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A review of frameworks, methods and models for the evaluation and engineering of factory life cycles

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ABSTRACT

Factories are complex systems, which are characterized by interlinked and overlapping life cycles of the constituent factory elements. Within this context, the heterogeneity of these life cycles results in life cycle complexity and corresponding conflicts and trade-offs that need to be addressed in decision situations during the planning and operation of factory systems. Also with respect to the transformation need towards environmental sustainability, there is a need for methods and tools for life cycle oriented factory planning and operation. This paper systematically reviews existing life cycle concepts of factory systems as well as frameworks, models and methods for the evaluation and engineering of factory life cycles. In order to respond to the above challenges, a general understanding about the factory life cycle, e.g. life cycle stages, related activities and interdependencies, is developed and action areas of life cycle engineering are discussed that could supplement factory planning. Following that, the paper presents an integrated, model-based evaluation and engineering framework of factory life cycles.

1. Introduction

Factories are places of industrial value creation and form an integral part of modern societies contributing to economic development, job security and innovation (Haraguchi et al., 2017; Herrmann et al., 2014). Meanwhile, the global challenge of mitigating climate change leads to a rising awareness of environmental sustainability. Rapid action is needed in order to avoid overcoming critical environmental thresholds that would place the Earth's ecosystem into an unstable state (Steffen et al., 2018). Having in mind that manufacturing is responsible for a third of global man-made greenhouse gas emissions and absolute emissions are still on a rise, the scale of challenge becomes obvious (Fischedick et al., 2014). The environmental impact of factory systems comes from different life cycle stages and is exposed to various influencing factors. As displayed on the case of a state-of-art automotive factory in Fig. 1, the use stage is the most prominent life cycle stage, which includes the value creation process and the operation of peripheral processes as well as of the factory building. However, the embodied environmental impact of production machines, technical building services (TBS) and the building shell plays also a significant role in the factory life cycle (Gebler et al., 2020). A further complicating factor for the life cycle evaluation is that these factory elements have different life cycle lengths (Schenk et al., 2014; Wiendahl et al., 2015). Therefore, their replacements and the associated environmental impacts as well as their influence on the life cycle behavior of other factory elements need to be accounted for.

Consequently, factory planners and operators are faced with a highly complex engineering situation, since the factory life cycle is characterized by multiple overlapping and interlaced life cycles, high diversity of factory elements, vast number of interrelationships and different life cycle options (e.g. maintenance or improvement measures). Considering this emerging complexity and the urgency to integrate environmental sustainability, there is a need for life cycle oriented methods and tools for planning and operating factories. These methods and tools should support factory planners and factory operators by sensitizing to the complex decision situation, creating a holistic understanding of the underlying mechanisms, calculating measurable economic and environmental performance indicators and essentially providing decision support on a strategic planning horizon.

The evaluation and engineering of factory life cycles has been yet an underrepresented topic in scientific literature. A preliminary publication of the group of authors gave already an overview of economic, environmental and social evaluation approaches on different system levels of

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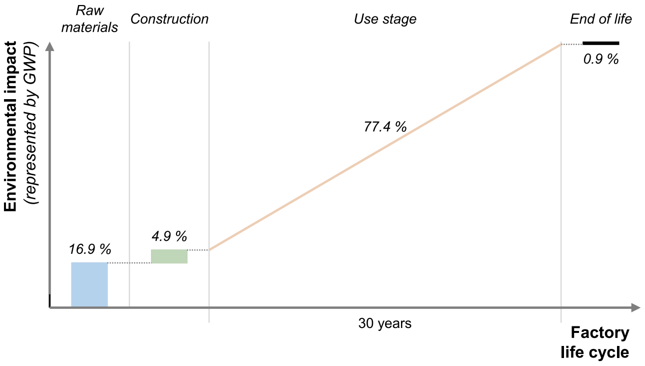


Fig. 1. Life cycle environmental impact of a state-of-art automotive factory, data based on (Gebler et al., 2020).

a factory and developed a first framework for quantitative factory life cycle evaluation (Nielsen et al., 2016). In another earlier publication, a qualitative life cycle evaluation approach of a factory system has been developed (Dér et al., 2021). So far, little attention has been paid to building up a systematic understanding of the factory life cycle. Likewise, there has been no detailed investigation of the linkage between factory planning and the life cycle performance of a factory and of methods and tools for planning the factory life cycle. Against this background, following research areas will be addressed in this paper:

- **Role of life cycle engineering (LCE) in factory planning:** While factory planning is an established process, life cycle orientation and the systematic planning of the factory life cycle has been often overlooked in the past. In this context, the question arises, what role life cycle engineering can play to support factory planning activities?
- **Methodological support with regard to planning the factory life cycle:** What kind of methodological support (i.e. frameworks, methods and tools) already exist that help factory planers and operators to evaluate and to plan the factory life cycle?

The first objective of the paper is to develop a generic understanding of the factory life cycle, which provides the conceptual foundation for upcoming methods and tools for evaluating and engineering the factory life cycle. The development of this understanding is based on a literature review. Building up on this, the second objective is to conceptually develop an integrated (meaning an environmental and economic), model-based evaluation and engineering framework of factory life cycles.

The remaining part of the paper is structured as follows. Section 2 recapitulates the background on life cycle engineering and life cycle concepts as well as factory systems and factory planning. In section 3, a common understanding of a generic factory life cycle is developed based on a literature review. Based on this understanding, action areas for supplementing factory planning by life cycle engineering are discussed. In section 4, existing literature is reviewed based on identified obstacles and requirements for a life cycle oriented approach. Based on the formulated research need, a conceptual framework is then developed and discussed (section 5).

2. Background on life cycle engineering and factory systems

2.1. Life cycle engineering and the concept of life cycles

Technical and socio-technical systems experience throughout their existence several life cycle stages. Flow oriented life cycle models outline chronologically sequential and logically linked stages, e.g. raw materials extraction, materials production, manufacturing, use, recycling and end-of-life. These life cycle models assign related activities to life cycle stages and simultaneously describe material and energy flows (Herrmann, 2010; Herrmann et al., 2007). In contrast, state oriented life cycle models describe the time-dependent evolution of relevant state variables of system. A preeminent example is the product life cycle concept that describes the characteristic shape of customer demand over the stages of introduction, growth, maturity and decline (Herrmann, 2010).

Throughout the life cycle, technical systems such as a factory are part of the technosphere and exchange material as well as energy flows with the ecosphere. This exchange of flows leads to environmental impacts. The methodological foundation for quantifying these environmental impacts is environmental life cycle assessment (Hauschild et al., 2020; ISO, 2006). Another life cycle engineering method is life cycle costing that focuses on the economic dimension (Hauschild et al., 2020; Herrmann et al., 2007; VDI, 2005). Considering the upcoming challenges associated with an absolute understanding of environmental sustainability, taking in a holistic life cycle perspective becomes inevitable (Hauschild et al., 2020). An obvious reason is to unveil hotspots across all life cycle stages and all system elements. This builds up the basis for a detailed system understanding with its relevant elements, contributing factors and cause-effect relationships. Using this knowledge, analyzing trade-offs between different goal criteria and avoiding problem shifting between different life cycle stages and/or impact categories becomes viable. Therefore, an up-to-date definition of LCE urges to bring the environmental dimension of sustainability to the focus (Hauschild et al., 2017). This is in contrast with earlier understandings, which were focusing on balancing trade-offs between the environmental, economic and social dimension of sustainable development (e.g. by the concept of eco-efficiency) (Alting, 1995; Hauschild et al. 2017, 2020).

2.2. Factory systems and factory planning

Systems theory have often been applied by various authors to describe factory systems (Schenk et al., 2014; Pawellek, 2014; Wiendahl et al., 2015). Factory levels (i.e. factory, section, and machine) are used for a vertical segmentation and factory design fields (technology, organization, space) for a horizontal segmentation. As a result, individual factory elements and their relationships to one another can be assigned to levels and fields (Heger, 2006). According to the CIRP Encyclopedia a “(…) factory represents the physical and logical means of performing production and manufacturing processes” (Chryssolouris et al., 2014). To this end, production factors such as material, facilities, work force, energy and information are combined to execute the value creating transformation process on products (Chryssolouris et al., 2014; Westkämper and Decker, 2006). With respect to a holistic understanding, factory systems incorporate several subsystems that consist of individual factory elements such as production (including machines, storage and transport equipment), technical building services (TBS) and the building shell (Posselt, 2016; Hesselbach et al., 2008). Manifold dynamic interdependencies between the factory subsystems and the factory system elements exist, e.g. TBS has to provide a defined room temperature whereas machines emit heat and the building shell interacts with the outside climate/weather (Hesselbach et al., 2008; Thiede, 2012).

Each factory has to fulfill a function that stems from the company’s business understanding and the customer demand (Müller et al., 2009). This function is composed of different individual tasks based on transforming, storing and transporting (Schenk et al., 2014; Helbing, 2018). Considering the turbulent factory environment and the corresponding constant adaptation demand, the processes and structures of a factory must be constantly redefined (Claussen, 2012). As a consequence, factory planning gradually merges with factory operation tasks (Wiendahl et al., 2015). There are many different descriptions of the factory planning process in literature, e.g. by (Aggteleky, 1987; Felix, 1998; Grundig and Claus-Gerold, 2018; Schenk et al., 2014; Kettner et al., 1984; Wiendahl et al., 2015; VDI 5200). It is generally characterized by a strong interdisciplinary character involving various disciplines

(Hilchner and Rick, 2012). Depending on the respective planning targets and system boundaries, experts from the following disciplines are involved: architecture/building, financial, logistics, personnel, process and specialist planning (IT, TBS) as well as product and technology development (Hilchner and Rick, 2012; Grundig and Claus-Gerold, 2018; Wiendahl et al., 2015; VDI 5200; Felix, 1998). The tasks of factory planning are mainly concerned with the design of the building shell, TBS, layout, personnel, technology, processes, information flow and operating resources (Nöcker and Jan, 2012). A study among factory planning practitioners confirms this perspective on involved disciplines and planning tasks (Hawer et al., 2017). Together, the literature presented in this section indicates that methods and tools of life cycle engineering are not yet regarded as part of the factory planning process.

2.3. *Evolution of factory systems and its impact on life cycle complexity*

Taking a look into the historic development of manufacturing in Fig. 2, it becomes obvious that the evolution of manufacturing paradigms and the industrial revolutions introduced new complexity in manufacturing systems and therefore intensified the requirements on factories (Koren, 2010; Hu et al., 2011; Herrmann et al., 2020). The development of manufacturing paradigms was constantly accompanied by changes in production volumes and product variants as well as specific production volumes per product variant. In addition, this evolution also shaped the location and the process of value creation. Early days of manufacturing took place in workshops and manufactories close to customers. Technological progress (e.g. steam power and the use of electricity) within the first and second industrial revolution displaced manufacturing more and more to factories. The world factory in the era of mass production indicates centralized production on one site, where high productivity is achieved by efficiency gains and economy of scales. Mass customization, as the latest paradigm, requires however a shift of production closer to markets and customers in decentralized and distributed manufacturing facilities. Along this evolution, disruptive as well as continuously developed technologies steadily move into factory systems, which increases the number and diversity of factory elements as well as their interactions over the life cycle. Taking the fourth industrial revolution as an example, cyber-physical production systems consisting of various hardware and software (e.g. sensors, networks, data storage and computing algorithms) increasingly continue to become an integrative part of modern factories and inseparably grow together with the value creation process and linked factory elements. The trend of cyber-physical production systems tends to accelerate the dynamization of the life cycle of factory elements. In general, the innovation cycle of information technology is shorter, more dynamic and may lead to conflicts due to incompatibilities (e.g. interface problems with factory elements such as the building shell, which have a much longer lifetime).

