t
	If needed, select potential suppliers required for the approved solution concept; integrate the suppliers in the subsequent activities a5.2 and a5.3 for planning the MC and the required measures.			
a5.2	**Plan MC in detail**	s5	s,e,o	t
	Plan required measures of the solution concept for the MC in detail (e.g., layout planning, machine planning, assembly planning, adaptation of documentation) and create a first detailed change plan proposal; review other MCs for new aggregation potential.			
a5.3	**Align detailed change plan with customer**	s5	s,o	t
	Align the detailed change plan proposal for the MC with the customer (if needed, e.g., if there is an obligation to inform the customer or another need / desire to inform the customer); Note: the integration of the customer can also already happen very early and continuously in the MCM process (e.g., during stakeholder identification and information) depending on the companies strategy and setup, the customer relations, and the specific MC.			
a5.4	**Make sourcing plan proposal**	s5	s,e,o	t
	Prepare a sourcing plan proposal as part of the detailed plan for the MC; the sourcing plan describes the required supply and possible supply chain for the MC – e.g., for the sourcing of required materials, equipment, but also the treatment of obsolete material, etc.			
a5.5	**Approve detailed change plan**	s5	s,o	t
	Review the detailed plan for the MC and approve it for further proceeding in the MCM process.			
a5.6	**Approve sourcing plan**	s5	s,o	t
	Review the sourcing plan for the MC and approve it for further proceeding in the MCM process.			
a5.7	**Compile final detailed change plan**	s5	s,e	t
	Aggregate all plans and planning information, review the MC profile and compile the final detailed MC plan for further proceeding; review other MCs for new aggregation potential.			
a6.1	**Make implementation plan proposal**	s6	s,e,o	t
	Create an implementation plan proposal based on the final detailed change plan; plan required implementation activities, resources, capacities, and develop a timeline / schedule. Consider especially if a stop of production might be required to implement the MC.			
a6.2	**Approve implementation plan**	s6	s,o	t
	Review and approve the implementation plan for further proceeding; if applicable, review other MCs for new aggregation potential.			

a6.3	**Procure technical equipment**	s6	s,e,o	t
	If needed, procure required technical equipment based on the sourcing plan and the selected supply chain; source required materials, equipment, but also treat obsolete material, etc.			
a6.4	**(Re-)assign roles and responsibilities**	s6	s,o	t
	Assign or reassign roles and responsibilities with respect to the detailed plan for the MC and the implementation plan, the MC attributes, and the availability of resources – i.e., one person or a full team might have to be (re-)assigned depending on the actual dimension and impact of the MC.			
a6.5	**Review change plan**	s6	s,o	t
	Review the change plan for the MC based on the progress of the MC, i.e., the fulfillment of deliverables and gates with respect to the change plan; plan / re-plan timeline for the next deliverables and gates based on the detailed plan, the implementation plan, the MC profile, the progress, and available capacities (of assigned roles).			
a6.6	**Review MC profile**	s6	s,o	t
	Review the MC profile, gather and update all relevant information, formally check all deliverables documented in the MC profile; if applicable, review other MCs for new aggregation potential; the reviewed MC profile then serves as a decision basis for the upcoming gate g6.			
a6.7	**Approve MC to be implemented**	s6	s	i&f
	Review and approve the MC; release the final detailed MC plan and the implementation plan.			
a7.1	**Implement MC**	s7	s,e	t
	Implement the required measures based on the final detailed MC plan and following the implementation plan.			
a7.2	**Check implemented MC**	s7	s,e,o	t
	Review the implemented MC, check if all measures have been successfully conducted.			
a7.3	**Make quality and performance test**	s7	s,e,o	t
	Make quality and / or performance test as required for the respective MC; e.g., check if production is ready for operations, if quality and performance targets are met; document the test results.			
a7.4	**Review and update information systems**	s7	s,e	t
	Review and update all information systems as required for the respective MC, i.e., for example, ERP system, related drawings, process descriptions.			
a7.5	**Make overall “go for production” check**	s7	s	i&f
	Aggregate all information about the conducted measures for the MC; conduct final check of production and MC documentation, and prepare for overall MC release: “go for production”.			
a8.1	**Review and evaluate the MC**	s8	s,e	t
	Review and evaluate the conducted MC and the MC documentation, i.e., the MC profile; check for improvement potentials for the MC (e.g., in case of quality issues, insufficient measures); decide on potential for “lessons learned”; optional: “1000 miles check” – the evaluation of sustainability and long-term success of the conducted MC (to be conducted about 1 to 6 months after closure of the MC).			
a8.2	**Describe and highlight lessons learned**	s8	s,e,o	t
	Conduct lessons learned for the MC, involve all stakeholders / roles involved in the MC; describe and document lessons learned, rank the lessons learned in overall lessons learned of MCs; ensure the dissemination to interested persons if appropriate.			

a8.3	**Clean up**	s8	s	i&f
	Clean up the MC documentation for archiving; apply "lean thinking" and store only final, useful versions of information / data (e.g., MC profile, forms, presentations, pictures, folders) in a structured manner, avoid an "information waste" and "information overflow" to enable a subsequent usage of the MC documentation and lessons learned.			
a8.4	**Close MC**	s8	s	i&f
	Conduct final review of the MC profile and the MCM process, check if all relevant deliverables have been documented and cleaned up; release MC documentation and lessons learned and finally close MC.			

s_i: stage   s: standard   e: extended   o: optional   i&f: independent & fixed   t: tailorable

Table A.7: Process Architecture Framework – Deliverables of the MCM process

	Name & Brief description	Parent	Mode	Deployment
d1.1	**Detected change cause for potential MC**	g1	s	i&f
	Results of change cause screenings or potential MCs identified in other ways.			
d1.2	**Change coordination: siblings and aggregation check**	g1	s	i&f
	Coordination of change: aggregation of equal, similar, linked, or dependent change causes and / or potential MCs.			
d1.3	**Risk and impact rating**	g1	s	i&f
	Determination of impacts on the factory and its elements as well as occurring risks.			
d1.4	**MC profile creation**	g1	s	i&f
	Creation of an MC profile (i.e., a potential MC) and compilation of first available information about the potential MC.			
d1.5	**Assignment of responsibility**	g1	s	i&f
	Assignment of a responsible person for the potential MC.			
d1.6	**Confirmation of relevance**	g1	s	i&f
	Confirmation of relevance of the potential MC based on available information.			
d2.1	**Stakeholder identification and information**	g2	s,e	t
	Identification and information of stakeholders possibly affected by the potential MC.			
d2.2	**Reviewed and updated risk and impact rating**	g2	s,e,o	t
	MC profile reviewed and updated with new information if applicable.			
d2.3	**Requirements of potential MC (to-be)**	g2	s,e,o	t
	Aggregated list of actual requirements for the affected parts of the factory, processes, documents, software, etc.			
d2.4	**Deviations (as-is vs. to-be)**	g2	s,e,o	t
	Deviations between the requirements for the factory and its current status detected (i.e., the delta of as-is vs. to-be).			
d2.5	**Change coordination**	g2	s	i&f
	Coordination of change: aggregation of equal, similar, linked, or dependent MCs and prioritization of the MC relative to the other MCs.			
d2.6	**Change plan proposal**	g2	s,e,o	t
	Change plan proposal (as part of the MC profile) created and communicated to the stakeholders.			
d2.7	**(Re-)assignment of roles and responsibilities**	g2	s,o	t
	(Re-)assignment of roles and responsibilities based on the MC profile.			
d2.8	**Review of MC profile**	g2	s,o	t
	Review of the MC profile as decision basis for the upcoming gate g2.			
d2.9	**Need for change (release of change request)**	g2	s	i&f
	Release of the MC request in case of a need for change.			

d3.1	**Detailed problem and target description** Detailed description of the need for change and targets regarding the desired future state (of the factory, processes, etc.) after an implementation of the MC.	g3	s,e,o	t
d3.2	**Solution concepts** First solution concept proposals with required measures developed and described.	g3	s,e	t
d3.3	**Change and change propagation analysis** Change and change propagation analysis for the prepared solution concept proposals conducted.	g3	s,e,o	t
d3.4	**Stakeholder review** Review of stakeholders and update of stakeholders (e.g., list of stakeholders selected) if needed.	g3	s,o	t
d3.5	**Invest and benefit estimation** Estimation of the required invest for the different solution concepts and their potential benefit.	g3	s,e,o	t
d3.6	**Formal approval of invest plan** Cross-check and formal approval of the invest plan.	g3	s,o	t
d3.7	**Solution concept proposal for the MC** Aggregation and final check of information for different solution concept proposals as evaluation and decision basis.	g3	s	i&f
d4.1	**Evaluation and pre-selection of solution concept proposal(s)** Evaluation of solution concept proposals and pre-selection of one (or more) concept(s).	g4	s,e,o	t
d4.2	**Alignment of concept proposal(s) with customer** Information about and alignment of solution concept proposal(s) with customer, i.e., integration of the customer to the processing of the MC.	g4	s,o	t
d4.3	**Detailed cost analysis** Detailed cost analysis of pre-selected solution concept proposal(s) and substantiation of the preliminary invest plan.	g4	s,e,o	t
d4.4	**Selection and approval of concept** Review, selection, and approval of the most favorable solution concept proposal.	g4	s,o	t
d4.5	**(Re-)assignment of roles and responsibilities** (Re-)assignment of roles and responsibilities based on the MC profile.	g4	s,o	t
d4.6	**Review of change plan** Review of change plan; (re-)planned timeline if needed.	g4	s,o	t
d4.7	**Review of MC profile** Review of MC profile as decision basis for the upcoming gate g4.	g4	s,o	t
d4.8	**Concept approval and release of change order** Solution concept approval and release of change order.	g4	s	i&f
d5.1	**Selection and integration of suppliers** Selection of suppliers and integration for planning the MC.	g5	s,o	t

