Demountable Buildings: Some of challenge and solution for trend of transformation in construction and

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ABSTRACT

The world is entering the era of Industry 4.0, where the demand for sustainable development is highly emphasized. Therefore, traditional construction is being re-evaluated due to their negative effects on the environment. These requirements have created a lot of opinions and discussions around innovative methods in the construction industry. The use of demountable buildings could serve as a suggestion for material reuse towards sustainable development in the construction industry. The article will consist of two parts: the first part will present some trends in transitions within construction methods (lifestyle, environment, digital) as well as solutions for implementing these transitions, highlighting the effectiveness of demountable building usage. The second part will focus on outlining challenges in designing demountable buildings (architecture frame, building assemblies), along with previous experiences in addressing these challenges. This article is situated in the introductory section of a doctoral thesis on developing a demountable node model aimed at advancing the typology of demountable buildings in the future.

Keywords: Demountable building, Assembly and disassembly, Modular buildings, Architecture grids, Module connections

I. INTRODUCTION

Civil engineering is the science of planning, constructing, operating, and maintaining buildings and infrastructure, including houses, bridges, and roads. It plays a crucial role in the economy but faces challenges such as labor intensity, low efficiency, and environmental impacts. Horta et al. (2013) state the construction industry accounts for about 9% of global GDP. Xu et al. (2020) find it to be the second-largest energy consumer in 2017, responsible for 20% of energy use, 23% of electricity consumption, and 30% of CO2 emissions. This has spurred interest in improving the sector's societal, economic, and environmental performance.

Efforts toward sustainable development have initiated transitions in lifestyles, environmental practices, and digital technologies. These aim to reduce carbon emissions and natural resource use, aligning with goals set by the Paris Agreement and COP 26 for net-zero emissions by 2050. Solutions like "Transformation building" and demountable structures support these objectives.

The article will be structured into two sections: the first examining construction trends and demountable building solutions, and the second detailing the challenges and architectural considerations in designing such buildings, particularly for low-rise structures. It will also share experiences in addressing these challenges and suggest areas for future research on construction nodes for demountable buildings.

In this context, a doctoral project jointly coordinated between ESTP and Artelia aims to develop a node model capable of meeting theoretical and practical requirements applicable to demountable buildings. Currently, the project is in the process of assessing the functional requirements for a node, thus a comprehensive model outcome is pending and will be disclosed in subsequent publications.

II. FORMAT DEMOUNTABLE BUILDINGS: SOLUTION FOR SOME OF TRANFORMATION IN CONSTRUCTION

The 21st century has ushered in significant technological advancements and heightened environmental awareness, prompting the need for substantial changes across various sectors, including construction. Research highlights the urgent necessity for shifts to tackle these challenges, focusing on urban redevelopment's multifaceted demands. These include addressing the structural integrity of old infrastructure, sustainable renovation challenges, and evolving urban aesthetics. Lifestyle changes, alongside international environmental regulations, demand significant adjustments within the construction industry. Concepts like the "green" and "circular" economies have seen significant evolution, driven by the Paris Agreement. Moreover, the incorporation of technology into construction practices is enhancing this transformation process (Samuelson 2023).

