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Environmental Sustainability Assessment Of Factories With BIM: Relevance And Challenges For A Holistic Approach

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Abstract

Environmental sustainability is increasingly seen as a central objective of a factory in order to ensure the long-term competitiveness of industrial companies. In addition to growing social and regulatory pressures, the urgency is further emphasized by the increasing sustainability awareness of companies. This not only enhances their attractiveness to customers and investors but can also help to reduce costs.
The assessment of the environmental sustainability of factories can be used in a variety of ways and in different planning and life cycle phases. For example, the ecological assessment can be used both in factory planning to select a preferred planning variant and in factory operation to record the current status. Conventional, often manual planning methods frequently prove to be insufficient to fulfil requirements such as the consideration of the entire life cycle of a factory or the demand for high data transparency. The use of Building Information Modeling (BIM) is a promising way of overcoming this challenge, as it is already used in practice to capture relevant information and data for the life cycle of a building.
This article demonstrates the importance and challenge of assessing the ecological sustainability of factories from a spatial and process perspective using BIM. Based on this, requirements are formulated for a standardized and application-oriented procedure that enables a life cycle-oriented sustainability assessment of factories.

Keywords

Factory planning; Sustainability assessment; Building Information Modeling (BIM); Life-cycle-assessment; Production system

1. Introduction

In recent years, sustainability has established itself as a key objective to ensure the long-term competitiveness of industrial companies, as a complement to economic efficiency [1] The focus is primarily on resource-intensive production processes and the associated factory buildings [2]. In addition to the global challenges of mitigating climate change [3] is also an increasing number of regulatory requirements promoting environmental sustainability awareness [4–6]. The industrial sector is responsible for around 25% of CO_2 emissions worldwide. Similar pattern can also be observed in Germany. In 2023, for example, 674 million tons of CO_2 were emitted in Germany, with 155 million tons of CO_2 attributable to manufacturing and industrial processes [7]. In order to limit the effects of climate change and prevent an irreversible tipping point, the industrial sector must be CO_2-neutral by 2035 [8–10]. Accordingly, the focus has shifted from the economic sustainability of companies alone to the resource intensity of production processes and the associated factory buildings. The ecological consideration of the factory building is primarily concerned with the production and realization process. In contrast, the ecological consideration of a factory concept,

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within the context of the production of climate-neutral goods and the avoidance of resource waste, focuses on the factory operation. This illustrates the need to consider the environmental sustainability over the entire life cycle of a factory in the early factory planning stage, as the majority of environmental impacts occur with a delay in the utilization phase [11]. FRANZ [12] shows that the potential for sustainability in industry has neither been fully realized in practice nor sufficiently addressed in research. Companies focus primarily on increasing the efficiency of individual systems, ignoring the fact that the individual systems are integrated into the overall factory system [13]. As a result, potentials from the interactions of the factory-inherent elements are not considered. An example of this is layout planning, in which the arrangement of systems during the planning or reorganization of a factory is based on the floor plan. In practice, energy-relevant building characteristics are often not taken into account in such planning processes and the process view (production and process planning) and the spatial view (building planning) remain decoupled from each other [1]. This can lead to processes with high heat emission being optimally designed in terms of material flow, but a low ceiling height or direct sunlight making it necessary to avoid cooling the area.

Although there are significant opportunities to reduce energy consumption in the industrial sector, so far only isolated measures have been adopted to exploit this potential. It is estimated that 25-30% of energy can be saved in the industrial sector [14]. There is a clear difference between large companies and small and medium-sized enterprises (SMEs) with regard to the implementation of measures to reduce emissions from buildings. For example, 42 % of large companies have already introduced such measures, whereas the share of SMEs is only 22 % [15]. Insufficient use of sustainability potential harbors considerable economic risks, especially for SMEs. On the one hand, SMEs in Germany finance themselves less via the capital market and more via banks. Sustainability criteria are playing an increasingly important role in creditworthiness checks, which gives sustainability particular importance for SMEs [16,17]. On the other hand, the price of electricity in Germany increased by 160 % and the price of gas by around 216 % between 2013 and 2023 [18,19]. In conjunction with the top energy price level in Europe and supply bottlenecks from abroad, this may mean that in the long term it will no longer be economically viable to invest in resource-intensive industries in Germany [20].

