Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 98 (2021) 418–423

www.elsevier.com/locate/procedia

28th CIRP Conference on Life Cycle Engineering

Factory life cycle evaluation through integrated analysis of factory elements

Antal Dér[a,*], Lennart Hingst[b], Alexander Karl[a], Peter Nyhuis[b], Christoph Herrmann[a]

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

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

* Corresponding author. Tel.: +49-531-391-65035; fax: +49-531-391-5842. *E-mail address:* a.der@tu-braunschweig.de

Abstract

In consequence of the technological advances of the last few decades, factories emerged to highly complex systems that consist of numerous factory elements like production machines, technical building services and the building shell. These factory elements are characterized by individual life cycles that differ in their duration and life cycle behavior. Consequently, the factory life cycle is composed of multiple overlapping life cycles. The fact that the life cycle of some factory elements (e.g. the building shell) exceeds the life cycle of other elements over many times (e.g. of machines) presents a challenge for factory planners. In particular, factory planners struggle to understand the contribution of single factory elements on the total factory life cycle. Consequently, it is hard to systematically synchronize the inherent life cycles of a factory while adhering to manifold requirements. Against this background, the goal of this paper is to develop a methodology that supports factory planners in the evaluation of the factory life cycle. The proposed methodology enhances the understanding of how factory elements contribute to the factory life cycle and what is the current life cycle state of the entire factory. To this end, the factory system is broken down on its constituting elements. A modified failure mode and effect analysis (FMEA) is applied to assess their life cycle priority according to economic, environmental and technical criteria. The methodology is exemplarily demonstrated on a pilot scale battery production system.

Keywords: Factory life cycle, Factory planning, Factory element, Life cycle priority

1. Introduction

Factories form a place of industrial value creation and are integral part of modern societies. With increasing awareness of climate change and global sustainability, and an accelerating rate of technological innovations, factory managers face the challenge to integrate an environmental dimension into factory planning and operation along already existing economic and technical goals. Shorter product life cycles, a higher number of variants and high requirements on product quality in pair with technological advancements, such as cyber-physical production systems drive factories towards complex engineering systems [1, 2]. The immediate consequence is the increased number of interrelationships between factory elements and resulting uncertainties regarding their life cycle behaviour. In this context, the understanding of the factory life cycle becomes inevitable. As shown in Fig. 1, the factory life cycle is composed of three main stages, factory planning, factory operation and factory end-of-life. The factory life cycle emerges from multiple interrelated and overlapping life cycles of factory elements (A-D) [3]. Another challenge from a factory planning perspective is that the life cycle of some elements exceeds the life cycle of other factory elements by far [2, 4]. As an example, the building shell exceeds the life cycle of machines and products over many times [4, 5].

In order to address these challenges, factory planners and factory operators need to be equipped with methods and tools for life cycle oriented factory planning and operation. The

10.1016/j.procir.2021.01.127

proactive planning of the factory life cycle and long-term factory operation at an optimal state from a life cycle engineering perspective requires a comprehensive model-based, quantitative understanding of the factory life cycle.

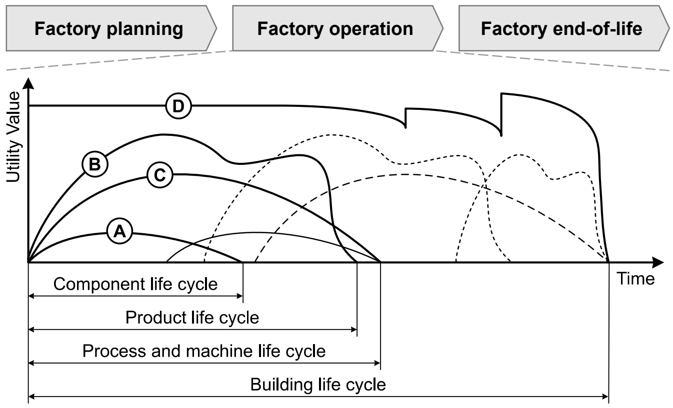

Fig. 1. Factory life cycle, based on [3, 6].