d5.2	**Detailed change plan proposal** First detailed change plan proposal with required measures.	g5	s,e,o	t
d5.3	**Customer alignment** Alignment of detailed change plan proposal with the customer.	g5	s,o	t
d5.4	**Sourcing plan proposal** Sourcing plan proposal for, e.g., equipment, materials, and treatment of obsolete material.	g5	s,e,o	t
d5.5	**Approval of detailed change plan** Approval of detailed change plan for the MC.	g5	s,o	t
d5.6	**Approval of sourcing plan** Approval of sourcing plan for the MC.	g5	s,o	t
d5.7	**Compilation of final detailed change plan** Aggregation of all plans and planning information to the final detailed change plan.	g5	s,e	t
d6.1	**Implementation plan proposal** Implementation plan proposal including a timeline / schedule and information about a potentially required stop of production for the implementation of the MC.	g6	s,e,o	t
d6.2	**Approval of implementation plan** Approval of the implementation plan for the MC.	g6	s,o	t
d6.3	**Procurement of technical equipment** Actual procurement of technical equipment for the MC.	g6	s,e,o	t
d6.4	**(Re-)assignment of roles and responsibilities** (Re-)assignment of roles and responsibilities based on the MC profile.	g6	s,o	t
d6.5	**Review of change plan** Review of change plan; (re-)planned timeline if needed.	g6	s,o	t
d6.6	**Review of MC profile** Review of MC profile as decision basis for the upcoming gate g6.	s6	s,o	t
d6.7	**Approval of detailed change and implementation plan** Approval of the MC for implementation and release of the final detailed change plan and the implementation plan.	g6	s	i&f
d7.1	**MC implemented** Measure for the MC implemented.	g7	s,e	t
d7.2	**MC implementation check** Check of the implemented MC.	g7	s,e,o	t
d7.3	**Quality and performance test** Test of quality and performance of the factory, its elements, etc. with the MC implemented.	g7	s,e,o	t
d7.4	**Review and update of information systems** Review and update of information systems for the MC.	g7	s,e	t

d7.5	**"Go for production"**	g7	s	i&f
	Final check of production and MC documentation; release of overall MC: "go for production".			
d8.1	**Review and evaluation of MC**	g8	s,e	t
	Review and evaluation of the conducted MC and the MC profile; identification of improvement potentials, decision on "lessons learned"; if needed: "1000-miles-check" to evaluate the long-term success and sustainability of the MC.			
d8.2	**Lessons learned**	g8	s,e,o	t
	Conduction and documentation of lessons learned.			
d8.3	**Cleaned up**	g8	s	i&f
	Cleaned up MC profile, forms, presentations, pictures, folders, etc.			
d8.4	**Closure of MC**	g8	s	i&f
	Review and closure of the MC.			

g_i: gate s: standard e: extended o: optional i&f: independent & fixed t: tailorable

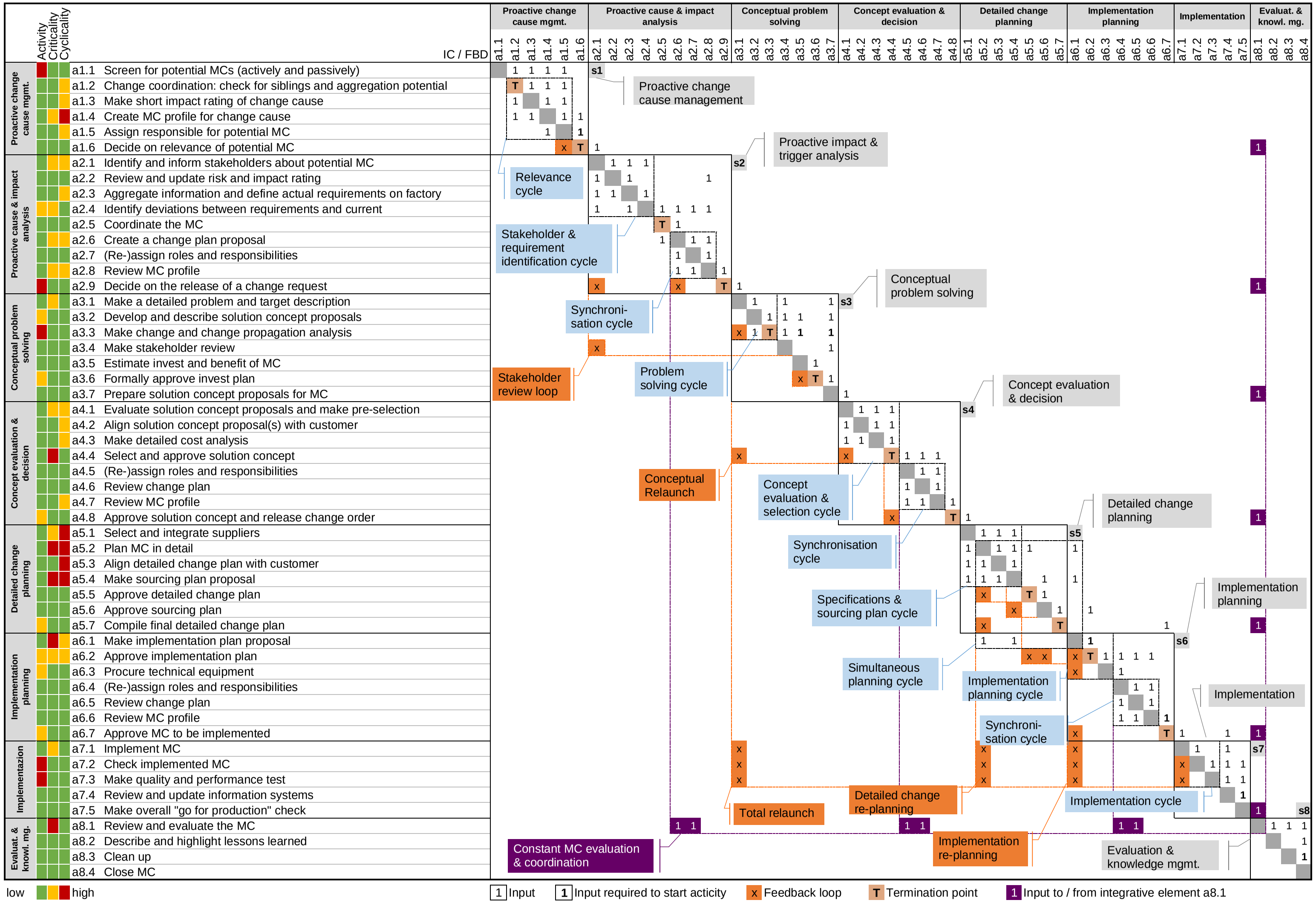

Figure A.1: DSM model of the MCM process architecture (complete)