As an immediate consequence of the evolution of factory systems, factory elements increasingly interweave among themselves. Thereby, each factory element is characterized by individual life cycles that differ in their duration, own life cycle behavior and impact on the total factory life cycle (Wirth et al., 2000). In addition, the life cycle of the products produced in factories further increases life cycle complexity. The multiple overlapping life cycles of products, production technologies, production equipment, TBS and building shell result in a complex engineering system (Herrmann et al., 2007). Over the factory life cycle, multiple product and technology changes take place (Schönmann et al., 2016). Consequently, the life cycle behavior of the factory system is shaped by interlaced and heterogeneous life cycles of the factory elements. Life cycle complexity is further intensified by the fact that physical (e.g. production machine) and intangible (e.g. organizational structure) factory elements as well as factory elements with a short innovation cycle (e.g. electric components) and with a long innovation cycle (e.g. building shell) coexist in a factory system.

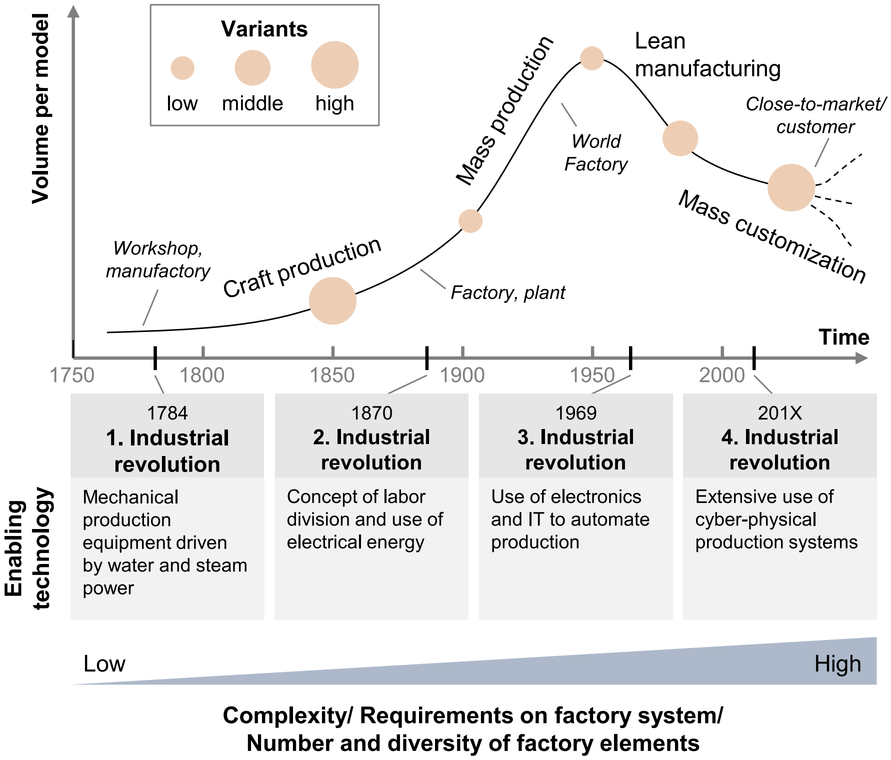


Fig. 2. Historic development of manufacturing paradigms, place of value creation, enabling technologies and corresponding effects on factories (based on Koren, 2010; Hu et al., 2011; Kagermann et al., 2013; Herrmann et al., 2020).

3. The factory life cycle

In order to provide a conceptual foundation for upcoming methods and tools for evaluating and engineering the factory life cycle, first, a common understanding is developed, what the factory life cycle embraces. Based on this understanding, action areas for supplementing factory planning by life cycle engineering are discussed.

3.1. *Review of factory life cycle concepts in literature*

A structured literature search was performed to reveal different factory life cycle concepts. This was the basis for merging them subsequently into a common understanding of the generic factory life cycle. The search was carried out in the Scopus database, with the exact search string being "TITLE-ABS-KEY (factory W/2 life AND cycle OR lifecycle)". In the final analysis, only contributions with an own understanding of the factory life cycle were considered (9 articles in total). Fig. 3 illustrates different perspectives on the factory life cycle and compares the corresponding life cycle stages as presented in literature. On a high abstraction level, the factory life cycle can be broken down in the stages: (1) factory planning and construction, (2) operation and (3) reconfiguration and end-of-life.

The factory life cycle concepts in literature differ in their granularity and naming conventions. For example, a rather simple concept consisting of three stages is presented in (Fantini et al., 2015). Opposed to that stands a more detailed concept presented in (Constantinescu et al., 2006). Most concepts present the factory life cycle in a linear manner, however, at the same time its cyclic character is implicitly acknowledged by considering a redesign, reconfiguration, refurbishment or modernization as an independent life cycle stage (Groβ et al., 2018; Fantini et al., 2015; Constantinescu et al. 2006, 2013b; Colledani et al., 2013). An exception to this is the concept by Erhardt et al., which represents a linear factory life cycle without a cyclic character (Ehrhardt et al., 2006). Francalanza et al. explicitly emphasize the recursive character of the factory life cycle that follows the factory's continuous adaptation need (Francalanza et al., 2018). Dombrowski et al. include reverse loops between the middle life cycle stages, as well (Dombrowski and Ernst, 2014).

The most prominent life cycle stage of a factory is factory operation, which can last up to several decades. Therefore, it represents the most relevant life cycle stage from an economic and environmental life cycle perspective, as most of the environmental impacts and life cycle costs occur during factory operation (Gebler et al., 2020; Herrmann et al., 2011; Abele et al., 2009). Beyond the flow oriented description of the factory life cycle, it can also be described in a state oriented manner by the time resolved evolution of performance curves of the constituting factory elements. In this context, the qualitative representation of the utility values of factory elements is often referred to, as displayed in Fig. 4. The figure illustrates selected factory elements with varying life cycle lengths and the evolution of their utility values (Wirth et al., 2000). Here, the factory life cycle is understood as an abstract concept that combines the individual utility value curves in a hierarchical structure. Since the factory life cycle emerges from the interconnected life cycles of the constituent elements, the factory life cycle cannot be planned directly but rather indirectly by engineering the constituent elements and their interactions over the life cycle (Dér et al., 2021).

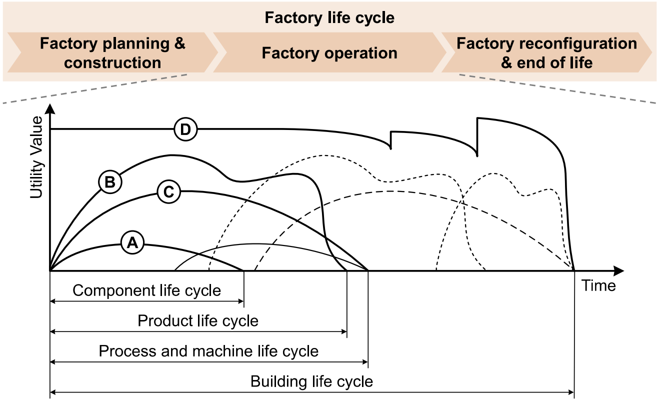
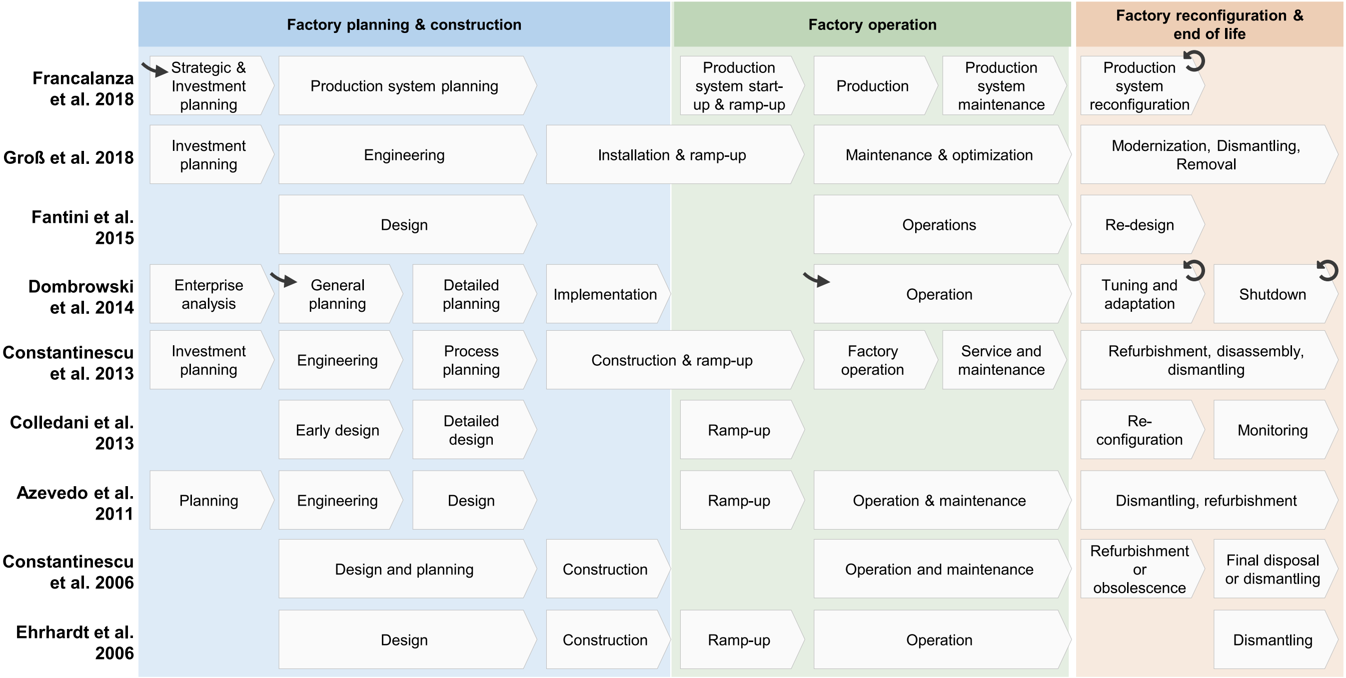


Fig. 4. Qualitative representation of the factory life cycle (inspired by Wirth et al., 2000; Nielsen et al., 2016).