Against the aforementioned motivation and challenges, the overarching goal of this paper is to develop an integrated evaluation methodology of factory element life cycles. The specific goal is to support factory planners in developing an enhanced understanding of how factory elements contribute to the factory life cycle and what is the current life cycle state of the factory. By this, the methodology forms an important basis towards the envisioned comprehensive quantitative factory life cycle model.

In particular, a decomposition approach is applied on the factory system. This is broken down on generic factory elements, which are analyzed independently. A life cycle priority number is derived based on a modified failure mode and effect analysis (FMEA). Subsequently, the factory life cycle is assembled based on the generic factory elements and their life cycle priority. The application of the methodology is exemplarily demonstrated on a pilot scale battery production facility.

2. Background

2.1. Factory planning and the factory life cycle

The factory is defined as a complex socio-technical system which is exposed to various influences through internal and external change drivers [1, 4]. From a systems theory perspective, factories are divided into different hierarchical factory levels (e.g. site, factory, section and workstation) [1, 4]. In addition, a segmentation of the factory into factory design fields is performed (technology, organization, space) [7].

The goal of factory planning is to synchronize all factory elements in order to achieve a factory configuration that meets future demands while maintaining low costs and environmental impact during the factory life cycle [4]. The factory planning process has been described by various authors and was defined for a uniform understanding in the VDI guideline 5200 [8]. It is structured into several sequential steps and ranges from setting of objectives (step 1) over concept and detailed planning up to start of production (step 7) [8]. Four generic planning cases are differentiated with regard to the factory life cycle [2, 4, 8]:

- *Greenfield planning:* development planning of a new factory. It is characterized by a high freedom in planning, when no constraints exist regarding the building structure.
- *Brownfield planning:* replanning of an already existing factory or of its sections (e.g. building refurbishment or upgrade). Constraints need to be taken into consideration regarding existing buildings, technical building services and production machines.
- *Clearance & demolition:* Preparing the site for non-industrial reuse at the end of the factory life cycle.
- *Revitalization:* preparing the site/ building structure for an industrial reuse.

An integrated analysis of factory elements for factory life cycle evaluation is seen as particularly relevant and challenging for brownfield planning cases. First, already existing building structures, technical building services and production machines have a different age distribution. Hence different constraints (e.g. remaining lifespan, functionality, operation cost and environmental impact) need to be addressed. These constraints culminate in goal conflicts, which have to be made visible and evaluated prior to decision making. Second, brownfield planning projects outweigh greenfield projects in industrialized countries due to a high number of existing manufacturing facilities [2, 9].

2.2. Factory life cycle evaluation

Two common methods for evaluation of the life cycle of product systems (i.e. also including entire factories) are environmental life cycle assessment (LCA) and life cycle costing (LCC) [10–12]. While LCA is a standardized methodology, it has some shortcomings for practical application (e.g. static and snapshot character of LCA calculations and difficulty for prospective assessments) [13, 14]. Therefore, a major concern of life cycle engineering in the context of factory planning is to enable the application of LCA and LCC in line with established planning activities.

In previous contributions, Nielsen et al. and Schmidt et al. reviewed existing models and approaches for qualitative and quantitative life cycle modeling and evaluation of factories on different hierarchical levels [6, 15]. According to their findings and updated from the latest state of research, there are several quantitative approaches on lower system levels, e.g. focusing on life cycle costs of machine tools, e.g. [5, 16], or on their environmental impact, e.g. [17, 18]. However, on higher system levels qualitative and conceptual models are predominant, e.g. [3, 19, 20]. These approaches characterize the life cycle of factory elements with their utility value, which, however, lacks a clear definition. Consequently, this abstract concept of utility value is not directly applicable for decision support during planning activities. To overcome these shortages, Nielsen et al. propose a conceptual model for an integrated assessment of economic and environmental performance indicators on factory level [6]. Some recent contributions present case studies with quantifiable performance indicators on factory level, e.g. [21, 22]. The estimation of life cycle costs and environmental impact is based on static calculations and the interrelationships between factory elements is out of scope.

