Development and Implementation of an OpenBIM–LCA Workflow for Factory Planning

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Abstract –

Factories are a key part of industrial value creation and have a significant impact on the environment throughout the entire supply and production chain. Therefore, a sustainability assessment of both the building and the production system requires a holistic, interdisciplinary perspective on the factory system, which cannot be achieved using conventional methods employed for other building types. This study therefore addresses a research gap concerning the automated integration of Building Information Modeling (BIM) and Life Cycle Assessment (LCA) in the context of factory planning. The objective is to address the key challenge of linking multiple data sources for the very different interdisciplinary requirements. Hence, based on literature current approaches for both building LCA and factory planning processes are analyzed, and a factory-specific openBIM workflow for ecological assessment is proposed and implemented using Desite md. To meet the requirements of the various disciplines involved in the factory planning project, the workflow considers processes at both the disciplinary and coordination levels. To integrate the databases containing the energy demand and LCA profiles of the machinery and building materials used, the implemented approach connects individual production system databases, as well as building-specific databases such as the German ÖKOBAUDAT. The findings demonstrate the current potential and challenges of applying the workflow in Desite md, revealing practical insights for assessing the ecological sustainability of factory buildings. Ultimately, this supports factory operators in making more sustainable decisions during the design phase, leading to significantly more sustainable building operations.

Keywords –

Building Information Modeling (BIM), Life Cycle Assessment (LCA), sustainability, openBIM

1 Introduction

The environmental sustainability of industrial value chains is gaining relevance in light of advancing climate change, stricter legal frameworks and growing social expectations [1–3]. In the context of factory planning in particular, there is considerable potential to reduce environmental impacts across all life cycle phases [4]. In practice, Life Cycle Assessments (LCA) of factories, including the building, technical building systems (TBS) and production equipment, are challenging due to the extensive effort required to capture all environmentally relevant factors and their interactions over the entire life cycle [5]. In contrast to the planning of conventional buildings, factory planning requires a multidimensional approach that takes into account not only the building and TBS, but also production processes [6]. Another significant difficulty stems from the substantial amount of data generated by the project's interdisciplinary nature and the requirement for consistent documentation and traceability of results within such a complex system as a factory [7]. Building Information Modelling (BIM) offers the possibility of capturing, linking and systematically evaluating information across domains [8]. This raises the central research question of how a BIM-based approach to the ecological sustainability assessment of factories is designed so that it serves as a basis for sustainable decisions throughout the entire life cycle of the factory. Although various ecological assessment approaches exist [9, 10], they primarily address conventional buildings. Existing methods for production facilities consider only the production system and are not yet fully digitally integrated [11, 12]. Consequently, this study aims to develop a holistic, BIM-supported methodology for life cycle–based ecological sustainability assessment of factory planning projects.

2 Background and related works

2.1 BIM-based LCA

Several approaches to integrating BIM and LCA already exist for building construction and infrastructure projects. The predominant classification of these approaches was defined by WASTIELS AND DECUYPERE, who identified five overarching strategies for integrating BIM and LCA. The first strategy involves the manual export of the bill of quantities to a spreadsheet, wherein the LCA is calculated either directly or in a LCA software. Materials and quantities are manually linked to corresponding LCA profiles, representing the current state of practice [13]. The second strategy adopts an openBIM approach by exporting an Industry Foundation Classes (IFC) file to LCA software, transferring geometry, material names, and Global Unique Identifiers, after which materials are manually associated with LCA profiles. The third strategy, also based on openBIM, introduces an intermediate BIM viewer to link materials to LCA profiles, prior to performing the assessment in a LCA software. The fourth strategy employs a closed BIM approach, in which a plug-in within the native BIM authoring environment links BIM objects to LCA databases and visualizes results directly in the 3D model. Finally, the fifth strategy entails the direct allocation of LCA data to BIM objects, facilitated by either database identifiers or explicit indicator values. This approach finds application in both openBIM and closedBIM workflows, employing either plug-ins or IFC-based LCA software [14]. There is an absence of research approaches integrating BIM-LCA in factory planning, which is necessary because current approaches do not allow for an integration of the production system and are not addressing key requirements of factory planning. The key requirements of this use case are outlined in the subsequent subchapter.

