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Research Article

Toward a Lifecycle-Oriented Design for X (DfX): A Framework for Industrialized Building Products

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DOI: https://doi.org/10.66408/abc2.2026.38

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Received: *27/12/2025*
Revised: *28/01/2026*
Accepted: *21/03/2026*
Published: *22/03/2026*

Volume: *2026*
Issue: *03*
Pages: *1-14*

Abstract

In the building sector, the trend towards industrialization is accelerating. Although industrialized building products offer significant advantages, they face challenges throughout their lifecycle, many of which are related to the design phase. Current research has focused primarily on Design for Manufacturing and Assembly (DfMA), which, while valuable, tend to limit the broader integration of these products across the entire project lifecycle. To deal with this limitation, this study expands the design lens by examining a broader set of considerations collectively known as Design for X (DfX) to address the needs of various project phases right from the design phase. The goal is to enable the development of industrialized products that are not only optimized for manufacturing and assembly but also adaptable across the entire lifecycle of industrialized building projects. To achieve this, a systematic literature review was carried out using the WoS and Scopus databases, covering publications from 2015 to 2025. After a thorough screening and selection process, a qualitative content analysis was conducted to identify key design aspects relevant to industrialized building products. Then, a comprehensive framework was developed to categorize DfX considerations across the entire lifecycle of industrialized building projects, from design, manufacturing, and assembly to transportation, on-site installation, and end-of-life. This framework supports a more comprehensive approach to the industrialized design of building products. It can serve not only as a foundation for future research but also as a practical tool for evaluating the industrialization potential of building products during the early design phase.

Keywords: Industrialization; Design for X; Building products; Framework

Highlights

- Identify a broad spectrum of design aspects applicable to industrialized building products across their entire lifecycle.
- Develop a structured DfX-based framework that integrates key design considerations from early design through to end-of-life phases.
- Provides a practical framework for early-stage evaluation of industrialization potential in building product design.

1 Introduction

The construction industry plays a vital role in a country's economy, but it has not achieved the desired level of project delivery on time and within budget while maintaining safety, quality, and sustainability (Alsharef, Ovid, Jamil Uddin, & Albert, 2024). While productivity has increased significantly in Manufacturing industries through mechanization and standardization, the construction industry still suffers from project-oriented, fragmented, and disjointed processes. This has increased the motivation for the use of industrialization in the construction industry (Mansoori, Harkonen, Haapasalo, & Annunen, 2024). Industrialization in construction is borrowed from manufacturing, generally referring to a certain portion of construction modules that are not cast in situ, but are manufactured at a precast yard or factory, in which various materials are combined to form a distinct component of a larger installation, such as modular integrated units (Hao et al., 2020). Then, units are installed on-site with minimal staff involvement (Al-Awag, Alaloul, Liew, Baarimah, & Musarat, 2023).

Industrialized construction boosts speed, quality, and safety by shifting work to controlled factories and using standardization and modularization (Hyun, Kim, & Kim, 2022). Considering the established benefits of industrialization, the advancement of industrialized building products requires focused efforts, akin to the development processes of other manufactured products (Schulz, 2014). The design phase of product development frequently turns out to be the most crucial since it has a significant impact on the final product's cost and market viability (Volotinen & Lohtander, 2018). Product design can be very important in preventing many issues that may arise in later phases, from factory production and transportation to erection, installation, and maintenance of the building (Jung & Yu, 2022).

To incorporate effective design considerations that help mitigate future issues, numerous concepts have emerged under the umbrella of Design for X (DfX). DfX, is a product and process development methodology that aims to optimize 'X' during the course of the product's lifecycle (Gatzen, Pemberton, Peters, & Krueger, 2013). "X" stands for any particular aspect or phase, including assembly and manufacturing (Maskell, 2013). One of the aspects that is debated the most is Design for Manufacturing (DfM) and Design for Assembly (DfA). in the field of DfM and DfA, a great deal of study has been done. While the DfA concept relates to designing a product for ease of assembly (Zhai, Sun, Li, & Tang, 2023), DfM is described as the design for ease of manufacture of the collection of parts (Wasim, Vaz Serra, & Ngo, 2022). Although other DfX aspects can be important in further optimizing industrialization processes, the broader DfX concept and its consequences, have not yet been widely discussed in the building context (Laovisutthichai, Lu, & Lau, 2021).

