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PRODUCTION MANAGEMENT

Concept for modeling and quantitative evaluation of life cycle dynamics in factory systems

Antal Dér[1] · Lennart Hingst[2] · Peter Nyhuis[2] · Christoph Herrmann[1]

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Abstract

Against the background of the climate crisis, fast innovation space in emerging technologies and the global competitive environment for manufacturing companies, a sound understanding of the life cycle behavior of factory systems becomes more and more important. The decision context of the factory life cycle conveys a high level of complexity, e.g. by the heterogeneous nature of factory element life cycles, manifold interactions between them as well as external change drivers. A model-based understanding as well as methods and tools are required that support factory planners and operators in this regard. This paper presents an approach for the modeling and quantitative evaluation of life cycle dynamics in factory systems while respecting the dynamic behavior of factory operation, as well. The purpose of the modeling is to deepen the knowledge of the prevailing life cycle mechanisms and their implications for factory planning and operation. The application of the approach is demonstrated in an exemplary case study.

Keywords Lifecycle · Factory · Evaluation · Planning

1 Motivation and background

Environmental targets such as the reduction of greenhouse gas emissions are increasingly drawing attention alongside the traditional corporate targets of cost, time and quality in manufacturing [1]. In order to positively influence the economic and environmental performance of factories, a life cycle perspective is required in planning and operation [2, 3]. In order to cope with the emerging complex decision situation of the factory life cycle, methods and tools are required for describing the factory life cycle, understanding the inherent interrelationships and evaluating the life cycle performance of factories. However, as a recent review in the context of factory life cycle engineering of the authors reveals, existing methods and tools in this context often focus only on single aspects of the factory life cycle and fail to provide a consistent methodology for quantitative factory life cycle evaluation, thus for an efficient decision support for factory planners and operators [4]. To close this gap and deepen the knowledge about the life cycle behavior of factory systems, a methodology for quantitative factory life cycle evaluation is proposed.

Acknowledging the complexity of the decision situation, a factory life cycle understanding is presented first, which acts as the theoretical foundation for the developed approach (Fig. 1). The figure differentiates between the operational (Part A) and the life cycle dynamics (Part B) in a factory system. Additionally, Fig. 1 also frames the evaluation of research approaches in this field in Table 1. The operational dynamics, i.e. the interaction of the main factory subsystems and the resulting dynamic energy, material and media flows as well as their effect on the environmental performance have been described in [5] and used in different planning and evaluation methods since then, e.g. [6–10]. The concentrically aligned rings in multiple layers around the factory system (Part B of Fig. 1) represent the factory life cycle. The layers represent the life cycles of the main factory elements: building, technical building services (TBS), production machines and the products. The corresponding life cycles are characterized by different cycle lengths and are connected

✉ Antal Dér
a.der@tu-braunschweig.de

[1] Chair of Sustainable Manufacturing and Life Cycle Engineering, Insitute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig, Langer Kamp 19B, 38106 Brunswick, Germany

[2] Institute of Production Systems and Logistics, Leibniz University Hannover, An Der Universität 2, 30823 Garbsen, Germany

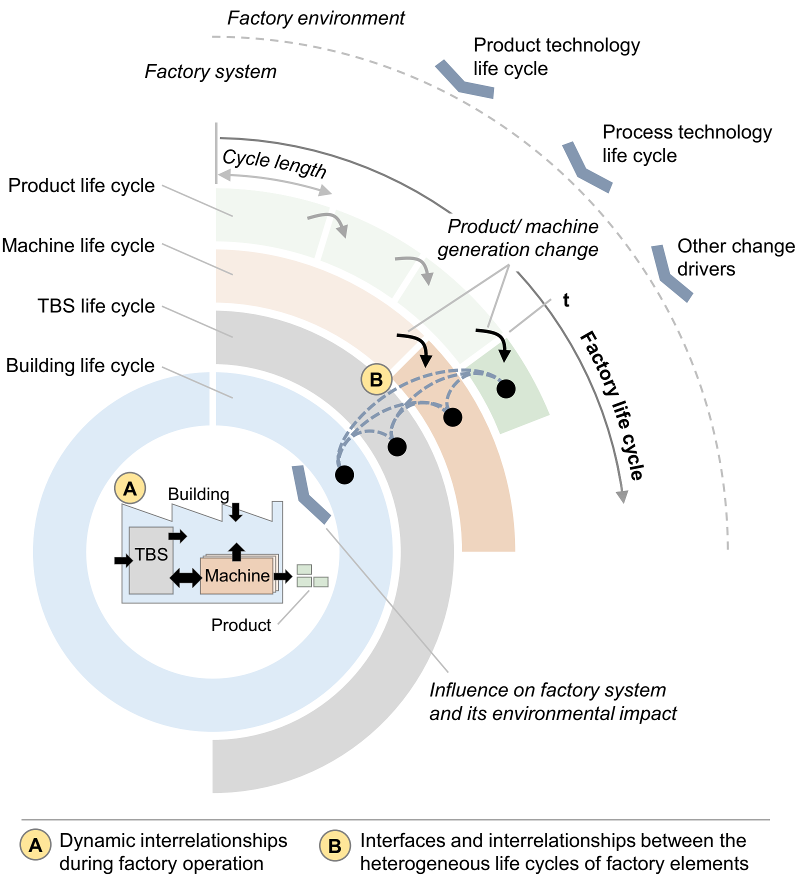


Fig. 1 Layer model of the factory life cycle focusing on life cycle and operational dynamics in a factory system

