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Design for Disassembly and Deconstruction – State of the Art

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Abstract. Construction waste management is crucial due to stricter regulations and limited landfills. Concepts like deconstruction, recyclability, and Design for Deconstruction (DfD) help reduce embodied energy. Building Information Modelling (BIM) is used for End-of-Lifecycle (EoL) scenario selection to minimize Construction and Demolition Waste (CDW). However, few buildings are designed for deconstruction, highlighting environmental, social, and economic benefits. Hardly any building designed and built today is designed for deconstruction. This study explores modern deconstruction design, challenges, and opportunities for future strategies. It discusses the reuse potential of building materials, available tools, implementation factors, and effective parameters for calculating Deconstruction Factors (DfD), along with previous case studies.

Keywords: Construction and demolition waste management, Deconstruction, Steel structures, Life Cycle Assessment, Building Information Modelling, embodied energy, Reuse, Recycle, Sustainability.

1. Introduction

This study reviews current literature on deconstruction, design for deconstruction, and material reuse with building information modeling. BIM aids in early design stages by providing detailed analytics on deconstructability, enabling informed decision-making in building facilities, and requiring sufficient deconstruction planning before demolition begins[1]. The focus of AEC's end-of-life cycle has shifted from the traditional methods of end-of-life building disposal to modern techniques such as deconstruction. Roslim summarizes EOL waste management techniques, as extracted from literature, which are: 1) Modern methods of construction (MMC), 2) deconstruction, and 3) material recovery or recycling [2]. This adoption is essential for advancing sustainability objectives and optimizing resource utilization. Additionally, it enables streamlined planning and execution of deconstruction activities while also supporting the development of environmentally friendly structures [3]. This study's main objective is to evaluate deconstruction, its principles, and social, economic, and environmental impacts. It examines Design for Deconstruction (DfD) as an efficient strategy for closing the construction material loop. Key implementation factors are established, and parameters for the deconstruction assessment score (DAS) are discussed. The study also evaluates the role of Building Information Modeling (BIM) in construction waste management, including its integration with life cycle assessment tools. This paper is the first phase of a research series, analyzing challenges in deconstruction and opportunities in Design for Deconstruction (DfD), aiming to conceptualize and develop methodologies for assessing and measuring their effectiveness and applying them all in a case study in Egypt. The paper showed the major connection between design for deconstruction and BIM either for using software techniques such as Revit to show the case study and its affecting factors numerically or BIM tools as LCA tools to show the environmental effects of deconstruction. This study aims to encourage design for deconstruction and to set rules to help in applying and making it more familiar in Egypt. It also showed that LCA tools are not applied or familiar in Egypt and there isn't any previous study comparing different tools (Tally and e-LCD tool).

2. Design for deconstruction- Literature

Design for deconstruction (DfD) is a crucial method for repurposing and reusing post-end-of-life building materials, but a lack of technical knowledge hinders its implementation. Kibert describes deconstruction as "construction in reverse," in which a building is disassembled to reuse its elements[4]. Researchers initially defined deconstruction, examining its timing, location, and purpose. They linked it to buildability, sustainable building, waste management, and the BIM approach. As defined by Akinade [1], Deconstruction refers to the systematic dismantling of structures, either in whole or in part, to promote the reuse of components and recycling of materials. The methodology which is used in this paper consists of 4 major steps as shown in **figure 1 .**