Taken together, a comprehensive and applicable approach is missing that is able to integrate all relevant factory elements for a prospective factory life cycle evaluation during factory planning.

3. Methodology development

3.1. Systematic approach

Against the aforementioned challenges and research gap, a methodology is proposed to support factory planners in developing an enhanced understanding of how factory elements contribute to the factory life cycle and what is the life cycle state of the entire factory (Fig. 2). The main idea is to decompose the factory life cycle into the life cycle of its constituting elements (Step I). These factory elements are analyzed independently (Step II). To this end, a life cycle priority number is calculated and the current life cycle state of the factory element is estimated on the basis of a rapid qualitative assessment. Afterwards, the factory element life cycles are composed on factory level and the life cycle state of the entire factory is determined (Step III). The results can be used subsequently to derive strategies for the factory depending on its current life cycle state.

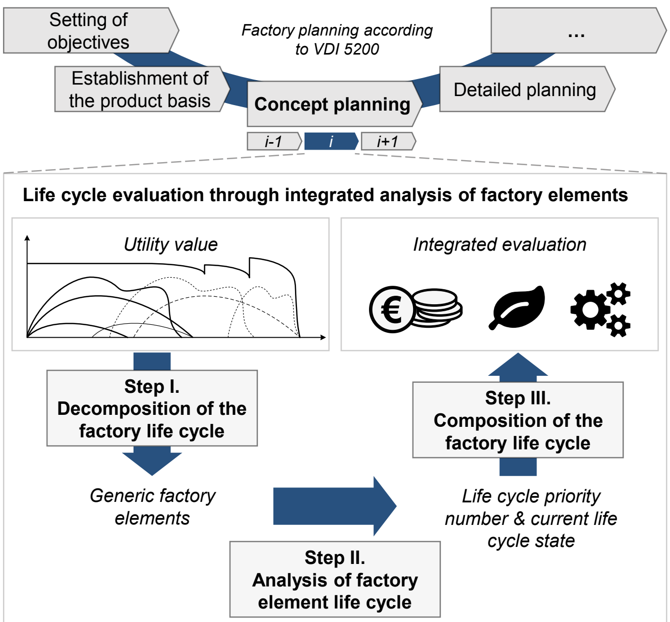

Fig. 2. Systematic approach for characterizing the factory life cycle.

The methodology is positioned in the concept planning phase of brownfield projects. At this stage, the site location is fixed and the future product portfolio is known. Due to the nature of brownfield projects, an already existing building shell, technical building services and production machines, each with a potentially different age, need to be taken into consideration. The methodology is intended for a rapid assessment, where the results are primarily used to identify fields of action, which will need a more detailed analysis.

3.2. Decomposition of the factory life cycle

As previously described, factory elements can be structured in a top-down approach hierarchically into factory levels and horizontally into factory design fields. Previous work from [4, 23] concentrated on the design fields of technology, organization and space. For the purposes of this methodology, this classification has been adapted and subsequently complemented. Table 1 presents the resulting classification scheme and the allocated generic factory elements. Compared to the work of [4, 23], the hierarchical factory levels were reduced to factory, section and workstation, whereby factory elements from the previous site and factory levels were combined on factory level. In order to integrate the human and product perspective, the according factory design fields were complemented in comparison to the initial classification from [4, 23]. Afterwards, the generic factory elements from the initial classification were consolidated and allocated to factory levels and design fields.

Table 1. Top-down classification scheme for factory elements (generic factory elements allocated to factory levels and factory design fields), adapted from [4, 23].