2.2 Requirements for a BIM-based LCA workflow for factories

Factory planning is highly interdisciplinary and presents specific requirements for integrating BIM and LCA. In factory planning projects, up to 100 different disciplines may be involved. These disciplines can be divided primarily into the domain of factory planning (e.g. layout or logistics) as well as the domain of object planning (e.g. architecture, TBS). Their collaboration requires an error-free exchange of large and heterogeneous data sets [15–17]. This heterogeneity is mainly caused by discipline-specific data formats, software applications and modeling logics [16, 17]. In addition, several of these disciplines are required to collaborate within a shared or coordinated model environment rather than exchanging data sequentially, in order to enable a holistic sustainability assessment across building-related and process-related elements. Consequently, technical interoperability constitutes a central requirement for a BIM–LCA workflow. Standardized data exchange via open formats, such as IFC, is required for enabling an interdisciplinary flow of information.

In addition to technical interoperability, a suitable workflow must consider the existing IT systems of the parties involved in the planning process. Especially in small and medium-sized enterprises (SMEs), IT infrastructures are often centralised, inflexible, and modernised only incrementally [18, 19]. This is largely due to high software and implementation costs [20, 21]. This challenge intensifies in factory planning because individual planning tasks are often outsourced to external offices while the manufacturing company retains overall coordination [22]. Therefore, a BIM–LCA workflow must integrate with existing software portfolios and operate without fundamentally restructuring the IT landscape to be practical, particularly for SMEs.

Another key requirement is the integration of LCA datasets for factory-specific objects. While standardized and high-quality environmental product declaration (EPD) databases such as ÖKOBAUDAT are already available for the building perspective [23], data availability for the process perspective is highly individualized. Factories differ from other types of buildings, especially due to the integration of production equipment and associated media supply systems. These systems significantly contribute to the overall environmental impact [24, 25]. Accordingly, a suitable BIM–LCA workflow must support the simultaneous integration of multiple and heterogeneous LCA data sources to ensure that all relevant factory elements can be assigned appropriate environmental profiles. This includes the combination of standardized databases for building-related components with non-standardized, manufacturer- or project-specific datasets for production-related elements. Hence, the integration of factory-specific LCA data cannot rely on a single database but requires a flexible data integration concept that accommodates diverse data structures and levels of detail.

Finally, the project-based nature of factory planning requires flexibility in influencing the underlying calculation principles of the LCA. Each factory represents an individual planning project [26], meaning system boundaries, input-output flows, service lives of individual factory elements, and the temporal scope of the assessment must be defined on a project-specific basis [25, 27, 28]. Therefore, a BIM–LCA workflow must allow for the adaptation of the calculation logic and must not rely exclusively on proprietary default assumptions of LCA software, as this could otherwise lead to simplified or non-representative results [29].

In conclusion, the existing strategies are only suitable for implementation in factory planning to a limited extent. Consequently, to address the factory-specific requirements, a new workflow for BIM-based LCA for factory buildings is proposed in the following section.

3 OpenBIM Workflow for the LCA of a Factory

This workflow builds on the fundamental elements of BIM-LCA strategies that have been established in the construction sector but extends them to meet the requirements of factory planning, so that a holistic LCA of a factory can be performed during the various stages of the planning phase. This ultimately results in enhanced decision-making processes with regard to sustainability, thereby optimizing the entire life cycle of a factory.

3.1 Sustainability assessment

Prior to the development of the workflow, it is necessary to outline the general conditions for the environmental sustainability assessment of a factory, which include the considered life cycle phases and ecological indicators.

This workflow considers the whole life cycle of the factory and is based on the life cycle modules used in the construction industry, that are defined in EN 15978 [30]. Based on this standard the following life cycle modules are included: the production stage (A1–A3) covering raw material extraction, transport, and manufacturing; the construction process stage (A4–A5) addressing transport to site and construction activities; the use stage (B1–B7) comprising operation, maintenance, replacement, and operational energy and water use; and the end-of-life stage (C1–C4) including deconstruction, waste processing, and disposal [30].

The ecological impact of a factory system can be measured using various midpoint indicators, as in a typical LCA. This workflow emphasizes the most critical indicators for factories but can be expanded to include more. An analysis of German certification systems like German Sustainable Building Council [31] and Assessment System for Sustainable Building [32], as well as research approaches from Gebler [33] reveals that the environmental indicators global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), ozone creation potential (POCP), renewable primary energy demand (PERT), and non-renewable primary energy demand (PENRT) are classified as relevant or necessary across all approaches considered. Therefore, it can be concluded that these indicators can act as a basis for ecological assessment in the context of factory planning.

