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Towards quantitative factory life cycle evaluation

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Abstract

Manufacturing companies face the challenge of understanding and improving complex factory systems in order to stay competitive in a turbulent environment. Interrelated and overlapping life cycles of products and physical factory elements (e.g. machine tools, technical building services, building shell) are challenges to be handled in factory planning and operation. This work discusses both qualitative and quantitative factory life cycle models, analyzing addressed sustainability goals. Due to the lack of quantitative life cycle description models on higher system levels, a concept for aggregating life cycle models from shop floor up to site level is developed. The concept is consequently applied in a case study where cost curves are calculated over the factory's life span and are aggregated to support factory planning and operation.

Keywords: Life Cycle Evaluation; Factory Life Cycle; Factory Planning; Life Cycle Prediction

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1. Introduction

To successfully compete in the market, companies need their factories to be flexible and changeable in order to be able to actively shape the required change processes. Economic goals are no longer the only criteria that need to be considered, as stricter legislation and customer awareness are forcing production to address environmental and social targets as well. The special challenge for factory planners lies in the fact that the life span of factory buildings as well as investment goods such as production machines or technical building services (TBS) exceeds the production period of the products. This results in numerous problems during planning and operation of factories, which need to be addressed.

This paper assesses the applicability of existing approaches to describe the life cycle behavior on different factory levels. As indicated by SCHMIDT ET AL., there is a lack of quantitative life cycle evaluation models on plant level [1]. Hence, a framework is proposed which aggregates different life cycle models to enable factory life cycle evaluation.

2. The factory as a system

The factory has to be considered as a complex socio-technical system [2]. It is for this reason, that an evaluation of the entire factory as one object is not applicable [3]. The factory as a system has to be differentiated in its factory elements and organized within a hierarchical structure. A generic description of all factory elements has already been provided by NYHUIS ET AL. [4]. For the purpose of structuring the factory elements, a top-down as well as a bottom-up approach can be conducted.

In the top-down analysis, the vertical breakdown of the factory in factory levels is a feasible approach to provide a hierarchical structure to the inherent objects. According to systems theory, a superior factory level includes subordinated levels, whereas the degree of detail decreases with increasing hierarchy levels [5]. As a compromise between level of detail and unequivocal allocation of factory elements to their related factory levels, a differentiation of the factory as a system into site, plant, section and workstation according to WIENDAHL ET

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AL. is employed [6]. Additionally, a horizontal segmentation of the factory in factory fields is performed, as displayed in Fig. 1. According to HEGER, these fields are defined as technology, organization and space [3].

In contrast, the bottom-up analysis originates from the single factory element. On this low level, the properties and interdependencies of factory elements can be analyzed in detail and subsequently be integrated upwards on a more abstract, but nevertheless coherent level [7]. The bottom-up analysis is especially suitable for a countervailing check of congruency and plausibility in a top-down model. Especially for validating factory life cycle models by utilizing case studies, the bottom-up analysis is of interest [8].

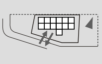
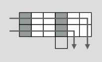
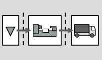
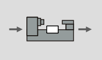
factory fields / factory levels		technology	organization	space
site level		▪ building services - centers	▪ hierarchical structure	▪ property ▪ site development plan ▪ outdoor areas
plant level		▪ building services – distribution facilities ▪ Information techn.	▪ production concept ▪ logistics concept ▪ structure	▪ layout ▪ building form ▪ building structure ▪ shell / appearance
section level		▪ storage facilities ▪ transportation facilities	▪ work organization	▪ development
work-station level		▪ production techn. ▪ production facilities ▪ other facilities	▪ quality management concept	▪ workplace design

Fig. 1. Factory levels and factory fields as top-down structuring approach for factories as systems with exemplary factory elements; adapted from [3, 6].

3. Factory life cycle models

The factory is situated in a field of tension between the push and pull factors that require a high changeability [6]. The technology push by the availability of new and more efficient processes and tools as well as the market pull consisting of e.g. cost pressures and customer expectations can exemplarily be mentioned [9]. The individual layers and elements of the factory as a system are thus subject to dynamic changes and undergo individual life cycles. Fig. 2 shows qualitatively how the life cycles of selected factory elements superimpose.

Similar to the illustrated utility curves, all elements have varying cost and ecological impacts over the life cycle. In general, not only the initial investments apply, but in particular during the use phase costs accrue resulting from operation, maintenance or component replacement, demand of consumables and energy etc. Costs are evaluated by the use of Life Cycle Costing (LCC), while the environmental impacts are assessed based on a Life Cycle Assessment (LCA). In combination with the Social Life Cycle Assessment (S-LCA), the Triple Bottom Line of sustainability is addressed.