	Factory levels		
Factory design fields	**Factory**	**Section**	**Workstation**
Technology	▪ Technical building services (TBS)	▪ Storage facilities ▪ Transportation facilities	▪ Production technology ▪ Production machines ▪ Information technology ▪ Other facilities
Organization	▪ Organizational structure ▪ Production concept ▪ Logistics concept ▪ TBS concept	▪ Work organization	
Space	▪ Site ▪ Building shell	▪ Zone	▪ Workplace
Human	▪ Staff		▪ Worker
Product	▪ Production program		▪ Part

While the classification scheme provides a generic framework for all kinds of factories, it needs to be refocused on a case-basis. To this end, one or more factory design fields need to be chosen for further evaluation. In this paper, the focus is set on physical factory elements within the design fields of technology and space, as these are expected to be relevant and easily assessable in the context of the proposed methodology. During a specific planning case, the generic factory elements can be seen as categories, to which the existing factory elements (with their current form on the shop floor) can be grouped to. In this context, Fig. 3 exemplarily lists various forms of selected generic factory elements in a morphological box. These were retrieved from [1, 24–26], where they are referenced as relevant factory elements.

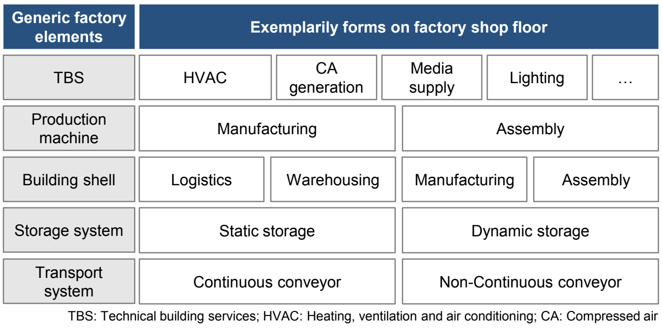

Fig. 3: Exemplary forms of selected generic factory elements.

3.3. Analysis of factory element life cycle

3.3.1. Life cycle performance of factory elements

In order to operationalize the abstract concept of utility values of factory elements and make it more tangible for factory planners, this term needs an amplification. Therefore, this paper proposes to define the utility value of a factory element with respect to its main function. As part of this definition, the utility value describes the technical performance/ functionality of the factory element. In this context, state variables can be used to describe this function and its progression over the factory element´s life cycle. Based on literature, Table 2 lists relevant factory elements, their functions and exemplary state variables.

Table 2. Selected factory elements, their functions and exemplary state variables

Factory element	Function	Exemplary state variables
Technical building services	Ensure required production conditions (e.g. temperature, moisture and purity) [25] Supply production machines with energy and media [25]	Failure rate, deterioration, capacity, utilization, power and media demand
Production machine	Perform the value-adding transformation process [4]	Failure rate, deterioration, quality rate, process rate, utilization, power and media demand
Building shell	Provide a spatial and functional shell for the transformation process [4]	Deterioration, Space utilization, floor bearing capacity, span width, ceiling height,
Storage system	Decouple production machines from up- and downstream processes by stockholding [4, 27]	Number of storage places, storage speed, deterioration, failure rate
Transport system	Manage material flows between production machines and storage facilities [4, 27]	Load capacity, transport speed, power demand, deterioration, failure rate

Moreover, the utility value can be understood as an integral part of the life cycle performance of a factory element (Fig. 4). In this regard, building up on the work from [6], the technical performance is integrated next to an economic and environmental dimension of the life cycle to describe factory elements. Fig. 4 depicts in this context qualitatively the life cycle performance of a factory element. The progression of the technical performance and cumulated life cycle costs and environmental impact is illustrated in accordance with generic life cycle stages.