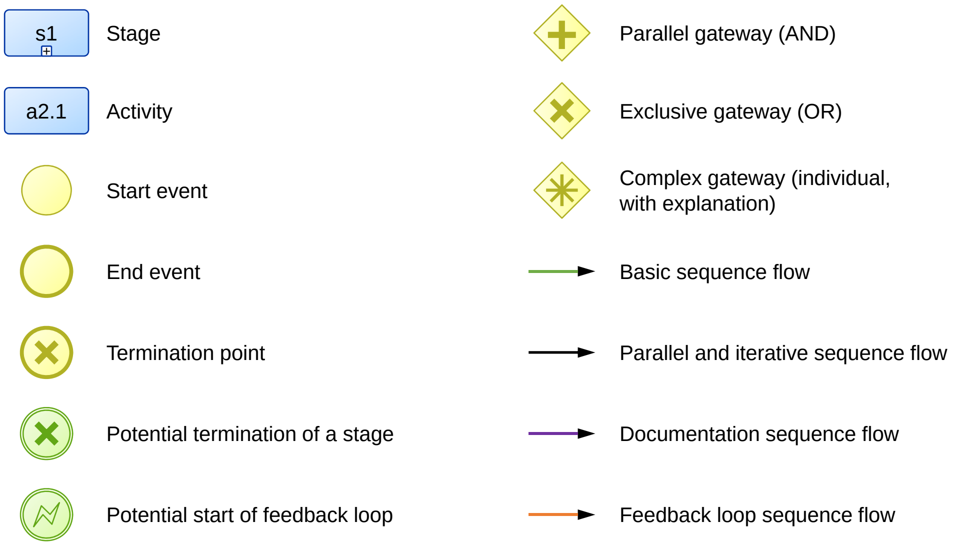

Figure A.2: BPMN notation for the MCM process

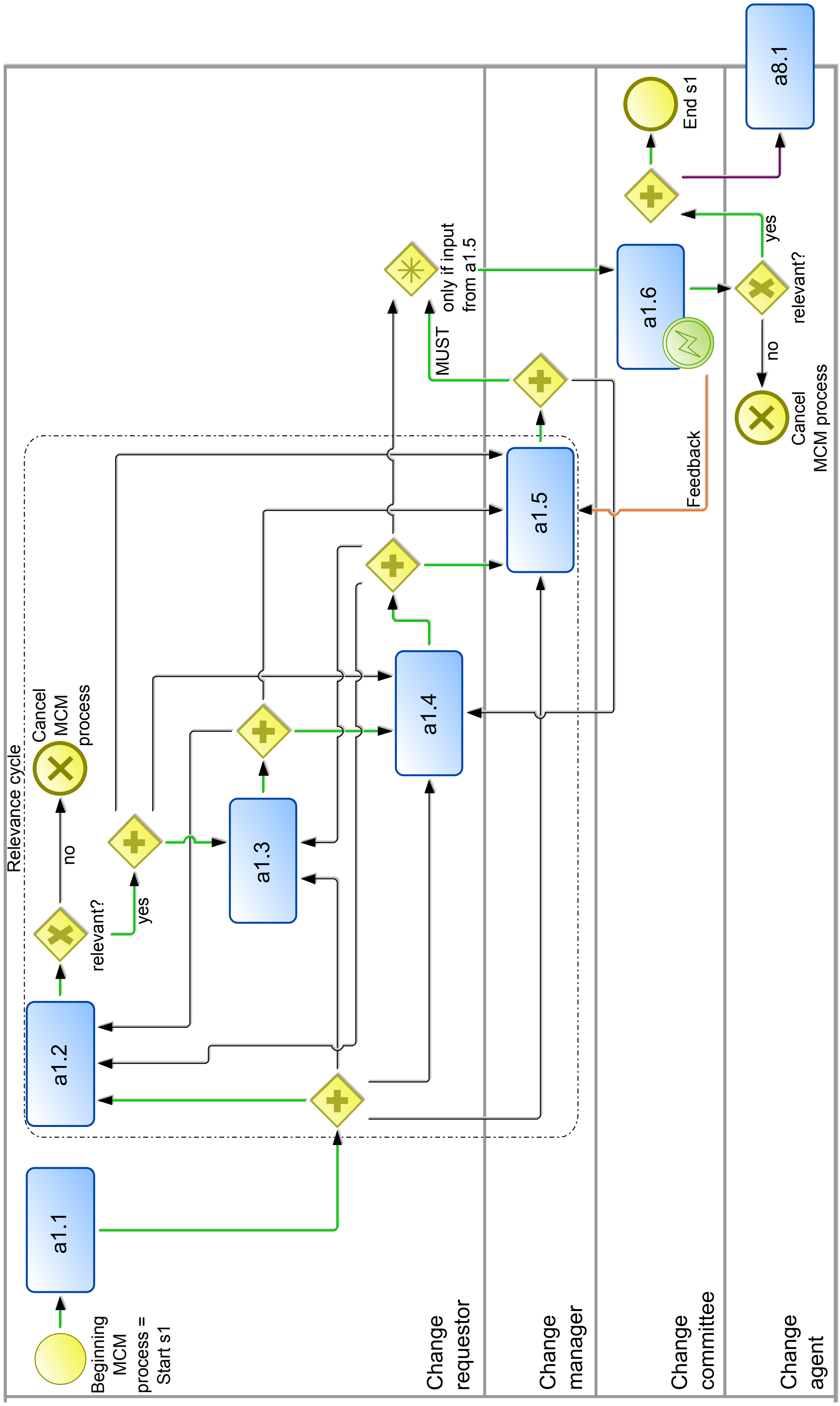

Figure A.3: BPMN flowchart model of the detailed MCM process, stage s1

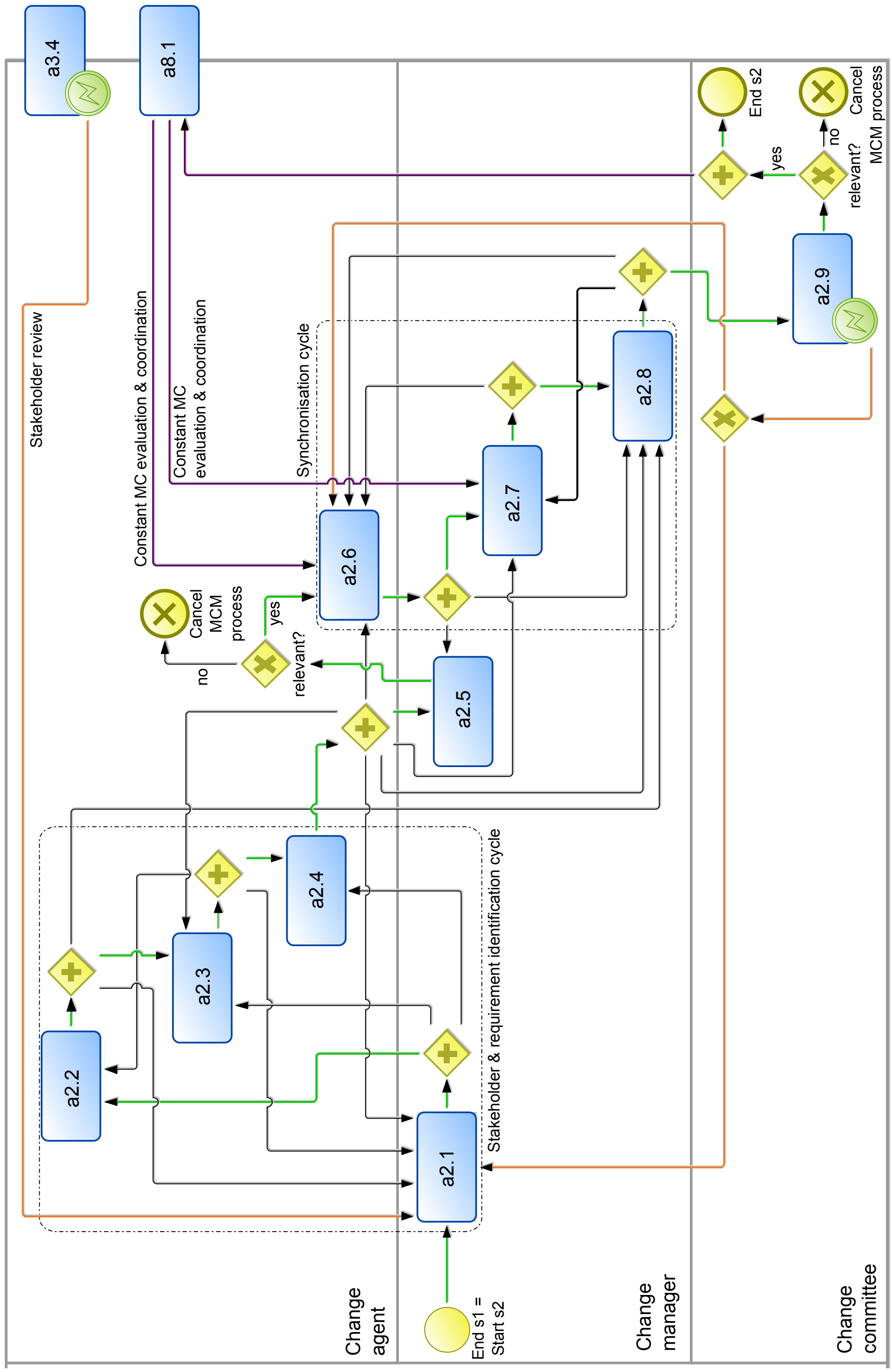

Figure A.4: BPMN flowchart model of the detailed MCM process, stage s2

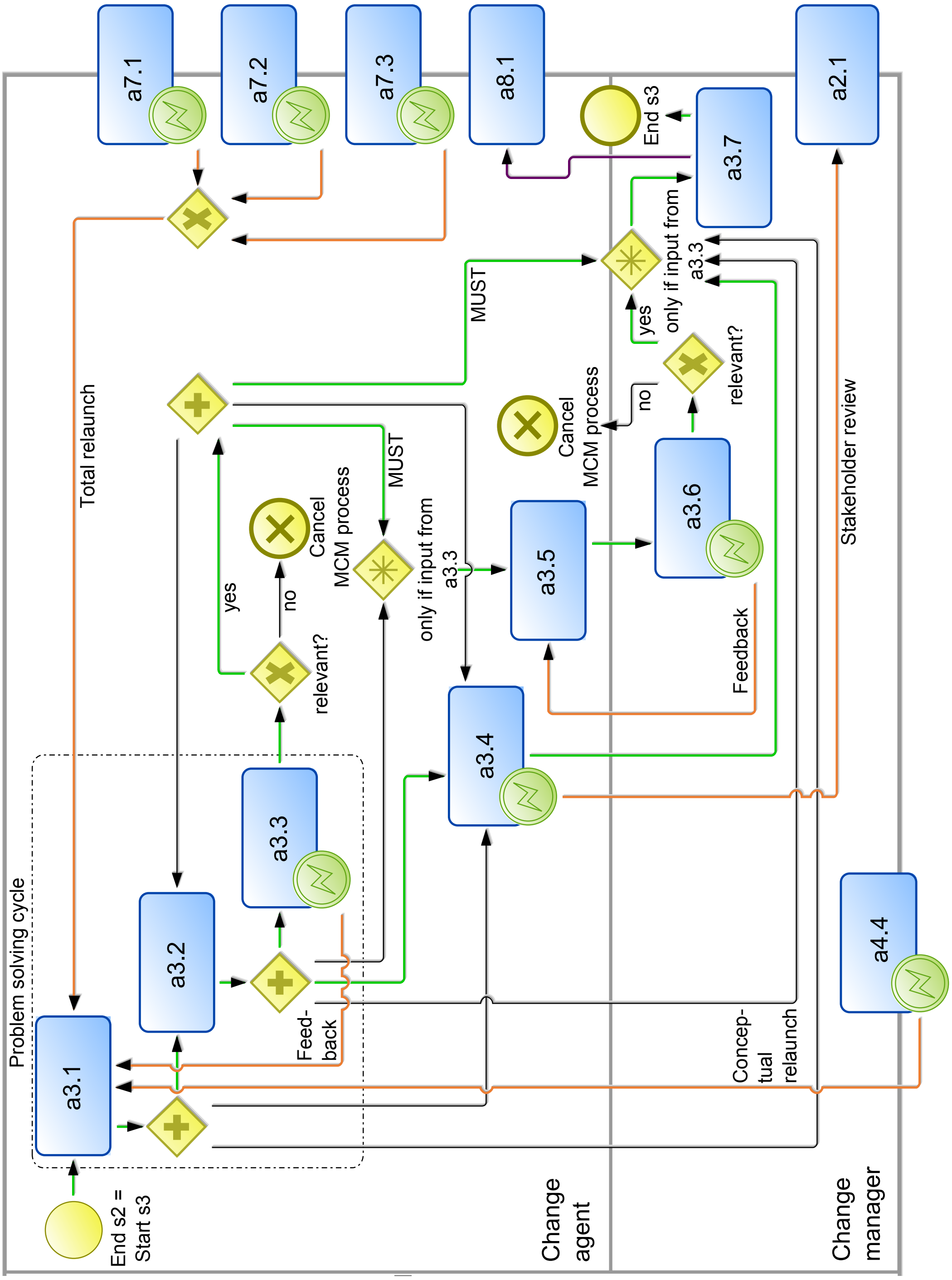

Figure A.5: BPMN flowchart model of the detailed MCM process, stage s3

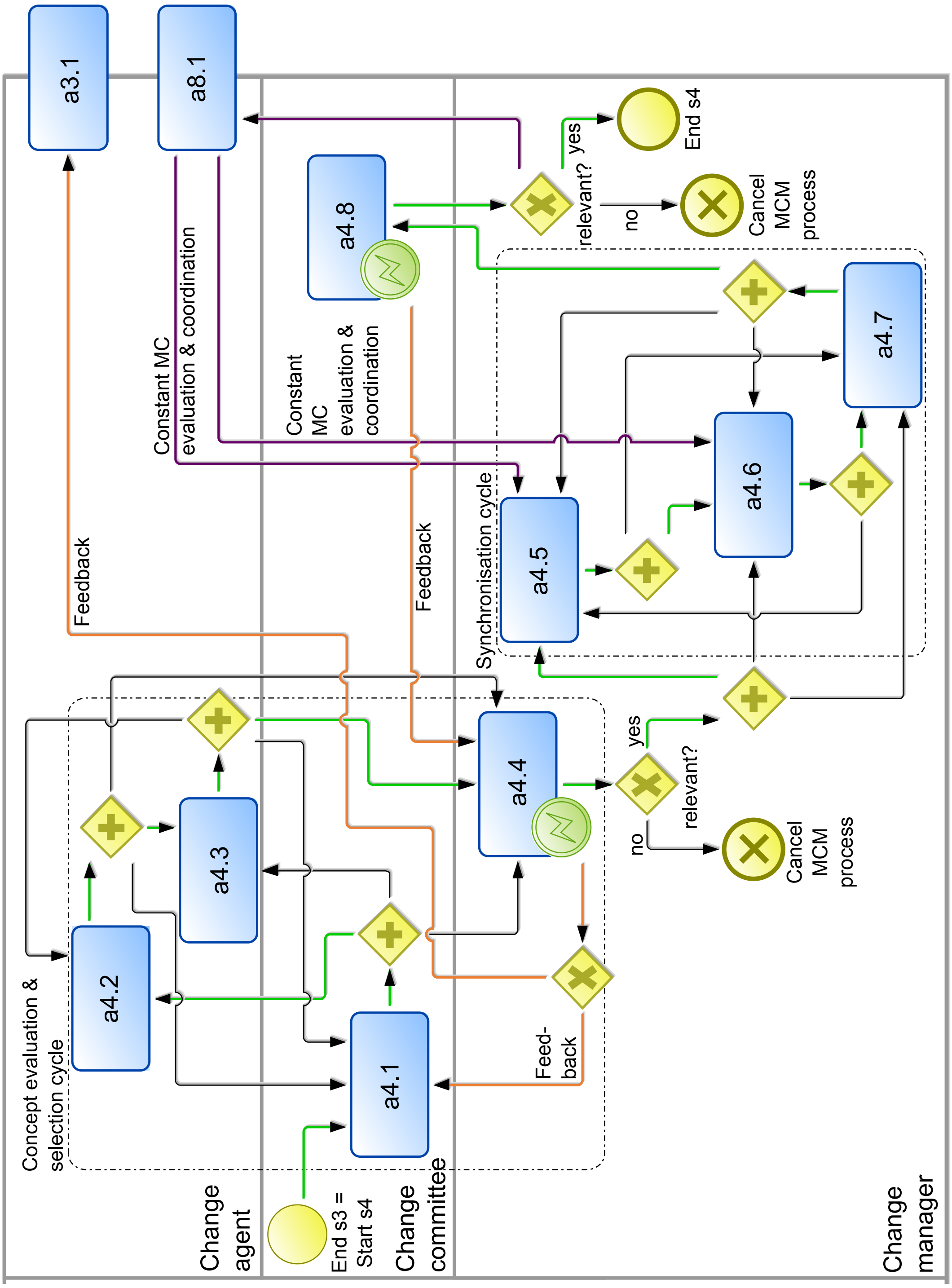

Figure A.6: BPMN flowchart model of the detailed MCM process, stage s4

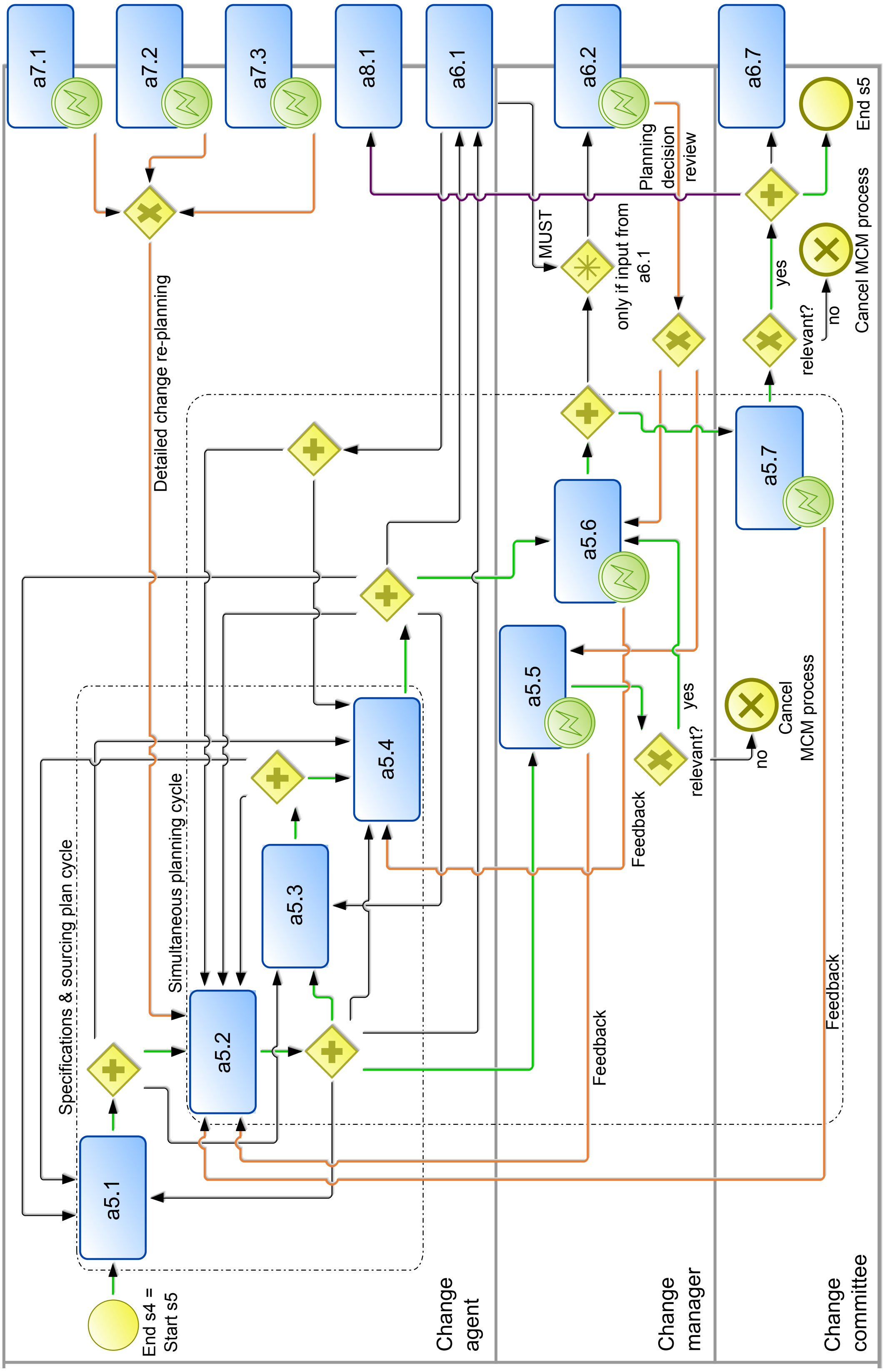

Figure A.7: BPMN flowchart model of the detailed MCM process, stage s5

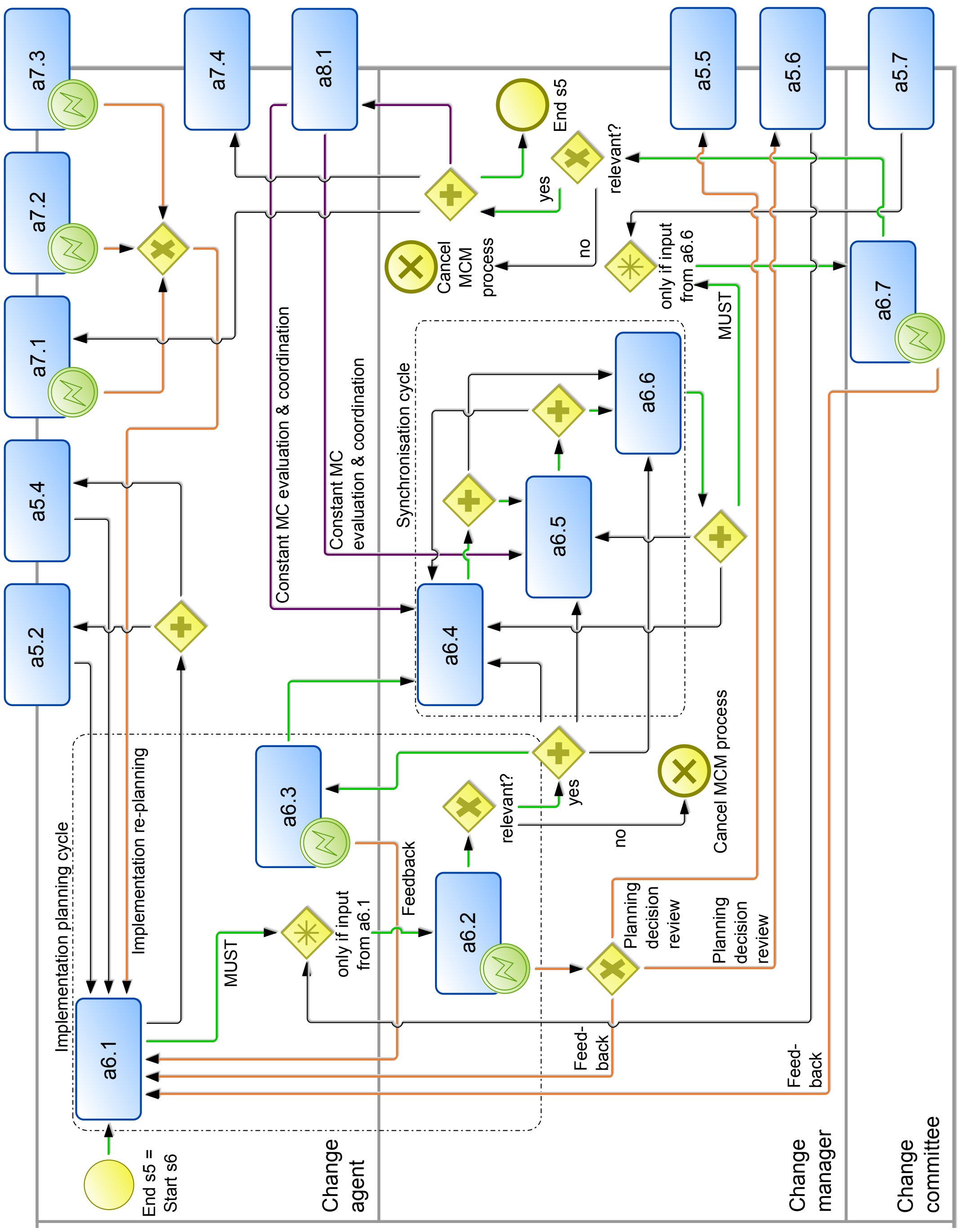

Figure A.8: BPMN flowchart model of the detailed MCM process, stage s6

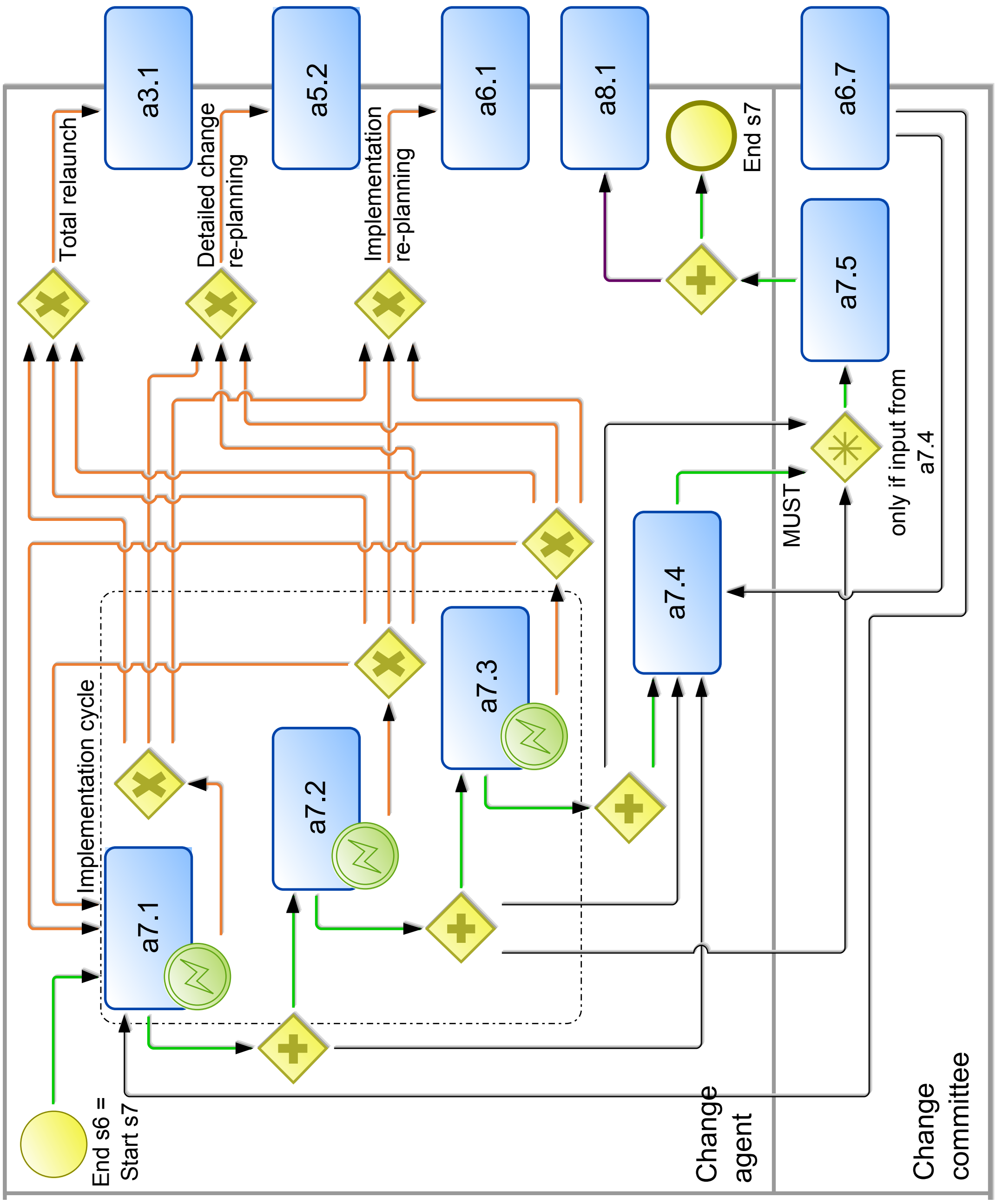

Figure A.9: BPMN flowchart model of the detailed MCM process, stage s7

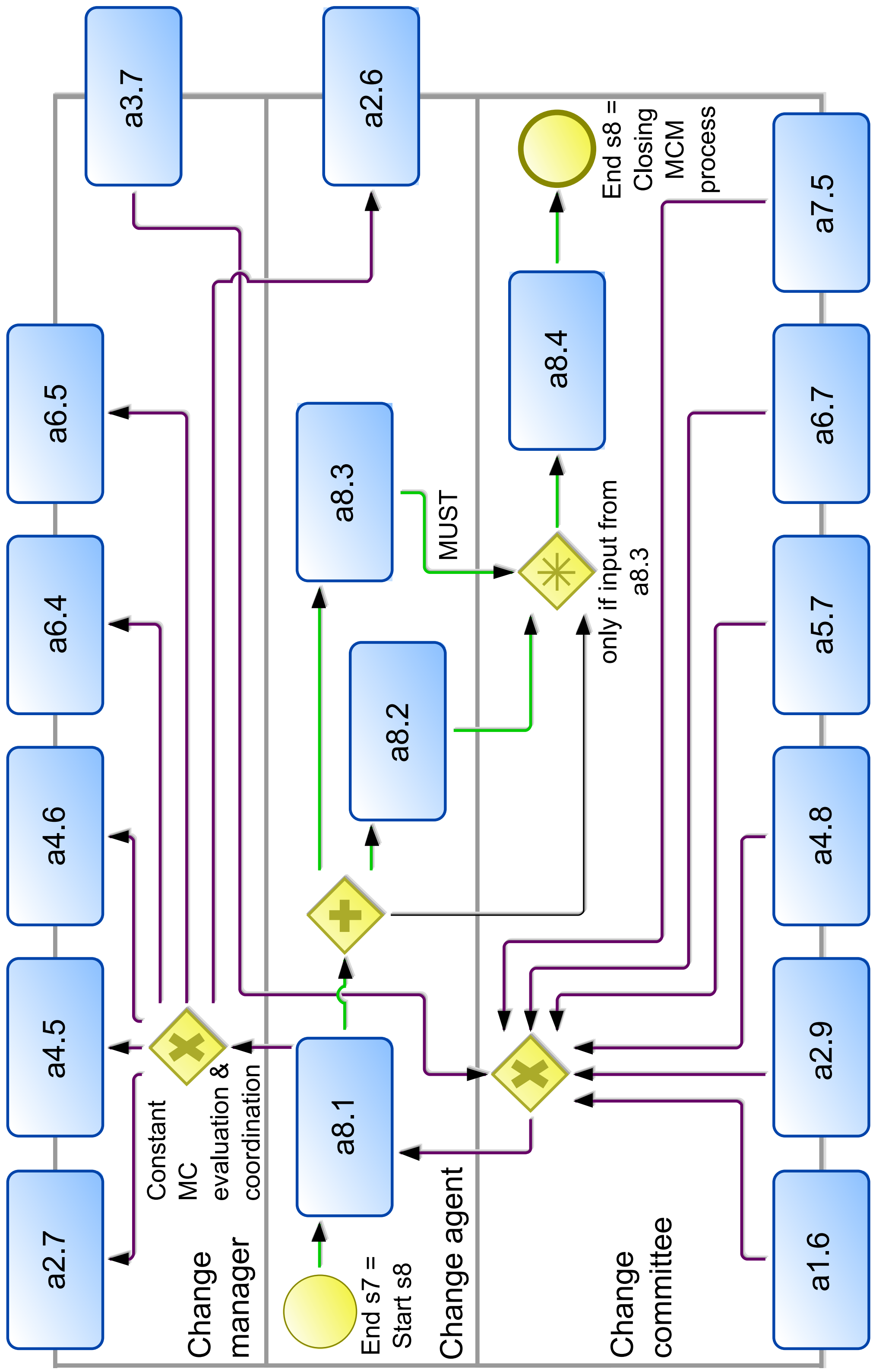

Figure A.10: BPMN flowchart model of the detailed MCM process, stage s8

Roles (IC / FBD)	Proactive change cause mgmt.					
	a1.1 Screen for potential MCs (actively and passively)	a1.2 Change coordination: check for siblings and aggregation potential	a1.3 Make short impact rating of change cause	a1.4 Create MC profile for change cause	a1.5 Assign responsible for potential MC	a1.6 Decide on relevance of potential MC