Table 1 Comparative evaluation of research approaches

		[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[22]	[19]	[20]
Focus	Operational dynamics	Fully	Fully	Fully	Fully	Fully	Fully	Not	Not	Not	Not	Not	Not	Not	Not	Not	Not
	Life cycle dynamics	Not	Not	Not	Not	Not	Not	Not	Partly	Partly	Partly	Partly	Partly	Partly	Partly	Partly	Fully
	Changeability & cyclic influences	Not	Not	Not	Not	Not	Not	Fully	Fully	Partly	Partly	Fully	Not	Not	Not	Not	Not
Approach	Descriptive	Fully	Fully	Not	Partly	Not	Not	Fully	Partly	Not	Fully	Fully	Fully	Fully	Partly	Fully	Fully
	Qualitative	Not	Not	Not	Fully	Not	Not	Fully	Partly	Partly	Partly	Partly	Partly	Not	Not	Not	Partly
	Quantitative	Fully	Fully	Fully	Partly	Fully	Fully	Not	Fully	Partly	Not	Not	Not	Not	Not	Not	Partly
Evaluation dimension	Technical	Not	Fully	Fully	Not	Not	Not	Partly	Partly	Partly	Partly	Partly	Not	Partly	Not	Partly	Partly
	Economic	Partly	Fully	Fully	Not	Not	Partly	Partly	Fully	Not	Not	Not	Not	Not	Not	Partly	Partly
	Environmental	Fully	Fully	Fully	Fully	Fully	Fully	Not	Not	Not	Not	Not	Not	Not	Not	Not	Partly

Fully addressed   Partly addressed   Not addressed

to each other. For example, the building has a longer life cycle than TBS and the production equipment. But as the products follow an even shorter life cycle, the factory elements closer to the center need to be adapted to the new requirements of every new product life cycle. Furthermore, the factory environment also influences the life cycles inside the factory system. Notable change drivers are product and process technology cycles [11]. These interactions between the heterogeneous factory element life cycles and external change drives influence the life cycle performance of the factory system and its operational dynamics.

Approaches focusing on the evaluation of changeability and cyclic influences in the context of factory systems were described for example by [12–15]. Partly, also the life cycle dynamics are described or qualitatively assessed within this context. However, quantitative models have not yet been presented that address the life cycle dynamics inside a factory system (Part B in Fig. 1). Representative contributions with this focus are for example [16–19], which provide high-level descriptive models of the factory life cycle (e.g. progression of utility value curves over the time). The models are, however, not suitable for direct planning support, but rather aim at raising awareness for life cycle thinking. The author team has also contributed to different aspects of the factory life cycle, e.g. qualitative modeling of interdependencies for an economic and environmental evaluation [] and a conceptual framework for hierarchical factory life cycle evaluation [20]. Nonetheless, life cycle related dynamics between factory elements, their effect on the factory system and methods for their quantitative evaluation have not yet been investigated in detail.

Based on the comparative evaluation of the approaches in Table 1, the specific research gap leading to the need for this paper is that models and methods are missing to describe and to quantitatively evaluate the life cycle dynamics of a factory system from a technical, economic and environmental perspective while respecting the dynamic behavior of factory operation. Hence, the objective of this paper is to describe an approach for the quantitative modeling of life cycle dynamics in factory systems from a technical, economic and environmental perspective. Furthermore, life cycle planning of factories will be outlined. Section 2 introduces the methodological aspects for the evaluation of the life cycle dynamics. Following that, Sect. 3 gives a perspective on how the modeling results could be used for life cycle planning of factories. Finally, Sect. 4 demonstrates the application at an exemplary use case and discusses the implications for factory planners and operators.

2 Modeling process for the evaluation of the life cycle dynamics in factory systems

A multi-step modeling approach is proposed for the investigation of the life cycle behavior and the evaluation of life cycle dynamics in factory systems (Fig. 2). The purpose of the modeling is to prospectively evaluate the life cycle behavior of a given factory configuration in terms of its technical, economic and environmental performance. With respect to the manifold interdependencies and uncertainties over the life cycle, the goal is not a precise prognosis but rather the development of a sound understanding for the prevailing life cycle mechanisms and their implications for factory planning and operation. Since the decision situation of the factory life cycle introduces a considerable complexity for factory planners and operators, first the problem domain is abstracted to a factory life cycle description model. The description model distinguishes between a system perspective and a life cycle perspective. Briefly, the system perspective breaks down a factory system into five design fields and corresponding factory elements. Thereby, active factory elements are directly involved into the value creation process or other activities and connected with operational costs and environmental impact. Thus, active factory elements directly affect the life cycle behavior and will be in the focus in the following. As discussed earlier, the life cycle perspective highlights the heterogeneous nature of individual factory element life cycles and their interfaces between each other.

The modeling process is structured in three subsequent phases: see, understand and evaluate. The first two phases focus on the identification of prevailing life cycle mechanisms and their analytical modeling at the level of factory elements. The third phase aggregates the individual life cycle models at factory system level and collectively evaluates their interactions in a factory model. Thereby, the factory model also represents the operational dynamics in a simplified manner. The combined modeling of life cycle and operational dynamics allows for an evaluation of given factory configurations in terms of quantifiable performance indicators.