In summary, it can be said that environmental sustainability is becoming increasingly important for companies on the one hand and for the factory planning process on the other in order to ensure long-term competitiveness in volatile and dynamic markets. In addition to its relevance for the climate, the exponential rise in energy prices, the high number of regulatory requirements and financing, among other things, make it economically necessary to identify sustainability potential. A comprehensive assessment of the ecological sustainability of a factory system requires the consistent inclusion of all factory elements and their interactions, including the environmental impact of the buildings (e.g. building materials) and emissions from the production processes [21]. Transparent documentation of the planning process and the transfer of data to factory operations are essential to meet regulatory requirements such as CO_2 balancing [22]. Because of the complexity of this assessment over the entire life cycle of a factory, conventional methods or procedures are often inadequate or require a large amount of manual effort [23,24]. Instead, using digital methods has become invaluable for the assessment of ecological environmental impacts [25,26]. Therefore, Building Information Modeling (BIM) offers a promising opportunity to present the factory planning process in a transparent and synchronized way, as well as to illustrate the evaluation and improvement of the ecological sustainability of factories.

The research project ‘ecoFIM – Assessment of ecological sustainability of factories using Building Information Modeling (BIM)’ addresses the problem described above and pursues the aim of application-oriented assessment and increasing the ecological sustainability of factories through BIM. In this article, the problem of life cycle sustainable factory assessment described at the beginning is first explained in detail by considering the essential components of the factory life cycle, sustainability assessment and BIM. The central research objective of the project ‘ecoFIM’ is then presented and the requirements for a solution concept to be developed are described. Based on this, an approach is presented. Finally, a conclusion and an outlook on the next steps in the 'ecoFIM' project are given.

2. Problem Statement and Research Gap

The realization of an eco-efficient factory in all stages of its life cycle and its evaluation is demanding in practice. A particular challenge is to include all ecologically relevant aspects and influencing factors over the entire life cycle of a factory [4]. In contrast to the planning and assessment of buildings, the assessment of factories requires a multi-dimensional approach that includes not only the building itself but also the production and its processes [1]. A further challenge in the ecological assessment of factories is the high data requirements and the associated documentation and traceability of all the results of a highly complex system such as a factory [22]. In the following, relevant components of the evaluation framework are explained in detail, to highlight the challenges and potential of each component. While the first part (section 2.1) focuses on life cycle considerations, the challenges of factory sustainability assessment and BIM implementation follow in section 2.2 and 2.3.

2.1 Factory planning in the life cycle

Factory planning can be regarded as a deciding factor for the economic success of companies [27]. This is mainly due to the fact that factory planning decisions are often of strategic and long-term relevance [27,1]. A large number of factory planning approaches exist in the literature [27–30]. In order to synchronize and systematize the various planning activities, different procedures have been consolidated in the guideline VDI 5200 [31,1]. The guideline divides the planning process into seven successive phases, which are executed sequentially during the planning process and thus lead to a successively detailed planning result [31,1]. The approach of synergetic factory planning made a significant contribution to VDI 5200 and is characterized by the coordination of the sub-disciplines of production and object planning in terms of time and content [32]. The approach developed by WIENDAHL, NYHUIS and REICHARDT meshes the phases of production planning (process view) with the phases of object planning (spatial view) in accordance with the Fee Structure for Architects and Engineers [32–35]. The aim is to take account of the interdisciplinary character of the factory by combining and coordinating the planning and design of the logistical and technological processes with the interior and exterior design of the factory from an architectural perspective [1].

The factory as a complex socio-technical system is also defined as the place of value creation [31] and can be divided into factory levels and factory fields according to the hierarchical concept of systems theory [13]. The factory levels represent the vertical subdivision of the factory. This article focuses on the plant, factory, area and workstation levels [36,13,37]. The horizontal subdivision can be achieved by the factory fields, which are embodied by the design fields of technology, organization and space and can optionally be supplemented by people and management [38,39]. When factory levels and fields are compared, a matrix is created that represents the factory's frame of reference [40,41]. Factory objects can be extracted from this matrix, which embody all physical (e.g. means of production) and non-physical components (e.g. production concept) of the factory [38]. Both the factory and the factory objects have different life cycles, which contain characteristic, cyclical process patterns of the system under consideration over time [42,43]. With regard to factories, a distinction can be made between component, product, process, plant and building lifecycles [44,45]. Figure 1 shows an extract of factory objects and the exemplary life cycles of the factory and its elements.