Research has also been conducted in other aspects such as design for safety, design for disassembly, and design for circularity, but these studies have predominantly focused on industries outside of Architecture, Engineering, and Construction (AEC). Nevertheless, recent efforts increasingly aim to apply DfX principles within the building industry. To date, no study has integrated all DfX aspects relevant to the building sector. Integrating the different aspects of DfX is very important, because some of these aspects have mutual influences on each other, without which the product design cannot be improved in a comprehensive way, considering the needs of the different disciplines involved in the product. For example, a cheaper material may be used considering design for cost, while this material may conflict with design for circularity principles and have low reusability. Consequently, what is important is the synergy that occurs by considering all DfX aspects. To address this gap, the research objectives of this study are to:

1. Identification of DfX aspects in the literature that can be applied to industrialized building products
2. Developing a comprehensive framework of the identified DfX aspects across the lifecycle industrialized building products

The following sections address the background, research methodology, then results and analysis, discussion, and finally the conclusion, limitations, and future directions.

2 Background

2.1 Design for X (DfX): From Other Industries to Building Industry

The process of developing a new product is called product design (Jiang & Jiang, 2015). According to Laovisutthichai et al. (2021), who cited Bralla (1996), "DfX is a professional practice to design both products and processes for lifecycle cost-effectiveness, time-to-market shortening, high quality, and downstream production." The practice was first used in the manufacturing industry. At the moment, specific DfX aspects have surfaced to maximize each of the "X." Before extending to other industries, such as the building sector, X aspects usually first show up in manufacturing.

DfMA is a prominent illustration of these aspects. By creating a checklist of DfMA principles to evaluate industrialization across four stages, manufacturing, transportation, on-site assembly, and operation and maintenance, Jung and Yu (2022) employed DfMA to create an optimum design plan for off-site construction (OSC) projects. In the building sector, digital transformation technologies have also spread into the DfX context. While robotic manufacturing and assembly processes were simulated in Rhino, researchers concentrated on product modularization aided by digital design. Therefore, the use of robotic arms reduced the amount of timber used by making it easier to manufacture and assemble prefabricated timber components (Tan, Mills, Papadonikolaki, Li, & Huang, 2023).

In a different study, BIM was integrated into DfM to simulate construction robot movement. Additionally, a BIM-based algorithm facilitated better human-robot collaboration, standardized production processes (Hsieh, Huang, & Lan, 2024). Another study suggested a new framework to improve OSC client-design team collaboration. The authors created a Prefabricated Information Model that compiles all information pertaining to the manufacture, assembly, and customization of prefabricated components by combining parametric and algorithmic design techniques with the capabilities of BIM and the DfMA approach. Finally, a prototype that focused on window customization was ultimately put into use (Bakhshi, Chenaghlou, Rahimian, Edwards, & Dawood, 2022).

Since the introduction of DfX aspects into the building industry, some aspects have been expressly developed for this industry. Design for safety, design for deconstruction, design for sustainability, and design for construction waste minimization are some of the DfX aspects that are especially specified for building products. For instance, using a preventive design strategy to reduce construction waste is known as "design for construction waste minimization" (Laovisutthichai, Lu, & Bao, 2022). The literature from the building industry has also examined some DfX aspects, including design for maintenance, design for adaptability, and design for change (Hasani & Riggio, 2025). These aspects have now entered the larger realm of DfX aspects and relate to various stages of the product lifecycle. Designing products for easier and better maintenance is known as "design for maintenance" (Ganisen, Mohammad, Nesan, Mohammed, & Kanniyapan, 2015).

Adaptability, which is defined during the product's use phase, has contributed to shaping design for adaptability. Designing products to be easily repaired, modified, and adapted over time is referred to "design for change" (Vandenbroucke, Galle, De Temmerman, Debacker, & Paduart, 2015). Similar to design for assembly, design for disassembly has also been extensively addressed in the literature. In the latter phases of a product's lifecycle, design for disassembly, which refers to creating products that make it easier to disassemble them for repair or recycling (Shetty, Poudel, & Xu, 2015). Laasonen and Pajunen (2023) identified several criteria for the disassembly of timber elements, including ease of access to parts, ease of disassembly, independence, simplicity, and standardization. In conclusion, DfX aspects have permeated many facets of the building sector. Nonetheless, there is a dearth of DfX literature on the building sector and industrialized building products, which requires more research.

2.2 Knowledge Gap Regarding DfX in Industrialized Building Products

The analysis of the current literature in section 2.1 shows that certain DfX aspects have been partially applied to building products, indicating that the building industry is familiar with these concepts.