In the unsettled environment of the factory it is the challenge to adapt and develop these curves to reach an economic and ecological optimum. For this purpose, the interrelated disciplines of e.g. investment appraisal, change management and the evaluation and measurement of flexibility are important analyses in order to support the spanning life cycle evaluation of factories [10, 11]. Against this background, a selection of methods for life cycle evaluation and description for the different factory levels according to Fig. 1 is provided in the following.

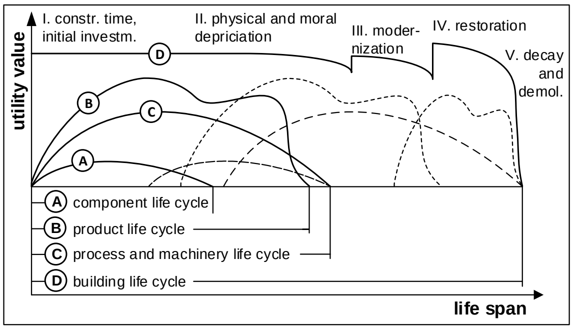


Fig. 2. Relations between life cycles of factory elements; adapted from [12].

3.1. Site level

A production site can consist of different locally interdependent factories. Research in the area of life cycle evaluation on site level was funded by the European Commission in the Pathfinder project. In the course of this research project, models describing the life cycles of single factories and interactions with their environment and infrastructure were developed. The considered goals of these models involve the economic, ecological and social dimension. Results of this project are a “Pathfinder Vision and Roadmap”, which contains the qualitative description of potentials that could arise from a comprehensive factory life cycle evaluation [13].

A life cycle model of the production site which integrates the manifold existing elements was developed by HARTKOPF. The focus of the model lies on capacity and technology requirements for the development of the site. In this matter, the capacity restrictions of machines, equipment and manufacturing facilities are integrated on site level. According to the current phase of their life cycles, recommendations for action are derived for achieving future economic goals of the entire site [14].

3.2. Plant level

On plant level, the production and logistics concept, technical building services as well as the building shell can be highlighted according to the horizontal differentiation of the factory (see Fig. 1). These factory elements are interdependent of each other which could result in difficulties to estimate priorities of improvement measures [15].

In the literature, various models describing the life cycle on plant level can be found. Originating from SCHMENNER, diverse phase models of the factory life cycle have been developed [16, 17, 18]. To give an example, MÜLLER ET AL. distinguish the life cycle phases of factory planning, construction, commissioning, factory operation and shutdown [19]. The objective of these process models is to identify the relevant influencing factors for each phase of the factory life cycle, in order to achieve a sensitization of the planning staff to take these aspects into account. In addition to that, NANDKEOLYAR ET AL. developed first qualitative descriptions of utility curves of different factory elements over the course of their individual life cycle [20]. WIRTH ET AL. refined these utility curves and derived recommendations for action in factory planning and operation [12].

In the last years, some approaches were developed to model the life cycles of factory elements in a quantitative manner and partially integrate the individual curves of performance indicators up to plant level [7, 8, 21, 22, 23]. These performance indicators can for example consist of data sets of energy usage, heat radiation, maintenance intervals and operating materials consumption of different technical building services, such as an air compressor. The evolved models are very specific (e.g. focused on energy efficiency or particular areas of a factory), which consequently results in falling short of achieving a comprehensive factory life cycle evaluation based on quantitative performance indicators.

3.3. Section level

From a life cycle evaluation perspective, it is the challenge on the section level that typical calculative life spans of machines are on average seven to ten years while the products being manufactured on the machines have a shorter life cycle [24]. Consequently, future operating costs of production machinery cannot be predicted precisely. Moreover, planners have to deal with the uncertainty that a new product generation might not be producible on the existing manufacturing equipment, due to technical or capacity restrictions.

The life cycle costs of new manufacturing processes which are about to be implemented can be estimated by applying the method of AURICH ET AL. who use similarity studies on existing technologies [25]. Process technological, technical and organizational cost effects can be quantified by using a process chain simulation. Subsequently, this can be compared with the expected benefits to support investment decisions [26]. POHL combines the quantitative modelling of the life cycle of production equipment with a mathematical description of product and technology life cycles under consideration of uncertainties [27]. RÖDGER ET AL. have introduced a framework for sustainability assessment of highly automated production lines [28].

3.4. Workstation level

The acquisition costs of machine tools account for only about 20 percent of the lifecycle costs. However, 80 percent account for the operating costs, with maintenance and inspection as well as energy costs being the largest items [29].