Furthermore, the selected indicators are suitable for incorporation into a BIM-LCA because they can be accessed in standardized life cycle assessment databases, such as ÖKOBAUDAT [34, 35].

3.2 Interoperability and openBIM

In order to meet the requirement of open data exchange and thus facilitate a comprehensive evaluation of the coordination model, the openBIM approach is employed. This approach ensures interdisciplinary information exchange via standardized data formats, particularly IFC [36]. While WASTIELS AND DECUYPERE identify three openBIM strategies, this workflow integrates the fifth strategy, which involves the semantic enrichment of BIM objects and their export to IFC, with the third strategy, which incorporates a BIM viewer. While many LCA software applications support importing IFC files, several studies demonstrate that differences in data structures between BIM and LCA systems often result in inefficient data exchange or lead to functional limitations [18–20]. Hence, utilizing a BIM viewer as a substitute and implementing the LCA calculation there can result in enhanced interoperability and minimal disruption to the BIM-based planning workflow. Additionally, implementing a BIM viewer fulfils the requirement for seamless integration with existing software portfolios, since BIM viewers are widely used for BIM-based planning.

In this workflow the semantic enrichment entails the addition of unique identifiers (ID) of LCA datasets to BIM objects, as opposed to the assignment of indicator values. Specifically, this implies that the materials contained in the respective discipline models are assigned corresponding IDs from environmental databases, for example the Universally Unique Identifier (UUID) in the ÖKOBAUDAT. This method reduces the impact on the quantity of data contained within the BIM model since fewer attributes need to be assigned.

Due to the large number of disciplines involved in factory planning projects, this workflow suggests a mapping process in which planners add the IDs to their discipline models in their authoring tools. Once this assignment has been done manually, the corresponding LCA indicator values can be automatically linked to the individual components in the model. A key advantage of this process is that the challenge of assigning the right data set is already solved at the level of the individual discipline models. The early and automated assignment of LCA IDs within the respective BIM objects ensures the consistency of the environmental data basis before the discipline models are merged into an overall coordination model. This is especially true in the context where the disciplines of factory and object planning interact, and a lack of expertise exists among sustainability experts to map the LCA data sets for both domains. Furthermore, as the transition to standardized, semantically enriched object libraries in BIM authoring tools continues, this effort can be minimized in the future [37].

3.3 Integration of multiple databases

Due to the different planning domains described in section 2.2, the integration of various databases is required. The following section explains which databases are considered in this workflow.

This workflow focusses on the database ÖKOBAUDAT as an environmental database for the domain of building and technical building systems. The ÖKOBAUDAT is the official database for German sustainability certification systems and comprises over 2,100 data sets that have been specially prepared for construction products [35, 38]. As a material-based database, the ÖKOBAUDAT provides specific environmental factors for individual materials, allowing for precise life cycle assessments based on material-specific data [39].

In contrast to the construction sector, there are no established environmental databases for production equipment in the factory planning domain. Therefore, manufacturer-specific EPDs are critical for ensuring consistent and robust LCAs in factory contexts. Instead of a standardized database, company-specific databases or Excel spreadsheets are used to assess the necessary data for evaluating the production system. Enterprise resource planning (ERP) systems, such as SAP, can also provide important data on machines and their media usage [11]. An ERP system is a business management software solution that aims to automate and integrate a company's central business processes and link them via a company-wide database. It enables access to real-time information, avoids data redundancy and ensures data integrity by providing a single source of truth. [40] Manufacturing companies use ERP systems as central data repositories for managing project-related information. This system stores and provides structured access to general project information and environmental data, technical parameters, cost overviews, maintenance intervals and measures, as well as process management information [11]. These data are necessary for sustainability assessments. For this reason, integrating different databases and ERP systems is recommended for this workflow to meet the aforementioned requirement of integrating databases from both planning domains. Although the implementation described below primarily uses CSV files, a direct connection via Application Programming Interfaces (API) is planned for future work to ensure accuracy.

3.4 Integration in planning process

Having described the theoretical basis of the key elements of the workflow in previous sections, this section summarizes the complete workflow and its integration into the planning process. The foundation of this workflow is based on existing standards and guidelines.