Certain aspects, such as design for sustainability, design for deconstruction, design for safety, and design for construction waste minimization, have been specifically created for the building industry and are used both conceptually and practically. Furthermore, several DfX aspects have been used more sparingly in a variety of industrialized products. However, there is still a noticeable disregard gap in the building industry, even with the recent growth of DfX aspects and their progressive adoption from other industries. The lack of a comprehensive framework that integrates all DfX aspects found in the literature across the whole lifecycle of industrialized building products is referred to as this gap. When DfX aspects are considered as islands, resources can be wasted. Because each DfX aspect may have different effects on the product that are in conflict with the others. In addition, designing simultaneously with different aspects of the DfX leads to a product that requires fewer future changes. The current study sought to fill this gap by identifying the various DfX aspects that have been presented in the literature and combining them into an integrated framework. This framework would indicate which aspects are considered in which phases of industrialized building products.

3 Methodology: Measuring Thresholds and Moderators

To achieve the research objectives, the researchers conducted a systematic literature review using two bibliographic databases: Web of Science (WoS) and Scopus. Searches were performed across the "Title, Abstract, Keywords" fields in two stages, as summarised in Table 1. In the first stage, an initial set of keywords was used to retrieve relevant publications. The results were then reviewed to identify additional pertinent terms, which informed a second, expanded search designed to ensure comprehensive coverage of the literature.

Table 1. Search string. (Source: Authors)

SLR steps	Search string
1	"Design for X" OR "Design for Assembly" OR "Design for Manufacturing" OR "Design for Robotic Assembly" OR "Design for Sustainability" OR "Design for Safety" OR "Design for Tracking" OR "Design for Logistics" OR "Design for Stacking" OR "Design for Transportation" OR "Design for Installation" OR "Design for Robotic Installation" OR "Design for Disassembly" OR "Design for Adaptability" OR "Design for Circularity"
2	“Design for Cost” OR “Design for Recycling” OR “Design for Recovery” OR “Design for Reusability” OR “Design for Deconstruction” OR “Design for Emotion” OR “Design for Remanufacturing” OR “Design for Upgrade” OR “Design for Maintenance” OR “Design for Flexibility” OR “Design for Reliability” OR “Design for Experience” OR “Design for Nonassembly” OR “Design for Variability” OR “Design for Change” OR “Design for Onsite Factory” OR “Design for Environment” OR “Design for Performance” OR “Design for Inspectability” OR “Design for Service” OR “Design for Multiple Lifecycle” OR “Design for Quality” OR “Design for obsolescence” OR “Design for supply chain” OR “Design for Autonomy” OR “Design for Packing” OR “Design for technological cycles” OR “Design for biological cycles” OR “Design for attachment and trust” OR “Design for durability” OR “Design for Compatibility” OR “Design for Longevity”

To ensure relevance to the research objectives, the selected papers were evaluated against several inclusion and exclusion criteria, including time period (2015–2025), English language, research area, document type, subject area, Web of Science categories, publication stage, keywords, and source title. Following this initial filtering, abstracts and titles were screened to remove remaining irrelevant papers, and duplicates across the two databases were eliminated. The dataset was further supplemented through forward and backward citation searching, which yielded 25 additional publications, and a review of DfX guidelines, best practices, and published reports, which contributed a further 16 documents. The complete search process is summarised in Figure 1.

Using NVivo software, 293 matching definitions and 44 unique DfX aspects were identified and extracted from the final corpus. A review of selected papers was then undertaken to establish the lifecycle of industrialised building projects aimed at delivering various types of building products. The content analysis results, together with the study objectives, were subsequently input into ChatGPT to categorise the DfX aspects according to their significance and applicability across the project lifecycle. Through iterative engagement with ChatGPT, a taxonomic framework mapping these DfX aspects to lifecycle stages was developed. Finally, the framework was validated by incorporating the expertise and experience of the supervisory team.