2.1 Identification of life cycle mechanisms

Factory systems create value by the combination of material, energy and information flows. The flows may vary over the course of the factory life cycle, as the factory is subject to certain internal and external influencing cycles. Figure 3 illustrates schematically a factory system with the corresponding design fields, input and output flows and the identified life cycle mechanisms marked in blue. These are divided into internal and externally induced mechanisms. Internal mechanisms comprise the technical ageing behavior of technical and spatial factory elements and the learning behavior of the staff. Externally induced mechanisms include the technological progress, product development and other change drivers. The technical ageing behavior expresses itself in a progressing deterioration caused by mechanical wear, material fatigue, overloading or weathering effects. The human learning behavior describes the improved performance capability of individuals or of the organization. The technical factory elements of the production system and the TBS as well as the shop-floor staff are actively involved into the value creation process. They are thus decisively responsible for the emerging energy, material and information flows and the corresponding economic and environmental indicators of factory operation. Technological progress is understood in this context as an external influencing factor, which describes the capabilities of factory elements. It unfolds its effect primarily during planning phases

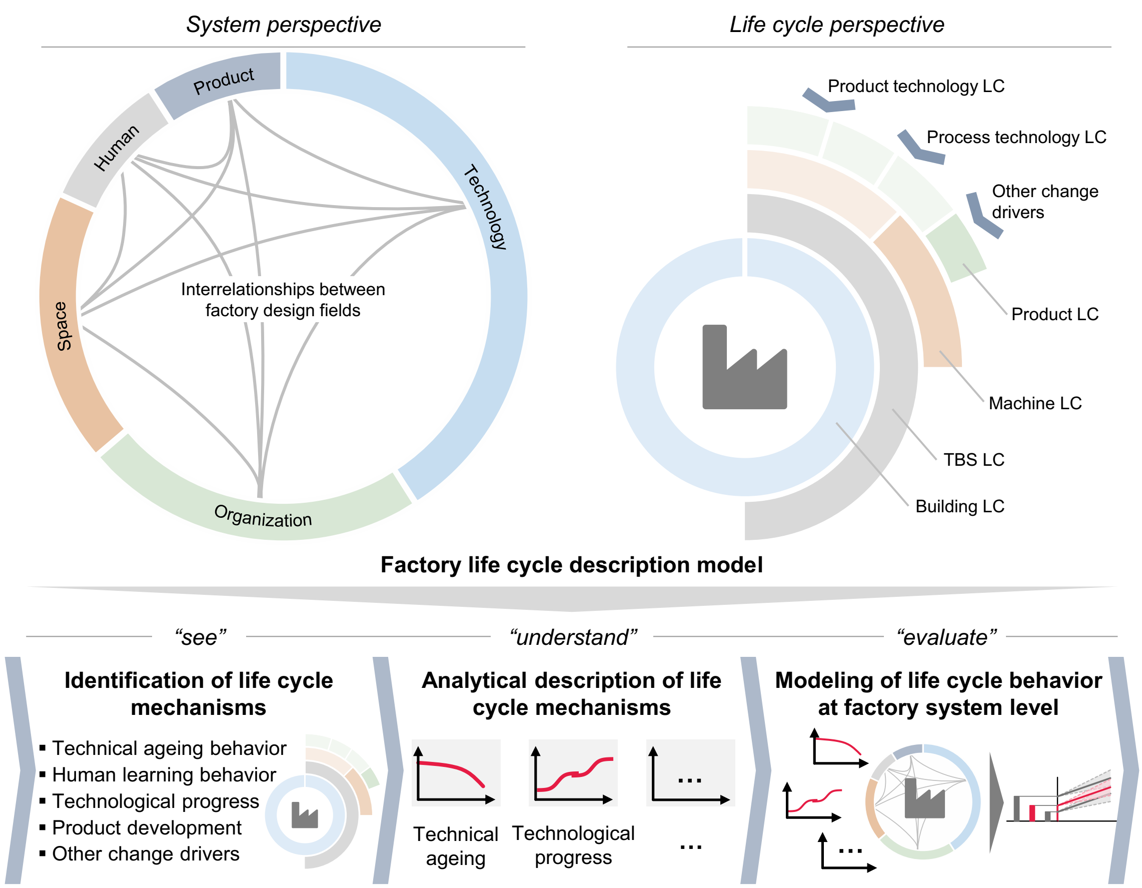
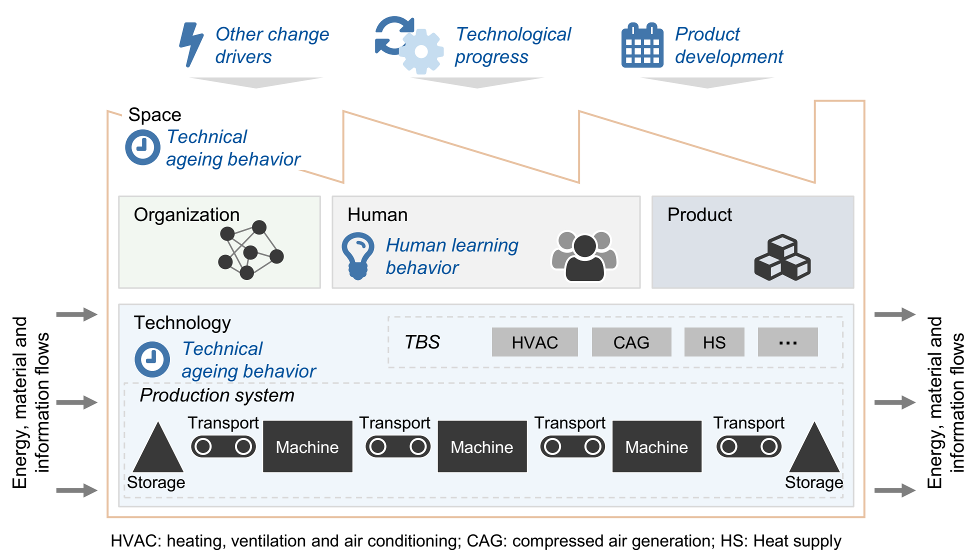