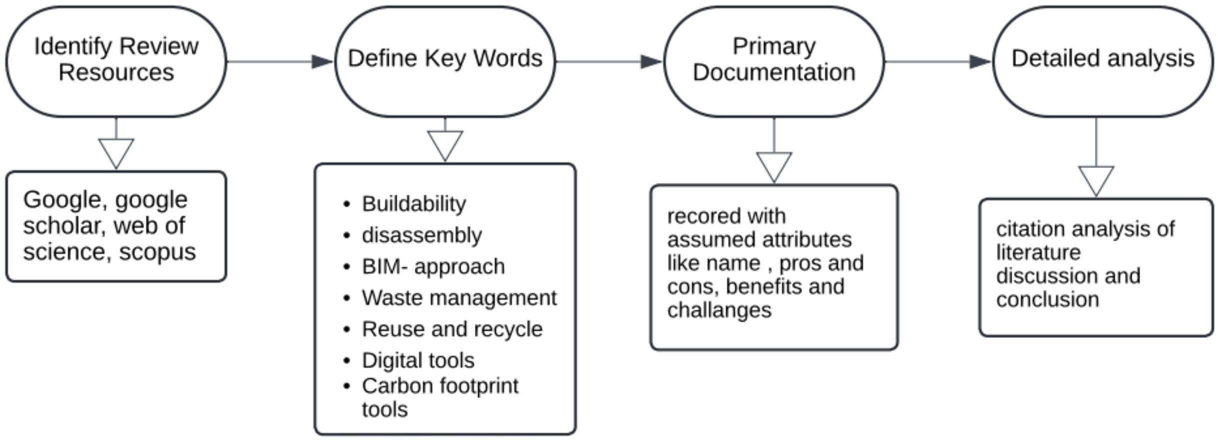

Fig. 1. The four-step review methodology

First, identify review resources, and second define the keywords that are used in the searching process. Then, primary documentation for papers is based on the main topic. Finally, detailed discussion, conclusion, and citation analysis based on the most recent papers.Design for Deconstruction is a research field promoting circular economy principles, focusing on selective dismantling structures for resource recovery and waste reduction, aiming for future revitalization and reuse [5]. Selective dismantling (SD) or building deconstruction is a systematic process aimed at maximizing the return of materials after the demolition of a structure [6]. By recovering recyclable components, deconstruction supports sustainability objectives by reducing reliance on new materials and creating markets for salvaged materials from the dismantled facilities [7]. The deconstruction process aims to minimize the need for destruction and maximize the retrieval of building components throughout the structure's lifespan and at its eventual decommissioning [8]. **Figure 2** illustrates how deconstruction aligns with the circular economy model's primary goal of maximizing resource utilization through collection, reuse, and recycling. Each stage of this model presents opportunities to reduce costs and dependency on natural resources as the sole input for construction[9]. The circular economy in the building sector requires construction materials to recover, reuse, and recycle, reducing landfill waste. Deconstruction-focused design, using structural steel framing systems, improves performance.

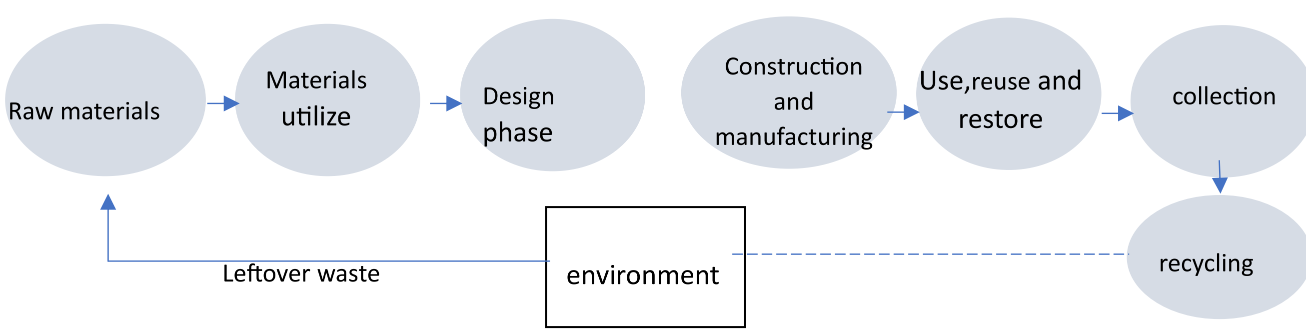

Fig. 2. Stages of the life cycle of materials in the circular economy.

2.1 Steps of deconstruction

When a structure approaches the conclusion of its functional lifespan, two alternatives are often available: destruction or deconstruction, as illustrated in **figure 3**. Deconstruction involves removing hazardous materials from buildings for safe disposal, promoting material recovery, allowing structure relocation, component reuse, reprocessing, and recycling, promoting resource conservation and waste reduction [1]. By incorporating DfD principles early in the design phase, architects can contribute to sustainable practices, ensuring structures have increased potential for future disassembly and component reuse. [10]. Building deconstruction involves removing trim work, kitchen appliances, plumbing, cabinets, windows, doors, floor coverings, insulation, wiring, pipes, roof, walls, frame, and flooring one story at a time. [11].