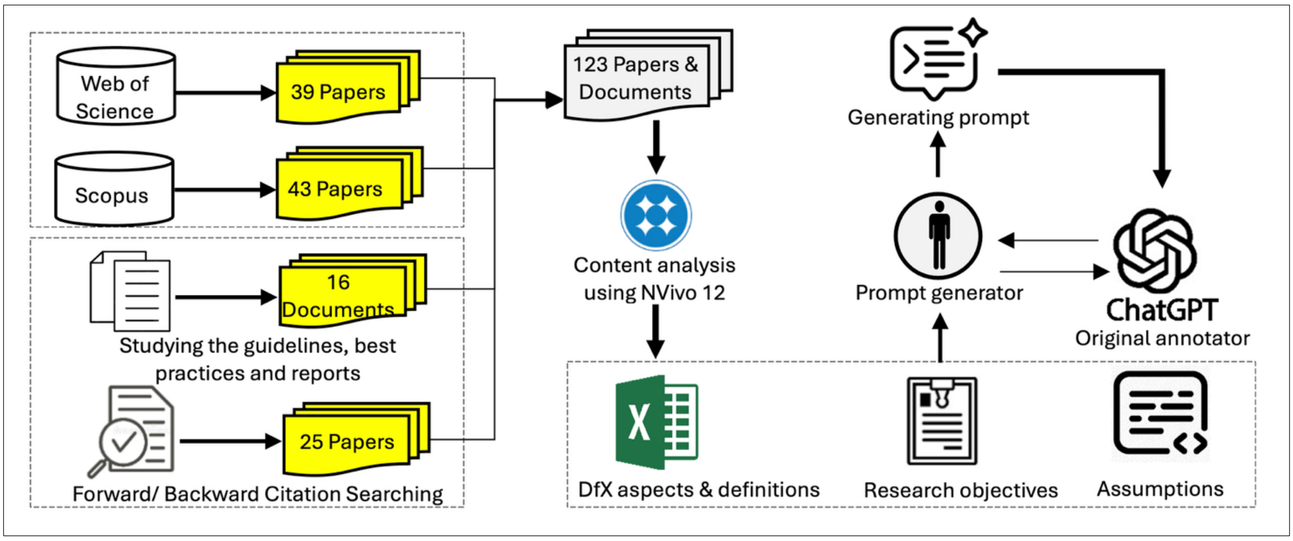

Figure 1. Research steps. (Source: Authors)

A human–AI collaborative approach, pairing researchers with ChatGPT was designed to leverage the complementary strengths of artificial intelligence and human cognition, following the human–ChatGPT interaction methodology proposed by Chen et al. (2024). First, an Excel file was compiled containing the DfX aspects and their corresponding definitions, as extracted through NVivo. A comprehensive prompt was then developed, incorporating definitions of the main and sub-phases, explanations of the DfX concept and the notion of 'X' (treated as underlying assumptions), and the research objectives. This file and prompt together formed the input for ChatGPT. Through a bidirectional iterative process, the researchers refined both the prompt and the outputs, with ChatGPT serving as the primary analytical tool for categorising the DfX aspects and mapping each category to the corresponding sub-phases of the industrialised building product lifecycle.

To validate the results, two human evaluators independently classified the 44 DfX aspects, and their classifications were compared against ChatGPT's output. The Cohen's Kappa coefficient between ChatGPT and the human raters was 0.87, indicating a high level of inter-rater agreement and confirming the reliability of the AI-assisted categorisation.

4 Results

The findings of this research are presented in the following section.

4.1 Lifecycle Phases of Industrialized Building Products

Since the design phase of a product should address requirements and priorities across its various lifecycle stages, it is essential to first identify the product lifecycle and the corresponding specifications that can be incorporated into the early design stage. For instance, during the production phase, emphasis is placed on aspects such as ease of assembly, whereas in the logistics phase, factors such as safe transportation and product traceability become more critical. Without categorizing the different DfX aspects along the lifecycle, some of them may be overlooked or applied at the wrong phase. Organizing DfX aspects by lifecycle phases makes sure each one is applied when it matters most, helping to reduce rework and prevent conflicts between aspects. Figure 2 shows the main phases and their key actions.

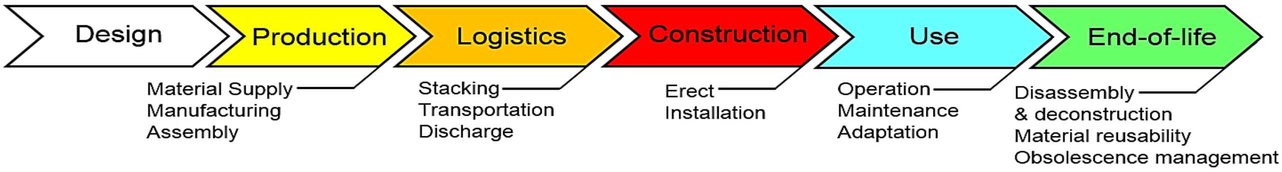

Figure 2. Main phases of the industrialized building products lifecycle (Source: Authors)

As shown in Figure 2, industrialized building products involve six main phases, which occur after design: production, logistics, construction, use, and end-of-life (Hasani & Riggio, 2025). Particularly in industrial construction projects, the production phase itself consists of a number of processes that start with the manufacturing and assembly of components (Abd Razak, Khoiry, Wan Badaruzzaman, & Hussain, 2022). According to Taheripour et al. (2025), the logistics phase of industrialized building projects consists of three main stages: module loading, transportation, and discharging at the project site. However, the discharging stage can be essentially omitted if the modules are prepared for erection and installation when they arrive. Some papers refer to the arrangement of modules side by side in the bed of a truck, trailer, or other transport equipment as stacking, rather than loading (Lee, Kim, Khanzode, & Fischer, 2021).