Fig. 2 Modeling process for the evaluation of the life cycle dynamics in factory systems

Fig. 3 Generic life cycle mechanisms in factory systems



and determines the degrees of freedom while planning spatial, technical and organizational factory elements. Similarly, product development is seen as an external influencing cycle, which are reflected here as new requirements for the factory as a whole as well as for single spatial, technical, human and organizational factory elements. Lastly, change drivers represent discrete events in the course of a factory life cycle that can abruptly change the boundary conditions for the whole factory and for single factory elements (e.g. stricter regulations or subsidies).

These mechanisms serve as a guide to question and understand the life cycle behavior of a given factory as well as to establish an awareness of possible effects on the economic and environmental life cycle performance of a factory. The first step in a real use case is to become aware of possible changes caused by these generic life cycle mechanisms and to estimate their impact on input and output flows at the level of single factory elements. For this purpose, the generic life cycle mechanisms need to be specified by observing and formulating hypotheses on their effects on the system state and the corresponding flows.

2.2 Analytical description of the life cycle mechanisms

In the second step, the hypotheses established before are described analytically. Figure 4 structures the life cycle mechanisms as internal or external mechanisms as well as gradual changes or discrete events. The time-dependent progression of the mechanisms is depicted either related to the performance or to the utility value of the factory element. The emerging patterns are described as evolutionary degraded or improved, revolutionary degraded or improved as well as incompatible and outdated. Furthermore, Fig. 4 classifies the patterns as challenges or opportunities. Challenges imply that the mechanism may decrease the life cycle performance (e.g. worsened key figures or a premature end of the life cycle). Opportunities describe the potential for improving the life cycle performance of the factory. In the real world, the ideal–typical patterns are not likely to appear in their pure form. Instead, a combination of them occurs, whereas depending on the current perspective one of them is predominantly prevailing and hence needs to be modeled.

The life cycle mechanisms from Fig. 4 have been formalized via mathematical functions. They can be adapted individually on factory elements. The evolutionary degrading progression describes the technical ageing behavior. The performance takes the shape of an exponential decay with a certain decay rate. The human learning behavior is characterized by an increasing growth curve of the performance, which has an upper limit and the growth rate. The pattern incompatible eventuates, when the constant performance of a factory element cannot keep up with the changed requirements. Thereby, the utility value decreases, accordingly. The progression of requirements are modeled according of an S-curve, which has a lower and upper limit as well as a growth rate. Similarly, the technological progress is modeled with multiple S-curves, whereby each of them has a horizontal and vertical offset representing the performance range of a given technology in a time window. An already utilized technology can get outdated when the same technology experiences a fast innovation pace or an emerging technology is ready to be employed. The revolutionary degraded or improved pattern is induced by other change drivers. Here, it assumed, that the boundary conditions change at a discrete event, i.e. existing conditions cease to exist or new conditions occur. Depending on the circumstances, this changes the utility value of the factory element from a start value to a fallen or risen value.

In order to integrate the life cycle mechanisms into the life cycle evaluation of factories, the patterns need to be parametrized case by case based on the prevailing circumstances and expected future developments. Furthermore, it needs to be elaborated, which system values are of interest

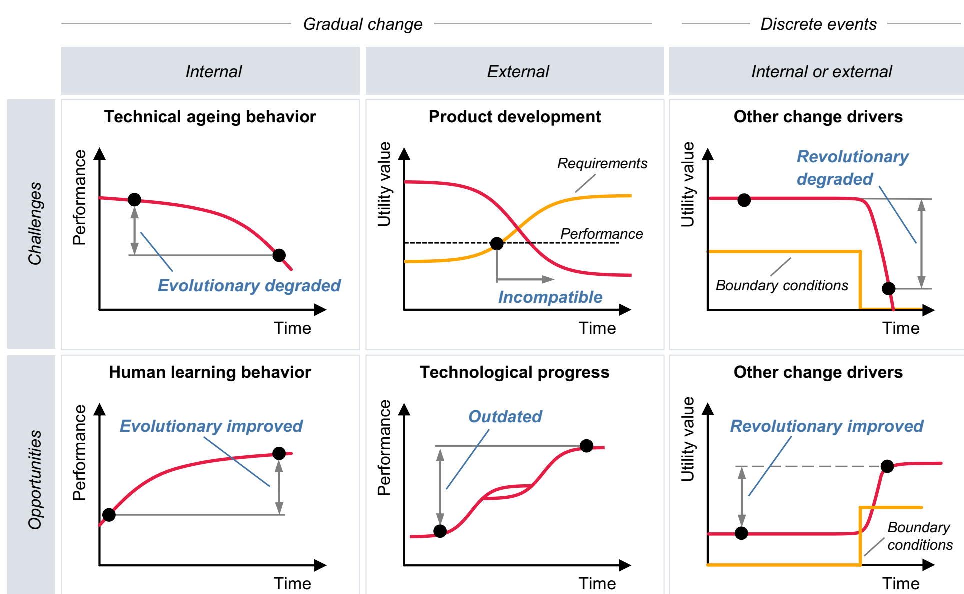


Fig. 4 Ideal–typical analytic description of the generic life cycle mechanisms

for the modeling. Depending on the goals of the analysis, a different set of system values may be relevant. Especially, system values with a direct linkage to the input and output flows (e.g. yield, quality rate or energy demand) are important for the economic and environmental evaluation.