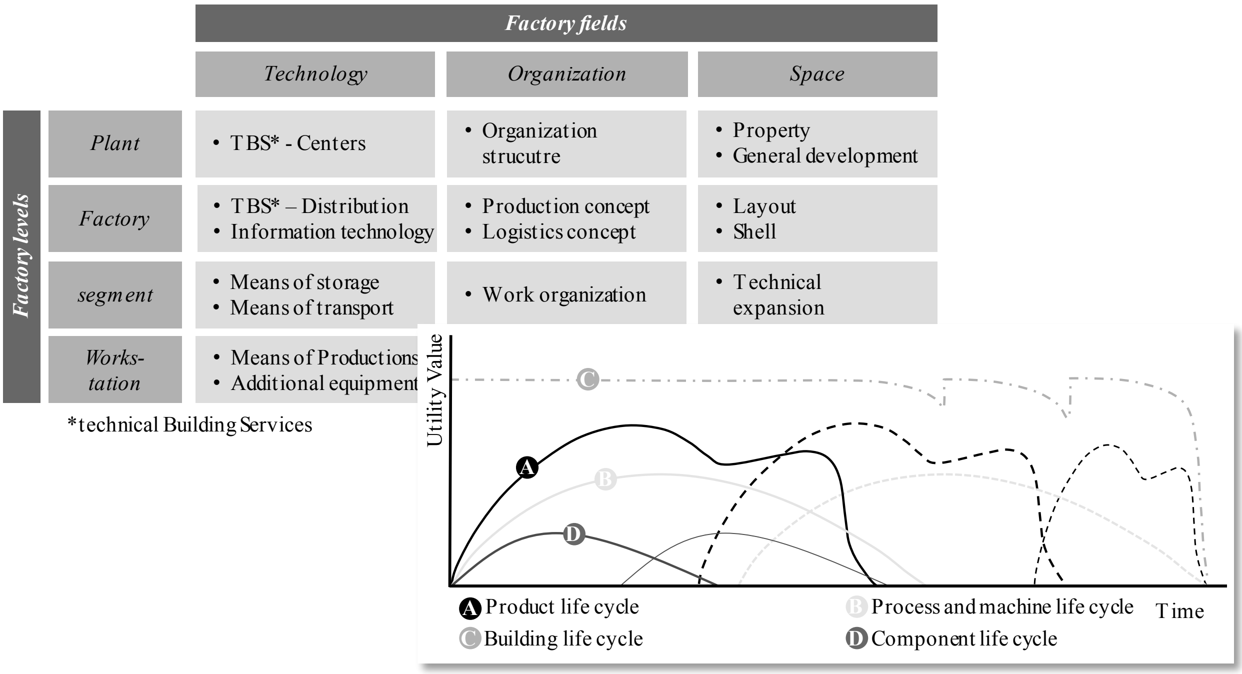

Figure 1: Extract of factory objects and exemplary representation of the life cycles in a factory (based on [11,38,44,45])

These different cycles must be synchronized in the best possible way to maximize the factory's potential [46]. The simultaneous management of these cycles is referred to as cycle management and has recently received increased scientific attention [47,44]. In general a factory is designed for a life cycle of around 30 to 50 years [48], whereby the inherent elements such as machines have a shorter life cycle [29]. Each factory object usually has the highest utility value at the beginning of its life cycle, which then decreases over time [49]. The longevity of a factory and its factory objects as well as the diverging life cycles within a factory demonstrate that is not sufficient to consider only one life cycle phase. Instead, the life cycle approach is necessary to make long-term economic and ecological decisions as early as the factory planning stage [50,51]. However, such an approach still presents a significant challenge, as it must consider both the factory and its objects, as well as their interactions across all life cycle phases.