As an alternative, on-site factories might be built to help design and test autonomous and flexible production systems. This would allow prefabricated parts to be manufactured and assembled at the project site (Martínez, Jardón, Gonzalez Víctores, & Balaguer, 2013). In such cases, logistical measures are minimized. User occupancy commences when the prefabricated modules are installed and put into place, and the operation and maintenance phase follows (Taheripour, Azizi, & Sobhieh, 2025). Buildings may need to be adapted during and after maintenance to accommodate shifting user needs (Roxas et al., 2023). Living in the building provides experiential value to the end-user, who is the main beneficiary of the use phase. Users are motivated to maintain and protect the building product during the operation phase if they have a strong emotional and functional tie to it (Sierra-Fontalvo, Gonzalez-Quiroga, & Mesa, 2023). The end-of-life phase comes after the use phase in the context of the circular economy. In this phase, the disassembly of components takes place.

Disassembly of modules becomes important when parts can be taken apart, gathered, moved, and used again. Then, the actions related to deconstruction are defined. A specific type of destruction called deconstruction concentrates on saving parts and materials for later use (Kamrath, 2023). In their illustration of the building lifecycle, Lausselet et al. (2023) stress that components may be treated using a variety of cyclical procedures following the disassembly phase. These tactics include recovery, remanufacturing, recycling, and reusing. In the end, a product enters a new lifecycle if it cannot be reused. In summary, the main phases are divided into sub-phases, which include manufacturing, assembly, stacking, transportation, discharge, erect, installation, adaptation, operation, maintenance, disassembly and deconstruction, product replacement & circularity, and second life.

4.2 Categorization of DfX Aspects in the Sub-Phases

Table 2 illustrates the outputs of ChatGPT categorization. Because there are so many DfX aspects, it is necessary to categorize them and combine those with very similar definitions. Prior to allocating each category to a particular sub-phase within the lifecycle sub-phases of industrialized building products, it discusses the categorization of DfX aspects. From left to right, respectively, the first and second columns are from the literature, while the remaining columns are the output of ChatGPT's classification.

Table 2 shows that aspects such as DfM and DfA, as well as design for disassembly and design for circularity, have attracted the most attention. Perhaps one reason for this is that these aspects are related to key industry concerns, namely simplifying the production process as well as responding to increasing environmental pressures. Many of them have also become mandatory for industry use. In contrast, aspects such as design for on-site factory, design for stacking, design for transportation, design for discharge, and design for installation have attracted much less attention. Perhaps this is because these aspects are project-oriented in nature and apply to specific industries, such as construction, and therefore have not been as generalized and widespread in the literature as more general aspects.

Table 2. Categorization of DfX aspects in the sub-phases of industrialized building products, (Source: Authors)