2.3 Modeling of factory life cycle behavior at factory system level

In order to model the life cycle behavior of the entire factory, the last step brings together the parametrized models of the factory elements at system level. To this end, a generic factory life cycle model has been developed based on agent-based modeling principles (Fig. 5).

First, the existing or the planned factory system within a given system boundary is transferred to a model-based factory configuration. The main factory elements are represented in generic agents, which are adapted by adjusting parameter values. The inner logic of the agents represents the relevant energy and material flows as well as communication rules to other agents. Together, these represent the operational dynamics during factory operation. A generic factory element agent (e.g. a machine) can be used to model multiple objects of the same type (e.g. machines in a process chain), but with different parameter values and life cycle mechanisms. Thereby, the parametrized functions of the respective life cycle mechanisms represent the life cycle dynamics of a factory system. Consequently, the parametrized factory system configuration gives a snapshot of the factory in its current life cycle state. Afterwards, factory operation is simulated by the interaction of the agents. The model logic is inspired from previous approaches focusing on the operational dynamics [7]. Starting point for the modeling is a production program, which is subsequently translated into equipment utilization as well as usage intensity on the level of each factory element. The energy and material flows are computed on an hourly basis. Thereby, the energy-oriented interrelationships between the main factory elements are balanced based on supply and demand to and from other connected factory elements. The life cycle state of the factory elements and the progression of the life cycle mechanisms is updated according to their usage intensity.

Different visualization methods help to analyze the factory system in a given scenario before, during and after a simulation study. Before conducting a simulation study, an interactive chord diagram was developed to analyze, explore and better understand the interrelationships between the factory elements. During the simulation run, every factory element has a graphical interface that displays the most important performance indicators as well as their progression over time. After the simulation was finished, special-purpose diagrams that are partially

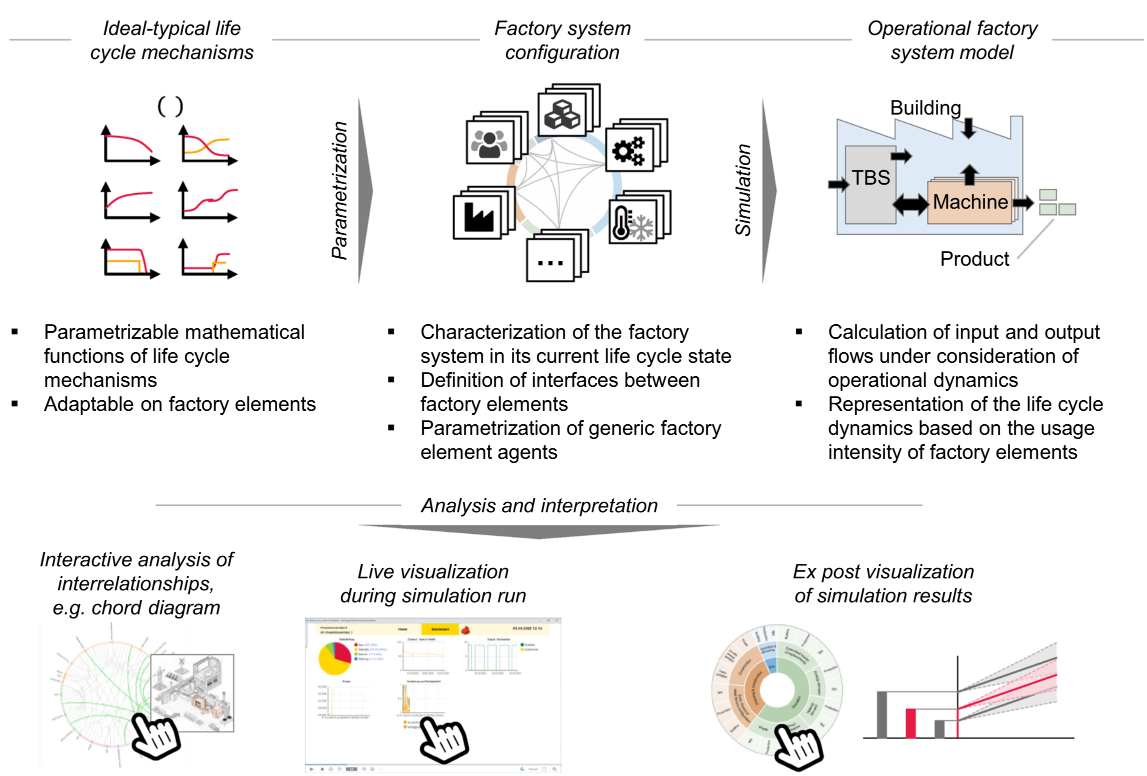


Fig. 5 Structure and prototypical implementation of the generic factory life cycle model

interactive allow for gaining a differentiated perspective on the economic and environmental life cycle behavior of the factory system. An example of this is an interactive sunburst diagram that displays the total life cycle environmental impacts of the factory system at different abstraction levels.