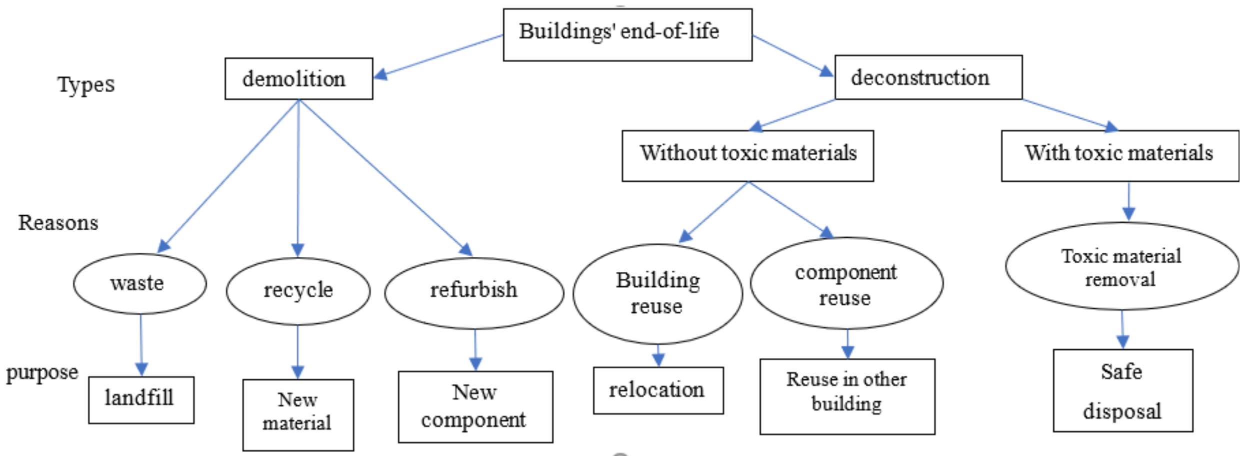

Fig. 3. End-of-life building kinds and purposes

2.2 Design For Deconstruction Techniques (Appropriate Time and Place)

Deconstruction principles are crucial for project success, influenced by architects and structural engineers. The time-related building layers theory helps determine when and where to deconstruct components [12].

- **The beginnings of the Theory of building layers:**
  Traditional Japanese domestic buildings consist of a primary frame of timber members, arranged according to the roof and wall structural requirements, and a secondary frame of timber members, which can be deconstructed and remodeled to meet occupants' needs without causing material wastage.
- **Developing and expanding the theory of building layers:**

  The Metabolisms concept identified four construction layers: Shell, Services, Scenery, and Set, with declining service life for each tier, placing a premium on component replaceability and flexibility [12]. H. Farouk emphasized the importance of adhering to construction design guidelines to enhance the deconstruction process[13]. These guidelines focus on maximizing flexibility and facilitating building modifications and disassembly. The concept of building layers supports this principle, in which construction components are organized into subsystems based on their life expectancy. Brand proposed six construction layers, as seen in Figure 4. The building's expected life depends on its site, structure, skin, services, space plan, and bare objects. The structure layer, including foundation and load-bearing elements, can last 30-300 years. The building's envelope skin layer can be replaced every 25 years, while services can be exchanged every 7-15 years [13]. The layering approach in building design facilitates easy change or replacement of upper-layer components, facilitating deconstruction and simple disassembly and prioritizing layer lifetime for technically and socially adaptive construction[12]. Micheal Pulaski's research on construction emphasizes durability, ease of disassembly, safety, and sustainability, suggesting reusable components, reducing material types, and avoiding harmful materials for efficient recovery, reuse, and recycling [14].

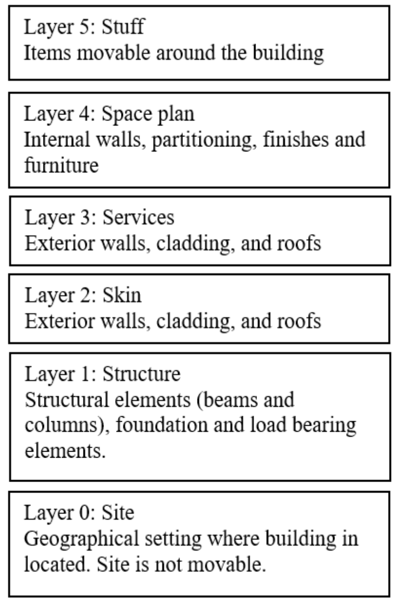

Fig. 4. Building layers and their expected lifetime

2.3 Principles of design for deconstruction

According to Philip Crowther's research, some of the designs for deconstruction and the recycling hierarchy were suggested, as shown in Table 1. Jouri Kanters reviewed articles and professional guidelines about general design and construction principles[14]. The author lacks an internationally agreed design for deconstruction and no requirements for its use in building codes. They propose using radio-frequency identification for material identification.