Reference	DfX aspects	Category (Definition)	Sub-phase
(Juniani, Singgih, & Karningsih, 2022) (Yang & Zhao, 2015) (Anane, Iordanova, & Ouellet-Plamondon, 2023) (Lager, 2017)	Design for manufacturing, Design for additive manufacturing, Design for robotic manufacturing, Design for nonassembly	**C1:** Design for manufacturing & production (Designing products for easy, cost-effective, and high-quality production)	Manufacturing
(Lorand & Nevelius, 2015; Zhai et al., 2023)	Design for assembly, Design for robotic assembly	**C2:** Design for assembly (Designing products for easy assembly)	Assembly
(Rosarius & García de Soto, 2021)	Design for onsite factory	**C3:** Design for onsite factory (Designing for temporary or mobile production setups near construction sites)	Onsite factory setup (before erect)
(Sutrisna & Goulding, 2019)	Design for logistics	**C4:** Design for logistics (Designing products around efficient stacking, transportation and handling on site)	staking, transportation & discharge
(Mora et al., 2020)	Design for installation, Design for safety	**C5:** Design for installation & safety (Simplifying the installation process for products in their final location with the aim of reducing installation time, costs and improving safety)	Erect & installation
(Laovisutthichai et al., 2022)	Design for supply chain, Design for construction waste minimization	**C6:** Design for construction efficiency (Designing products and processes to enhance efficiency, reduce costs, and minimize waste across the supply chain)	From manufacturing to installation
(Jiang & Jiang, 2015) (Paganin & Borsato, 2017) (Hasani & Riggio, 2025) (Carlsson, Mallalieu, Almefelt, & Malmqvist, 2021) (Bakker, Den Hollander, Van Hinte, & Zijlstra, 2014)	Design for performance, Design for reliability, Design for durability, Design for longevity, Design for compatibility	**C7:** Design for operational performance (Designing to enhance product performance during operation)	Operation
(Ganisen et al., 2015) (Masood et al., 2015) (Jiang & Jiang, 2015) (Cantero-Chinchilla, Booker, Croxford, Hughes, & Goudswaard, 2024) (Merati, Karbasian, Ashlaghi, & Haleh, 2024)	Design for maintenance, Design for service, Design for supportability, Design for inspectability, Design for availability	**C8:** Design for maintenance & serviceability (Designing for easy maintenance and repair, minimizing downtime and service costs)	Maintenance
(Hasani & Riggio, 2025) (Kamal & Arif, 2015) (Vandenbroucke et al., 2015) (Boer & Boer, 2018)	Design for adaptability, Design for flexibility, Design for change, Design for variety	**C9:** Design for adaptability & flexibility (Designing products to adapt to future changes)	Adaptation
(Sierra-Fontalvo et al., 2023) (Zhu & Qin, 2021) (Ramakrishnan, Kumar, & Chandran, 2019) (Mulet, Chulvi, & Royo, 2022)	Design for quality, Design for emotion, Design for customer satisfaction, Design for attachment & trust	**C10:** Design for user experience (Designing to ensure user satisfaction and create positive emotional and functional experiences)	The entire of use phase
(Shetty et al., 2015) (Cai & Waldmann, 2019)	Design for disassembly, Design for deconstruction	**C11:** Design for disassembly & deconstruction (Designing for easy disassembly components, and enable deconstruction of load-bearing components)	Disassembly & deconstruction
(Kamp Albæk, Shahbazi, McAloone, & Pigosso, 2020) (Iacovidou & Purnell, 2016) (Martinez-Leal, 2019) (Soh, Ong, & Nee, 2014) (Aziz, Wahab, Ramli, & Azhari, 2016) (Pruhs, Kusch, Woidasky, & Viere, 2024)	Design for recycling, Design for reusability, Design for recovery, Design for remanufacturing, Design for upgrade, Design for circularity	**C12:** Design for material reusability and circularity (Designing to maximize material reusability (recycling, reuse, recovery, remanufacture and upgrade))	Product replacement & circularity

(Proske & Jaeger-Erben, 2019) (Lasthein, Lingås & Johansen, 2021)	Design for obsolescence, Design for industrial symbiosis	**C13:** Design for obsolescence management (Designing to extend product lifespan through using component for produce new products)	Second life
(Sierra-Fontalvo et al., 2023) (Go, Wahab, & Hishamuddin, 2016)	Design for sustainability, Design for environment	**C14:** Design for sustainability (Designing products with economic, environmental, and social sustainability in mind)	All sub-phases
(Wekerle, Loures da Costa, & Trabasso, 2016)	Design for autonomy	**C15:** Design for autonomy (Designing national products to minimize dependency on external components or control)	
(Xiaochuan, Jianguo, Beizhi, & Xin-An, 2004)	Design for cost	**C16:** Design for cost (Optimizing design to reduce production and lifecycle costs)	

On the other hand, the various categories appear to overlap with one another. Design for assembly (C_2) and design for disassembly (C_{11}) can be enhanced simultaneously by standardizing and modularizing products. Another example is designing module discharging on the construction site (C_4) to increase design for safety (C_5). Also, using inexpensive materials lowers the product's price, thereby supporting design for cost (C_{16}), but they might not be recyclable, which would hinder their ability to be reused (C_{12}). Additionally, incorporating sensors into product design aids in tracking them (C_4), but it may also raise costs (which would have a detrimental effect on C_{16}). The implementation of various DfX aspects should therefore be approached from an integrated perspective. Following the categorization of the DfX aspects, the final framework was developed and is explained in the subsequent section.

4.3 Developing an Integrated Lifecycle Framework

The study's developed framework is shown in Figure 3. A circular representation was chosen for several reasons.