	Factory planning & construction				Factory operation			Factory reconfiguration & end of life	
Francalanza et al. 2018	Strategic & Investment planning	Production system planning			Production system start-up & ramp-up	Production	Production system maintenance	Production system reconfiguration	
Groß et al. 2018	Investment planning	Engineering		Installation & ramp-up		Maintenance & optimization		Modernization, Dismantling, Removal	
Fantini et al. 2015		Design				Operations		Re-design	
Dombrowski et al. 2014	Enterprise analysis	General planning	Detailed planning	Implementation		Operation		Tuning and adaptation	Shutdown
Constantinescu et al. 2013	Investment planning	Engineering	Process planning	Construction & ramp-up		Factory operation	Service and maintenance	Refurbishment, disassembly, dismantling	
Colledani et al. 2013		Early design	Detailed design		Ramp-up			Re-configuration	Monitoring
Azevedo et al. 2011	Planning	Engineering	Design		Ramp-up	Operation & maintenance		Dismantling, refurbishment	
Constantinescu et al. 2006		Design and planning		Construction		Operation and maintenance		Refurbishment or obsolescence	Final disposal or dismantling
Ehrhardt et al. 2006		Design		Construction	Ramp-up	Operation			Dismantling

Fig. 3. Overview of factory life cycle concepts (own illustration based on literature).

3.2. *Mapping factory planning cases and action areas of LCE in the factory life cycle*

As indicated in Fig. 5, different factory planning situations arise during the life cycle of a factory. The planning cases are characterized by different goals and scope as well as design freedom (Schenk et al., 2014; Wiendahl et al., 2015; VDI 5200). Greenfield planning at the very beginning of the factory life cycle is the planning case with the fewest restrictions. Only the terrain restrictions and any existing infrastructure on the site need to be taken into account. Within factory operation, the factory planning process can be re-initiated as part of brownfield projects. Brownfield planning is the adaptation of an existing factory to changed requirements. This can include for example the reorganization or extension of the factory. Various structural and organizational restrictions from the ongoing factory operation have to be addressed in brownfield planning. At the end of the factory life cycle, clearance and revitalization are carried out to prepare the site for a subsequent, potentially non-industrial use. Since the purpose of the last planning case is termination rather than enabling of manufacturing, it is excluded from the further scope of the paper.

As discussed in Section 2.2, factory planning tasks have not embraced methods and tools of life cycle engineering until now. With respect to the gradual merging of factory planning and factory operation and the need for considering environmental sustainability, factory planning needs to move towards life cycle orientation in planning and decision making. In order to discuss the opportunities, how LCE can complement factory planning, Fig. 5 further illustrates derived action areas for life cycle oriented factory planning and operation. Since such action areas have not been discussed yet for factories, an analogy is drawn with product-oriented LCE. Generic action areas of a LCE-based approach regarding the product life cycle are building up a system understanding and identifying hotspots and trade-offs (Herrmann et al., 2018; Hauschild et al., 2020). Transferring these generic action areas from the product life cycle to the factory life cycle and synthesizing them with the respective factory planning cases emerge in three factory-specific action areas:

- **Concurrent evaluation of environmental impacts**: Although the major part of a factory's environmental impact emerges during operation, the boundary conditions for the life cycle behavior during factory operation are already predefined during planning. Therefore, the estimation of the environmental impacts in different planning phases is essential. Such an estimation must respect the phase-specific availability, detail level and uncertainty of planning data.
- **Assessment of different factory design configurations and operation scenarios**: Considering the life cycle complexity of factory systems, it becomes obvious that different factory configurations, operational strategies and scenarios are linked with changing environmental impacts. Also, costs and the operational performance varies, which may initiates an earlier rescheduling of planning projects. These trade-offs need to be made visible on a qualitative basis at early planning phases. More advanced planning phases require, however, quantifiably results.
- **Life cycle oriented decision support**: In order to achieve an effect that goes beyond building up knowledge about life cycle complexity and the life cycle performance of a factory system, the results need to be integrated into the planning process. To this end, effective visualizations and a life cycle oriented decision support are required. This should support factory planners in interpreting the evaluation results, understand the leverages and break them down on the level of single planning objects.

4. Frameworks, methods and models for the evaluation and engineering of factory life cycles

In contrast to the product life cycle, the factory life cycle and corresponding evaluation and planning methods and tools are a less researched area (European Commission, 2014). In the following, obstacles and key requirements are derived, which is followed by a systematic review of literature regarding the existing methodological support of life cycle oriented factory planning and operation and the derivation of research gaps.

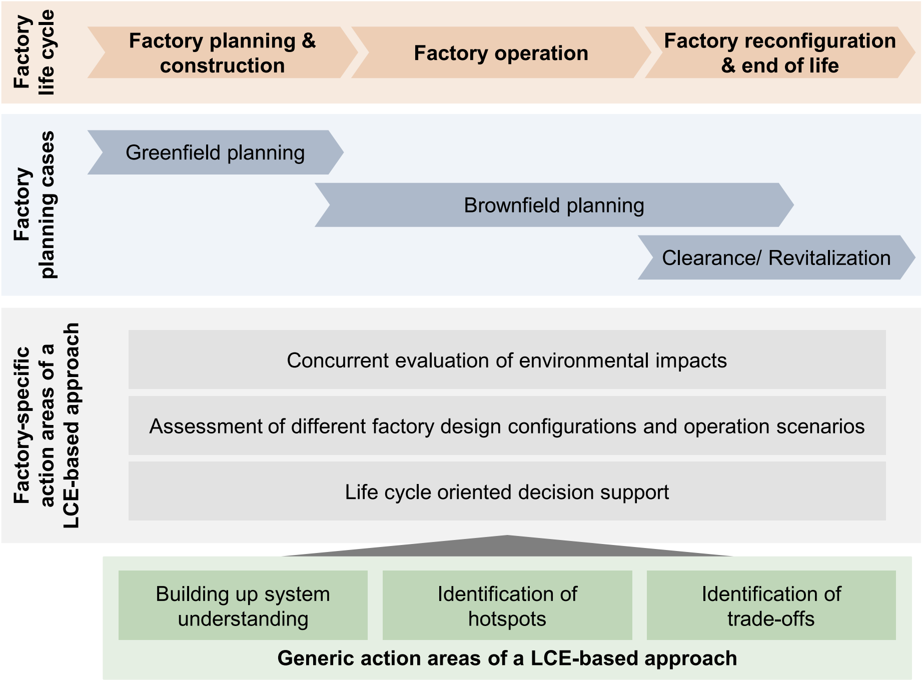


Fig. 5. Mapping factory planning cases and action areas for a LCE-based approach within the factory life cycle.

4.1. Obstacles and key requirements for life cycle oriented factory planning and operation

Based on the previously built up understanding of factory systems and the factory life cycle as well as the derived action areas, obstacles are compiled that substantiate the need for developing methods and tools that respect the heterogeneous nature of the factory life cycle and the resulting engineering complexity. Obstacles for the life cycle oriented planning and operation of factories comprise several methodological and practical challenges:

- Interrelationships between single factory elements may be understood on a narrowed-down view on single elements but are hard/impossible to grasp in their collectivity on a systems level (e.g. Colledani et al., 2014). These interrelationships are diverse, e.g. in from of dynamic energy and media flows between production machines, TBS and the building shell during factory operation (Hesselbach et al., 2008; Thiede, 2012), functional interrelationships in terms of requirements and capabilities between the product and the factory life cycle (Politze et al., 2010; Kutin et al., 2016; Pedrazzoli et al., 2007; Hürkamp et al., 2020) and interrelationships resulting from the different life cycle lengths of factory elements (Wiendahl et al., 2015; Nandkeolyar et al., 1993).
- High diversity of factory operation strategies and life cycle options, which already need to be handled during factory planning. For example, during factory planning, factory strategies need to be implemented e.g. low cost or a highly automated factory that will later have an impact on the factory's life cycle performance (e.g. Schmidt et al., 2017; Dér et al., 2019; Rothe et al., 2019; Süße et al., 2022). Regarding factory operation, different life cycle options are available, e.g. maintenance strategies, refurbishment or upgrade of production machines that also have an impact on their later life cycle performance (VDMA, 2020).
- The effects of changing one system element are unknown on systems level (Bauer et al., 2017). Its intensity and influence on other system elements are hard to predict, which has for example been discussed on the case of battery cell manufacturing (Schönemann et al., 2019; Thomitzek et al., 2021). Therefore, there is a risk of problem shifting when neglecting a holistic system perspective. The problem shifting can concern different operational, economic or environmental performance indicators (e.g. Wiese et al., 2021; Müller et al., 2018), which can result in trade-offs between them (e.g. Thiede et al., 2016). Moreover, life cycle stage-overarching problem shifting and problem shifting between environmental impact categories is also possible (Cerdas et al., 2017a; Rödger et al. 2018, 2021; Gebler et al., 2020).
- The long planning horizon encompasses uncertainties and variabilities and may amplify them. For small and medium-sized companies, but also for large manufacturing companies, risks and challenges arise here from a planning perspective in qualifying older production machines and existing factory elements to changed requirements (Wiendahl et al., 2007; Roth, 2016). From a life cycle evaluation perspective, the long-lived factory elements entail the consideration of temporal and spatial aspects (Herrchen, 1998). Beyond that, there exist several other factors that act as a barrier for implementing LCA in manufacturing (Cerdas et al., 2017b).

This list of obstacles is not meant to be exhaustive and could therefore be extended by other aspects, as well. However, the identification of such methodological and practical challenges is the starting point for deriving requirements for a life cycle oriented factory planning and operation approach. Following requirements were derived based on these obstacles and the action areas from Section 3.2:

- An integrative and holistic approach is needed. An integrative view is required to consider an economic and environmental perspective but also functional aspects (e.g. production volumes). A holistic view proposes to consider relevant factory elements along their life cycle, which includes the planning and operation stage of a factory. One methodological challenge in this context is to identify life cycle relevant factory elements and the main aspects that compose their life cycle behavior.
- The approach should be applicable in the planning stage of a factory (both greenfield and brownfield). Among others, this requires an interface to the factory planning process, a prospective evaluation based on parametrizable models, employing planning phase-specific information and dealing with data and planning uncertainties.
- Provide decision support by means of measurable economic and environmental performance indicators, sensitivity and scenario analysis and appropriate (e.g. interactive) visualizations. In addition to that, the approach should foster life cycle thinking on systems level and the understanding of cause effect chains as well as enable the identification of life cycle relevant hotspots and compare the life cycle performance of different factory configurations.
- The approach should be able to represent the factory operation on longer time scales. While operational aspects, e.g. scheduling, are too detailed on a strategic planning horizon, the aging behavior of factory elements resulting from their usage pattern and connected energy and material flows need to be estimated. To this end, the approach should consider different operation strategies. With respect to broad applicability to a wide range of factory types in discrete manufacturing, the modeling of operation strategies need to follow a generic and flexible logic. A crucial point with that regard is finding an appropriate abstraction level for modeling single factory elements as well as their interaction over the factory life cycle.
- While in-depth modeling of the changing external factory environment exceeds the scope of production engineering, the changing boundary conditions and their effects on the factory system still need to be anticipated during the planning horizon. To this end, the model-based approach have at least to provide a parametrization interface or connectivity to expert models of the factory environment from other disciplines.