In accordance with the guideline of the Association of German Engineers [41], planners assign the ID parameter to match the LCA data sets of their BIM objects, as explained in chapter 3.2. After enriching the model, planners are responsible for conducting plausibility and validation checks to ensure that all BIM objects are assigned the correct LCA datasets. This includes verifying the completeness and correctness of the required datasets. Subsequently, the BIM coordinators of each discipline upload the approved IFC files to the Common Data Environment (CDE) [41]. The overall BIM coordinator is responsible for merging the IFC files in a coordination software (e.g., Desite md) and performing the second validation step. This involves a rule-based model check within the coordination software that detects missing attributes, such as IDs, and documents them in the form of a report. These reports are serve as the foundation for the corrective measures by the involved planners. Subsequent to validation and quality testing, a holistic LCA calculation is performed based on the enriched coordination model by the LCA expert. Consequently, the overall coordination model is automatically linked to the databases via an API within the coordination software. Based on this, the rule-based LCA calculation is performed. Figure 1 provides a graphical summary of the workflow.

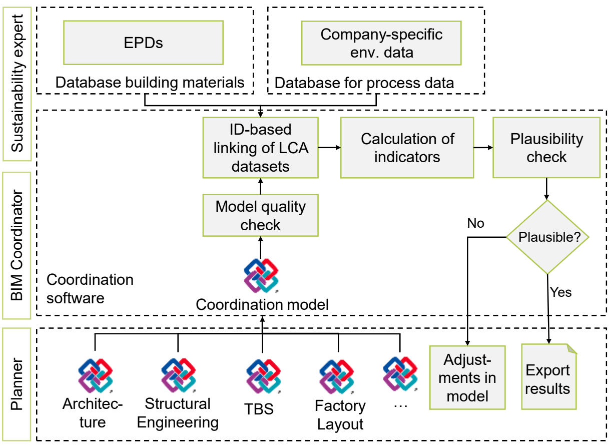

Figure 1 BIM-based factory sustainability assessment

3.5 Modelling requirements

For this workflow to be executed, it is essential that certain modeling requirements are met. First, the aforementioned ID is written as a shared parameter and, in the context of IFC data exchange, is assigned to a user-defined Pset, such as 'Pset_LCA'. It should also be noted that the UUIDs are version-dependent and that both the

UUID and the version number (e.g. as LCA_Version) must be stored in the model during the mapping process. In addition, the type and material information should be assigned for the purpose of simplifying the plausibility check later on.

While this procedure applies to all elements of the object planning domain, additional aspects must be considered for the technical building equipment. According to the findings of GENOVA [42], the technical elements can be divided into two main categories: technical routing and technical devices. The technical routing system covers all components such as pipes, air ducts, electrical cables, lighting systems and cable trays and their fittings. These are typically characterised by the fact that they are generated by extruding a cross-section along a line path. These elements are usually not represented in detail geometrically, while the information content is nevertheless retained in full. However, a technical deficit arises from the fact that, for example, authoring tools like Revit do not allow direct access to volumetric geometry data for these components. This makes it considerably more difficult to calculate material masses. A practical solution is to determine the area resulting from the thickness of the pipe and the circumference and multiply it by the length of the corresponding reference line. Based on this, mass values of the components can be calculated [42]. The second category, technical devices, includes all industrially manufactured products installed in a building whose dimensions and material composition are usually specified by the manufacturer per piece. The correct reference flow of the matched LCA data set should therefore be automatically read out so that no errors occur in the calculation and the correct unit is assigned.

In the scenario where SAP is used as the company-specific data repository and therefore needs to be integrated with BIM, the BIM objects, along with their properties such as dimensions and material definitions, are assigned to the corresponding SAP identifiers and attributes. This data mapping process between BIM and SAP is carried out using a classification system. The use of classification systems supports the assignment of BIM data to corresponding structures in the SAP system [43]. The classification system must be adapted for factory planning, as established classification systems are designed for building construction in accordance with the ISO 12006-2 standard [44]. For this purpose, it is recommended that the ECLASS classification system is used. ECLASS is an internationally recognized standard for the uniform description and structuring of products, machines, components and services [45, 46].

For a consistent BIM-SAP link, it is necessary to store the ECLASS codes as type parameters in the BIM model. This makes it possible to uniquely identify, for example all CNC milling machines in the model using an eight-digit code. When exporting to IFC, these parameters must be assigned in IfcClassificationReference [47]. The ECLASS codes and versions stored in the SAP system can be exported in the form of structured data records (e.g. as CSV or Excel files). These usually contain the material number, the equipment ID, a textual product description, the associated ECLASS code and the ECLASS version used. Integration with the BIM model is achieved by mapping the data exported from SAP to the model objects available in the authoring software.