The agent-based modeling technique enables a modular and extendable model structure. Accordingly, other expert models, e.g. a detailed HVAC simulation, could be coupled with the factory life cycle model. Such model coupling is beneficial in studies with an emphasis on specific factory elements and their interactions.

3 Towards strategic life cycle planning of factory systems

The aggregation of the factory element life cycles regarding their technical, economic and environmental performance results in the life cycle behavior of the whole factory system. Strategic life cycle planning needs to comprehend the life cycle dynamics and design as well as operate a factory in accordance with them. As already discussed earlier, the qualitative curves of the utility values based on 17 represent a technical perspective on the lifetime of factory elements. Building up on the considerations from the previous sections, it seems to be reasonable to differentiate between different perspectives on the lifetime of factory elements. Lifetime definitions of products in general are provided in [22–25]. In the context of a factory system, the value, physical, economic and environmental lifetime give an adequately sophisticated perspective and are defined as follows:

Value lifetime: A period with an actual need for the factory element, when it is able to fulfil the imposed requirements.

Physical lifetime: A period, when the factory element operates without a major breakdown that is beyond economic repair.

Economic lifetime: A period, when the factory element has less life cycle costs than a comparable alternative. The comparison is based thereby on the whole life cycle including initial, running (energy, maintenance, labor, etc.) and disposal costs.

Environmental lifetime: A period, when the factory element has less life cycle environmental impact than a comparable alternative. The comparison is based thereby on the whole life cycle including raw materials, manufacturing, operation and end of life.

The definition of the lifetime of factory elements gives a frame for the economic and environmental evaluation. In doing so, the corresponding performance indicators such as the total costs or global warming potential can be calculated for each interval. Thereby, the economic and environmental performance of factory element life cycle can also be described by ideal–typical curves. In this regard, Fig. 6 exemplarily depicts the environmental performance of an active factory element at four life cycle scenarios. The logic of the description of the environmental performance can be adapted to the cost curves analogously. The curve follows in the base scenario a linear progression with an initial offset representing the embodied emissions. The slope of the curve depends on the specific environmental impacts of the usage, i.e. energy and material intensity, utilization as well as external factors such as the specific impacts of the energy system. Maintenance and repair events are associated with additional impacts, increase, however, the physical lifetime. Similarly, a retrofit has an environmental burden, as well. However, it has the potential do decrease the slope of the curve. Finally, a replacement incurs entirely new initial embodied impacts, which are considered in the cumulated curve.

Studying the ideal–typical economic and environmental curves together with the life cycle mechanisms in an integrated manner allows for the analysis of projected as-is and

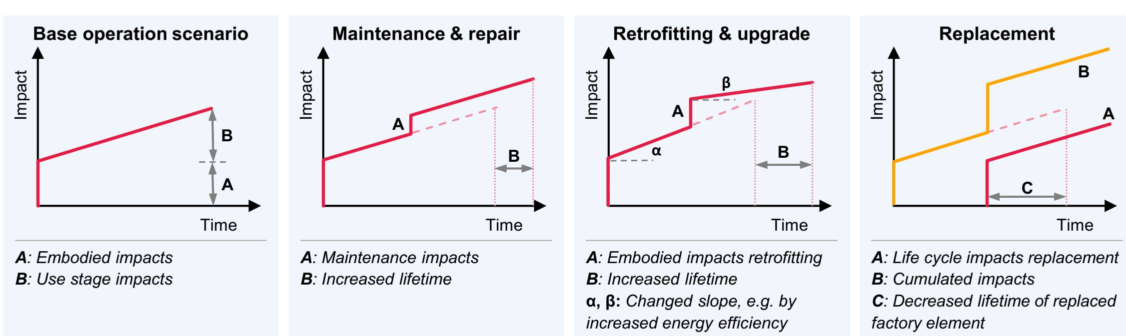


Fig. 6 Ideal–typical environmental performance of active factory elements at four life cycle scenarios

hypothetical what-if scenarios. This is exemplarily demonstrated in Fig. 7 on the case of an energy efficiency retrofit. The improvement of the power demand of the machine tool is described analytically with the logistic function (commonly referred to as the S-curve). For this example, it is assumed, that the electric power demand during the processing state $P_p(t)$ is improved, all other parameters remain constant. The comparison is limited to the electricity demand and thereof resulting environmental impacts. Furthermore, the retrofit has a constant embodied impact, regardless of the point in time, when it is implemented. First, (1) the point in time t_m is determined, when the expected improvement m is available. Subsequently, (2) the slopes k_0 and k_1 are determined, which describe the machine tool operation before and after the retrofit. Thereby, the slope considers the global warming potential of the supplied electricity and the dynamic energy load profile of the machine tool, i.e. processing as well as standby energy demands and the utilization of the machine tool. Finally, (3) the environmental advantageousness is checked over the value lifetime. This condition is met, when the environmental impacts of the retrofit scenario are lower than that of the base scenario during the value lifetime.

Although this is a rather simple example, it demonstrates how the logic can be applied to life cycle planning of factory systems. The current example demonstrated the case, when the improvement rate of the energy efficiency was given. Instead, the modeling can also be turned around, when required improvement rates are determined for the technology life cycle that are needed to achieve an expected improvement of the life cycle performance of the factory system. Both perspectives are beneficial for factory planners and operators.