4.2. Review and screening methodology

A systematic search procedure was applied to ensure comprehensiveness and to minimize the risk of bias in selecting relevant articles (Fig. 6). The search process focused on the one hand on articles in the context of factory, production system and manufacturing system and on the other hand on the subjects of life cycle, planning, modeling and life cycle evaluation. The search process covered the titles, abstracts and keywords of publications. Where applicable, the search focused on publications written in English. However, since a considerable amount of literature in this context is only available in German, these were also included in the review process. The search process was delimited on the domain of production engineering with a focus on discrete manufacturing applications. Articles from other application fields, e.g. process industry, are not included in the review. In case of multiple contributions filed from the same author team, the most representative paper was selected to avoid duplications. As a quality criteria, the review included peer-reviewed scientific journals, peer-reviewed conference proceedings, PhD/doctoral theses and other peer-reviewed contributions. Afterwards, abstracts and full papers were screened successively to sort out duplications and thematically irrelevant articles. Case studies without a novel methodology were also excluded from the detailed analysis. With respect to the high number of potentially relevant approaches, clusters have been built during the screening process to simplify the identification of contributions for the detailed analysis. Five clusters were identified based on their thematic or methodological focus. Thereby, each article is assigned to only one cluster. This classification was based on the proximity of the main focus of the article. The clusters are used in the detailed analysis, as well, in order to give a

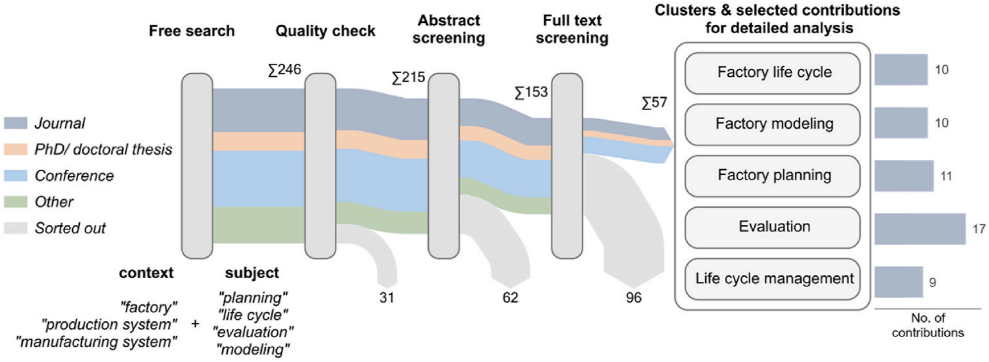


Fig. 6. Search methodology and identified clusters.

guiding structure to the descriptive presentation of the contributions. A total of 57 contributions are analyzed in this paper.

The cluster *factory life cycle* includes contributions that explicitly address the factory life cycle as a whole, the life cycle of factory elements or the resulting challenges for factory planning and operation. Contributions from the cluster *factory modeling* incorporate model-based approaches with the objective of better understanding the interaction of factory elements or as a decision support during planning or operation. The cluster *factory planning* contains contributions that present explicitly a planning procedure and have a relation to life cycle aspects. The cluster *evaluation* encompasses contributions targeting an economic, environmental or an integrated assessment of a production environment on different levels of a factory system. Only contributions with a production perspective were included. Product-centric articles, e.g. those determining environmental impacts per product or eco-design of machine tools from supplier perspective, were excluded. Finally, the cluster *life cycle management* comprises approaches for the systematic analysis and life cycle oriented design of manufacturing systems. Concerning the number of publications, the cluster *evaluation* stands out with 17 contributions, which is followed by 11 articles in the cluster *factory planning* and each 10 articles in the clusters *factory life cycle* and *factory modeling*. The cluster *life cycle management* is represented by 9 papers.

4.3. Detailed analysis of selected literature

4.3.1. Cluster "factory life cycle"

Research focusing the factory life cycle has started in the 1980′s and 1990′s. Approaches from this early days emphasize a qualitative description of the factory life cycle by different consecutive stages and indicators from several dimensions, e.g. costs or utilization (Schmenner, 1983; Nandkeolyar et al., 1993). Subsequent contributions focused on the descriptive discussion of different life cycles in a factory system, mostly on the interrelationships between the product life cycle and the factory life cycle (Westkämper et al., 2006; Constantinescu et al., 2006; Politze et al., 2010; Kutin et al., 2016), but also between the life cycle of information and communication technologies (Constantinescu et al., 2013a). The life cycle of different elements is often characterized by their utility value, which, however, lacks a clear definition. Consequently, approaches based on the utility value are not directly applicable for decision support during planning activities. A recent contribution made attempts to break down the abstract concept of utility values to the life cycle performance of factory elements, which is measured in the technical/functional, economic and environmental dimension (Dér et al., 2021). A further article investigates the effect of climate change on the factory life cycle in a semi-quantitative description model to analyze risks and derive adaptation strategies (Dombrowski and Ernst, 2014). The impact of the turbulent factory environment on the life cycle of factory elements was embraced in another work, which focused on qualitatively modeling an effect chain starting from megatrends over change drivers to factory elements (Hingst et al., 2021).

Taken together, approaches from the cluster *factory life cycle* discuss the resulting challenges for factory planning and operation from different dimensions. However, besides a high level description of interconnected factory elements, they provide little or no methodological support, when it comes to evaluating, planning or harmonizing the life cycles of different factory elements.

4.3.2. Cluster "factory modeling"

The majority of model-based approaches focus on the dynamic modeling of energy and media flows inside and between the main subsystems of a factory. Although different naming conventions are used for these sub-systems in literature, these are in essence the production system including multiple production machines in process chains, the technical building services and the factory building. Most of these approaches were developed for a special purpose, e.g. energy efficiency (Herrmann and Thiede, 2009; Weeber et al., 2018), energy and resource efficiency (Hopf and Müller, 2016; Ball et al., 2013) and on industrial ecology (Despeisse et al. 2012a, 2012b). A further article discusses multiscale modeling and simulation of a battery production system (Schönemann et al., 2019). Such an integrated approach complements traditional operational performance indicators by material and energy flows and corresponding economic and environmental performance indicators (Schönemann et al., 2019). These approaches were not explicitly developed for analyzing the life cycle of factory systems. Nevertheless, they discuss concepts that are needed for the evaluation of the environmental impacts of a factory system, i.e. the interrelationships between the subsystems of a factory and the resulting energy and media flows.

In order to allow for a qualitative assessment of changeability in factory systems, an ontology-based descriptive factory model has been developed (Plehn et al., 2015b). The model provides a generic basis to describe a factory system as a graph with the constituting factory elements, relationships and parameters. An extension of this approach is used in a methodology for change impact analysis in factory systems (Bauer et al., 2017). Its goal is to model the propagation of a change on a factory element on further factory elements and arbitrary performance indicators of the factory system. Another conceptual model investigates the changeability transition process of a production system by applying an integrated system dynamics and discrete event simulation (Albrecht et al., 2014). The emphasis of this approach lays on analyzing the flexibility corridor of a production system and its response to different changeability measures (Albrecht et al., 2014). Economic and environmental impacts are beyond the scope of this approach.

Overall, the approaches from the cluster factory modeling provide important insights into the modeling of energy and media flows, which contributes to the environmental evaluation of factory systems. Besides one quantitative approach for analyzing the changeability transition process, the modeling of the temporal evolution of the life cycle of relevant factory elements or of the whole factory system is not addressed.

4.3.3. Cluster "factory planning"

Two main directions exist within the selected approaches in the cluster *factory planning*. The first one is focusing on integrating life cycle and sustainability related aspects into the planning process. The second direction concentrates on considering changeability and the adaptation need of factories along their life cycles. A qualitative framework for life cycle and sustainability oriented production system design is presented in (Herrmann et al., 2009). The framework builds up on the manufacturing system design decomposition model (cf. Cochran et al., 2001), extends it with sustainability related functional requirements and design parameters as well as a cross-impact analysis between strategic goals, change drivers and design parameters (Herrmann et al., 2009). Another model investigates the relationships between factory planning steps, factory elements, their interfaces and sustainability dimensions (Chen et al., 2012). Although sensitizing to life cycle and sustainability related aspects during the planning stages, these models don't provide quantifiable performance indicators for a decision support.

The approaches with measurable performance indicators strongly correlate with model-based approaches for energy-oriented process chain modeling from the cluster *factory modeling* (Section 4.3.2) (Stahl et al., 2013b; Schmidt, 2021). However, these approaches are embedded into a planning process with an application procedure. Common in both analyzed approaches are the dynamic modeling of energy flows of production machines and the technical building services (Stahl et al., 2013b; Schmidt, 2021). Another work proposed a life cycle simulation approach to support environmental-conscious decision making during layout design (Harun and Cheng, 2011). To this end, energy and material flow simulation is integrated into a LCA workflow (Harun and Cheng, 2011).

Regarding the second research direction, the continuous adaptation need of a factory and the interactions between the product, process and factory life cycle were discussed and a framework was developed for requirements analysis during the planning process (Da Piedade Francisco et al., 2010). A planning procedure was presented in another study that is striving for a continuous prognosis of a factory's resource balance, i.e. supply and demand, as a bases for investment decisions (Hartkopf, 2013). Considering the future supply and demand is based on continuous and discontinuous developments in the production resource structure, factory layout and personnel structure as well as change drivers affecting the product and process technology and production volumes (Hartkopf, 2013). A second approach analyses the impact of product and technology changes on a factory (Wulf, 2011). The goal is to determine the monetary adaptation demand for relevant factory elements and derive a migration path for the factory, which are qualitatively assessed in different scenarios (Wulf, 2011). Another work investigates, whether the restructuring of a factory system is necessary on account of internal and external change drivers (Lübkemann, 2016). To this end, a methodology was developed to describe factory system configurations and analyze the effect of change drivers in a qualitative manner (Lübkemann, 2016). A further methodology assesses the adaptation demand of a production structure from a cost perspective (Pohl, 2013). To this end, internal and external developments are monitored and forecasted. While considering uncertainties and interrelationships between the product, production resource and technology life cycle, adaptation scenarios are studied in a given period (Pohl, 2013). Another contribution looks into a planning procedure based on fuzzy planning data (Hawer, 2020). The overall goal is to increase the net present value of a factory by coordinating and dimensioning of changeability enablers (Hawer, 2020).

Taken together, attempts to integrate life cycle and sustainability related aspects into the planning process as well as considering changeability and the adaptation need of factories along their life cycle exist. However, none of the above approaches brings together both perspectives and allows for a prospective economic and environmental evaluation of the factory life cycle during planning.

4.3.4. Cluster "evaluation"

A recent case study presented a LCA focusing on climate change of a state-of-art automotive factory based on empirical data and analyzed different pathways towards decarbonization of the factory (Gebler et al., 2020). The use stage of the factory with 30 years of operation is the most prominent life cycle stage and is dominated by the energy demand of production machines and the TBS. The second most important factor comes from the embodied emissions of production machines, TBS and the building shell, which are primarily allocated to the planning stage of the factory but embodied emissions also emerge during factory operation, when factory elements are replaced or upgraded (Gebler et al., 2020). Another LCA-based approach was presented for the environmental evaluation of factory operation (Favi et al., 2016). Also here, the approach strongly relies on data acquisition from the ongoing factory operation (Favi et al., 2016).

In a previous contribution, Nielsen et al. already reviewed existing models and approaches for qualitative and quantitative life cycle evaluation of factories (Nielsen et al., 2016). According to their findings and updated from the latest state of research, approaches on lower system levels tend to be more specific with regards to their application scope and ability for decision support. Approaches on factory level are more conceptual and at current stage rather less suitable for a practical decision support.