HERRMANN ET AL. developed a simulation-based method for calculating life cycle costs on the basis of static and dynamic assessment approaches and partial consideration of stochastic effects. It takes into account the failure mechanisms and lifetime predictions. Furthermore, it integrates appropriate maintenance strategies and a retrofitting of more energy-efficient components [30]. This component-based approach is also applied by the LCC-Navigator which focuses on the extrapolation of the life cycle costs during machine tool development [24]. Another approach subdivides the machine tool into single cost elements for which the individual energy flows are quantified to conduct an economic assessment [31]. A framework for an integrated assessment of the economic and ecological life cycle performance of machine tools has been developed by NIGGESCHMIDT ET AL. [32]. Additionally, methods from life cycle assessment can be employed to enhance the resource efficiency of machine tools with life cycle-oriented services [33].

3.5. Preliminary conclusion and research gap

To complement the aforementioned findings, Fig. 3 uses the level framework to provide an analysis of previous publications concerning factory life cycle evaluation. The models are assessed in terms of their approach being either quantitative or qualitative, as well as their addressed goals which are economic, ecological or social, reflecting the Triple Bottom Line of sustainable development. If the assessed model focuses on an evaluation criterion, a full rating is given. When the model partly covers a criterion, a semi rating is the result, whereas neglecting the criteria results in a blank rating.

In summary, it can be stated that there are several detailed models for the description of the life cycle on the lowest level of the factory as a system. These models address outcomes such as life cycle costs and environmental impacts in a quantitative way, so they can be used very well for decision support. In general, a considerable effort is required for adapting these models to the respective planning case and for data collection. It should also be noted that previous publications focus mainly on machine tools and, the transferability of the methods cannot be ensured.

As the majority of existing models generally analyzes single workstations or whole plants, literature concerning the section level or site level is relatively rare. For the higher factory levels, however, qualitative description models are predominant, which primarily address abstract variables such as the utility value. Thus, these models are not suitable for direct planning support but rather to sensitize the planners for life cycle thinking. The recent quantitative approaches according to the bottom-up approach are based on an aggregation of models for the lower levels. They are, however, very specific with regard to target values as well as considered cases and are thus of poor transferability. The social aspect is rarely treated in the models on all levels.

It can be stated that especially on the planning level of factories distinct uncertainties need to be handled. Mastering these uncertainties in order to continuously optimize the factory in terms of costs and environmental impacts comes more and more into focus. This is especially important in the context of stricter environmental legislations as well as increasing cost pressure and competition. However, there is no comprehensive method available yet to support planners in quantitatively forecasting factory life cycles in factory planning and operation. A generic quantitative description integrating the factory elements onto site level is lacking.

factory level	evaluation criteria	qualitative	quantitative	economic	ecological	social
site	European Commission 2014 [13]	●	○	●	●	●
	Hartkopf 2013 [14]	○	●	●	○	○
plant	Schmenner 1983 [16]	●	○	●	○	○
	Nandkeolyar et al. 1993 [20]	●	○	●	○	○
	Wirth et al. 2000 [12]	●	○	●	○	○
	Zäh et al. 2004 [17]	●	○	●	○	○
	Constantinescu et al. 2006 [18]	●	○	●	○	○
	Westkämper et al. 2006 [34]	●	○	●	○	○
	Müller et al. 2009 [19]	●	○	●	○	○
	da Piedade Francisco et al. 2010 [35]	●	○	●	○	○
	Jufer et al. 2012 [21]	○	●	●	○	○
	Götze et al. 2013 [22]	○	●	◑	◑	○
	Heinemann et al. 2013 [7]	○	●	●	◑	○
	Dombrowski et al. 2014 [23]	○	●	◑	●	○
	Heinemann et al. 2014 [8]	○	●	◑	◑	○
	Cerdas et al. 2015 [36]	●	○	◑	●	○
section	Aurich et al. 2009 [25]	◑	◑	○	◑	○
	Denkena et al. 2010 [26]	○	●	●	○	○
	Pohl 2014 [27]	○	●	●	○	○
	Rödger et al. 2016 [28]	○	●	●	●	○
workstation	Osten-Sacken 1999 [37]	○	●	●	○	○
	Briel 2002 [38]	○	●	●	○	○
	Mateika 2005 [39]	◑	◑	●	○	○
	Denkena et al. 2006 [24]	●	○	●	○	○
	Nebl 2009 [40]	●	○	●	○	○
	Herrmann et al. 2011 [30]	○	●	●	◑	○
	Niggeschmidt et al. 2010 [32]	○	●	●	●	○
	Mattes et al. 2011 [29]	○	●	◑	◑	○
	Lindner et al. 2011 [31]	●	○	◑	◑	○
	Mert et al. 2014 [33]	●	○	○	●	○

legend ● focus ◑ partly covered ○ not covered

Fig. 3. Assessment of approaches concerning factory life cycle evaluation.