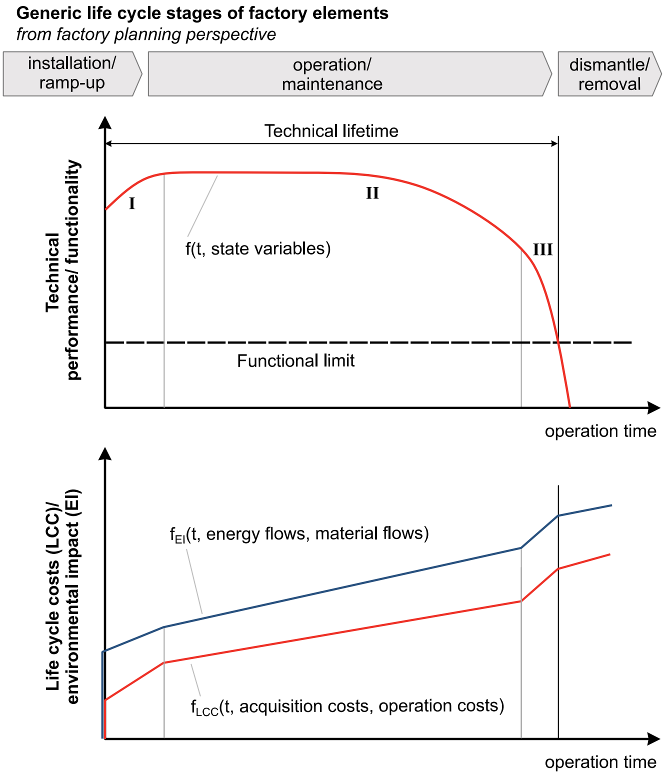

Fig. 4. Qualitative representation of the life cycle performance of a factory element over its life cycle.

3.3.2. Identification of the current life cycle state of factory elements

The operation stage of the factory element´s life cycle in Fig. 4 is divided into three sub-states I to III, specified by the progression of the technical performance curve. The knowledge of the current life cycle state (LCS) would place factory planners into the position to anticipate the remaining life of the factory element and synchronize it within the factory system. Table 3 compares exemplary characteristics of the respective life cycle states. The description in the table provides the basis for a rapid assignment of life cycle states to factory elements.

Table 3: Rapid assessment of the current life cycle state of a factory element based on its characteristics

LCS	**Description** (examples, not-comprehensive list)
I.	Relatively short period with a performance below the planned target; performance is rising
II.	Relatively long period with steady performance that slowly starts to decrease; regular maintenance keeps performance level constant
III.	Rapidly falling performance, more frequent and longer downtimes, increasing number of quality issues and cases where requirements are not fully satisfied

3.3.3. Calculation of a life cycle priority number for factory elements

Inspired from the FMEA methodology, a life cycle priority number (LPN) is calculated for each factory element by quantifying its relevance, severity and vulnerability from a technical perspective on the entire factory. Each aspect is rated on a scale from one to ten, with one meaning a weak conformity and ten a strong conformity.

- *Relevance:* expresses the degree, to which the factory element is required for the value adding process in regard with the production program. As an example, factory elements, which are utilized for multiple product variants and do not have a substitution, are rated with a high relevance.
- *Severity:* expresses the number and quality of cross-links to other factory elements. It describes the influence of a given factory element on other related factory elements that would be affected in case of a failure. As an example, a compressed air generator, whose failure would lead to a stop of a production line, gets a high rating.
- *Vulnerability:* describes the possibility for a malfunction of the factory element. Factory elements that are likely to break down are rated high.

The LPN of a factory object is calculated by a multiplication of the three terms.

$$LPN = Relevance \times Severity \times Vulnerability \qquad (1)$$

3.4. Composition of the factory life cycle

On the level of the entire factory, the question needs to be answered, what is the specific contribution of a factory element on the life cycle of the factory as a whole. In order to transfer the individual life cycles of single factory elements on the life cycle of the factory, their LPN is used as a weighting factor w_i. This describes their contribution to the life cycle of the entire factory.

$$w_i = \frac{LPN_i}{\sum_{i=1}^{n} LPN_i} \qquad (2)$$

Consequently, the current life cycle state of the factory is calculated as the sum of the weighted life cycle states of the inherent factory elements.

$$LCS_{Factory} = \sum_{i=1}^{n} w_i \times LCS_i \qquad (3)$$

The current life cycle state of the entire factory and the distribution of its inherent factory elements regarding their life cycle priority and current life cycle state build the basis for deriving further action. To this end, the factory elements can be placed for a high-level overview in a life cycle portfolio (Fig. 6). This can be used to anticipate and roughly schedule future factory planning demands. Critical factory elements are placed in the upper left corner of the portfolio. For these elements, a more detailed assessment need to elaborate operational (e.g. increased maintenance frequency) and strategic (e.g. relocating production capacities) options to further sustain their functionality.

