Structure for the classification of disassembly applied to BIM models.

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ABSTRACT

To consider disassembly from project inception is becoming an essential part of the design process. This approach enables the reuse and recycling of materials at the end of the life cycle of buildings, reducing the need for raw materials to produce new products whilst increasing a building's flexibility during any potential reconfiguration. Above all, disassembly contributes to sustainability within the sector.

Little is known however about designing for future disassembly. In general, the design phase of construction projects tends to focus efforts on constructability, with the value of disassembly only becoming apparent during the decommissioning of a building. The construction sector is unfamiliar with the disassembly approach and the comprehensive information management process, linking design and decommissioning for over 60 years. Regarding this latter aspect, advances in Building Information Modelling (BIM) research offer opportunities for further developing the field of design for disassembly (DfD) in construction projects. Addressing this knowledge gap, this research explores the structuring of DfD information enabled by BIM to support integrated design decision-making in construction. This applied research project is inherently exploratory and based on design science research. DfD principles were identified through a literature review. Primary data was collected through case-study research, informing the development of an integrated DfD information model for measuring disassembly levels, restricted to the most common materials and construction systems used in Brazil. This research presents both a contribution to practice, by developing an information model structure to support DfD and integrated design, and also to DfD knowledge by proposing a disassembly classification system.

Keywords: design for disassembly; building information modelling; integrated design

1 INTRODUCTION

Scientists and professionals within the AECO (Architecture, Engineering, Construction and Operations) sector widely acknowledge that the volume of resources used in the construction industry worldwide makes the sector one of the largest yet least efficient consumers of raw and processed materials. This poor performance is aggravated by inefficiencies in the management of construction projects. Circa 30% of the total construction waste generated in most European countries ends in landfills (Dyer, 2012). In 2014, the UK alone generated an estimated 202.8 million tonnes of waste, demonstrating how problematic this issue is becoming. Construction, demolition, and excavation contribute circa 60% to this total (DEFRA, 2016), with demolition accounting for approximately 26% (CRWP, 2009). Thus, to design buildings considering their disassembly becomes essential to reducing waste whilst increasing the reuse and recycling of materials.

The argument for Design for Disassembly (DfD) as an alternative for tackling waste is plausible as research results from the last twenty years converge. Early research such as Couto and Crowther (2005); Guy and Rocha (2005); Manzini and Vezzoli (2008); Klohn and Ferreira (2009); Romeiro Filho (2010); and Santini et al. (2010) were essential in the development of principles for disassembly tailored to the AECO sector. These pioneering pieces of research greatly influenced more recent and impacting studies such as Go et al. (2011); Akbarnezhad, Ong and Chandra (2014); Akinade et al. (2016); Eckelman et al. (2018) and Akanbi et al. (2019) as further described below. Nonetheless, there is agreement that DfD can significantly contribute to the reuse of materials and extend their lifecycle. Despite the varying levels of evidence strength, the argument for DfD remains strong and cogent.

According to Akanbi et al. (2019), the disassembly and deconstruction analysis system ensures that buildings are designed considering the principles of disassembly and deconstruction that ensure efficient recovery of materials. In DfD, materials recovered from old buildings can be reused directly in new projects, eliminating the costs of waste disposal, the manufacture of new materials and the processing associated with recycling (Eckelman et al., 2018). However, much of the DfD research focuses on measuring disassembly levels for a building and the associated impact on waste generation. Kanters (2018) showed that the research focus has been on building characteristics. The review of over 200 articles for this research shows this is still mostly the case, and that very little is known about operationalizing and embedding DfD in construction design.

Of particular importance in this area is Akbarnezhad et al. (2014), who first approached the subject by exploring information already available within BIM models. Despite data collection limitations, their proposed disassembly BIM-based economic and environmental indicators were created to support design decision-making, opening up an entirely new research area, i.e. BIM-enabled DfD. Although promising, very little is still known. Thus, this research explores the structuring of DfD information enabled by BIM to support integrated design decision-making in construction. According to Akanbi et al. (2019), it is still not common for BIM to be used at the end of the building's life cycle, even though there are global requirements that buildings should reduce environmental impact throughout their useful life.