Application areas of life cycle costing or total cost of ownership approaches at lower system scales have been machine tools (Osten-Sacken and Detlev von der, 1999; Niggeschmidt et al., 2010; Heinemann et al., 2014), automated intralogistics systems (Dreier and Wehking, 2016), automated manufacturing/assembly systems (Müller et al., 2018; Kampker et al., 2013) or rather generic approaches (Herrmann et al., 2011; Roda et al., 2019). Regarding the economic evaluation at factory level, one approach developed an energy-oriented life cycle costing method to analyze the economic effect of energy efficiency measures during factory planning (Götze et al., 2013). Another approach proposed the transformation of non-monetary planning objectives into an extended net present value evaluation of a factory (Brieke, 2008).

Hierarchical approaches target a multi-level assessment of economic and environmental factors in a factory system (Heinemann et al. 2013, 2014; Nielsen et al., 2016). While each factory level is addressed by tailored methods and tools, e.g. by energy-oriented machine tool modeling and energy-oriented process chain modeling (Heinemann et al., 2014), the aggregation principles are rather generic (Heinemann et al., 2013; Nielsen et al., 2016). A qualitative maturity-based assessment approach aims at supporting factory planners to design factory elements according to the sustainability dimensions (Mersmann, 2015). Another approach investigates the influence of factory site selection on its environmental impact (Sihag et al., 2019). To this end, the environmental impact of factory operation (processes and TBS) estimated. Furthermore, the factory's role in the supply chain (transport distances from suppliers and to customers) is analyzed, as well (Sihag et al., 2019). A further study developed in a case study a high-level system dynamics model to analyze the influence of the factory environment on strategic production goals, i.e. production capacity, costs and CO_2-emissions (Mostert, 2007).

In view of that has been mentioned in this section so far, many approaches exist for the economic and or environmental evaluation of factory systems. These approaches differ in their focus area on single factory levels, performance indicators and coherency. Overall, the variety of above approaches highlight the need for practicable methods and tools for a comprehensive and prospective factory life cycle evaluation based on quantitative performance indicators. The logic of the evaluation concept of (Nielsen et al., 2016) comes close to fulfill this need, but needs to be elaborated regarding modeling depth of internal system influences, performance indicators and the consideration of external change drivers.

4.3.5. *Cluster "life cycle management"*

The various intersecting life cycles in factory systems and manufacturing companies lead to life cycle complexity, which needs to be managed (Herrmann et al., 2007). The framework of total life cycle management combines life cycle phase related and life cycle spanning disciplines to support to understand life cycle complexity (e.g. goal conflicts, uncertainty and cause-effect relationships between life cycles) and manage this complexity (Herrmann et al., 2007). In the past decade, several approaches emerged from the discussion of cyclic influences in manufacturing companies. Qualitative approaches focused on developing description models of cycles in the manufacturing context, e.g. by (Koch et al., 2014) and discussing the nature and effects of internal and external cycles on production planning, e.g. (Zaeh et al., 2010) for production resource planning and (Schönmann et al., 2016) for production technology planning. A more detailed understanding of cyclic influences is aspired in quantitative approaches, e.g. by applying the fuzzy theory to describe cycles (Stahl et al., 2013a) or developing high-level system dynamics models (Plehn et al., 2015a). Other quantitative approaches also apply fuzzy logic in the context of production technology planning. An example is the identification of a suitable time window for changing a technology (Greitemann et al., 2015). An extension of this approach takes uncertainties into account while anticipating future scenarios and determining a suitability index of a production technology based on its maturity, potential and profitability (Schönmann et al., 2018). Another quantitative model aims at identifying investment needs based on the current life cycle stage of production machines (Schönmann et al., 2017). This approach regards maintenance costs, downtimes, the technical performance and the age of the machines, neglects, however external change drivers (Schönmann et al., 2017).

Summing up the cycle management cluster, both qualitative and quantitative approaches exist. Quantitative approaches have been developed for special use cases, i.e. strategic production technology planning and production resource planning, which are motivated by economic considerations. Thus far, none of the above approaches reflects an environmental life cycle perspective, an integrated view on the relevant factory sub-systems and external change drivers in a quantitative manner.

4.4. *Discussion of the research demand*

The previous sections investigated the existing methodological support of factory planners and operators with regard to the life cycle evaluation and life cycle oriented planning of factory systems. Fig. 7 summarizes the results of a comparative assessment of the relevant research approaches. In spite of a considerable amount of work focusing on selected aspects of factory system modeling, planning and evaluation, a research gap is still identified for a comprehensive model-based planning and evaluation approach. Currently, factory planners lack of a life cycle oriented methodological support for forecasting the economic and environmental performance of factory operation. It is not yet possible to adequately map the dynamic interactions between the individual factory elements over their life cycle and to plan, develop and operate the factory elements in a targeted manner that results in an economically and/or environmentally favorable factory configuration. Taken together, a comprehensive and applicable approach is missing that is addressing the life cycle complexity of factory systems and is able to integrate all relevant factory elements for a prospective factory life cycle evaluation during factory planning. In particular, the model-based representation of the life cycle of relevant factory elements and their interactions over the life cycle, their prospective evaluation based on parametrizable models and quantified performance indicators while considering external and internal change drivers as well as their cause-effect chains are emphasized for future research.

5. Conceptual development of a framework for the model-based evaluation and engineering of factory life cycles

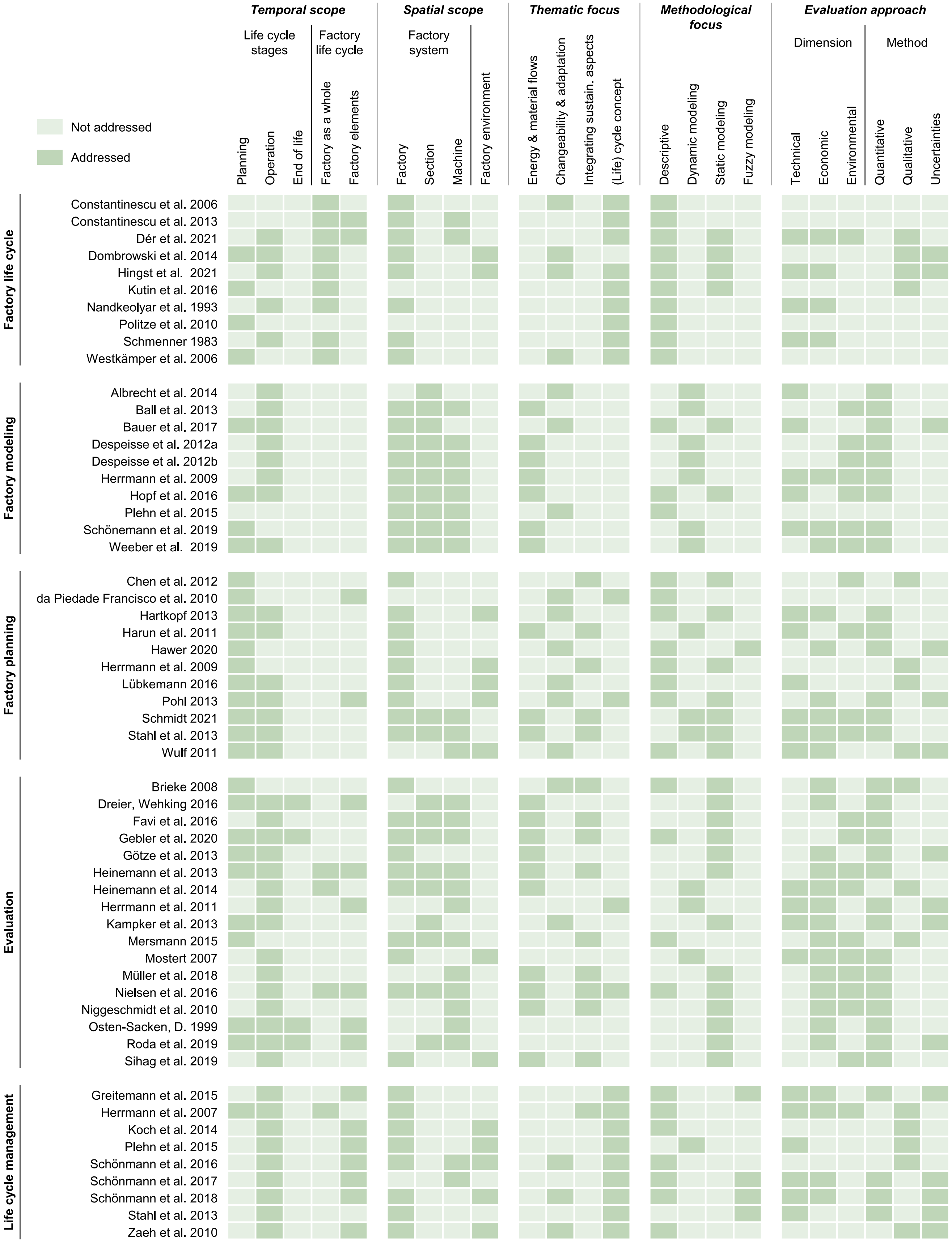
The following chapter presents the framework development based on the findings and the research gaps identified in the review. First, the general concept is introduced regarding its objectives and scope. Then, detailed aspects of the framework are described in more detail.

5.1. *Framework description*

When a new factory is planned or an existing factory configuration adjusted, different planning variants and life cycle options exist. The factory planner's task is to design and choose a factory configuration that is compliant with higher lever strategic goals, e.g. economic and environmental sustainability. This is the point, where the framework for the model-based evaluation and engineering of factory life cycles comes in (Fig. 8). Evaluating and engineering the factory life cycle respects the life cycle behavior of the constituent factory elements and their interactions over time. It includes the model-based representation of a factory configuration, the prospective evaluation and prognosis of the factory life cycle and the derivation of feedback and its integration into the planning process. The objective is comprehending the dynamics within the factory life cycle and allowing to link engineering decisions to the environmental and economic performance of a factory system. Fig. 8 shows the main elements of the framework. Since relevant decisions about factory configuration are made during factory planning, the starting point of the framework is the factory planning process, where, depending on the planning phase, a factory configuration is designed. In order to provide feedback about the life cycle performance of the given factory configuration to the factory planner, it is subsequently evaluated on an economic and environmental perspective. To this end, first the factory configuration is transferred in the framework to a model-based representation, which includes the representation of physical and intangible factory elements, their life cycles, their interactions over the life cycle and the emerging energy, cost and material flows. A subsequent evaluation module collects life cycle data and prepares the modeling results for an economic and environmental evaluation. The results are then transferred back to the factory planner, at which point they are compared with the initial strategic objectives and factory targets. If deviations occur, a modification of the factory configuration will be necessary and the evaluation loop starts again.

As already described earlier, the factory's life cycle performance is subject to numerous influencing factors. When improving the factory's life cycle performance, the question is, which influencing variables can be changed at which life cycle stage by factory planners and factory operators. Therefore, the framework considers actuating, state and outcome variables. Actuating variables (e.g. layout, process chains, logistics concept, etc.) are defined at the stage of planning. These variables are only changed actively at discrete points of time as a result of a planning activity. Otherwise, they remain constant during factory operation. State variables (e.g. power demands, failure behavior, deterioration, etc.) represent the properties and behavioral pattern of factory elements over time. The evolution of state variables strongly correlates with the usage profile of factory elements. They follow a characteristic profile over time but can also be influenced actively (e.g. by maintenance activities). Outcome variables (e.g. utilization, life time availability, etc.) describe the result of the interaction of state variables and actuating variables. The evaluation condenses life cycle data to decision relevant economic and environmental outcome variables.