4 Implementation

For the exemplary implementation of the calculation part of the workflow, Desite md and therein WebForms are used to demonstrate the automatic linking of LCA data sets and BIM objects based on their common ID for elements of the building as well as the production system.

For this purpose, two types of databases are integrated: the ÖKOBAUDAT and a spreadsheet-based database containing LCA data for production equipment, both provided in CSV format. The ÖKOBAUDAT is available as a CSV file on their website. [35] The second CSV acts as examples of ERP system exports or other company-specific data that could be queried via an API in the future. The CSV requirements and IFC export information can be found here [48].

The internal functioning of the WebForm is based on a multi-stage processing sequence. This sequence includes reading the CSV files, recognizing and aggregating the relevant data records, mapping them to the model objects, and assigning the sustainability indicators via the Desite md API. The logic is controlled entirely by JavaScript, while the user interface is implemented in HTML. Both components interact closely with each other via the Desite md API, so that all data is processed directly in the model. The script links the environmental indicators from the ÖKOBAUDAT with the corresponding component instances in the model in Desite md. This is based on reading the UUIDs from the ÖKOBAUDAT and the associated identification attributes in the model. The relevant field names for identification and assignment parameters can be defined by the user directly in the user interface. This allows the script to be flexibly adapted to different model structures, data exports and attribute names.

First, the UUID column is searched for the ID in the model and the indicator columns for example for GWP and PERT are identified. In the next step, the BIM objects are read into Desite md. Here, either all objects or only the currently selected elements can be processed, so only a selection of relevant objects can be evaluated as well. Objects without valid identification are given the status ‘no match’. If there is a valid match, the corresponding sustainability values are assigned to the BIM objects. The process is the same for the production system, except a company-specific equipment ID is used to link the database.

During processing, a tabular overview of the processed objects is created. This overview contains not only object names and IDs, but also the mapping status and all transferred sustainability indicator values, their reference units, and the indicator totals. Since the reference unit of the LCA data set is identified automatically, the indicator total is calculated by automatically multiplying the indicator value by the correct unit of measurement. In addition, several key figures are calculated automatically. These include the total number of objects in the model, the number of objects with a valid UUID, the number of objects without a match, and the sum of the calculated GWP values, separated by buildings and production equipment, as well as the total. While there are 4,202 objects in the tested model, 14.8% of them are unmatched. This is because some of the objects, such as rooms or small parts of the façade, do not have a UUID. The result can be saved as a CSV file using the export function. The key figures are then written back to each BIM object as attributes and are therefore suitable as a basis for variant comparisons, optimization and heatmap visualizations.

To test and evaluate this WebForm, an example model containing objects of building construction and production equipment is used.

The result is an evaluation of the entire factory, including the building and the production equipment. For this evaluation, multiple databases are linked to the BIM model, allowing the results to be written back to the BIM objects.

4.1 Discussion

The results of this study are to be interpreted with consideration of the following limitations, which also represent potential for further research. First, there is currently insufficient availability of environmental datasets to consistently establish one-to-one links between BIM objects and LCA data using unique identifiers, such as UUIDs. Consequently, future work will require a mixed linking approach combining identifier-based assignment with direct assignment of LCA indicator values to BIM objects. Second, component service lives are not yet integrated into the assessment framework. As a result, the replacement of building elements and technical components over the life cycle is not yet accounted for. Addressing this limitation will require either an enrichment of the underlying databases with service life information or the introduction of classification-based matching using external databases for typical life spans of different construction and equipment types. Third, energy demand is considered exclusively at the level of production equipment. Energy consumption associated with technical building systems beyond machinery is not included, leading to an unrealistic representation of operational impacts. Nevertheless, this exemplary implementation indicates the potential and feasibility of the proposed workflow.

Despite existing limitations, the workflow fulfills the initially outlined requirements by enabling a holistic assessment of a factory, including the building and the production system. Additionally, the logic can be transferred and expanded to various factory elements. Overall, the proposed LCA data set matching workflow based on unique identifiers in the IFC model can significantly reduce the effort required for a factory sustainability assessment.