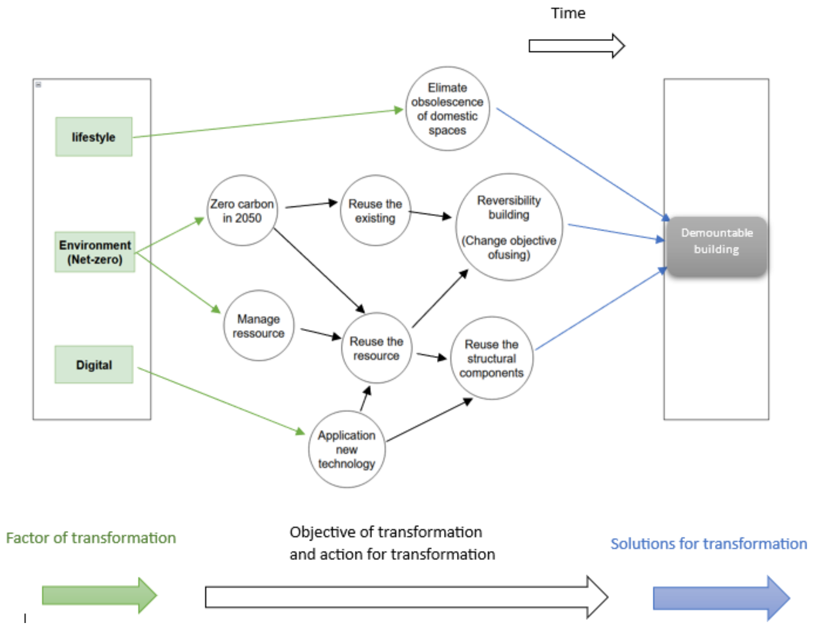

FIGURE 1. The transformation of construction

This article aims to explore sustainable urban development, particularly through the lens of low-rise buildings, which are a prevalent feature of urban landscapes and a key area of construction activity. Given their substantial environmental impact due to extensive land use and energy inefficiency, demountable buildings are presented as an effective solution to these issues, aligning with sustainable development objectives. This approach is illustrated in Figure 1, underlining the strategic importance of adaptable construction methods in achieving sustainability goals.

II. 1: Factor of transformation

Firstly, domestic spaces are one of the most crucial factors in a home, directly impacting the quality of life for its occupants. In recent years, societal developments have led to changes in the demand for domestic space. However, many current homes still fall short of meeting the new requirementsfor domestic space. Obsolescence of domestic spaces can be understood as the mismatch between domestic spaces and the new societal demands (Cieraad 2017, OECD 2020). These demands include:

- **Utility Requirements**: Domestic spaces needs to be designed for convenience, meeting the usage needs of family members.
- **Aesthetic Requirements**: Domestic spaces should be aesthetically pleasing, harmonizing with the aesthetic preferences of family members.
- **Sustainability Requirements**: Domestic spaces should be designed sustainably, energy-efficient, and environmentally friendly.

Traditional domestic spaces often fail to meet these requirements due to limitations such as (Lawrence 1982):

- **Failure to Meet Usage Needs**: Traditional domestic spaces are often designed based on the usage needs of past eras, not catering to the modern usage needs. For instance, many traditional European houses have small kitchens and dining areas, inadequate for the cooking and dining needs of modern families.
- **Lack of Aesthetic Appeal**: Traditional domestic spaces are often simplistic in design, lacking aesthetic appeal. For example, many traditional European houses have small, dimly lit living rooms that do not provide a comfortable atmosphere for family members.

The obsolescence of domestic spaces has several negative impacts:

- **Inconvenience for Family Members**: Obsolescence of domestic spaces often do not meet the usage needs of family members, causing inconvenience and discomfort. For example, a house with a small kitchen may make cooking and dining challenging for family members.
- **Deterioration of Home Aesthetics**: Obsolescence of domestic with low aesthetic appeal can lead to a loss of the home's overall aesthetic. For instance, a house with a dark and cramped living room may create a gloomy and unwelcoming atmosphere.
- **Economic Loss**: Obsolescence of domestic often have a short lifespan and are prone to damage, leading to economic losses for homeowners. For example, a house with a deteriorating wooden balcony may incur repair or replacement costs.

Redeveloping existing structures offers a viable solution to the challenges posed by the rapid evolution of human needs and the ensuing standards' obsolescence. The traditional approach of demolishing and rebuilding is both impractical and environmentally unsustainable. An innovative solution is the concept of buildings with dismantlable components, akin to the interchangeable pieces of a child's Lego set, addressing these challenges efficiently.

Furthermore, the global commitment to combating climate change has heightened the focus on achieving carbon neutrality—balancing emitted carbon with an equivalent amount sequestered or offset. This paradigm shift significantly impacts various sectors, including construction. In

Europe, the construction industry is navigating the complexities of transitioning to a carbon-neutral future, confronting both the challenges and opportunities this change presents (OECD 2021).

The construction industry stands as a substantial contributor to greenhouse gas emissions due to energy-intensive processes, raw material extraction, and transportation. The quantification of greenhouse gases emitted during construction considers the entire life cycle of a building. However, the categorization of these stages lacks standardization; various authors have assigned different names to them (Lu, 2019; Seo, 2001). While this analysis primarily focuses on direct emissions (Scope 1) associated with construction activities, a comprehensive assessment must also encompass indirect impacts (Scopes 2 and 3), particularly those arising from the building's operational phase. Recognizing the broader environmental footprint, including energy consumption over a building's life span, is vital for a holistic view of sustainable construction. According to the Kyoto Protocol, greenhouse gases comprise six categories: CO2, CH4, N2O, HFCs, PFCs, SF6 (IPCC, 2022), each exhibiting varying global warming potentials (GWPs) depending on the considered age limits.