4. Towards quantitative factory life cycle evaluation

Against this background the conceptional framework for quantitative factory life cycle evaluation has been developed (see Fig. 4). Following the idea of a bottom-up approach, it aggregates elements of one factory level to describe the respective superordinate level. This course of action is chosen since the elements of the lower factory levels can be modeled with comparably high accuracy. Analogies for manufacturing system composition can be found in [41, 42, 43].

Each factory element (e.g. machine tool) can be modeled as a transformation process box with quantifiable inputs (e.g. materials, energy, consumables, workers) and outputs (e.g. product, waste, emissions). Moreover, selected state variables (e.g. failure probability, process rate) of the transformation process can be tracked and calculated over the life time of the process. This reflects the technical perspective as depicted in Fig. 4. In- and outputs of the transformation process as well as process states can additionally be expressed in an aggregated and descriptive way via KPIs which address the Triple Bottom Line of sustainability and should be calculated for each element of the respective factory level. Both the derived KPIs and the process states can then be employed on the next hierarchical level (e.g. process chain as a section consists of multiple machine tools). They can be the basis for balancing and assessment purposes of the superordinate factory level. To give an example, the in- and output flows of energy and resources of the single machine tools aggregate to the respective flows of the section. Other examples are failure probabilities of single machine tools which aggregate to the operational availability of the process chain on section level.

Obviously, appropriate methods for aggregation have to be chosen which spread from simple summation to complex calculations of e.g. aggregated probabilities. Moreover, for all factory elements considered in a specific factory planning case, the individual state variables, KPIs and interrelations with other elements need to be identified and modeled.

Knowledge about the process states as well as KPIs can be employed as decision fundament for controlling processes on higher factory levels. As an example, electrical load profiles on workstation level can be utilized for load management purposes on higher levels. Possible outcomes of planned changes can be made transparent and quantifiable throughout the factory levels to ensure directionally safe decisions and avoid problem shifting.

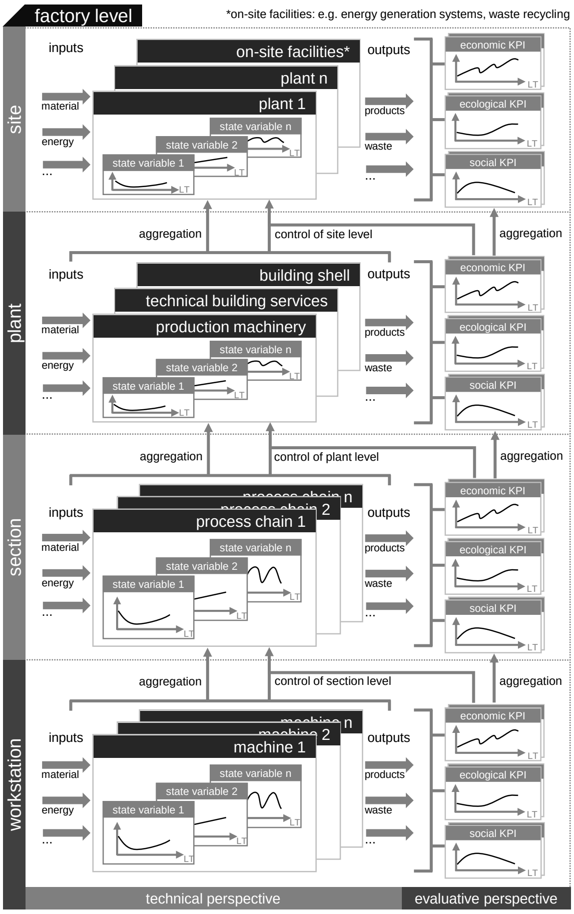


Fig. 4. Bottom-up concept for the quantitative factory life cycle evaluation.

The proposed conceptional framework enables significant advancements in life cycle-oriented factory modelling and planning by overcoming the limitations of existing methods: Bottom-up approaches such as [7] simply aggregate state variables like cost and energy demand but do not consider dynamic changes due to the factory elements’ life cycles. This life cycle consideration is the strength of approaches such as [30] which focus, however, only on the machine level.