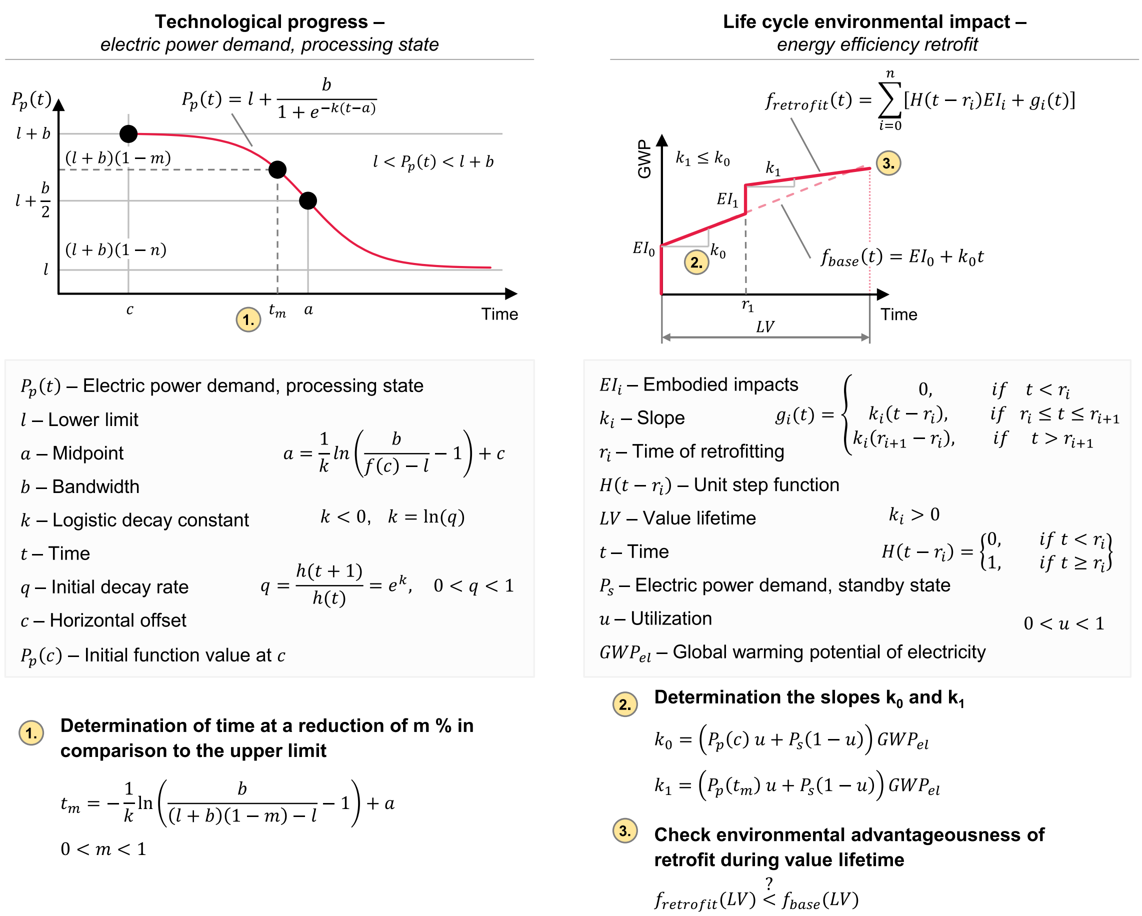


Fig. 7 Integrated evaluation of life cycle mechanisms in life cycle scenarios—example of energy efficiency retrofit and its life cycle environmental impact

4 Exemplary application

The approach has been exemplary applied based on data from an industrial crankshaft production line in an automotive factory. It serves merely the demonstration of the applicability, thus refrains from a detailed investigation of the whole factory. The case study investigated theoretically the effects of replacing an old machine on the performance of the process chain. Figure 8 (A-K) illustrates the key results. The production line consists of 17 process steps with altogether 22 interlinked production machines. First, an energy value stream was set up to gain an overview of the involved processes, their utilization and respective energy demands. The line balancing as well as the process chain structure is illustrated in Part A of the figure. Taking a look at the age distribution of the machines in Part C, it becomes apparent that a few machines exceed the average age by far. In the following, the oldest machine, which is placed at process step 20 is analyzed in detail. Based on field data from other process chains, the S-curves of the electric power demand and the output were parametrized and their values predicted for the year 2022 (Part D and E). These were used to parametrize the simulation model, which computes the energy demand (Part G) in processing and standby machine states. The comparison of the simulation results of the initial process chain configuration with measured data showed a high accordance with the actual output and energy demand. Altogether, the energy demand per part could be decreased by 9%. However, the