2.2 Sustainability assessment of factories

As the construction industry becomes increasingly sustainable, smaller companies face particular challenges. From a financial perspective, the transition to investing in more sustainable factories has the potential to affect the distribution of costs over the life cycle of the factory. As a consequence of sustainable design, construction costs increase, while operating costs, which arise over most of the life cycle, tend to decrease [52]. For example, photovoltaic systems illustrate this dynamic as construction costs initially rise, while operating costs decrease due to self-generated electricity This is a challenge, as price differences in construction costs still often serve as the primary decision criterion and thus determine the contract awards for construction companies. In addition, SMEs are confronted with higher costs for training and further education for employees when switching to a more sustainable operation. SMEs often lack the resources and experience to deal with these innovative methods and materials [52,53]. Moreover, current sustainability certificates and certification systems pose a major challenge in the implementation. In particular, the large number of different assessment methods, databases and quality seals for building products causes confusion and often presents companies with significant obstacles [54].

In sustainability assessment, a distinction is made between methods for assessing construction products and methods for determining the sustainability of buildings, as well as methods for process assessment, which are also relevant for factories. There are both international and national certification methods for assessing the sustainability of buildings. The largest international organizations include BREEAM (UK), LEED (USA) and the German Sustainable Building Council (DGNB) [54]. Alongside the German Assessment System for Sustainable Building (BNB), which is applied to the public sector, DGNB certification is the acknowledged procedure for the sustainability of buildings in Germany. DGNB certification is intended for application in the private sector and is, therefore, most relevant to factory buildings. The certification system assesses environmental, economic, socio-cultural and functional quality as well as technical process quality and conditions on the construction site. The focus of this paper lies on the environmental quality and in particular the LCA. The individual indicators are evaluated by performing a LCA for each phase of the building's life cycle. Environmental indicator data sets from several sources are also used in the assessment. The most established database, the ÖKOBAUDAT, is provided by the German Federal Ministry of the Interior and Community and contains general and specific environmental product declarations (EPDs). Additionally, the IBU database, DGNB Navigator or ECO Platform can be applied [55]. The main challenge of these databases is their suitability for factory buildings and especially the production processes, as their main focus is building materials. In order to establish an efficient assessment method for factories, it is necessary to evaluate the suitability of different databases and assessment systems for factory buildings. Integrating the assessment of the building as well as the production elements and thus providing a holistic view of ecological sustainability is both the challenge and the goal of the approach outlined in section 4.

2.3 Building Information Modeling

As shown in the previous sections, to assess the sustainability of a factory at both the building and production process levels, it is necessary to have a comprehensive and reliable data foundation [23]. Furthermore, the traditional LCA procedure is time-consuming and prone to errors. In particular, SMEs are confronted with the financial and technical challenges associated with implementing a factory LCA [56]. The collaborative method of BIM represents a potential solution to the identified obstacles [26]. BIM is a collaborative and digital planning method that allows for efficient information exchange between all stakeholders [57]. Furthermore, the generation of an object-based model, a BIM model, indicates that the 3D-model not only embodies geometrical information, but also incorporates semantic information for each building component. Thus, materials and their quantities, as well as other relevant information for the LCA, can be obtained from the BIM model [58].Building Information Modeling offers the potential for cost and time reduction in planning and construction processes [59,60]. Through the implementation of BIM, errors in the design phase can be reduced and, as a result, the planning time and costs during the construction phase are lowered [2]. Besides the more general benefits, BIM can be used to create semi-automated LCA and can therefore serve as a decision-making aid [61]. BIM offers benefits not only in LCA, but also in linking to material passports, life cycle costing and simulation, making it an important tool in the field of sustainable construction [62]. WASTIELS and DECUYPERE identified five general strategies for performing LCA using BIM, as illustrated in Figure 2:

- The first strategy proposes that the bill of quantities is exported from the native BIM model and imported directly into the LCA software. The building components and their quantities are then manually linked to the EPD in the LCA software, which implies certain obstacles in the iterative planning process.
- According to the second strategy, an Industry Foundation Classes (IFC) file of the BIM model is imported to the LCA software, where the building components are then linked to the associated EPDs. Hence, an iterative design process can be supported, as the GUID stays linked to the associated EPD when updating the IFC model.
- The third strategy includes a BIM viewer as an intermediate step between the generation of the BIM model and the LCA software. The assignment of the EPD to the building component occurs in the BIM viewer. Like strategy three, this approach allows for the preservation of the link between the geometric data and the EPD.