r1 Change requester	2	2	2	2	1	1
r2 Change agent						
r3 Change manager			(2)	(2)	2	2 / (3)
r4 Change committee						3
r5 Department functions						

Roles (IC / FBD)	Proactive cause & impact analysis								
	a2.1 Identify and inform stakeholders about potential MC	a2.2 Review and update risk and impact rating	a2.3 Aggregate information and define actual requirements on factory	a2.4 Identify deviations between requirements and current	a2.5 Coordinate the MC	a2.6 Create a change plan proposal	a2.7 (Re-)assign roles and responsibilities	a2.8 Review MC profile	a2.9 Decide on the release of a change request
r1 Change requester									1
r2 Change agent	(2)	2	2	2	(2)	2	(2)	(2)	1
r3 Change manager	2	(2)	(2)	(2)	2	(2)	2	2	2 / (3)
r4 Change committee						(2)			3
r5 Department functions	1	(2)		(2)					(1)

Roles (IC / FBD)	Conceptual problem solving						
	a3.1 Make a detailed problem and target description	a3.2 Develop and describe solution concept proposals	a3.3 Make change and change propagation analysis	a3.4 Make stakeholder review	a3.5 Estimate invest and benefit of MC	a3.6 Formally approve invest plan	a3.7 Prepare solution concept proposals for MC