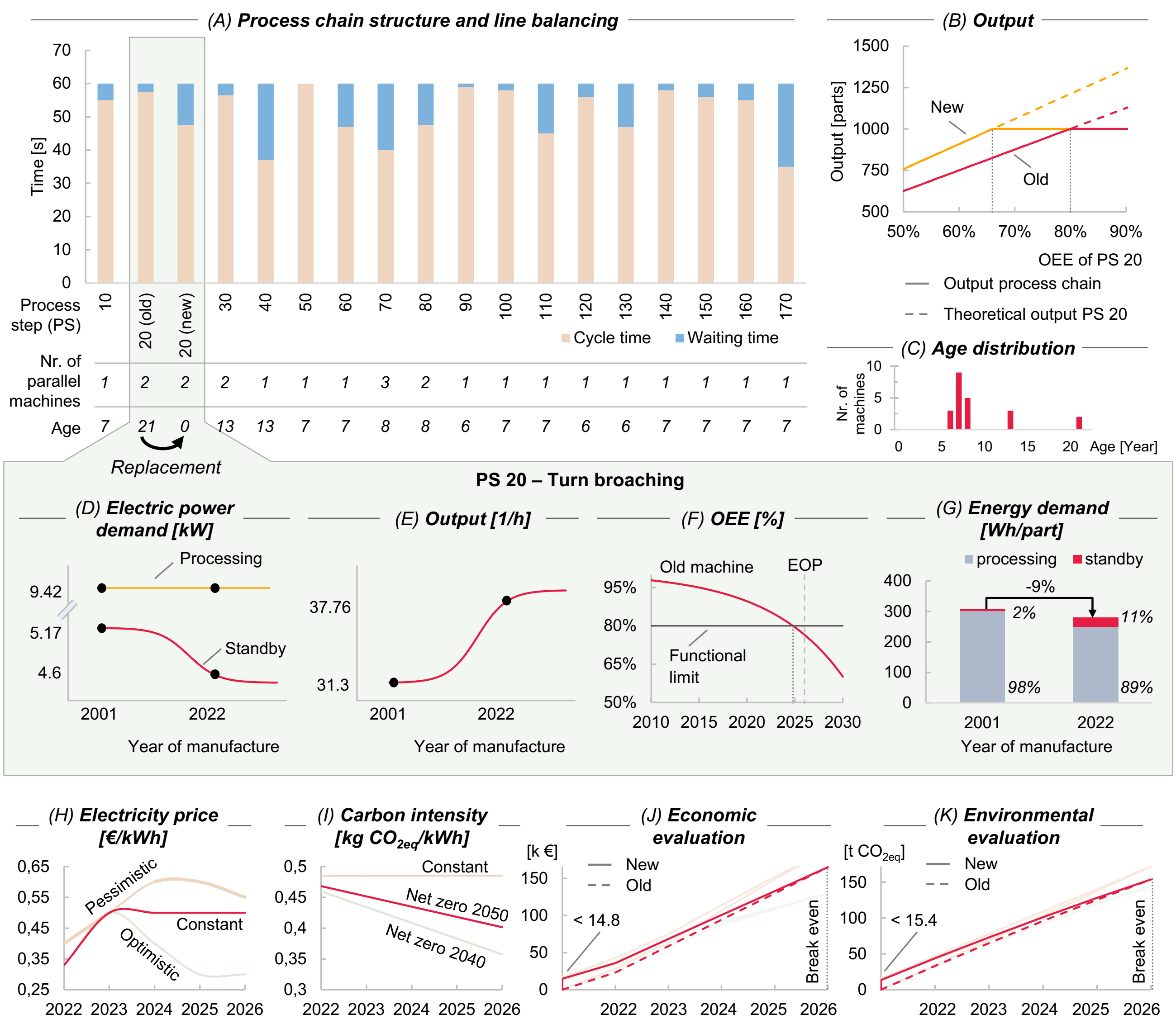


Fig. 8 Results of the exemplary application

increased output of the machine does not improve the output on process chain level. This is due to the interlinked machines and the fact that the process step 20 was not a bottleneck process.

When the technical ageing behavior of the machine is reflected on the overall equipment effectiveness (OEE) and predicted for the coming years, another trend is observed (Part F and B). Part B outlines the output on machine and process chain level depending on the OEE of the of process step 20. Extrapolating the trend of the OEE degradation (Part F) and assuming that no other improvement measures are taken, the OEE is expected to reach a limit of 80% before 2025. Below this limit, this machine slows down the whole process chain. This is insufficient, since the end of production is set to be in 2026.

Whether a replacement or an upgrade is economically or environmentally advantageous over the remaining value lifetime (Part H–K) is investigated with a scenario-based modeling of electricity prices and the carbon intensity of electricity as external influencing factors. It is assumed that a break even point is reached latest at the end of 2026. Following that, thresholds are determined that cannot be exceeded by the initial costs and environmental impact. Even if, no exact data is available for the necessary investments and the embodied impact of a new machine, the thresholds give a frame for the evaluation and thus serve as a decision support.

5 Conclusion and outlook

Next to the product life cycle, the evaluation of the factory life cycle becomes more and more important for reaching environmental targets. Therefore, an approach for the quantitative modeling of life cycle dynamics in factory systems was presented and strategic life cycle planning of factories was outlined. This supports factory planners and factory operators in assessing factory configurations and planning decisions over their life cycle. An exemplary case study illustrated how the approach could be put into practice. The application of the approach is especially relevant in brownfield planning projects, which are characterized by existing structures, heterogeneous factory elements and their interrelationships, which together affect the operational, economic and environmental performance at factory level. With respect to the high engineering complexity resulting from the heterogeneous factory life cycles the modeling methods need to be further sophisticated. A limitation is that the addressed life cycle mechanisms are based on a set of hypotheses and are not yet validated. Nor was it intended to provide an exhaustive list of life cycle mechanisms. Further work should focus on data acquisition from planning and operation as well as on the transfer into engineering processes such as life cycle oriented factory planning.

Authors' contributions AD: conceptualization, methodology, investigation, software, formal analysis, writing—original draft, visualization. LH: conceptualization, methodology, software, writing—original draft. PN: funding acquisition, writing—reviewing and editing, supervision. CH: funding acquisition, writing—reviewing and editing, supervision.

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Availability of data and materials The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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