5. Case study

The approach of a quantitative factory life cycle evaluation shall be exemplified by means of a case study. In this example, the interrelations of several factory elements over the factory life cycle are demonstrated by cost indicators on different factory levels. For reasons of simplicity state variables of the system components (productivity, quality rate etc.) as well as inputs and outputs of factory elements (material, energy etc.), which constitute the technical system perspective, are assumed to be stable over time.

The case study is performed by using the factory life cycle evaluation tool of HEINEMANN ET AL. [7]. The tool focuses on economic and ecological evaluations from a factory planner perspective by predicting costs and CO_2 emissions over the life cycle, depending on chosen machines, TBS and building shell. A generic case of a small company was set up and evaluated from the cost perspective. General model parameters and assumptions are summarized in Table 1. Besides investments, variable costs caused by energy and material demands, maintenance and labor are calculated for the assessed period of 30 years. Factory elements are replaced when reaching the end of their life span, leading to repetitive investments (see Table 2).

Table 1. General model settings.

Model parameter	Value	Model parameter	Value
Assessed period	30 a	Space costs	8 €/m²*a
Operating hours	6,000 h/a	Interest rate	3 %
Electricity price	0.1 €/kWh	Inflation	1 %

Table 2. Considered factory elements.

Factory level	Factory element	Life span	Invest per element
Plant	1x building shell	180,000 h	2,000,000 €
	1x air compressor	90,000 h	180,000 €
Workstation	4x turning mach.	30,000 h	150,000 €
	4x grinding mach.	30,000 h	220,000 €

Fig. 5 illustrates the derived cost curves for the factory elements, consisting of the described fixed and variable cost components. Starting with the machine costs on workstation level (see bottom of the Fig.), a comparably high slope of the curves due to relevant resource consumptions in the use phase can be stated. On section level, the single machine cost curves are aggregated, resulting in a stair curve due to the repetitive investments for machine replacements every ten years. On plant level, an additional cost curve for the building shell has to be integrated, which is characterized by a high initial investment but a very slight slope, resulting from marginal maintenance costs in the use phase. The cost increase at the end of its life time is due to the financial efforts for factory disposal. By contrast, the cost curve of the compressor is comparable to the machine cost curves. When merging the section level curves with the shell and compressor curves, a total cost profile for the factory can be obtained, containing characteristics from all aggregated cost curves. It can be used as decision support in factory planning, allowing to assess the economic consequences of different planning alternatives.

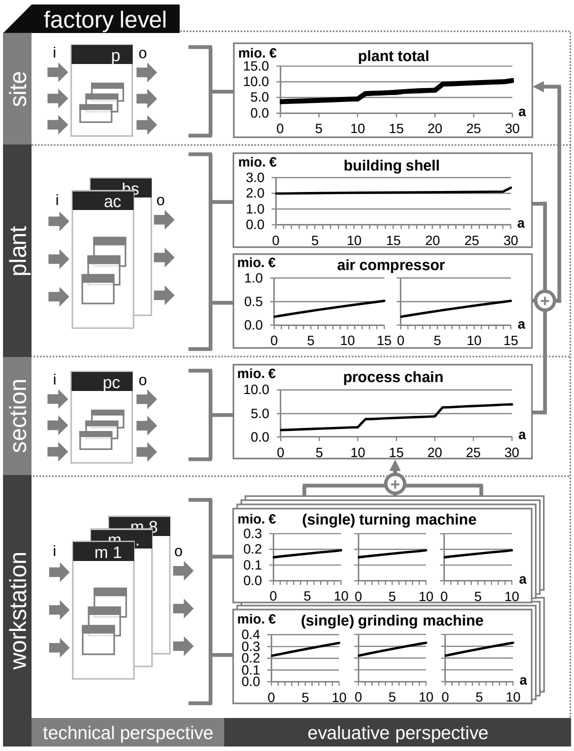


Fig. 5. Modeled case study cost curves for workstation up to site level.

6. Conclusion

This paper offers a first framework to quantitatively describe the interrelations of factory elements on different levels over the factory’s life cycle. The proposed aggregation or combination of state variables and KPIs can be straight forward from a mathematical perspective, as long as indicators from lower levels can be added independently to receive the indicators of higher levels. However, the dynamic behavior of state variables such as productivity or quality rates over the factory’s life cycle must be known and non-linear interdependencies between different variables and KPI must be considered in practice. As an example, such interdependencies exist between utilization rates of interconnected machines or between media inputs of machines and in-/outputs of the connected TBS.

The general applicability of the developed concept was demonstrated in a case study, in which the influence of dynamic state variables was not considered. Further research will be necessary to identify the relevant interdependencies between factory elements and quantitatively describe the corresponding indicators. A special focus must be put on further aggregation methods, which will include both empirical but also physical approaches.

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