Table 1 Principles of design for deconstruction with the level of relevance [7].

Legend - level of reference: ⬤ highly relevant ● revenant, • not typically relevant

No.	Principle	Material recycling	Component manufacture	Component reuse	Building relocation
1	Use recycled and recyclable materials.	⬤	⬤	•	•
2	Minimize the number of different types of materials.	⬤	⬤	•	•
3	Avoid toxic and hazardous materials.	⬤	⬤	•	•
4	Make inseparable subassemblies from the same material.	⬤	⬤	•	•
5	Avoid secondary finishes to materials.	⬤	⬤	•	•
6	Provide identification of material types.	⬤	⬤	•	•
7	Minimize the number of different types of components.	•	●	⬤	⬤
8	Use mechanical, not chemical, connections.	•	⬤	⬤	⬤
9	Use an open building system, not a closed one.	•	•	⬤	●
10	Use modular design	•	•	⬤	●

Oulugbanga O. Akinade reviewed the critical success factors of the deconstruction projects shown in **figure 5** [8] :

- **Design-related factors**
- **Building materials-related factors**
- **Human-related factors**

It is important to note that previous research focused primarily on the fundamental DfD principles related to material selection, as seen in **table 2.** Michael Pulaski's research highlights the benefits of prefabricated assemblies, bolt-and-nut connections, and sustainable construction practices, emphasizing the need to avoid harmful materials during specification, which are the critical factors in calculating DAS.

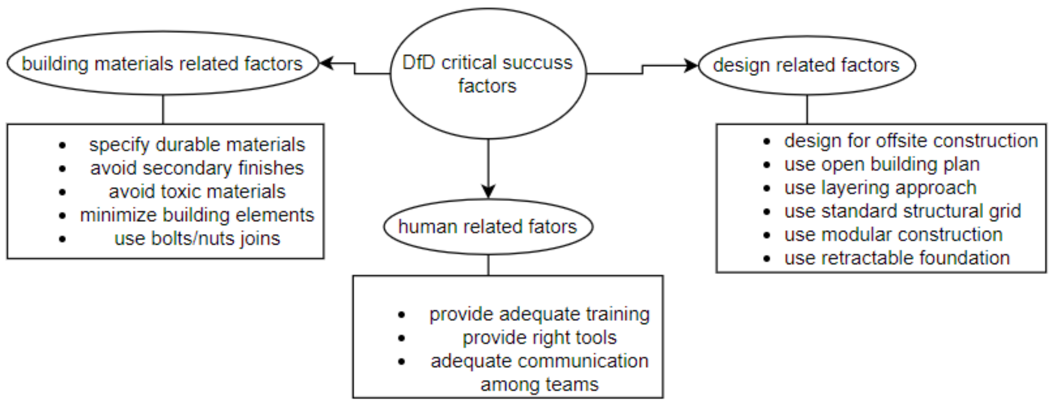

Fig.5. Design for deconstruction-related factors

Table 2 Design principles for deconstruction related to materials selection[7]

Design principles for deconstruction:
• Use reusable/recyclable materials
• Use bolts instead of welding
• Use prefabricated assemblies
• Avoid composite/complex materials
• Minimize the number and types of building components
• Avoid hazardous materials
• Avoid secondary finishes

2.4 Benefits of Deconstruction

2.4.1 Environmental impacts

Deconstruction and Design for Deconstruction are key concepts in closing material loops, similar to nature's biological metabolism. This cycle transforms waste into feed, transforming reused and recycled materials into new building materials. Figure 6 shows how the materials flow into a cycle when reusing and recycling activities are implemented[16]. Environmental benefits include extending raw material mine life, lowering material costs, and reducing the construction industry's embodied energy and carbon emissions.