- The fourth strategy applies a different approach, using an LCA plugin for the BIM software. Consequently, linking LCA data directly to the components when modeling in the software is possible. This enables the LCA to be performed partially automated directly in the BIM software. The evaluation is then carried out using separate LCA software. This strategy can create awareness of potential ecological hotspots during the modeling process.
- Finally, the EPD data is attributed to the building components from the start of the fifth strategy. For example, when a generic wall is modeled earlier in the design stage, the generic EPD data is already attributed to the object. In the same way, if a manufacturer-specific wall is added to the BIM model, the specific EPD data is attributed. The final assessment is done through a LCA plugin or alternatively in a separate LCA software. This fifth strategy allows for real-time feedback on the sustainability of the used materials and can be used as a decision support tool early on [58].

A study from 2022 found, that strategy one and four are most applied in the German construction industry [63]. Strategy one is the most labor-intensive strategy, but requires the lowest BIM maturity level. The strategies must therefore be evaluated for applicability in SMEs.

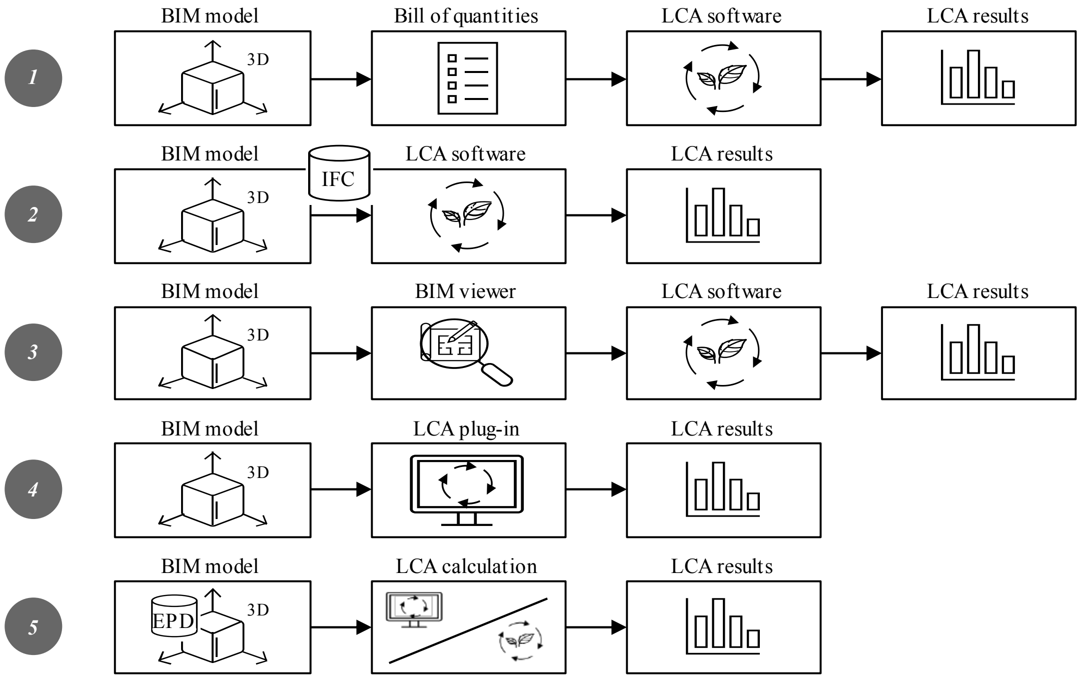

Figure 2: Strategies for LCA integration in BIM (based on [63,58])

While the implementation of BIM is relevant to both large and small companies, smaller companies often lack the knowledge and experience to implement complex and technically in-depth processes [64]. This low level of digitalization results in even more labor-intensive LCA processes. Simultaneously, there is increasing pressure on companies to operate efficiently and to be able to demonstrate the sustainability of the company's assets [16,17]. Therefore, the goal is to create a process of model-based sustainability assessment, that is suitable for small and medium-sized companies. There are several inherent challenges to this process, the most important of which appear to be the quality or incompleteness of BIM models and the lack of requirements for the level of information needed. Data exchange between stakeholders and between LCA and BIM tools is another significant challenge for BIM and LCA integration practitioners [65]. The project ecoFIM aims to address these challenges, as shown in section 4. There are also certain obstacles to implementing BIM in the factory design process. An essential challenge, also in the context of sustainability, is the lack of data structures in the open BIM context for some production processes and systems in a factory [66]. In conclusion, the objective is to create a methodology that incorporates data regarding production procedures into a BIM model while simultaneously developing a process accessible to SMEs. As a result, there is a need for the development of a data structure that organizes all the necessary information.