This applied research project is inherently exploratory; thus, design science research was deemed the most appropriate research strategy. The principles of DfD for construction projects were identified through an extensive literature review, which informed the development of a DfD information model for measuring disassembly levels of design solutions. Also, a disassembly classification method was proposed for key materials and construction methods. Data was collected while testing the proposed information model. Also, interviews with professionals within the construction sector were conducted for validation purposes. This research presents a contribution to practice by developing an information model structure to support DfD. It also contributes to DfD knowledge by proposing a disassembly classification system.

2 DESIGN FOR DISASSEMBLY

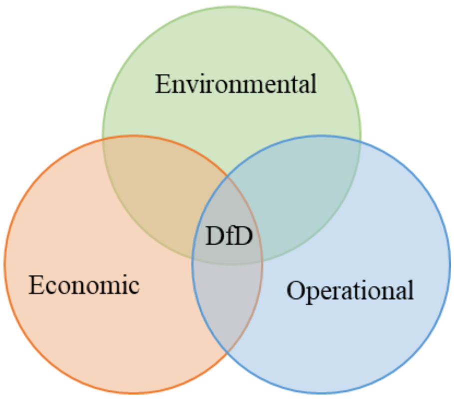
Design for disassembly (DfD) is a term borrowed from manufacturing literature. Early DfD publications go back to the 1960s and refer to a body of knowledge relating to materials and components characteristics and how they are put together in a way that makes disassembly easier. Within the AECO sector, the practice of disassembling buildings pre-dates any scientific literature in manufacturing. Well known buildings, such as the Crystal Palace or the Eiffel Tower, are examples of buildings designed for subsequent disassembly. However, in research, it seems that the term first appeared in Lawson (1994). The term *design for deconstruction* was used to refer to DfD, and both terms have been used interchangeably since. In this paper, the term disassembly is used as it refers to a wider body of existing knowledge.

Early work within AECO was published in the UK (Lawson, 1994), the USA (Lund and Yost, 1997) and Australia (Crowther, 1999). Lawson (1994) and Crowther (1999) were focused on understanding the principles of DfD. They contributed by tailoring DfD principles to inform building design. Complementary work by Lund and Yost (1997) focused on understanding the cost-benefit of DfD. Their research, although limited, can be considered the first study to provide a method for assessing the labour, time, cost, and environmental impacts of disassembling in construction, creating a reference for further comparisons.

The need for DfD was and still is related to the environment. Growing concern for the environment and an increasing focus on sustainable construction means DfD is becoming a requirement, not just a desirable product feature. The argument for DfD is valid and sound: it is morally and environmentally correct to repurpose materials and components resulting from disassembly because they have an extended life cycle. That is because DfD enables and increases the probability of reusing components and materials before they are recycled and subsequently disposed of. From a design perspective, it creates a whole new industry focused on designing for adaptive reuse (Sanchez and Haas, 2018). It also creates a new industry related to buying and selling disassembled goods.

According to Sanchez, Rausch and Haas (2019) standardized procedures and tools assist in decision making when planning the deconstruction of a building and it is important to analyze options for disassembly in an objective way to enact adaptive reuse. Sanchez et al. (2020) consider that the adaptive reuse of buildings contributes significantly to sustainable development in the constructions industry, although disassembly planning, as a green design method, is still embryonic in comparison to other industries. This demonstrates the importance of seeking objective solutions for the disassembly and reuse of building elements and materials.

The benefits of DfD can be classified into three main interrelated categories (Figure 1). Environmental benefits such as increased life-cycle of materials mean that less material is extracted, fewer products are made and disposed of in landfills. Operational benefits refer to the effort needed for maintenance and at the point of disassembly. These also have positive economic benefits due to the reduced need for labour and the potential for selling disassembled goods. Finally, there are also economic benefits emerging from reducing wastage, energy, and the need for landfills, which have a positive environmental impact. Although the evidence varies in strength, there is consensus regarding these benefits.



	Increased materials' life-cycle	Reduced Pollution	Decreased environmental damange	Easier building maintenance	Increased reutilisation	Increased economic benefits	Reduced waste	Increased recycling	Increased energy savings	Reduced need for landfills
Guy and Rocha (2005)	x		x			x				
Crowther (2005)	x						x			
Couto; Couto; Teixeira, 2006					x			x		x
Manzini and Vezzoli (2008)	x	x								
Klohn and Ferreira (2009)			x	x	x	x				
Romeiro Filho (2010)				x			x			
Akinade et al. (2016)		x				x			x	
Eckelman et al. (2018)					x	x	x	x		
Akbarieh et al. (2020)	x			x	x	x	x			

Figure 1. Benefits of DfD

Despite the strong argument in support of DfD, adoption and implementation are not straight forward. Tingley and Davison (2011) discussed various DfD barriers associated with additional risks, costs, and time when prescribing previously used materials in the design process. More recent evidence gathered by Akbarieh et al. (2020) and Akinade et al. (2020) reinforces this view. For them, several barriers still prevent further adoption including: a lack of legislation for DfD, a lack of adequate information during building design, the lack of a large enough market for recovered components, difficulties related to developing a business case for DfD and the lack of effective design for deconstruction tools. The above evidence indicates that a paradigm shift is needed before the AECO sector embraces DfD.