5 Conclusion

This work introduces a semi-automated openBIM workflow for the LCA of factories, integrating building construction and production systems within a digital process. By embedding LCA-relevant information directly into BIM objects through standardized identifiers, the workflow enables a consistent linkage between planning models and environmental datasets. The exemplary implementation using Desite md and WebForms illustrates the technical feasibility of identifier-based data linking for both building components and production equipment using a BIM viewer. However, the workflow must be tested on several different, more complex BIM models as a next step. Future work also requires incorporating component service life data into the employed databases and integrating technical building systems. Implementing these changes will improve the accuracy and comprehensiveness of the proposed workflow and build on the demonstrated potential and feasibility of this study.

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6 References

[1] S. Kadner, J. Kobus, M. R. Stuchtey, and T. Weber, "Circular Economy Roadmap für Deutschland.," acatech Studie. R. acatech/SYSTEMIQ, München/London, 2021.

[2] M. Landherr, M. Neumann, J. Volkmann, and C. Constantinescu, "Digitale Fabrik," in *Digitale*

Produktion, E. Westkämper, Ed., Berlin, Heidelberg: Springer Vieweg, 2013. [Online]. Available: https://doi.org/10.1007/978-3-642-20259-9_12
[3] M. Roesch, J. Köberlein, M. Goldmanns, and A. Hohmann, "Green-Lean-Digital als Leitbild für die nachhaltige Fabrik der Zukunft," *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, vol. 116, 1-2, pp. 29–33, 2021, doi: 10.1515/zwf-2021-0006.
[4] L. Philipp, L. Große-Wilde, L. Rieke, S. Hartmann, M. Schmidt, and K. Klemt-Albert, "Environmental Sustainability Assessment Of Factories With BIM: Relevance And Challenges For A Holistic Approach," in *Conference on Production Systems and Logistics*, Lima, Peru, 2025.
[5] J. H. Franz, *Nachhaltige Entwicklung technischer Produkte und Systeme: Der Ingenieurberuf im Wandel,* 1st ed. Wiesbaden: Springer Fachmedien Wiesbaden; Imprint Springer Vieweg, 2021.
[6] L. Rieke, J. Kerstgens, M. J. Kaufmann, C. Blanke, J. Reichardt, and M. Schmidt, "Bewertung der Zirkularität und Minimierung von CO_2-Emissionen im Gesamtsystem Industriebau – Case Study einer Gebäudebewertung mit madaster," (in ger), 2024, doi: 10.15488/17979.
[7] H.-P. Wiendahl, J. Reichardt, and P. Nyhuis, *Handbuch Fabrikplanung: Konzept, Gestaltung und Umsetzung wandlungsfähiger Produktionsstätten,* 3rd ed. München: Hanser Verlag, 2024.
[8] U. Bracht, D. Geckler, and S. Wenzel, "Anwendungen der Digitalen Fabrik," in *VDI-Buch, Digitale Fabrik: Methoden und Praxisbeispiele*, U. Bracht, D. Geckler, and S. Wenzel, Eds., 2nd ed., Berlin, Heidelberg: Springer Vieweg, 2018, pp. 259–373.
[9] Deutsche Gesellschaft für Nachhaltiges Bauen, *Das DGNB-Zertifizierungssystem.* [Online]. Available: https://www.dgnb-system.de/de/system/index.php (accessed: May 20 2022).
[10] Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, Ed., "Bewertungssystem Nachhaltiges Bauen (BNB)," Accessed: Feb. 18 2025. [Online]. Available: https://www.bnb-nachhaltigesbauen.de/bewertungssystem/buerogebaeude/