3. Objectives and requirements for the solution concept

A research objective can be derived from the problem description and the presentation of its relevant components: The aim of the research project 'ecoFIM' is to develop a standardized procedure with the help of a guideline for the application-oriented evaluation and increase of the ecological sustainability of factories through BIM. The initial stage of the process is to define the requirements for the procedure. The following requirements were derived from an analysis of the problem described and the challenges.

1. **Application in factory planning and operation** – The method is suitable for use in both the evaluation of the ecological sustainability of layout concepts in factory planning and in the assessment of existing factories in operation.
2. **Holistic view of the factory -** By taking a synergetic view from a process and spatial perspective, it is possible to ensure that the interactions between the two planning disciplines and the entire factory system are considered.
3. **Life cycle assessment** – By considering the different life cycle phases of a factory, all environmental impacts can be considered for throughout the entire factory life cycle.
4. **Data integration** – As a large amount of information and data is required to assess the environmental sustainability of a factory using BIM, a standardized data structure is required to consolidate and process the data.
5. **Simple and targeted application –** Due to its intuitive and simple design, the application can also be used by SMEs without in-depth prior knowledge. In addition, an application-oriented guide is intended to enable users to use the system independently.

4. Approach and methodological concept of the ecoFIM research project

In order to do justice to the problem described, an approach is presented below with which the research objective of the project 'ecoFIM' is to be achieved. The procedure consists of five consecutive steps as shown in Figure 3.