r1 Change requester							1
r2 Change agent	2	2	2	2	2	1	(2)
r3 Change manager			(2)	(2)		2	2
r4 Change committee							
r5 Department functions			(2)				(1)

Roles (IC / FBD)	Concept evaluation & decision							
	a4.1 Evaluate solution concept proposals and make pre-selection	a4.2 Align solution concept proposal(s) with customer	a4.3 Make detailed cost analysis	a4.4 Select and approve solution concept	a4.5 (Re-)assign roles and responsibilities	a4.6 Review change plan	a4.7 Review MC profile	a4.8 Approve solution concept and release change order
r1 Change requester	1							1
r2 Change agent	(2)	2	2	2	(2)	(2)	(2)	1
r3 Change manager	2			3	2	2	2	2 / (3)
r4 Change committee	3							3
r5 Department functions	(1)							1

Roles (IC / FBD)	Detailed change planning						
	a5.1 Select and integrate suppliers	a5.2 Plan MC in detail	a5.3 Align detailed change plan with customer	a5.4 Make sourcing plan proposal	a5.5 Approve detailed change plan	a5.6 Approve sourcing plan	a5.7 Compile final detailed change plan
r1 Change requester							1
r2 Change agent	2	2	2	2			1
r3 Change manager					2 / 3	2 / 3	2
r4 Change committee							3
r5 Department functions							1