The factory system model is created based on the previously mentioned design fields and factory levels and enables the evaluation of factory configurations at different points in time. The framework pursues the prospective evaluation of the operation stage of a given factory configuration. However, for a targeted evaluation, it seems more realistic to evaluate only a period of the factory life cycle, e.g. the project duration of a new product, as uncertainties will increase with an



□ Not addressed

■ Addressed

		Temporal scope					Spatial scope				Thematic focus				Methodological focus				Evaluation approach					
		Life cycle stages			Factory life cycle		Factory system												Dimension			Method		
		Planning	Operation	End of life	Factory as a whole	Factory elements	Factory	Section	Machine	Factory environment	Energy & material flows	Changeability & adaptation	Integrating sustain. aspects	(Life) cycle concept	Descriptive	Dynamic modeling	Static modeling	Fuzzy modeling	Technical	Economic	Environmental	Quantitative	Qualitative	Uncertainties
Factory life cycle	Constantinescu et al. 2006	□	□	□	■	□	■	□	□	□	□	■	□	■	■	□	□	□	□	□	□	□	□	□
	Constantinescu et al. 2013	□	□	□	■	■	■	□	■	□	□	□	□	■	■	□	□	□	□	□	□	□	□	□
	Dér et al. 2021	□	■	□	■	■	■	□	■	□	□	□	□	■	■	□	■	□	■	■	■	□	■	□
	Dombrowski et al. 2014	■	■	□	■	□	■	□	□	■	□	■	□	□	■	□	■	□	□	□	□	□	■	■
	Hingst et al. 2021	□	■	□	■	□	■	□	□	■	□	■	□	■	■	□	■	□	■	■	□	□	■	■
	Kutin et al. 2016	■	□	□	■	□	□	□	□	□	□	□	□	■	■	□	■	□	□	□	□	□	■	□
	Nandkeolyar et al. 1993	□	■	□	■	□	■	□	□	□	□	□	□	■	■	□	□	□	■	■	□	□	□	□
	Politze et al. 2010	■	□	□	□	□	□	□	□	□	□	□	□	■	■	□	□	□	□	□	□	□	□	□
	Schmenner 1983	□	■	□	■	□	■	□	□	□	□	□	□	■	■	□	□	□	■	■	□	□	□	□
	Westkämper et al. 2006	■	□	□	■	□	■	□	□	□	□	■	□	■	■	□	□	□	□	□	□	□	□	□
Factory modeling	Albrecht et al. 2014	□	■	□	□	□	□	■	□	□	□	■	□	□	□	■	□	□	■	□	□	■	□	□
	Ball et al. 2013	□	■	□	□	□	■	■	■	□	■	□	□	□	□	■	□	□	□	□	■	■	□	□
	Bauer et al. 2017	■	■	□	□	□	■	■	□	□	□	■	□	□	■	□	■	□	■	□	□	■	□	■
	Despeisse et al. 2012a	□	■	□	□	□	■	■	■	□	■	□	□	□	□	■	□	□	□	□	■	■	□	□
	Despeisse et al. 2012b	□	■	□	□	□	■	■	■	□	■	□	□	□	□	■	□	□	□	□	■	■	□	□
	Herrmann et al. 2009	□	■	□	□	□	■	■	■	□	■	□	□	□	□	■	□	□	■	■	■	■	□	□
	Hopf et al. 2016	■	■	□	□	□	■	■	■	□	■	□	□	□	■	□	■	□	■	□	■	■	□	□
	Plehn et al. 2015	□	□	□	□	□	■	■	■	□	□	■	□	□	■	□	□	□	□	□	□	□	□	□
	Schönemann et al. 2019	■	□	□	□	□	■	■	■	□	■	□	□	□	□	■	□	□	■	■	■	■	□	□
	Weeber et al. 2019	■	■	□	□	□	■	■	■	□	■	□	□	□	□	■	□	□	□	■	■	■	□	□
Factory planning	Chen et al. 2012	■	□	□	□	□	■	□	□	□	□	□	■	□	■	□	■	□	□	□	■	□	■	□
	da Piedade Francisco et al. 2010	■	□	□	□	■	□	□	□	□	□	■	□	■	■	□	□	□	□	□	□	□	□	□
	Hartkopf 2013	■	■	□	□	□	■	□	□	■	□	■	□	□	■	□	■	□	■	■	□	■	□	□
	Harun et al. 2011	■	■	□	□	□	■	□	□	□	■	□	■	□	□	■	□	□	■	□	■	■	□	□
	Hawer 2020	■	□	□	□	□	■	□	□	□	□	■	□	□	■	□	□	■	□	■	□	■	□	■
	Herrmann et al. 2009	■	□	□	□	□	■	□	□	■	□	□	■	□	■	□	■	□	□	□	□	□	■	□
	Lübkemann 2016	■	■	□	□	□	■	□	□	■	□	■	□	□	■	□	□	□	■	□	□	□	■	□
	Pohl 2013	■	■	□	□	■	■	□	□	■	□	■	□	■	■	□	■	□	□	■	□	■	□	■
	Schmidt 2021	■	■	□	□	□	■	■	■	□	■	□	■	□	□	■	■	□	■	■	■	■	□	□
	Stahl et al. 2013	■	■	□	□	□	■	■	■	□	■	□	■	□	□	■	■	□	■	■	■	■	□	□
	Wulf 2011	■	■	□	□	□	□	□	■	■	□	■	□	□	■	□	■	□	■	■	□	□	■	■
Evaluation	Brieke 2008	■	□	□	□	□	■	□	□	□	□	■	■	□	■	□	■	□	□	■	□	■	■	□
	Dreier, Wehking 2016	■	■	■	□	■	□	■	■	□	■	□	□	□	□	□	■	□	□	■	□	■	□	□
	Favi et al. 2016	□	■	□	□	□	■	■	■	□	■	□	■	□	□	□	■	□	□	□	■	■	□	□
	Gebler et al. 2020	■	■	■	□	□	■	■	■	□	■	□	■	□	■	□	■	□	□	□	■	■	□	□
	Götze et al. 2013	■	■	□	□	□	■	□	□	□	■	□	□	□	□	□	■	□	□	■	□	■	□	■
	Heinemann et al. 2013	■	■	□	■	■	■	■	■	□	■	□	■	□	□	□	■	□	□	■	■	■	□	□
	Heinemann et al. 2014	□	■	□	■	□	■	■	■	□	■	□	□	□	□	■	□	□	■	■	■	□	■	□
	Herrmann et al. 2011	□	■	□	□	■	□	□	■	□	□	□	□	■	□	■	□	□	■	■	□	■	□	■
	Kampker et al. 2013	■	■	□	□	□	□	■	□	□	□	■	□	□	□	□	■	□	■	■	□	■	□	■
	Mersmann 2015	■	□	□	□	□	■	■	■	□	□	□	■	□	■	□	□	□	□	■	■	□	■	□
	Mostert 2007	□	■	□	□	□	■	□	□	■	□	□	□	□	□	■	□	□	■	■	■	■	□	□
	Müller et al. 2018	□	■	□	□	□	□	□	■	□	■	□	■	□	□	□	■	□	□	■	■	■	□	□
	Nielsen et al. 2016	□	■	□	■	■	■	■	■	□	■	□	■	■	■	□	■	□	□	■	■	■	□	□
	Niggeschmidt et al. 2010	□	■	□	□	□	□	□	■	□	■	□	■	□	□	□	■	□	□	■	■	■	□	□
	Osten-Sacken, D. 1999	■	■	■	□	■	□	□	■	□	□	□	□	□	□	□	■	□	□	■	□	■	□	□
	Roda et al. 2019	■	■	■	□	■	□	■	■	□	□	□	□	□	□	□	■	□	□	■	□	■	□	■
	Sihag et al. 2019	□	■	□	□	□	■	□	□	■	■	□	■	□	□	□	■	□	□	□	■	■	□	□
Life cycle management	Greitemann et al. 2015	□	■	□	□	■	■	□	□	□	□	□	□	■	■	□	□	■	■	■	□	■	□	■
	Herrmann et al. 2007	■	■	□	■	□	■	□	□	□	□	□	■	■	■	□	□	□	■	■	■	□	■	□
	Koch et al. 2014	□	■	□	□	■	■	□	□	■	□	□	□	■	■	□	□	□	□	□	□	□	■	□
	Plehn et al. 2015	□	■	□	□	■	■	□	□	■	□	□	□	■	□	■	□	□	■	□	□	□	■	□
	Schönmann et al. 2016	□	■	□	□	■	■	□	■	■	□	■	□	■	■	□	□	□	□	□	□	□	■	□
	Schönmann et al. 2017	□	■	□	□	■	□	□	■	□	□	□	□	■	■	□	□	■	■	■	□	■	□	■
	Schönmann et al. 2018	□	■	□	□	■	■	□	□	■	□	■	□	■	■	□	□	■	■	■	□	■	□	■
	Stahl et al. 2013	□	■	□	□	□	■	□	□	□	□	□	□	■	□	□	□	■	■	□	□	■	□	■
	Zaeh et al. 2010	□	■	□	□	■	■	□	□	■	□	■	□	■	■	□	□	□	□	□	□	□	■	■

Fig. 7. Comparative assessment of relevant research approaches.

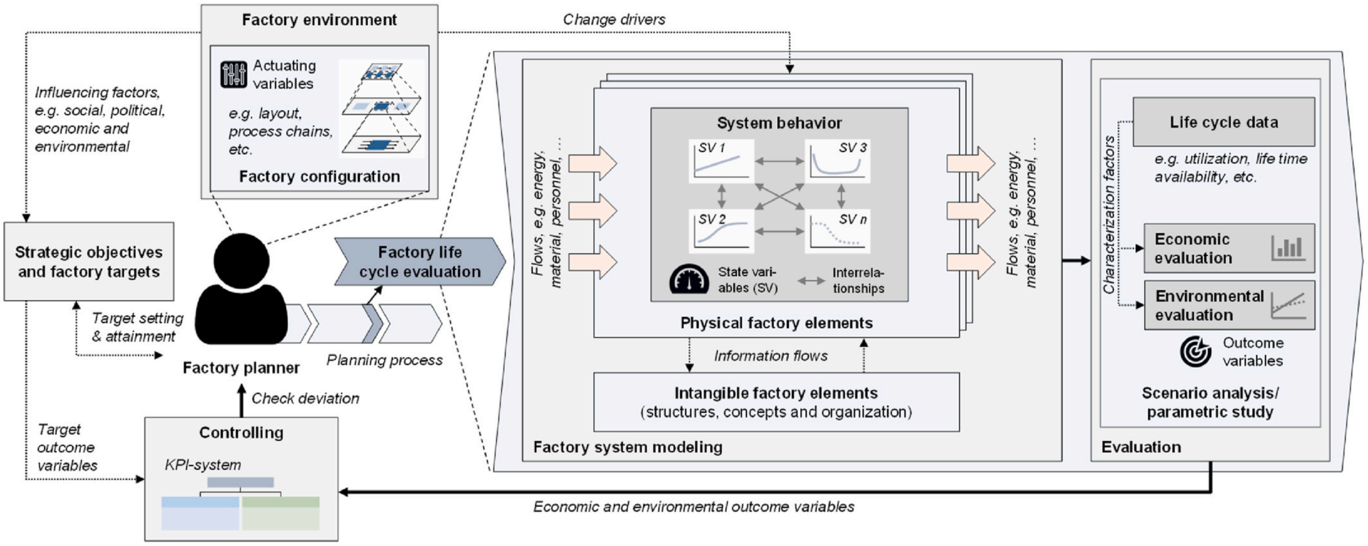


Fig. 8. Framework for the model-based evaluation and engineering of factory life cycles.

increasing observation period. Greenfield and brownfield planning projects are equally addressed. Considering the uncertainties and the high variability of change drivers, the goal is not to calculate costs and the environmental impact of a factory on an exactly precise scale. The motivation is rather to enable a directionally reliable forecast of the expected economic and environmental performance in given scenarios, which is expected to support decisions during factory planning. The framework follows the logic of a control loop, where the factory planner compares the results with strategic objectives. If deviations are noticed, a new factory configuration with adjusted actuating variables can be analyzed. Generally, the framework can be applied iteratively at different phases of the factory planning project. Earlier engineering phases are characterized by a higher planning freedom and more fuzzy information. More advanced planning phases present in contrast detailed information and less decision space. At the same time, there is a higher data collecting and modeling effort as well as an increasing model complexity. Consequently, the detail level of the underlying models and the result quality also varies.