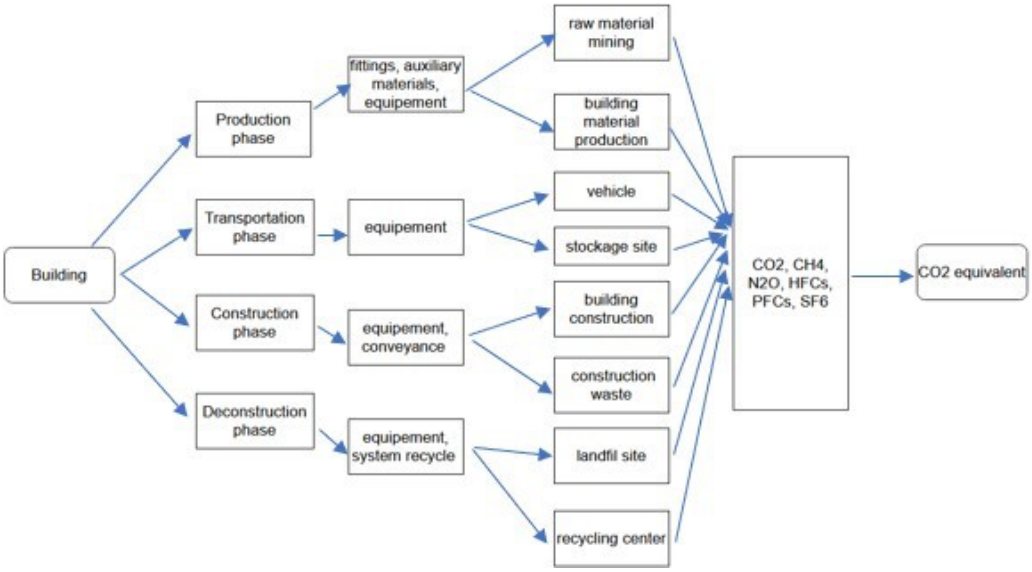

FIGURE 2. **The transformation of construction**

According to the 4th assessment report by the Intergovernmental Panel on Climate Change (IPCC), the total carbon emissions from buildings have reached 3 gigatons per year. With the carbon credit price at 70-100 USD per ton of carbon (Permits 2023), the construction industry would have to allocate an additional 210-300 billion USD. In this context, the production phase accounts for the majority of carbon emissions, making it a top priority to minimize the manufacturing of components.

From the Table 1 the amount of carbon emissions generated during production constitutes the majority of the overall carbon footprint (approximately 85%). Therefore, to achieve carbon neutrality by 2050, the production process needs to be curtailed through the reuse of resources or the recycling of readily available components.

TABLEAU 1. Comparison carbon emissions at each stage in some of buildings

Author	Architectural type	Structure system	Floor	Production (tone carbon)	Transportation (tone carbon)	Construction (tone carbon)	Deconstruction (tone carbon)
Peng (2016)	Office building	Reinforced concrete	15	10369	234	227	1659
Li (2016)	Residential building	Masonry-concrete	4	561	33	24	25
Zhang (2014)	Residential building	Reinforced concrete	15	1528	151	171	17

Finally, the digitalization waves in the field of construction cannot be overlooked. Research studies highlight the benefits of utilizing Building Information Modeling (BIM) in construction management. A significant challenge in resource reuse is effectively managing used resources (storage, quality, etc.). Big data and Artificial Intelligence (AI) emerge as solutions to this issue. Furthermore, the advancements in 3D printing technologies are gradually eliminating barriers in producing intricate details. In their research, the authors have successfully manufactured assemblies with complex shapes using 3D printing technology (Alzarrad 2019, Strauss 2016) (Figure 3)