Roles (IC / FBD)	Implementation planning						
	a6.1 Make implementation plan proposal	a6.2 Approve implementation plan	a6.3 Procure technical equipment	a6.4 (Re-)assign roles and responsibilities	a6.5 Review change plan	a6.6 Review MC profile	a6.7 Approve MC to be implemented
r1 Change requester							1
r2 Change agent	2		2	(2)	(2)	(2)	1
r3 Change manager		2 / 3		2	2	2	2 / (3)
r4 Change committee							3
r5 Department functions							1

Roles (IC / FBD)	Implementation				
	a7.1 Implement MC	a7.2 Check implemented MC	a7.3 Make quality and performance test	a7.4 Review and update information systems	a7.5 Make overall "go for production" check
r1 Change requester					1
r2 Change agent	2	2	2	2	2
r3 Change manager		(2)			2 / (3)
r4 Change committee					3
r5 Department functions					(1)

Roles (IC / FBD)	Evaluation & knowledge mg.			
	a8.1 Review and evaluate the MC	a8.2 Describe and highlight lessons learned	a8.3 Clean up	a8.4 Close MC
r1 Change requester				1
r2 Change agent	2	2	2	1
r3 Change manager	(2)	(2)	(2)	2 / (3)
r4 Change committee				3
r5 Department functions	(2)	(2)		1

1 gets information
(1) gets information (optional)
2 executes
(2) executes (optional)
3 approves
(3) approves (optional)