5.2. Factory system modeling

The purpose of factory system modeling is to model the system behavior over time. To this end, knowledge about the system elements, their interrelationships and external influencing factors is required. Given the complexity of an entire factory system, it needs to be broken down to manageable factory elements. To this end, an existing decomposition of the factory system in factory levels and design fields and corresponding factory elements has been adapted (Dér et al., 2021 based on Heger, 2006). The adapted factory system decomposition differentiates between the factory levels of workstation, section and factory. Furthermore, the formative structure has been complemented by considering the design fields of human and product next to technology, organization and space. In the course of the adaptation, the constituting factory elements were adjusted, as well. Factory elements without added value for the life cycle evaluation were discarded or combined where applicable. At the same time, new life cycle relevant factory elements were included, e.g. human workforce or the production program. An overview of the final adjustments is made in (Dér et al., 2021). Besides the assignment to factory levels and design fields, factory elements are classified as physical or intangible factory elements. In addition to a material representation on the shop floor, physical factory elements (e.g. production machines, TBS, etc.) are directly involved in energy and resource flows. In contrast to that, intangible factory elements (e.g. the production or logistics concept, work organization, organizational structure, etc.) specify the coherence of physical factory elements, i.e. they define the relationships between physical factory elements.

Analogous to the concept of (Nielsen et al., 2016), the modeling of the system behavior of the factory system is done by describing and quantitatively modeling relevant state variables of the factory elements as well as their influences among themselves. The system behavior emerges from the interaction of the modeled elements and their aggregation up to factory level. Additionally, external influences in form of change drivers have an impact on the system behavior of single factory elements, thus on the whole factory system. In order to be able to identify and understand the turbulences in the course of the factory life cycle, an effect chain starting from megatrends over change drivers and to factory elements has been developed and discussed in (Hingst et al., 2021 based on Klemke, 2014). Change drivers can influence the state variables of factory elements and thus represent an interface for modeling the external dynamics of the factory environment on factory elements.

Deriving life cycle-oriented strategies for factory planning and operation essentially implies transparency and an understanding of the underlying life cycles and their interconnections. Fig. 9 illustrates with this regard exemplarily the heterogeneous nature of the life cycles in a factory system. The life cycles of factory elements cannot be seen independently but rather in their interweaving to other coupled life cycles. The fundamental premise for this understanding is that the product and technology life cycles are the impulse generators for the factory life cycle as a whole and the life cycle of its factory elements. On the one hand, the product life cycle (i.e. production volumes and production length) is significantly shaped by the industry sector and thus determines the frequency and impact of changing requirements on factory elements. On the other hand, the technology life cycle is coupled to innovation processes and innovation cycles. Both life cycles impact the factory system and trigger changes in factory elements. Factory elements that are directly involved in the value creation process (e.g. production machines) are most severely affected. Factory elements with a supporting function of the value creation process (e.g. technical building services) are also affected, albeit indirectly. Intangible factory elements (e.g. organizational structure) take in a coordinating position to harmonize the interaction of physical factory elements that accomplish the value creation and supporting processes. In order to respond to changing requirements, the organizational structure also has to evolve successively with the factory.

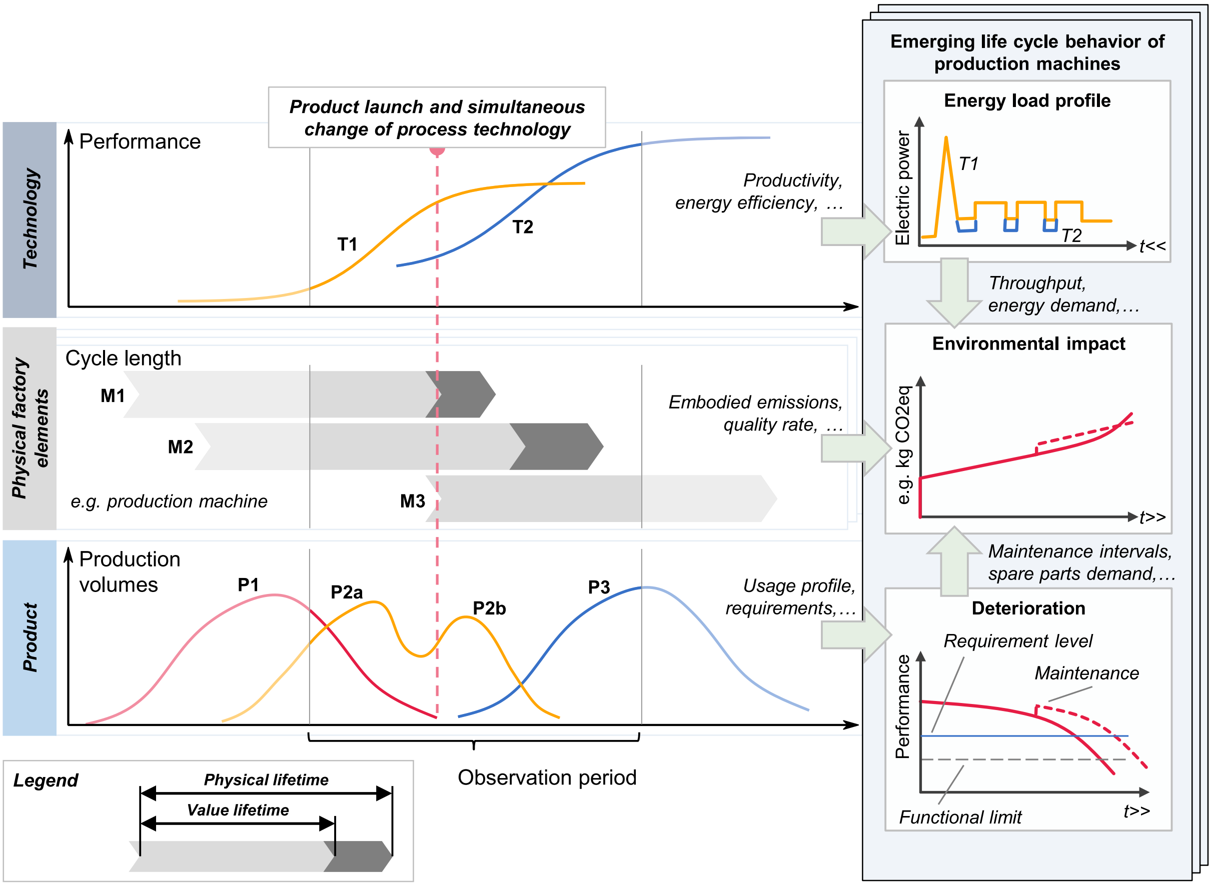


Fig. 9. Heterogeneous life cycles and emerging life cycle behavior of factory elements.

The life cycle of factory elements can be interpreted according to different conceptions. Several views and terminology has been used to describe these understandings for (generic) products, e.g. physical, value, functional, economic, legal, etc. lifetimes (Ashby, 2013; Woodward, 1997; Allwood et al., 2012; Kobayashi, 2005). With regard to changing requirements and technological developments over the long factory life cycle, the physical lifetime and value lifetime of factory elements need to be emphasized especially. Merging different definitions from literature, physical lifetime stands for the period, over which the factory element operates without a major breakdown that is beyond economic repair (Ashby, 2013; Woodward, 1997; Kobayashi, 2005). In contrast, value lifetime is rather influenced by external factors such as technology improvements or changed customer needs. Consequently, value lifetime stands for the period, where there is an actual need for the factory element in its current form (e.g. regarding performance, capacity, function, etc.) (Kobayashi, 2005).

Fig. 9 illustrates the relevance of different lifetime conceptions on a simplified example. It displays in a given observation period the impact of the product and technology life cycle on physical factory elements. At the middle of this period, a product launch (P2a → P2b) and a technology change (T1 →T2) is marked. At the same time, the predecessor product P1 comes to the end of its market cycle and thus production in this factory. The life cycle of physical factory elements (exemplified here on production machines) is aligned according to these changes. The technology change and simultaneous end of production of P1 make the machine M1 obsolete. This happens despite the fact that the physical lifetime of M1 is not over yet, however, due to these changes, its value lifetime in this factory configuration ends (end-of-use instead end-of-life). The technology change in this illustrative example also implies a shift in the productivity of the production machines. This results in a transition period, when the productivity of the new technology T2 is below of the productivity of T1. However, after this transition period, T2 outperforms T1, which again reduces the need for production machines (M2 in this case). Consequently, the machine M2 also becomes obsolete, when the production of P2b comes to an end and the production of P3 takes up.

Fig. 9 displays on the right hand side exemplarily the emerging life cycle behavior of factory elements on the case of a production machine. As illustrated, the environmental impact of the production machine is subject to different influencing factors. Machine-specific variables, such as its embodied emissions (from raw materials and production stage of the machine) and the machine's interaction in the factory system with the life cycle of other factory elements collectively form its emerging environmental impact. The product life cycle defines production volumes and therefore the usage pattern and also requirements on the machine. This leads to an aging behavior of the machine and a performance declines due to deterioration, e.g. wear, fatigue, overloading. In order to preserve the performance of the machine and to extend its physical lifetime, maintenance is required. Maintenance activities and spare parts also contribute to the machine's environmental impacts in its use stage. Another important factor that defines the use stage environmental impact of a production machine is its energy demand. Next to the usage intensity, which is influenced from the product life cycle, the innovation cycle of the production technology (e.g. regarding productivity and energy efficiency) play an important role. For example a new production technology may decrease the electric base load of a machine (switch from T1 to T2 in Fig. 9), which will result in lower total energy demand and corresponding environmental impacts. As another example, continuous energy efficiency improvements over the machine's life cycle would led to a steadily flattening curve of its environmental impact.