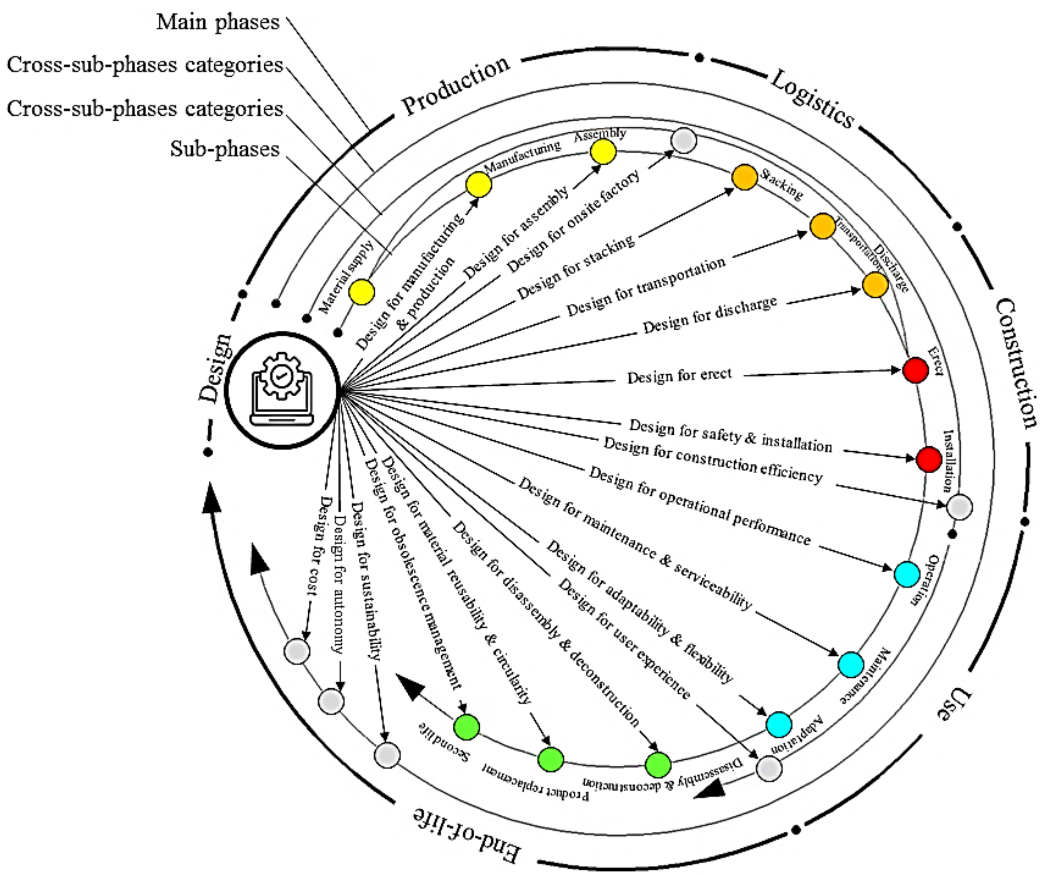

Figure 3. Integrated framework. (Source: Authors)

- First, it emphasizes the continuity and interconnection between different lifecycle phases, highlighting the iterative nature of design and its downstream implications.
- Second, the radial layout makes it possible to compactly and coherently visualize primary phases, sub-phases, and cross-phase DfX aspects all at once.
- Third, by centring the design phase, the diagram emphasizes how important design is in shaping the other lifecycle phases, which is consistent with the study's goals.

The major phases of the lifecycle are represented by the outside circle, while the sub-phases are shown by the inner circle. DfX categories that fall between two or more sub-phases are represented by the intermediate circles. The onsite factory design, for example, covers both the manufacturing and assembly sub-phases, with the exception that the operations are conducted in an onsite factory situated at the project site. Consequently, fewer logistical steps are needed, and parts are set up and installed right away. An additional illustration is design for construction efficiency, which includes the design of the product and process from sub-phases of manufacture to installation with the goal of increasing efficiency, reducing costs, and minimizing waste throughout the supply chain. To improve end users' satisfaction, design for user experience encompasses the whole use phase. Additionally, three DfX aspects, design for cost, design for autonomy, and design for sustainability, are established throughout the whole product lifecycle, encompassing all main and sub-phases. Other DfX aspects, on the other hand, are linked to particular phases of the lifecycle.