Figure A.11: DMM model of roles and the MCM process

	s1						s2									s3							s4								s5							s6							s7					s8				
Methods & Tools IC / FBD	a1.1	a1.2	a1.3	a1.4	a1.5	a1.6	a2.1	a2.2	a2.3	a2.4	a2.5	a2.6	a2.7	a2.8	a2.9	a3.1	a3.2	a3.3	a3.4	a3.5	a3.6	a3.7	a4.1	a4.2	a4.3	a4.4	a4.5	a4.6	a4.7	a4.8	a5.1	a5.2	a5.3	a5.4	a5.5	a5.6	a5.7	a6.1	a6.2	a6.3	a6.4	a6.5	a6.6	a6.7	a7.1	a7.2	a7.3	a7.4	a7.5	a8.1	a8.2	a8.3	a8.4	Σ
Meeting	x	x		x	x	x	x		x		x		x	x	x				x		x	x		x		x	x	x	x	x	x		x		x	x	x		x		x	x	x	x	x	x			x	x	x			35
Check list		x	x	x		x		x			x			x		x		x											x	x															x		x	x	x	x	x	x	x		x	20
Survey / Questioning	x		x						x	x	x						x	x	x					x	x				x			x		x				x								x	x	x			x	x			19
Effort estimation methods		x		x								x	x		x							x								x	x														x	x		x	x							12
Eisenhower method		x		x		x					x	x		x														x	x								x				x	x										11
Cost estimation		x		x								x			x							x			x		x				x								x						x									10
Change profile		x	x	x				x			x			x				x											x																x										9
KPI systems	x			x							x				x														x															x								x	x			8
Questionnaire	x	x									x					x	x																																			x	x			7
Observation	x																																												x	x	x			x	x			6
Scenario planning	x		x				x											x					x													x																6
FMEA	x		x				x											x					x													x																6
Fault tree analysis	x		x				x											x					x													x																6
Target-performance comparison										x																		x																	x	x			x	x			6
Augmented Reality			x				x								x	x															x																					5
Computer Aided x			x				x								x	x															x																					5
Simulation			x				x								x	x															x																					5
Virtual Reality			x				x								x	x															x																					5
Effort trend analysis																												x																	x	x			x	x			5
Cost trend analysis																												x																	x	x			x	x			5
Milestone Trend Analysis																												x																	x	x			x	x			5
Workforce Matrix					x								x													x														x			x										5
Status report																												x																	x	x			x	x			5
Responsibility matrix					x								x													x														x			x										5
Change database				x										x			x										x														x												5
Continuous improvement (CIP)	x															x																																	x	x			4
Quality test methods	x																																														x		x	x			4
Quality function deployment	x		x				x										x																																			4
Process analysis	x		x				x										x																																			4
Value stream analysis	x		x				x										x																																			4
Flowchart			x				x										x														x																					4
Material flow / transportation matrix			x				x										x														x																					4
Amount-transportation diagram			x				x										x														x																					4
Sankey diagram			x				x										x														x																					4
Change project plan												x																x										x				x											4
Bar graph (e.g., Gantt chart)												x																x										x				x											4
Reporting																								x							x		x				x																		4
Earned value analysis																																														x	x			x	x			4
Network plan technique												x																x										x				x											4
To do list												x																x										x				x											4
Product Data Management			x				x		x								x																																			4
Workshop																	x																																	x	x			3
Trend analysis	x																						x														x																3
Change impact analysis			x				x										x																																			3
Change Prediction Method			x				x										x																																			3
Benchmarking	x																																																	x	x			3
DSM			x				x										x																																			3
Ishikawa			x				x										x																																			3
Risk analysis	x																						x														x																3
Analysis of weak points	x																						x														x																3
Network analysis			x				x										x																																			3
Static invest calculation																							x		x											x																3
Dynamic invest calculation																							x		x											x																3
Life cycle costing																							x		x											x																3
Progress measurement methods																												x																	x	x								3
ABC / XYZ analysis																																		x						x														2
Similarity analysis		x									x																																										2
Requirements list									x							x																																					2
Lessons Learned																																																			x	x			2
Keyword list																	x																																				x		2

x Method / Tool supports activity

Figure A.12: DMM model of methods & tools and the MCM process

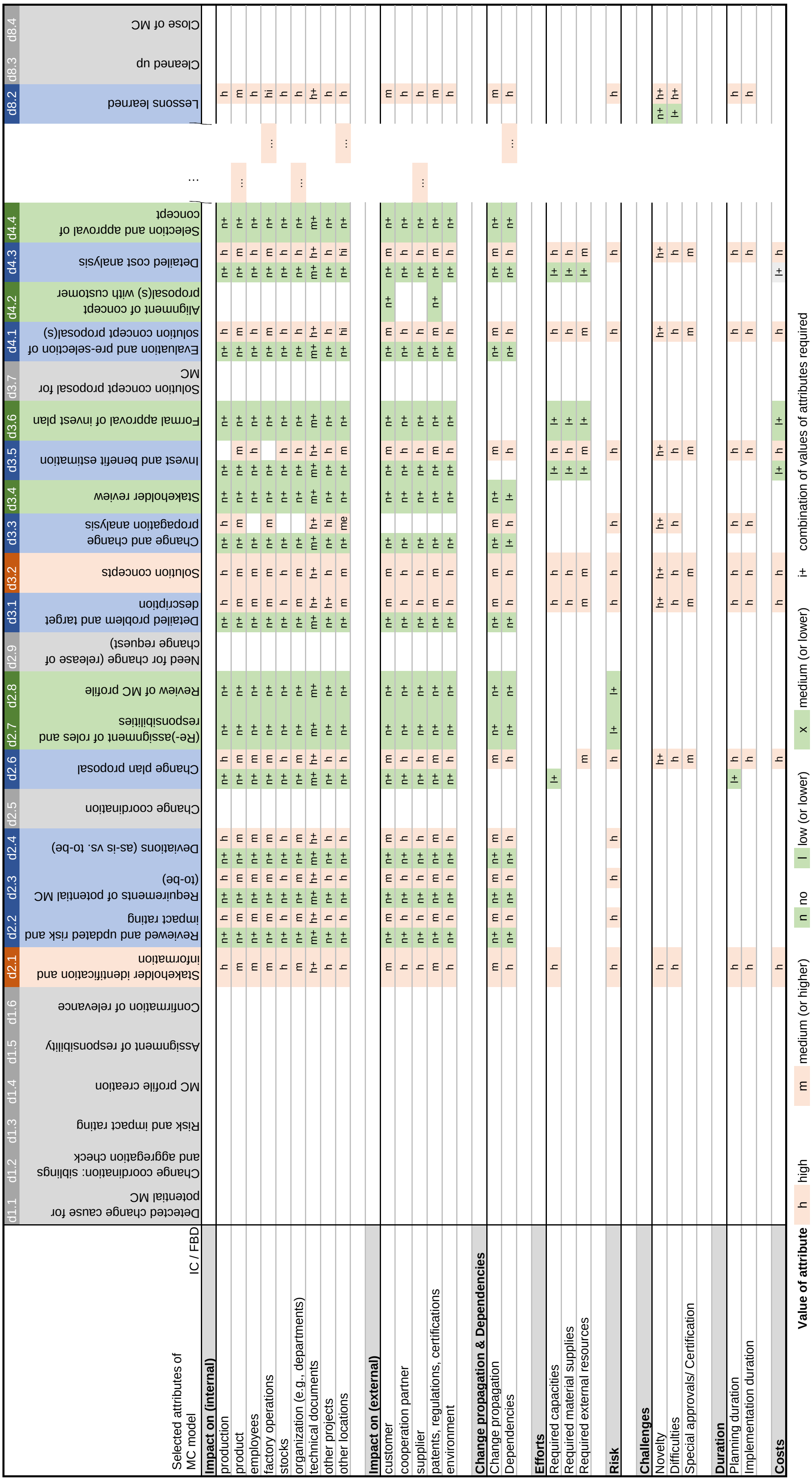

Figure A.13: DMM model of the tailoring approach for the MCM process (excerpt)

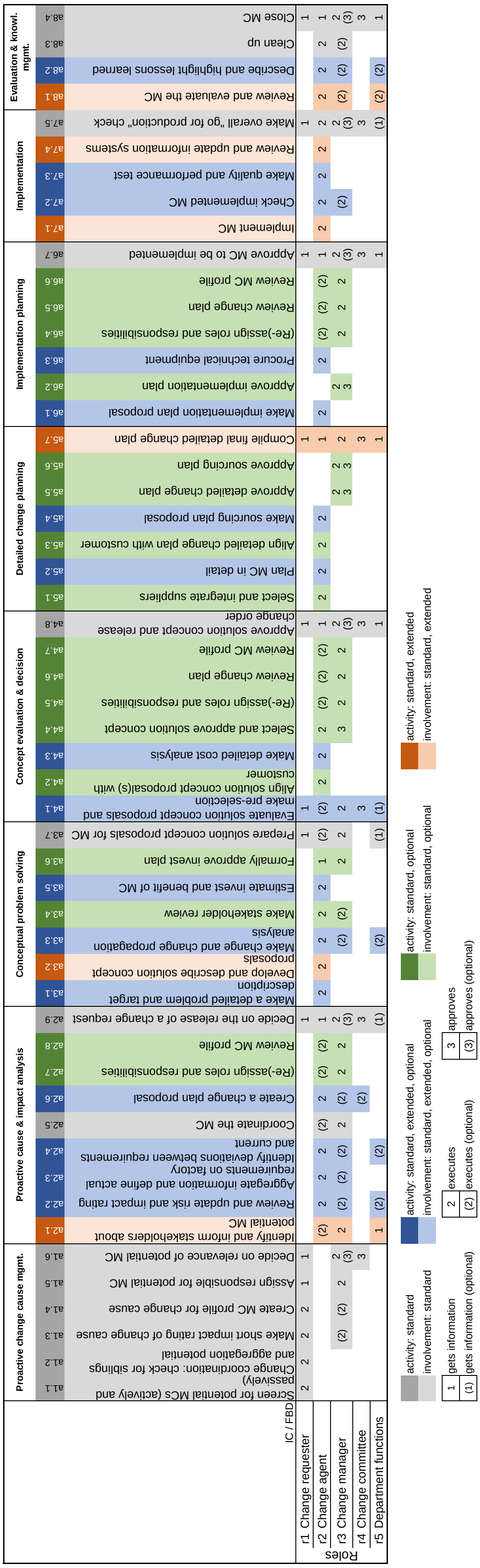

Figure A.14: DMM with a visualization of the scalable involvement of roles based on the MCM process tailoring