4. Case study on battery cell manufacturing

The pilot scale lithium-ion battery cell production of the Battery LabFactory Braunschweig (BLB) serves as a case for an exemplary application of the developed methodology. The process chain of the BLB incorporates three main steps: electrode production, cell assembly and cell finishing [28]. The final products leaving the BLB are pouch cells for lithium ion traction batteries. The production program is characterized by a high variety and small batch sizes. The BLB is a good example for a brownfield planning case. The building structure has been extensively restored before state-of-the art battery cell production equipment (i.e. mixers, coating and drying machine, calender, laser cutter and assembly machines, etc.) and technical building services (i.e. dry room air handling units, ventilation, chiller, adsorber, etc.) moved in [29]. The shop floor is divided into multiple zones. While electrode production and cell finishing take place under normal atmospheric conditions, cell assembly is performed in dry rooms. The dry rooms in particular set very high standards for precisely controlled production conditions [28]. Storage and transportation processes are characterized by manual handling operations. Fig. 5 illustrates schematically the layout of the BLB and highlights exemplary factory elements, their life cycle state and life cycle priority number. According to the results, production machines and technical building services are in the second life cycle state. Despite the restoration, the building shell starts to show deficiencies, which grants itself the third life cycle state. The life cycle priority numbers are diverse. Production machines, whose function can be substituted with alternatives or are not required for pouch cells, tend to have a lower LPN. In contrast, production machines without substitution (e.g. coating and drying machine) and technical building services that provide essential functions for the value adding process (e.g. air handling units for dry rooms) are apt to be rated with a higher LPN.

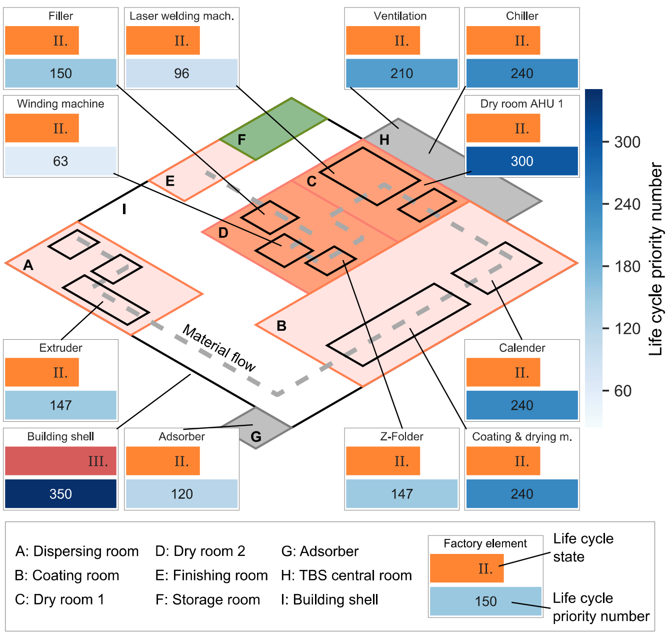

Fig. 5. Exemplary visualization of the factory elements of the BLB.

The factory elements of the BLB are also illustrated in a portfolio diagram (Fig. 6). It displays every assessed factory element from the BLB broken down on the generic factory element classes. The dashed line illustrates the current life cycle state of the BLB. Currently, only the building shell is in its third life cycle state. At the same time, it retains a high LPN in comparison to other factory elements. In order to avoid incompatibility and negative effects on other factory elements, the building shell needs to be in special focus of future factory planning activities. However, a more detailed assessment is needed for assessing the interdependencies between the factory elements and for answering how to extend life cycle of the building shell.