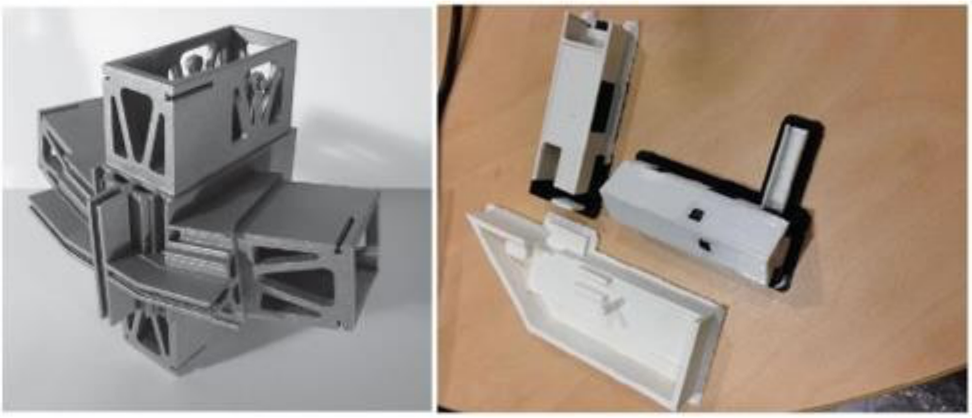

FIGURE 3. **Example of assemblies created by 3D printing (Alzarrad 2019, Strauss 2016)**

II. 2: Action and solution for transformation

Reversibility building

According to Durmisevic (2018) ‘Reversibility' is defined as the process of transforming buildings or dismantling their systems, products, and materials without causing damage. In her work, Durmisevic (2018) has divided 'Reversibility' into three levels as illustrated in the Figure 4

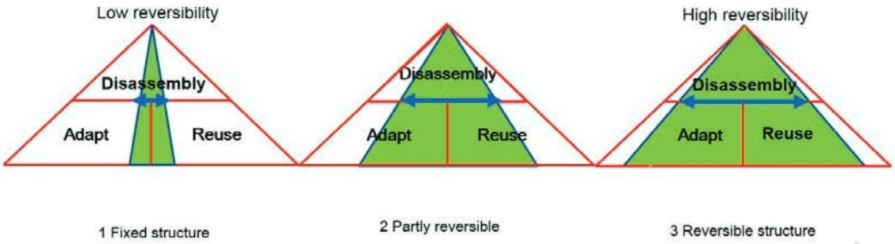

FIGURE 4. **The core of the three dimensions of reversibility (Durmisevic 2018)**

Disassembly, adaptability, and reuse constitute the core of the three dimensions of reversibility, determining the spatial and structural levels of reversible buildings. In the same work, Elma Durmisevic (2018) has identified two aspects of 'Reversibility' as Spatial Reversibility and Technical Reversibility.

- **Spatial Reversibility**: Adapt space.
- **Technical Reversibility**: Reconfigure structure and Separate materials.

French architect Patrick Rubin (2007) champions 'Reversibility' in construction as a forward-looking trend, observing that recent decades have seen more building activity than previous centuries combined, with vast potential for future transformations. Rubin advocates for rehabilitation over new construction, foreseeing it becoming a prevalent practice. However, he acknowledges the challenges in repurposing buildings that lack appeal or seem unfit for new functions, highlighting the need for a design approach that separates the construction program from the design phase to enhance flexibility for various uses.

Research into 'Reversibility' is now concentrated on adapting buildings for different purposes to reduce construction-related carbon emissions. Yet, the complete transformation of spaces for alternate uses remains a complex task. Thus, demountable buildings are seen as an effective strategy to support 'Reversibility.' This approach allows for the spatial reconfiguration of buildings without changing their core structural elements, offering a practical solution to the challenges posed by the need for versatile building use and sustainability goals.

Reuse structural component.

The construction industry is witnessing the emergence of "Reutilization" as a pivotal trend, aligning with legislative developments like France's Environmental Code Article L541-1 (2001), which defines "Reutilization" as repurposing objects for their original intended use. This concept, distinct from 'Reversibility' which focuses on altering use with social modifications, targets a technical approach through scientific methods or new materials to achieve reusability.

In the realm of construction, movable elements such as furniture and fixtures represent the most straightforward opportunities for reuse due to their ease of dismantlement. Yet, the environmental impact of construction largely stems from structural elements, which account for over 17% of the construction industry's climate impact, according to the Building and Carbon Energy Observatory (2022). Thus, reusing structural components, particularly wood and steel, due to their assembly ease, emerges as a significant challenge. Concrete structures, however, pose difficulties in reuse, and despite ongoing research, practical applications remain scarce. Notably, buildings designed for modularity, such as De Drie Hoven by Herman Hertzerberg, have faced conventional demolition, indicating the necessity for advancements in dismantling capabilities for various materials, especially concrete.