	Department functions														
Attributes of MC model relevant for role selection — IC / FBD	r5.1 Production management / Factory planning	r5.2 Production / Shop floor	r5.3 Quality Management	r5.4 Operations excellence / Lean	r5.5 Logistics/Supply chain	r5.6 Technology & product planning	r5.7 Product development	r5.8 PLM & ECM	r5.9 Management / Board	r5.10 HR / Work council	r5.11 Purchasing & Supplier management	r5.12 Sales and Marketing	r5.13 Legal	r5.14 Business development & Strategy	r5.15 External resources
Cause															
Factory life cycle	x	x		x		x					x				
Manufacturing Change	x	x													
Complications	x	x	x	x											
Product life cycle	x	x				x	x	x	x		x	x		x	
Engineering Change	x	x	x				x	x				x			
Errors & Failures	x	x	x				x	x				x			
Laws & Regulations	x							x	x	x			x	x	
Technology	x		x	x		x	x	x	x						
Procurement	x				x			x		x	x		x		
Business operations	x	x	x	x	x		x		x					x	
Kaizen	x	x		x			x	x							
Localization (affected object)															
Impact on (internal)															
production / production process	x	x	x	op	x		op	op	op						
product	op	op	x		op		x	x	x		op	x			
employees	op	op							x	x			op		
factory operations	x	x	op	op	x			x	x		op	op			
stocks	op				x		op	x	op		op	op			
organization (e.g., departments)	x	op							x	x				x	
technical documents	x	x		op			op	op							
other projects	x				op		op		x					x	
other locations	x	x		x					x					x	
Impact on (external)															
customer									x			x	x		
cooperation partner					x				x		op	x	x		
supplier					x			op	x		x		x		
patents, regulations, certifications							op		x				x		
the environment				x					x				x		
Change propagation & Dependencies															
Change propagation															
Dependencies															
Efforts															
Required capacities									xh						
Required material supplies									xh		x				
Required external resources									xm						x
Risk									xm						
Challenges															
Novelty															
Difficulties									xh						
Special approvals/ Certification									xh				xm		
Duration															
Planning duration															
Implementation duration															
Costs									xh						

l: low m: medium h: high — x required — op optional, but recommended — xl / xm / xh required

Figure A.15: DMM model of the role selection approach

A.5 Software used

- Adonis:CE 3.0: Business process analysis tool to model and visualize business processes. Used for the BPMN models of the MCM process.
- Citavi™ 5: Reference management program
- Microsoft Excel® 2013: Spreadsheet application. Used for the matrix-based models of the MCM context model and the MCM process.
- Microsoft PowerPoint® 2013: Slide show presentation program. Used for the graphical illustrations (except the BPMN models).
- TeXstudio 2.8.4: Integrated development environment for LaTeX typesetting.

A.6 Student's theses supervised

As part of the superior research project B5 "Cycle-oriented planning of changeable production resources" and this PhD thesis on MCM, the following chronologically listed theses (Master and Diploma) and semester papers have been written at the Institute for Machine Tools and Industrial Management (iwb). During this collaborative research, the students have been extensively guided and supervised by the author in terms of the research clarification, objectives, research questions, approach, activities, and content. Selected parts of the results have partly contributed to this dissertation. The author expresses his sincerest thanks to all students for their great commitment in supporting this research on MCM.

Name	Title of thesis / semester paper	Type	Year	Input for
Gerking, K.	Change Management in Engineering and Manufacturing	SP	2014	2, 3.3
Heckelsmueller, M.	Development of a methodologies- & tools-landscape for the Manufacturing Change Management process	SP	2014	6.3.4
Gritsch, A.	Manufacturing Change Management - Development of a change process	MT	2014	6.3.2
Michels, N.	Framework design for Manufacturing Change Management	MT	2015	5.1, 5.2, 5.3, 6.1
Brandl, F.	Design of a manufacturing change process based on methods of structural complexity management	DT	2015	6.3.2, 6.3.3
Glossner, J.	IT-based process modeling and design for Manufacturing Change Management	SP	2015	6.3.3
Hofer, A.	Study on the application of Manufacturing Change Management in Industry	SP	2015	1.1, 1.4
Ruzok, T.	Development of a proactive and learning Manufacturing Change Management	MT	2015	6.3.3
Gerking, K.	Testing and evaluation of Manufacturing Change Management in industrial case studies	MT	2016	7.1, 7.2
Grossmann, D.	Development of a concept for modeling and analyzing Manufacturing Change Management	MT	2016	6.3.3

MT: Master's thesis, DT: Diploma thesis, SP: Semester paper

A.7 Publication list

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

KOCH et al. 2014a
Koch, J.; Plehn, C.; Reinhart, G.; Zäh, M. F.: Cycle Management for Continuous Manufacturing Planning. In: Enabling Manufacturing Competitiveness and Economic Sustainability. Ed. by M. F. Zäh. Springer. 2014, pp. 9–12.

KOCH et al. 2014b
Koch, J.; Maisenbacher, S.; Maurer, M.; Reinhart, G.; Zäh, M. F.: Structural modeling of extended manufacturing systems – an approach to support changeability by reconfiguration planning. In: Procedia CIRP. Vol. 17. 2014, pp. 142–147.

KOCH et al. 2015a
Koch, J.; Brandl, F.; Reinhart, G.: A system-based approach to further design the concept of Manufacturing Change Management. In: DSM 2015: Proceedings of the 17th International DSM Conference. 2015, pp. 197–208.

KOCH et al. 2015b
Koch, J.; Brandl, F.; Hofer, A.; Reinhart, G.: Studie: Änderungsmanagement in der Produktion. (Survey: Change management in manufacturing). Munich: Institute for Machine Tools and Industrial Management (iwb), TUM. 2015.

KOCH et al. 2016a
Koch, J.; Michels, N.; Reinhart, G.: Context model design for a process-oriented Manufacturing Change Management. In: Procedia CIRP. Vol. 41. 2016, pp. 33–38.

KOCH et al. 2016b
Koch, J.; Gritsch, A.; Reinhart, G.: Process design for the management of changes in manufacturing: Toward a Manufacturing Change Management process. CIRP Journal of Manufacturing Science and Technology 14 (2016), pp. 10–19.

List of Figures

List of Tables

List of Abbreviations

Adonis:CE	Adonis Community Edition
BPMN	Business Process Model and Notation
CIRP	College International pour la Recherche en Productique (The International Academy for Production Engineering)
CPN	Colored Petri-net
CRC	Collaborative Research Center
CSV	Comma-Separated Values
DMM	Domain Mapping Matrix
DRM	Design Research Methodology
DSM	Design Structure Matrix
EC	Engineering Change
ECM	Engineering Change Management
ECR	Engineering Change Request
eEPC	extended Event-driven Process Chain
ERP	Enterprise Resource Planning
FMEA	Failure Mode and Effect Analysis
GTM	Grounded Theory Method
ICED	International Conference on Engineering Design
IC / FBD	Input in Columns / Feedback Below Diagonal
ID	Identifier
IDEF	ICAM Definition for Function Modeling, where ICAM is an acronym for Integrated Computer Aided Manufacturing
IDEF0	Integrated Definition, Version 0
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
iwb	Institute for Machine Tools and Industrial Management
IR / FAD	Input in Rows / Feedback Above Diagonal

IT	Information Technology
KPI	Key Performance Indicator
LMU	Ludwig-Maximilians-Universität München
MC	Manufacturing Change
MCM	Manufacturing Change Management
MCO	Manufacturing Change Order
MCR	Manufacturing Change Request
MDM	Multiple-Domain Matrix
OC	Organizational Change
OCM	Organizational Change Management
OEM	Original Equipment Manufacturer
OM	Operations Management
OMG	Object Management Group
PAF	Process Architecture Framework
PLM	Product Life Cycle Management
PPS	Production Planning and Scheduling
QFD	Quality Function Deployment
SIPOC	Supplier-Input-Process-Output-Customer
SME	Small and Medium-sized Enterprise
SSM	Soft Systems Methodology
SysML	Systems Modeling Language
TUM	Technische Universität München
UML	Unified Modeling Language
wt	Werkstattstechnik
ZWF	Zeitschrift für wirtschaftlichen Fabrikbetrieb