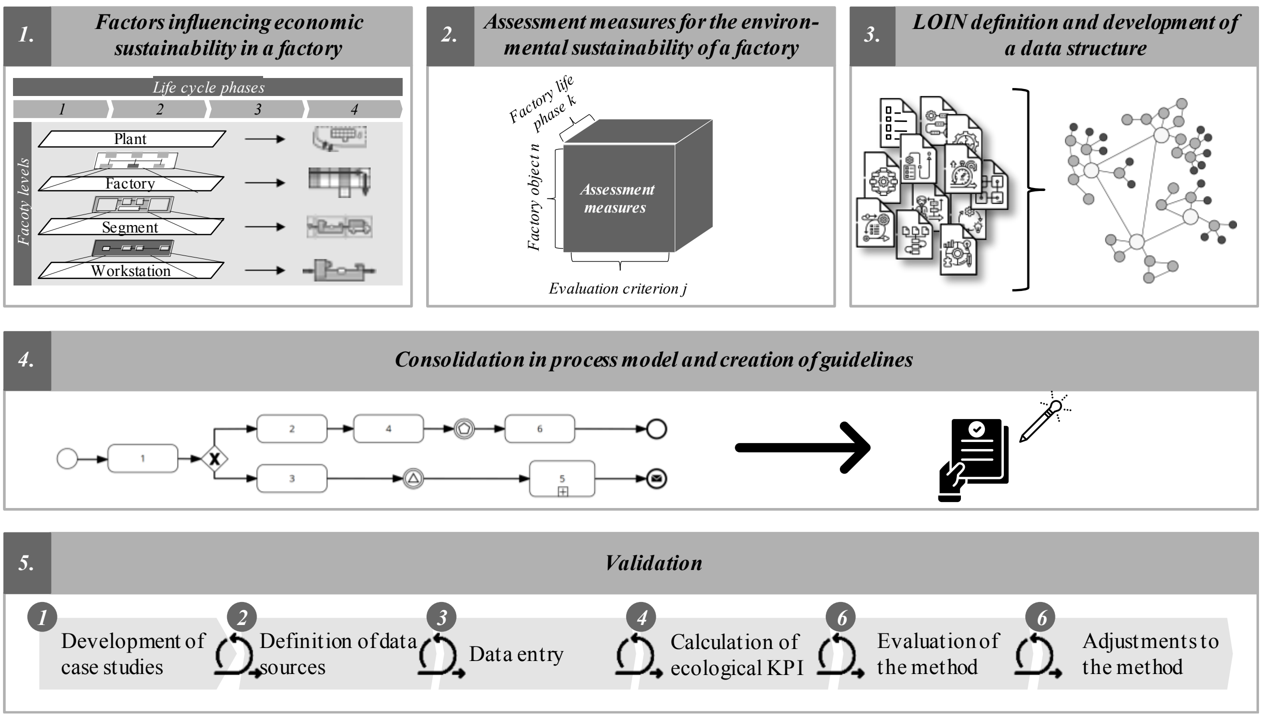

Figure 3: Methodology and approaches of ecoFIM

In the first step, all relevant factors influencing the environmental sustainability of a factory must be identified and structured for further processing. The first step is to analyze regulations such as DNGB certification and the current state of research with regard to relevant factors for assessing the environmental sustainability of factories. The factory is analyzed in two dimensions to ensure holistic coverage of its complex subject. The vertical analysis is carried out by looking at the factory objects presented in section 2.1 at the different factory levels. This ensures that the relevant elements are considered and evaluated from both the process view and the spatial view, while also considering their interactions. For example, at the lowest factory level (workstation), the foundation (spatial view) can be considered, in which all loads of a means of production (process view) are transferred to the subsoil, for example, via foundations or piles. In this context, the effects on environmental sustainability are suspected to be mainly determined by the choice of materials used in the construction phase. In contrast, the technical building equipment for heat or power supply can be considered at the factory level. Here, the focus is less on the construction materials and more on the energy requirements of building systems and production operations. This shows the relevance of the life cycle assessment, which is carried out in the horizontal analysis. For this purpose, the analysis runs along the typical life cycle phases of a factory and thus ensures that all life cycles of the factory and its factory objects are fully considered. In the second step, quantitative assessment measures for ecological sustainability are to be developed for the identified and structured influencing factors from the first step. In this step, the data requirements necessary for the calculation are determined and categorized, and data availability requirements are defined. In the third step, the necessary levels of detail for the various BIM objects are defined and cataloged in a Level of Information Need (LOIN) concept. Based on this, the cataloged information requirements are transferred into a logical data structure that can be integrated into BIM modeling in the digital factory planning process. It is essential to ensure that the data structure includes all relevant factory elements, along with the necessary information and specific calculation formulas. To facilitate the integration into the planning process, concepts are being developed to incorporate the information requirements into the employer's information requirements (EIR). In the subsequent fourth step, the results from the previous steps are summarized and the developed procedure is described in a guideline. The guideline will describe how a BIM model with the integrated data structure and the parameterized factory objects can be used to assess life cycle-oriented ecological sustainability. The project concludes with the implementation of case studies to validate the results achieved. The validation is to be carried out in an agile procedure by testing partial aspects during the development of the guideline in the fourth work step using previously selected case studies. The case studies should represent various life cycle phase of a factory so that environmental sustainability can be determined across different life cycle phases using the developed data structure and calculation formulas. To meet the requirement of applicability in factory planning and operation, different planning variants will also be evaluated for the case studies and compared with regard to their results to achieve the highest possible ecological sustainability.

5. Conclusion and outlook

As a result of the increasing number of regulatory requirements, growing customer awareness of environmental sustainability and the challenge of limiting climate change, companies are being forced to make their factories more sustainable in order not to risk their economic success. To harness the existing sustainability potential in factories and to plan factories ecologically throughout their life cycle, a holistic and life cycle-oriented assessment of environmental sustainability is needed initially. While these assessments have become increasingly important in the building sector in recent years, such an assessment for a factory remains a complex undertaking. The holistic assessment from a process and spatial perspective as well as the divergent life cycles of factory objects present particular challenges and require a high level of data. In this article, the challenges presented were first described in detail and the requirements for a solution approach were defined. Finally, an approach consisting of five steps was presented, with which a concept for the holistic and life cycle-oriented assessment of the ecological sustainability of a factory with BIM is to be made possible in the future. The outlined solution approach is to be further elaborated in further research work in the 'ecoFIM' research project.

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