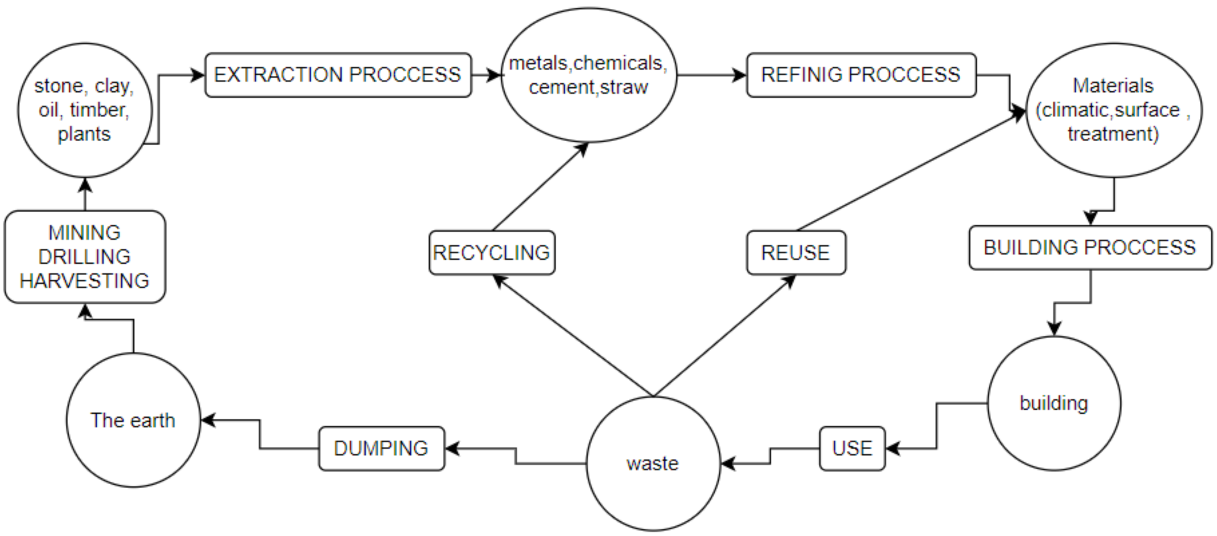

Fig.6. Closing the loop in the material lifecycle

2.4.2 Economic impacts

The equation that represents the net cost of deconstruction is as follows: (Price Paid by Owner 1 Salvage Value) - (Pre-Deconstruction 1 Deconstruction 1 Processing + Transportation + Disposal) [15]. Deconstructability in design stages can lead to successful material recovery, sustainable development, and economic profits. The US Department of Defense and EPA support this, with recycling materials saving $1 to $2 per square foot. However, deconstruction costs may be 17%-25% higher than demolition.

2.4.3 Social impacts

Deconstruction, a labor-intensive process, has the potential to create jobs for unskilled workers, particularly minorities and economically disadvantaged individuals. A successful case study showed that 40% of workers were women who were trained before joining the industry. According to Jouri Kanters, the social benefit of DfD is creating jobs for unskilled workers [14].

2.5 Benefits of Using Steel in Deconstruction

Steelwork contractors are key in deconstruction and design, utilizing reusable materials and components for adaptable structures. Steel construction offers high recycling potential, minimal energy and waste production, and can be reused without losing quality [8]. Previous studies implied that buildings with steel structures have the highest level of support for disassembly and deconstruction based on end-of-life evaluation [9]. Three case studies were designed with three different major types of material, i.e., steel, timber, and concrete. The study analyzed the salvage performance of steel, timber, and concrete structures, finding steel-based buildings have the highest value due to demountable connections and prefabricated assemblies [7]. The study reveals that steel structures have the highest DAS score due to high demountable connections and prefabricated components, while timber structures have a higher DAS score due to their higher recyclable and reusable potentials.

2.6 Main challenges in deconstruction implementation

Proper design can slow down deconstruction, including Design for Disassembly techniques, which involve pre-planning, documentation, and training. Costs can be reduced through resale value, partnerships, financial incentives, and equipment savings, while governments can increase salvaged material value[16].
Heba Farouk's study in Egypt reveals barriers to implementing Design for Disassembly, including financial and time constraints, lack of information about parts, and loss of craft skill, affecting over 50% of the sample [13].
Hayford identified the lack of effective design for deconstruction tools as a major hindrance to implementing Deconstruction for Deconstruction (DfD) in the construction industry [17].