[11] D. Schneider, P. Jordan, J. Dietz, M. F. Zaeh, and G. Reinhart, "Concept for Automated LCA of Manufacturing Processes," *Procedia CIRP*, vol. 116, pp. 59–64, 2023, doi: 10.1016/j.procir.2023.02.011.
[12] T. Heinemann, S. Thiede, K. Müller, B. Berning, J. Linzbach, and C. Hermann, "Life cycle evaluation of factories: Approach, tool and case study," in *11th Global Conference on Sustainable Manufacturing*, 2013, pp. 479–484.
[13] R. Schumacher *et al.,* "Analysis of current practice and future potentials of LCA in a BIM-based design process in German," *E3S Web Conf.*, no. 349, 2022. [Online]. Available: https://doi.org/10.1051/e3sconf/202234910004
[14] L. Wastiels and R. Decuypere, "Identification and comparison of LCA-BIM integration strategies," *IOP Conference Series: Earth and Environmental Science*, no. 323, 2019. [Online]. Available: doi://10.1088/1755-1315/323/1/012101
[15] A. Meckelnborg, *Integrative Fabrikplanung durch effiziente Koordinationsmodelle*. Zugl.: Aachen, Techn. Hochsch., Diss., 2015, 1st ed. Aachen: Apprimus Verlag, 2015.
[16] C.-G. Grundig, *Fabrikplanung: Planungssystematik – Methoden – Anwendungen,* 7th ed. München: Hanser, 2021. [Online]. Available: https://www.hanser-elibrary.com/doi/book/10.3139/9783446470064
[17] P. Burggräf and G. Schuh, *Fabrikplanung*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2021.
[18] D. Lindner and C. Leyh, "Digitalisierung von KMU – Fragestellungen, Handlungsempfehlungen sowie Implikationen für IT-Organisation und IT-Servicemanagement," *HMD*, vol. 56, no. 2, pp. 402–418, 2019, doi: 10.1365/s40702-019-00502-z.
[19] D. Lindner and C. Leyh, "Organizations in Transformation: Agility as Consequence or Prerequisite of Digitization?," in *Lecture Notes in Business Information Processing, Business Information Systems*, W. Abramowicz and A. Paschke, Eds., Cham: Springer International Publishing, 2018, pp. 86–101.
[20] F. H. Abanda, C. Vidalakis, A. H. Oti, and J. Tah, "A critical analysis of Building Information Modelling systems used in construction projects," *Advances in Engineering Software*, vol. 90, pp. 183–201, 2015, doi: 10.1016/j.advengsoft.2015.08.009.
[21] A. Criminale and S. Langar, "Challenges with BIM Implementation: A Review of Literature," *Conference: 53 rd ASC Annual International Conference Proceedings*, 2017.
[22] J. Mohr, N. Schmidtke, and F. Behrendt, "Design of Matrix Production Systems: New Demands on Factory Planning Methods," *Procedia Computer Science*, vol. 232, pp. 1972–1981, 2024, doi: 10.1016/j.procs.2024.02.019.
[23] S. Theißen *et al.,* "BIM integrated automation of whole building life cycle assessment using German LCA data base ÖKOBAUDAT and Industry Foundation Classes," in *IOP Conference Series: Earth and Environmental Sciences*, 2020.
[24] M. Despeisse, P. D. Ball, S. Evans, and A. Levers, "Industrial ecology at factory level – a conceptual model," *Journal of Cleaner Production*, vol. 31, pp. 30–39, 2012, doi: 10.1016/j.jclepro.2012.02.027.
[25] M. Gebler, J. F. Cerdas, S. Thiede, and C. Herrmann, "Life cycle assessment of an automotive factory: Identifying challenges for the decarbonization of automotive production – A case study," *Journal of Cleaner Production*, vol. 270, 2020, doi: 10.1016/j.jclepro.2020.122330.