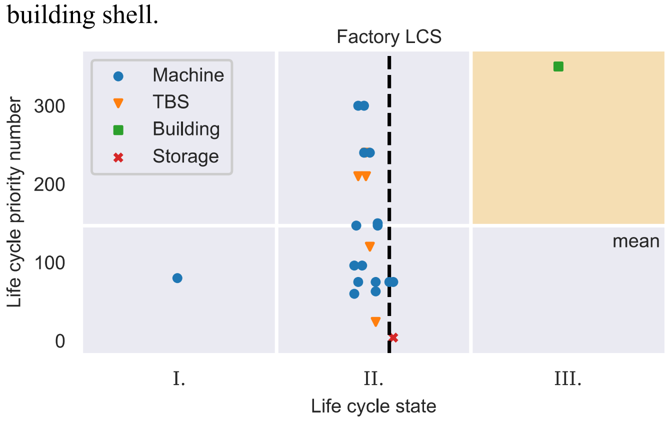

Fig. 6. Life cycle portfolio of the BLB (jittering added to avoid overplotting).

5. Discussion and summary

Factory planners and operators constantly face the challenge to adapt a factory to future demands and optimize its life cycle behavior. At the same time, comprehensive methods and tools supporting a life cycle oriented factory planning and long-term factory operation are lacking. With the vision for a comprehensive model-based, quantitative understanding of the factory life cycle, this paper presented a first methodology for quantifying the contribution of single factory elements to the factory life cycle. Based on a rapid assessment of factory elements, the current life cycle state of the factory can be identified, which builds the base for deriving strategies. The added value of the presented methodology in comparison to previous contributions is that it develops the abstract concept of utility values towards more tangible and applicable indicators for factory planners.

While the proposed approach makes a first step towards a comprehensive understanding of factory life cycles, further questions remain unanswered. An isolated view on single factory elements is not sufficient for the purposes of the envisioned factory life cycle model. The influence of external and internal change drivers (e.g. climate change and digitalization) on the life cycle and interdependencies between factory elements need to be integrated with more detail into the methodology.

Acknowledgements

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 412409961.