5.3. Evaluation

The evaluation module of the framework structures the modeling results from factory system modeling, condenses life cycle data to decision relevant outcome variables and forwards them to the comparison with the target system within controlling. As discussed previously, the meta-goal of the factory is shifting from solely economic efficiency to an absolute understanding of environmental sustainability. Fig. 10 shows how sustainability dimensions can be embedded in a target system. The strategic targets on corporate level provide the target values for factory planning. They form the basis for the control loop in factory planning and serve as threshold, which under- or overrun is checked during controlling. The formal targets of the factory regarding the sustainability dimensions are derived from the strategic targets on company level. Content targets are placed below the formal targets and consist of the target fields of a factory (Wiendahl et al., 2015). They cannot be influenced directly, but are determined indirectly through the design of factory elements. The design of factory elements is essentially oriented at the content targets and contribute indirectly to the formal factory targets of economic, environmental and social sustainability. The target system can be interpreted both ways: deriving targets from higher level objectives and controlling target attainment on underlying layers.

External and internal change drivers influence the target system on different levels. Change drivers lead top-down to a shift in the strategic targets and thus in the formal targets of the factory, e.g. due to changed market conditions or societal pull. Change drivers also influence factory elements bottom-up, which affects their life cycle behavior during operation and consequently also the target achievement. On this basis, a distinction is made between process and element drivers and target drivers (Klemke, 2014). Process and element drivers, e.g. new process technology for large-scale production, directly influence the changing state of the factory elements over their respective life cycles. When process and element drivers occur, the behavior of the factory element changes, influencing the formal targets bottom-up. Target drivers, e.g. increasing awareness for absolute environmental sustainability, on the contrary have an effect on strategic targets. When target drivers occur, strategic and in the end content targets have to be reprioritized. If a factory configuration cannot meet the reprioritized targets, a factory planning process must be initiated and the life cycle of the factory configuration in its current form comes to an end. For example, in the case of a production ramp-up of a new product or scarcity of resources, the factory must be adjusted to the new general conditions.

In order to estimate the target achievement of a factory configuration over the life cycle, a performance measurement system is intended to make the formal goals measurable by means of outcome variables (Fig. 11). The overarching goal of the performance measurement system is factory sustainability, which primarily includes economic and environmental sustainability. For the sake of completeness, the social aspect of sustainability is highlighted also, but not further addressed as out of scope from the intended framework. The performance measurement system further differentiates between the planning and the operation life cycle stage of a factory. The data basis of the evaluation is based on life cycle data, which is collected during factory system modeling and divided into aging and technical performance indicators and well as material and energy flows. The data is transformed with the help of characterization factors to economic and environmental outcome variables. Since the focus of factory system modeling lies on the operation stage of a factory, it can only provide data for the operation stage. For evaluating the planning stage, a reference is made to existing methodologies like product and building LCA's and the economic calculation of factory planning projects developed in (Brieke, 2008). Within the economic perspective, only payments are considered, so that all variables must have a payment reference. This means that depreciation or changes in capital commitment costs, for example, are not included as a direct factor, as they do not relate to payments. The payment types during the planning stage include payments for planning and acquisition as well as

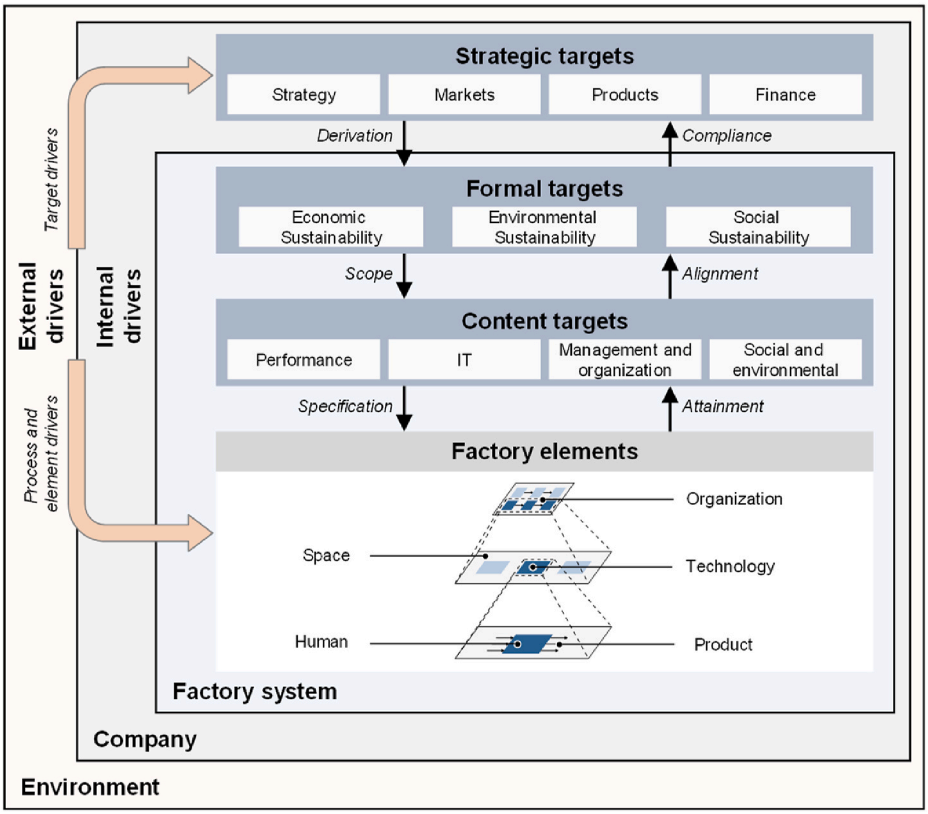


Fig. 10. Extended target system of a factory for the developed framework.

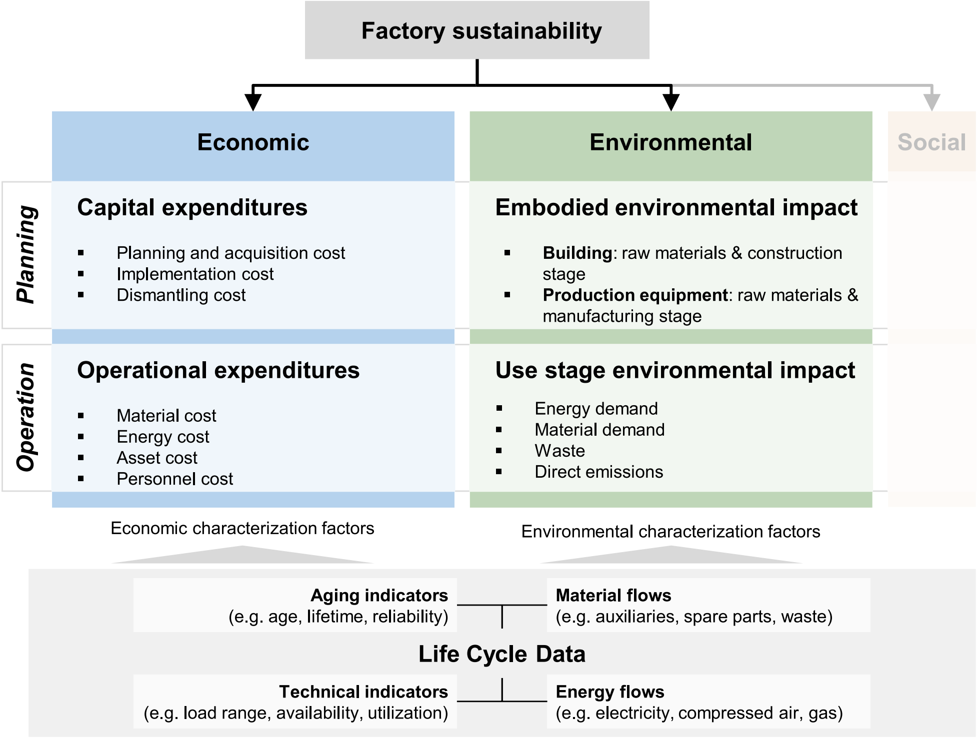


Fig. 11. Performance measurement system for the life cycle evaluation of factory systems.

for implementation and dismantling of fixed assets. Payments during factory operation cover material, energy, asset and personnel costs. The environmental evaluation considers arbitrary impact categories, e.g. global warming potential. The impact categories are chosen based on the formal targets of the factory. The environmental impact during the planning stage considers the initial impact of the factory configuration at the beginning of its operation stage. This includes embodied emissions from raw materials and the construction process of the factory building as well as the embodied emissions from the raw materials and the manufacturing life cycle stage of the production equipment. The environmental impact during factory operation is the result of the underlying energy, material and waste flows as well as direct emissions resulting from the value creation and auxiliary processes as well as from the building itself.

Within the evaluation, different scenarios can be analyzed by means of a parametric study. The underlying goal is to better understand cause-effect relationships and the main drivers for factory sustainability, thus increasing the forecast quality for a directionally reliable evaluation. By taking uncertainties and variability of change drivers into account, the robustness of the investigated factory configuration is checked with respect to its target fulfillment. The parametric study can be done in two ways: analyzing different factory configurations in the same life cycle scenario or analyzing the effect of different life cycle scenarios on a given factory configuration. Here, the factory life cycle model serves as a forecast to confirm the alignment of a given planning variant and operation scenario to the formal targets of factory planning. Either way, the factory life cycle model serves as a decision support for the selection of factory planning variants and shows corresponding need for action, if certain targets are not achieved.

6. Conclusion and outlook

Motivated by a strong need for a fast transition towards environmental sustainability, factory planners are increasingly forced to incorporate an environmental perspective next to traditional criteria into the planning process. Taking in a holistic life cycle perspective has a particularly high relevance in case of new factories, since their planned life cycle spans several decades. But also the replanning of existing factories should not be underestimated in light of their high number in industrialized countries. Here, prevailing circumstances and the heterogeneous life cycles of the existing factory elements and thereof emerging limitations (e.g. smaller design freedom and shorter remaining life of factory elements) need to be handled. This paper reviewed and merged existing life cycle concepts of factories into a common understanding and discussed action areas of life cycle engineering to supplement factory planning. After identifying obstacles and requirements for a life cycle oriented approach for supplementing factory planning and operation, approaches for the methodological support of factory planners were reviewed in this context. Addressing the derived research need, a conceptual framework for the integrated, model-based evaluation and engineering of factory life cycles was developed. The objective of the framework is to provide decision support by comprehending the dynamics within the factory life cycle and allowing to link engineering decisions to the environmental and economic performance of a factory system.

While the proposed framework discusses life cycle orientation during factory planning and operation in greater detail than previous approaches, the conceptual development is not exhaustive and a practical implementation is pending. The outlined concepts and ideas serve to illustrate the importance for developing methods and tools to support life cycle oriented factory planning and operation. Further research should address several open issues when detailing and operationalizing the framework:

- What are relevant interrelationships between factory elements that need to be modeled over the life cycle?
- Which modeling principles and abstraction levels need to be applied to ensure comprehensiveness and a directionally reliable evaluation in a broad range of factories?
- How to synthetize the life cycle oriented approach in the generic procedure model of factory planning?

- What are appropriate methods and tools to address uncertainties and the variability of influencing factors?
- How to communicate the results to factory planners and factory operators?

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Antal Dér: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization. **Lennart Hingst:** Conceptualization, Methodology, Writing – original draft. **Peter Nyhuis:** Conceptualization, Funding acquisition, Writing – review & editing, Supervision. **Christoph Herrmann:** Conceptualization, Funding acquisition, Writing – review & editing, Supervision.

Declaration of competing interest

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