5 Discussion

Creating a comprehensive framework of DfX aspects pertinent to the industrialized building products lifecycle, this study adds to the body of knowledge. Some DfX aspects are more specific to certain industries. In a similar vein, design for safety, which emphasizes reducing risks, is especially pertinent to building projects. The fact that several DfX aspects have only been explored in a small number of studies is another important insight from the study. The designs for stacking, transportation, discharge, and tracking are some of these aspects. For example, creating products with improved supply chain traceability may be referred to as "design for tracking".

One possible explanation for this could be that certain DfX aspects are more applicable to building products, which have likewise gotten less attention because of the general paucity of DfX research in the building sector. Certain sub-phases are given more attention in the literature. The manufacturing and assembly sub-phases, for instance, highlight their extensive history in the manufacturing sector. Perhaps as a result of the growing focus on sustainability and the circular economy of products, the disassembly and circularity sub-phases also make a substantial contribution. This study's emphasis on the significance of incorporating pertinent DfX aspects at the early design stage is one of its main contributions.

The performance and expense of later stages are significantly impacted by decisions made during the conceptual, schematic, and detailed design phases. By considering DfX aspects across all sub-phases, potential issues such as installation bottlenecks, material incompatibilities, or limited disassembly options can be anticipated and resolved before many issues arise during the project. This framework can also be beneficial for many of the project's stakeholders. It allows designers to gain a deeper understanding of the requirements and constraints of other project phases and stakeholders. By considering the DfX aspects, they can implement value engineering more effectively in their designs and ensure that solutions are optimized not only in terms of cost and performance, but also in terms of constructability, sustainability, and stakeholder needs.

Contractors can use the results of this paper to make better decisions at different project phases. For example, by focusing on design for erection and design for installation, contractors can experience a simpler erection and installation process, fewer reworks, and cost and time savings on site. Or by considering the principles of design for safety, the level of safety in construction operations can be improved. In the later stages, attention to design for disassembly can help reduce maintenance costs and provide end users with a better user experience throughout the useful life of the building. Also, attention to less-considered aspects such as design for stacking, design for transportation, and design for discharge can provide many areas of improvement for transportation contractors. For example, if the modules are designed in such a way that they can be optimally stacked together without damage, storage and truck space can be optimized, and the modules can be transported more safely, especially over long distances.

6 Conclusion

In contrast to other studies that concentrated on discrete aspects like DfM and DfA, the suggested paradigm comprehensively integrates 16 primary DfX categories throughout the lifecycle, a method that turns each DfX aspect's island view into an integrated view of them all. From a theoretical and practical standpoint, this paradigm can offer profound insights. In particular, by taking into account the relationships and synergies between various aspects, designers of building industrialization companies can enhance product creation. Additionally, industrialized building businesses that manage integrated module engineering, procurement, construction, and installation (EPCI) as a whole can benefit substantially from the lifecycle approach in the suggested framework.

The suggested framework must be gradually incorporated into the enterprise departments and project phases workflows in order to be adopted effectively. Implementation strategies can include pilot projects to show the benefits and targeted training. Training workshops can be used to introduce DfX aspects to engineers and designers. Additionally, implementation can begin at the project level and work its way up to the enterprise level. Potential obstacles, however, can include resistance to change, limitations in project data, intricacy during the design phases, and the requirement for interdepartmental cooperation.

Overcoming these obstacles and enabling the useful implementation of the suggested framework can be accomplished with proactive tactics like transparent communication and appropriate support. Although DfX aspects are interrelated, the exact relationship between them and the intensity of this relationship are among the proposed future research directions. One of the study's limitations is that it has only been studied theoretically thus far; it has not been used or assessed in the context of industrialized building projects. Another limitation of the proposed framework is its restriction to the building industry and its associated products. Consequently, future research could draw upon this work to adapt and apply the methodology to other industries and product domains.

The framework has the potential to serve as a foundation for developing a decision support system (DSS) aimed at evaluating the industrialization level of construction products during the early design stage, while accounting for the full spectrum of lifecycle requirements. Overall, the developed framework helps the industrial building sector to play a significant role in improving the productivity of the industry by shifting the focus of industrial building design from discrete issues to an integrated lifecycle perspective.

Acknowledgements

This work was supported by the ByWall project.

Ethical Approval Declaration

The study was conducted in accordance with established standards for research integrity and ethics. The authors declare that this research did not involve human participants or animals, and therefore, ethical approval was not required.

Informed Consent Statement

Not Applicable

Funding
This study is funded by ADEME (French Environment and Energy Management Agency).

Data Availability Statement
The data supporting this study's findings are available on reasonable request to the corresponding author.

Conflicts of Interest
The authors declare no conflict of interest.

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