[26] M. Schenk, S. Wirth, and E. Müller, *Fabrikplanung und Fabrikbetrieb: Methoden für die wandlungsfähige, vernetzte und ressourceneffiziente Fabrik,* 2nd ed. Berlin, Heidelberg: Springer Vieweg, 2014.

[27] M. Perau, N. Laubach, T. Schröer, W. Boos, and G. Schuh, "Information-based Integration of Life Cycle Assessment into IT Landscapes of Manufacturing Companies," *IFAC-PapersOnLine*, vol. 58, no. 19, pp. 1204–1209, 2024, doi: 10.1016/j.ifacol.2024.09.089.

[28] A. Dér, L. Hingst, P. Nyhuis, and C. Herrmann, "A review of frameworks, methods and models for the evaluation and engineering of factory life cycles," *Advances in Industrial and Manufacturing Engineering*, vol. 4, p. 100083, 2022, doi: 10.1016/j.aime.2022.100083.

[29] C. Bueno and M. M. Fabricio, "Comparative analysis between a complete LCA study and results from a BIM-LCA plug-in," *Automation in Construction*, vol. 90, pp. 188–200, 2018, doi: 10.1016/j.autcon.2018.02.028.

[30] *DIN EN 15978 - Nachhaltigkeit von Bauwerken – Bewertung der Umweltleistung von Gebäuden – Methodik,* DIN-Normenausschuss Bauwesen (NABau), 2024.

[31] Deutsche Gesellschaft für Nachhaltiges Bauen - DGNB e.V., *Sustainable building with the DGNB: Europe's largest network for sustainable building, the globally recognised DGNB certification and much more.* [Online]. Available: https://www.dgnb.de/en (accessed: Dec. 19 2025).

[32] BBSR, *Evaluation Criteria for Laboratory Buildings.* [Online]. Available: https://www.bnb-nachhaltigesbauen.de/en/assessment-system/laboratory-buildings/ (accessed: Dec. 19 2025).

[33] M. Gebler, *Planung und Gestaltung einer Positivfabrik als Beitrag für eine absolute Nachhaltigkeit*. Wiesbaden: Springer Vieweg, 2022.

[34] M. Lambertz, S. Theißen, J. Höper, R. Wimmer, A. Meins-Becker, and M. Zibell, "Ökobilanzierung und BIM im Nachhaltigen Bauen," Forschungsendbericht im Auftrag des Bundesinstituts für Bau-, Stadt- und Raumforschung im Bundesamt für Bauwesen und Raumordnung, 2019.

[35] Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, "ÖKOBAUDAT," Accessed: Feb. 28 2025. [Online]. Available: https://www.oekobaudat.de/

[36] buildingSMART international, *OpenBIM.* [Online]. Available: https://www.buildingsmart.org/about/openbim/ (accessed: Dec. 19 2025).

[37] A. Hollberg, G. Genova, and G. Habert, "Evaluation of BIM-based LCA results for building design," *Automation in Construction*, vol. 109, 2020. [Online]. Available: https://doi.org/10.1016/j.autcon.2019.102972

[38] K. Forth, J. Abualdenien, and A. Borrmann, "Calculation of embodied GHG emissions in early building design stages using BIM and NLP-based semantic model healing," *Energy and Buildings*, vol. 284, p. 112837, 2023, doi: 10.1016/j.enbuild.2023.112837.

[39] R. Ayman Mohamed, Z. Alwan, M. Salem, and L. McIntyre, "Automation of embodied carbon calculation in digital built environment- tool utilizing UK LCI database," *Energy and Buildings*, vol. 298, p. 113528, 2023, doi: 10.1016/j.enbuild.2023.113528.

[40] H. Madathala, G. Yeturi, V. Mane, and P. D. Muneshwar, "Navigating SAP ERP Implementation: Identifying Success Drivers and Pitfalls," in *International Conference on Intelligent Data Communication Technologies and Internet of Things*, India, 2025, pp. 75–83.

[41] *VDI 2552 Sheet 7: Building information modeling — Processes*, 2552, VDI – The Association of German Engineers.

[42] G. Genova, "BIM-based LCA throughout the design process: A dynamic approach," *WIT Transactions on The Built Environment*, Vol 192, pp. 45–56, 2019, doi: 10.2495/BIM190051.

[43] V. Sagarkar, *Bridging the Gap: How BIM Integration with SAP Transforms Construction Project Management into 5D BIM process.* [Online]. Available: https://www.desapex.com/blog-posts/bridging-the-gap-how-bim-integration-with-sap-transforms-construction-project-management (accessed: Dec. 16 2025).

[44] *Building construction - Organization of information about construction works - Part 2: Framework for classification*, 12006-2, DIN German Institute for Standardization, Jul. 2020.

[45] ECLASS e.V., *ECLASS.* [Online]. Available: https://eclass.eu/ (accessed: Dec. 20 2025).

[46] Mittelstand Digital Zentrum, *ECLASS product data standard: Standardized classification and description of products and services.* [Online]. Available: https://www.mittelstand-digital-wertnetzwerke.de/interoperabilitaet/standards-im-e-business/klassifikation/eclass/ (accessed: Dec. 20 2025).

[47] *Building Information Modeling Klassifikationssysteme: Blatt 9*, 2552, Verein Deutscher Ingenieure e. V., 2020.

[48] *External Link for CSV and IFC export settings.* [Online]. Available: https://www.dropbox.com/scl/fo/u1kom999hajeah6ejxjo0/AITDWfCj9pc7ZNPj_Rd2w0M?rlkey=0wo30l1kwhxwv7qm7oss1iy7x&st=3i9rxv2q&dl=0