Precast construction methods are recognized for their efficiency but are underutilized in reuse applications. Noteworthy is the rapid construction achievements in China, such as a 57-storey building in Changsha completed in 19 days. Yet, there's a gap in applying precast methods for effective material reuse, which will be explored further in section III.2 regarding assemblies between precast and demountable buildings.

In conclusion, the shifting demands within the construction sector call for sustainable development strategies that not only enhance materials but also promote demountable housing models as solutions for component reuse. In the circular economy framework, efforts like Reversibility building and structural component reuse are vital, offering resource conservation and maximizing existing structures' value. Demountable buildings represent a future-focused solution to these sustainability challenges.

III. DEMOUNTABLE BUILDINGS: SOME OF CHALLENGES

This section addresses the challenges associated with the widespread adoption of deconstructable building models in the industry. There are various difficulties; however, based on the research, the two most significant challenges pertain to architecture (Section III.1) and assembly (Section III.2).

III.1: Architectural frame

The purpose of demountable buildings is to facilitate the reuse of components; however, a significant challenge lies in ensuring that these components meet the diverse frames required for each construction project. These requirements are dependent on the architects of the projects, and currently, design standards for architects are not overly restrictive.

In France, the design practices for an office architect's plan are based on experience as follows:

- For working in a shared space (coworking, flex office, open space, etc.), the minimum required area is 15 m² per person.
- For working in an individual office, the minimum required area is 8 m² per person.
- For working in a closed collective office (several offices within a partitioned room), the minimum required area is 10 m² per person.

Unlike residential buildings such as apartments, the typical structural typology used in offices is column-beam and column-slab. Therefore, architects often use common architectural frames for office constructions. Here are some examples:

- Current standards set the thickness of offices grouped around a central strip at 15m, and the width of single-oriented residential buildings at 12 m.
- Since the 1960s, the floor heights vary depending on the programs, with 3.30 m being the standard height for offices.
- The usual facade grid for offices follows a module of 1.35m

The trend of "Reversibility" in construction is gaining momentum, promoting a versatile construction framework designed for adaptability across various uses. This approach is underpinned by research and real-world projects such as Patrick Rubin's "Construire Réversible," CANAL Architecture's 2007 initiatives, and Thierry Roche's "Guide réversibilité" by Artelia in 2010, as well as the practical application in the Black Swans project. Rubin underscores the need for a unified model to enable seamless transitions between office and residential uses. He identifies key architectural distinctions between these functions, such as the standard 1.35m grid for office facades leading to spaces around 13.5m² with ceiling heights of 2.7m to 2.8m, compared to the typically 2.5m ceiling height in residential buildings, which feature more diverse grid patterns. These differences exemplify the essential design considerations for implementing reversibility effectively.

Rubin proposes seven solutions aimed at optimizing user comfort within these adaptable structures. He advocates for a unified architectural framework that accommodates both office and residential uses, suggesting a plane frame with a 1.5m grid and a uniform height of 2.7m, as depicted in Figure 5. This proposal aims to establish a common ground for the functional conversion between office spaces and homes, emphasizing the practicality and efficiency of employing a single, adaptable framework to meet the diverse needs of both environments.

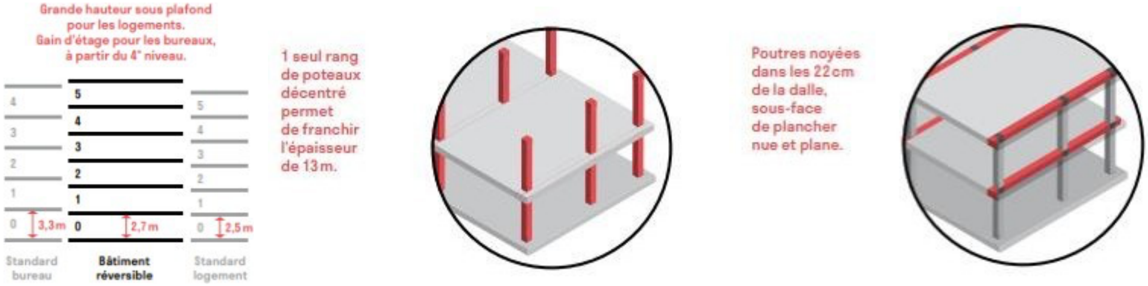

FIGURE 5. **Proposal for a universal frame for residential building and office building by Patrick RUBIN (2007)**

Meanwhile, Roche approaches the issue by subdividing a building into "modules." (Figure 6) This approach facilitates buildings in easily meeting standards-related requirements, such as those pertaining to people with reduced mobility (PMR) in France. These "modules" will vary in size from 5.4m * 5.4m to 8.1m * 8.1m, and all frames will be multiples of 1.35m.