2.7 BIM and Deconstruction

2.7.1 Establishing Bımfd İmplementation Factors Analysis

Johnny Zhou and Johnny Wong have developed an integrated approach to holistic management, utilizing building information modeling for comprehensive planning and operational phases, thereby promoting a circular economy[18]. Jouri Kanters has developed a BIM framework that promotes sustainable practices like deconstruction, disassemblability, recyclable materials, and harmless production. This approach integrates design processes with circular economy goals, enhancing building performance analysis, cost-effectiveness, and environmental sustainability. Researchers have integrated design processes with circular economy goals, including Building Information Modeling for Deconstructability Assessment Scores (BIMfDAS) [14]. Tools evaluate BIM implementation, export model data, and aid decision-making in optimal deconstruction scenarios. [19]. DfD principles influence successful integration, highlighting factors affecting successful deployment in Egypt. A qualitative literature analysis reveals several characteristics that can affect successful BIM deployment, as shown in Table 3. Successful BIM implementations require effective communication, teamwork, and software interoperability.

Key characteristics include collaboration, responsive business models, vision, comprehensive standards, and sustainable modeling frameworks, which ensure seamless information exchange and integration throughout the project lifecycle.

Table 3. BIM for deconstruction implementation factors[11]

BIM for deconstruction implementation factors
• Top management support to support BIM for deconstruction practices in the project life cycle management
• Industry's acceptance to embrace change from traditional working practice
• Software interoperability of BIM design tools and deconstruction Tools
• Evidence of BIM for deconstruction on the return on investment
• Information management and knowledge sharing in BIM for the deconstruction process
• Availability of BIM for deconstruction experts and client advisors
• Comprehensive BIM for deconstruction standards/policies to support practice
• Cost of software and equipment to support BIM for deconstruction practice
• Longer design lead time to allow deconstruction analytics during design
• Client understanding of BIM for deconstruction benefits
• Collaboration among project design and deconstruction teams

2.7.2 Life cycle analysis tools within BIM

Scholars are exploring interactive, dynamic techniques for creating Bills of Quantity and material mapping across multiple platforms, such as commercial Life Cycle Assessment software like Tally and e-tool LCD. Some academics have created embedded Revit and dynamo tools, aiming to develop adaptable tools for digitized and automated BIM processes.

"eTool LCD" describes a software program or disassembly platform used in the construction sector for LCA. Tally® Revit plugin is the first LCA tool that allows you to determine the environmental effects of your construction material choices inside an Autodesk Revit model.

There are many other tools but those two have free online access and they are the most common tools to use, but they haven’t been compared with case study results before.

3. Previous Deconstruction Case Studies:

3.1 Case study worldwide

Case study in Portugal:

The Lisbon Expo 98 Macao Pavilion, a two-story building with bolted metallic elements, underwent disassembly in three stages, resulting in a cost savings of $268,000. The steel structure was reused, preserving 43% of the total Embodied Energy value.
However, effective labeling of components and their connections could have reduced reassembly time by 25%. The reassembling process would have been quicker if the original information on the building design and plans had been available [20].

3.2 Case study in Egypt

schoolyard canopy:

A schoolyard canopy was installed over a playground to protect children from sun and heat. It was dismantled, reused for the school bus yard, and moved to Alexandria Desert Road. The dismantling process started by removing the roof covering, and then they removed the scissors and the purlins weeping by securing or tying the trusses and columns with ropes or tie rods. They installed the canopy using a winch. The old canopy saved about 50% of its price. If it was maintained well, they would have used it often more.

4. Discussion

The study explores the Design for Deconstruction (DfD) concept in the construction industry, combining focusing on its principles and implementation factors and exploring BIM-DAS and BIMfD techniques for calculating deconstruction, highlighting their potential for promoting sustainable construction and circular economy principles. Successful implementation requires top management support, industry acceptance, software interoperability, and collaboration.

5. Conclusion and Recommendations

This paper tried to set the basic fully comprehensive base for design for the deconstruction concept with its benefits and challenges, setting a base for the main factors that affect deconstruction and its implementation factors. Finally, the paper showed the major connection between design for deconstruction and BIM either for using software techniques such as Revit to show the case study and its affecting factors numerically or BIM tools as LCA tools to show the environmental effects of deconstruction in the same case study which will be discussed at other papers in the series to encourage design for deconstruction and to set rules helping in applying and making it more familiar in Egypt.

Future research should improve DAS methodology, evaluate BIM-based tools' effectiveness, and incorporate AI and machine learning for deconstruction. Future studies shall assist practitioners in reducing buildings’ environmental impact for different building stages by paying more attention to the study and comparing different LCA tools with deconstruction case studies.

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