References

[1] Wiendahl, H.-P., ElMaraghy, H.A., Nyhuis, P., Zäh, M.F. *et al.*, 2007. Changeable Manufacturing - Classification, Design and Operation *56*, p. 783.
[2] Schenk, M., Wirth, S., Müller, E., 2014. *Fabrikplanung und Fabrikbetrieb*. Springer Berlin Heidelberg, Berlin, Heidelberg.
[3] Wirth, S., Günter, U., David, T., 2000. Durchgängiges Planungskonzept mit ganzheitlicher simulationsbasierter Layoutplanung, in *Vortragsband "Vernetzt planen und produzieren"*, Chemnitz, p. 56.
[4] Wiendahl, H.-P., Reichardt, J., Nyhuis, P., 2015. *Handbook Factory Planning and Design*. Springer Berlin Heidelberg, Berlin, Heidelberg.
[5] Denkena, B., Harms, A., Jacobsen, J., Möhring, H.-C. *et al.*, 2006. Lebenszyklus-orientierte Werkzeugmaschinenentwicklung: Wie Lebenszykluskosten schon bei der Maschinenentwicklung berücksichtigt und gesenkt werden können *96*, p. 441.
[6] Nielsen, L., Schmidt, C., Blume, S., Schmidt, M. *et al.*, 2016. Towards Quantitative Factory Life Cycle Evaluation *55*, p. 266.
[7] Nyhuis, P., Kolakowski, M., Heger, C.L., 2005. Evaluation of Factory Transformability – a Systematic Approach.
[8] Verein Deutscher Ingenieure, 2011. *Factory planning - Planning procedures: VDI 5200*.
[9] Nyhuis, P., Elscher, A., Kolakowski, M., 2004. Prozessmodell der Synergetischen Fabrikplanung: Ganzheitliche Integration von Prozess- und Raumsicht *94*, p. 95.
[10] Herrmann, C., Bergmann, L., Thiede, S., Halubek, P., 2007. Total life cycle management-an integrated approach towards sustainability, in *3rd International Conference on Life Cycle Management, Zurich*.
[11] International Organization for Standardization, 2006. *Environmental Management: Life Cycle Assessment; Principles and Framework*. ISO.
[12] VDI 2884. Purchase, operating and maintenance of production equipment using life cycle costing (LCC). VDI Düsseldorf,, Germany, 2006.
[13] Brondi, C., Carpanzano, E., 2011. A modular framework for the LCA-based simulation of production systems *4*, p. 305.
[14] van der Giesen, C., Cucurachi, S., Guinée, J., Kramer, G.J. *et al.*, 2020. A critical view on the current application of LCA for new technologies and recommendations for improved practice *259*, p. 120904.
[15] Schmidt, C., Nielsen, L., Thiede, S., Schmidt, M. *et al.*, 2016. Analyse und Gestaltung von Fabriklebenszyklen *111*, p. 333.
[16] Herrmann, C., Kara, S., Thiede, S., 2011. Dynamic life cycle costing based on lifetime prediction *4*, p. 224.
[17] Zeng, D., Cao, H., Jafar, S., Tan, Y. *et al.*, 2018. A Life Cycle Ecological Sensitivity Analysis Method for Eco-Design Decision Making of Machine Tool *69*, p. 698.
[18] Mert, G., Bohr, C., Waltemode, S., Aurich, J.C., 2014. Increasing the Resource Efficiency of Machine Tools by Life Cycle Oriented Services *15*, p. 176.
[19] Nandkeolyar, U., Subba Rao, S., Rana, K., 1993. Facility Life Cycles *21*, p. 245.
[20] Zaeh, M.F., Reinhart, G., Karl, F., Schindler, S. *et al.*, 2010. Cyclic influences within the production resource planning process *4*, p. 309.
[21] Gebler, M., Cerdas, J.F., Thiede, S., Herrmann, C., 2020. Life cycle assessment of an automotive factory: Identifying challenges for the decarbonization of automotive production – A case study *270*, p. 122330.
[22] Heinemann, T., Thiede, S., Müller, K., Berning, B. *et al.*, 2013. Life cycle evaluation of factories: Approach, tool and case study, in *Proceedings / 11th Global Conference on Sustainable Manufacturing: Innovative solutions ; Berlin, Germany, 23rd - 25th September, 2013 ; proceedings*, Univ.-Verl. der TU, Berlin, p. 479.
[23] Heger, C.L., 2007. *Bewertung der Wandlungsfähigkeit von Fabrikobjekten*. PZH, Produktionstechnisches Zentrum, Garbsen.
[24] Herrmann, C., Thiede, S., 2009. Process chain simulation to foster energy efficiency in manufacturing *1*, p. 221.
[25] Hesselbach, J., Herrmann, C., Detzer, R., Martin, L. *et al.*, 2008. Energy efficiency through optimised coordination of production and technical building services, in *LCE 2008: 15th CIRP International Conference on Life Cycle Engineering*, CIRP.
[26] Chen, D., Thiede, S., Schudeleit, T., Herrmann, C., 2014. A holistic and rapid sustainability assessment tool for manufacturing SMEs *63*, p. 437.
[27] Schulte, C., 2017. *Logistik: Wege zur Optimierung der Supply Chain*, 7th edn. Verlag Franz Vahlen, München.
[28] Kwade, A., Haselrieder, W., Leithoff, R., Modlinger, A. *et al.*, 2018. Current status and challenges for automotive battery production technologies *3*, p. 290.
[29] Schönemann, M., 2017. *Multiscale Simulation Approach for Battery Production Systems*. Springer International Publishing, Cham.

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.