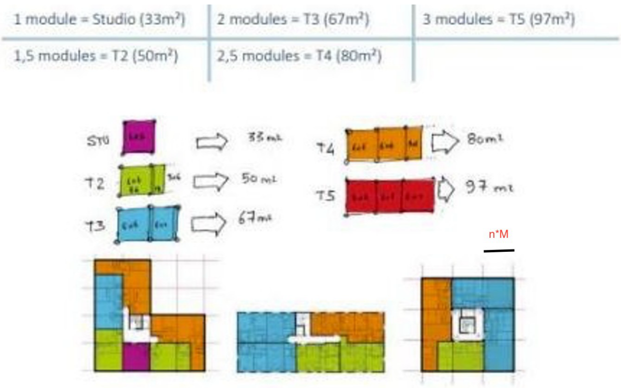

FIGURE 6. **Concept « Module » (Roche 2010)**

In addition, Roche emphasizes that the use of architectural frames is a "sensitive" value that highly depends on the specifics of each project. For example, the 1.35m frame is no longer widely favored by architects due to evolving work patterns. The 1.50m frame, more suitable for open workspaces, is gaining popularity. Furthermore, the adoption of a 1.50m frame size facilitates the use of a 30 cm modular coordination system, thereby easing the process of modularizing

In summary, the studies have demonstrated the feasibility of establishing a universal architectural frame for both office and residential constructions. However, a more comprehensive approach is needed through the synthesis of previous research (not only focusing on user comfort as proposed by Patrick Rubin or meeting current standards as suggested by Roche). To guide future research, we propose the following recommendations:

- Define a common "architecture frame" for these two types of buildings. Instead of aiming for an absolute value, we should establish an appropriate range of values that align with current standards and regulations. The node model should be adaptable to various construction projects, so the structural grid should be designed to fit current construction conditions, ranging from 4-6m.
- By implementing these suggestions, we can establish a more standardized and flexible approach to design that promotes reusability and adapts well to both collective buildings and offices.

III. 2: Building assemblies

Building assemblies are indispensable components for demountable buildings. Numerous sources indicate that due to the complexity of modular connections, as well as constraints related to installation, compactness, and compliance with tolerance limits, building assemblies often face significant limitations in terms of deconstruction, especially in the case of concrete structures.

Currently, building assemblies are classified based on various criteria. For example, Messler (2004) , Durmisevic (2002) , have provided different purposes for classifying assembly by the common purposes that appear in most works. To truly align with the principles of sustainable development, the classification of construction components should prioritize environmental goals alongside Functionality, Manufacturability, Cost, and Aesthetics. Integrating these considerations reflects the potential for reusing components, thereby committing to minimizing the ecological footprint of construction projects. Durmisevic (2006) put forth a classification method that is rooted in the theoretical level of joint flexibility:

- Direct chemical connection.
- Direct connections between two pre-made components.
- Indirect connection with third chemical material.
- Direct connections with additional fixing devices.
- Indirect connection via dependent third components
- Indirect connection via independent third component.
- Indirect with additional fixing device.

From a more structural perspective, Rajanayagam (2021) categorizes building assemblies into threetypes (Figure 7)

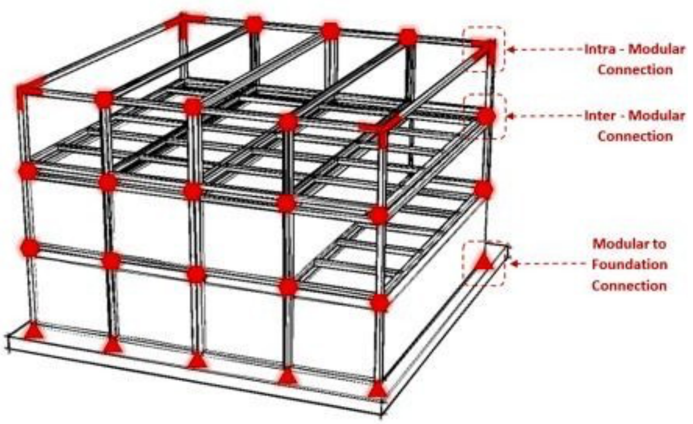

FIGURE 7. **Taxonomy connections in building (Rajanayagam 2021)**

- Inter-modular connections: horizontal connections in two plane directions from neighboring modules and a vertical connection within stacked modules
- Intra-modular connections: are generally referred to connections within a module, which are similar to conventional connection features.
- Foundation connection: connections between the column and foundation.

Research highlights the significance of Design for Manufacture and Assembly (DfMA) techniques to improve manufacturing and assembly processes. DfMA is divided into stages, focusing initially on Design for Assembly (DfA) to simplify product structure, as noted by Boothroyd (1994). This approach emphasizes selecting materials and processes early and making cost comparisons to support decision-making. After choosing materials and processes, a detailed Design for Manufacture (DfM) analysis follows, aiming to reduce manufacturing costs through standardization and optimization of component design and assembly.

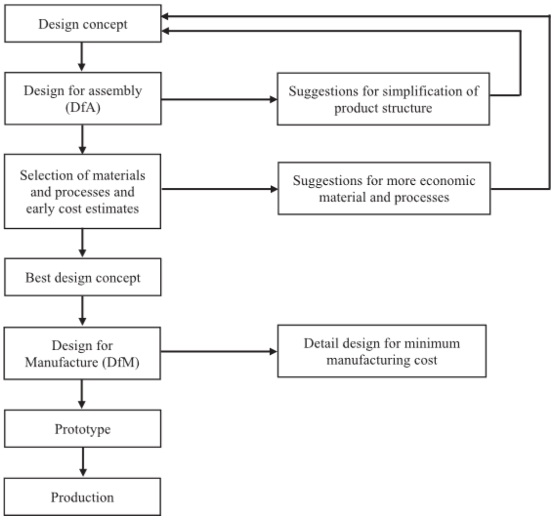

FIGURE 8. **Typical stages in a DfMA procedure. (Boothroyd (1994))**

In summary, the current classification and design of assemblies primarily rely on their mechanical functionality. For buildings that can be dismantled, the issues go beyond mere mechanical aspects, and there is a need for classifying assemblies based on this criterion. Consequently, assembly designs will be more comprehensive, enhancing applicability in buildings with higher dismantling capabilities.

To achieve these objectives, the application of principles such as Design for Manufacture and Assembly (DfMA) is crucial in establishing a standardized process. However, alongside this, in our future research, we will approach the issue more comprehensively by utilizing design tools such as Functional Analysis, Engineering Systems or Life Cycle Assessment:

- The Functional Analysis method can aid in constructing a well-defined solution that meets all the "requirements," wherein building assemblies designed for disassembly are considered a central object of design.
- Engineering Systems can contribute to the creation of an optimized manufacturing and fabrication system for these assemblies.
- LCA aids in quantifying potential environmental benefits throughout the life cycle of a structure, including production and dismantling stages.

IV. CONCLUSION

This study synthesizes a meticulous exploration of the necessity of demountable building models and the associated challenges in their creation. It highlights the pressing need for the construction industry to adapt to evolving requirements, underscoring the role of research in addressing these complexities. Constructing new buildings that incorporate demountable features presents a promising avenue to meet societal and environmental transitions while conserving resources.

To enhance the practical application of demountable building models, specific research into their challenges is essential, as highlighted in the introduction. We are currently undertaking a doctoral project on a demountable node model with the aim of contributing to the development of future demountable building models.

V. DISCUSSION

Below are some directions for our future research that significantly impact the node model's outcomes:

- **Diversify Materials in Demountable Buildings**: Further develop ideas for demountable buildings that use a variety of materials. Combining different materials can optimize both architectural and structural aspects. Additionally, these buildings can serve as a repository of diverse materials for the future.
- **Explore Other Influential Factors**: Besides factors like architecture and assemblies, many other aspects influence the use of demountable buildings, such as modular coordination and circular economy. Further research is needed to understand these factors and their impact on the feasibility of demountable structures

Applying design methods and industrial testing in designing the node model to optimize design choices is crucial. In addition to using DfMA methods in subsequent studies, we will employ other methods such as Functional Analysis (FA) and System Engineering (SE). Furthermore, applying Life Cycle Assessment (LCA) methods is essential.

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