In this respect, Akinade et al. (2020), conducted research addressing the lack of effective design for deconstruction tools. They argued that DfD requires more robust BIM compliant tools to assist decision making (Akinade, Oyedele, Ajayi, et al., 2017; Akinade et al., 2016; Bilal et al., 2015). It is within this area that this research contributes to the DfD body of knowledge by proposing BIM-enabled functionalities, such as identifying materials, the detail of fittings, and the relationship between building components, to support decision making.

Precedent work related to this topic includes van den Berg et al. (2021), Basta et al. (2020), Denis et al. (2018) and Akinade et al. (2017b). According to Akinade et al. (2017b), BIM can contribute to deconstruction in the following ways: better collaboration between stakeholders, visualization of the deconstruction process, quantification of recoverable materials, development of the deconstruction plan, performance analysis and alternative end–of–life simulation, optimization of building life-cycle management and interoperability with BIM software. While some of the suggested points directly influence disassembly (e.g. deconstruction plan), others are more focused on enhancing collaboration (e.g. interoperability).

More specific to the disassembly tools is the work of Denis et al. (2018) who have developed a method to quantify the impact of DfD. Impact is measured in material flows generated during the disassembly of a building element. This research builds on the work of Lund and Yost (1997) by using new theoretical lenses and benefitting from BIM technology in the assessment of disassembly processes. The model was considered still embryonic by the authors. However, this is an insightful proposal that can be considered alongside information about materials that influence DfD.

Within the same line of research is the work of Basta et al. (2020), who developed a Deconstructability Assessment Scoring (DAS) methodology for quantitative assessment of Steel Structures deconstructability. This is also insightful and complements the work of Denis et al. (2018) by considering materials (steel) characteristics. Because it focuses on steel elements only, this is also a limitation of the work.

Also important is the work of van den Berg et al. (2021). These authors depart from the analysis of existing building materials and their qualities for disassembly and reuse. Although it does not influence building design, it provides an insightful discussion concerning building elements characteristics. Similar research was carried out by own authors (Mattaraia, Martins and Fabricio, 2016; Mattaraia, 2013).

Based on the precedent research shown above, Figure 2 was developed to depict how BIM models can be developed to incorporate information relevant to DfD and consequently improve the reuse of materials. BIM design software is parametrically structured to store a large amount of information about materials, details about connections and models in three dimensions. It is even possible to simulate disassembly and provide for more favourable situations to enable reuse.

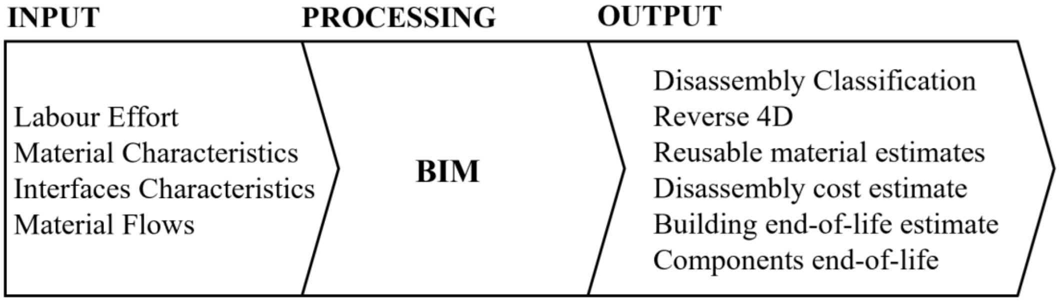


Figure 2 – Ways by which BIM can contribute to DfD.

3 RESEARCH METHOD

This applied research project is inherently exploratory. Ultimately, the research aimed at making building design solutions more sustainable. The chosen research path builds on precedent research (e.g., van den Berg et al., 2021; Basta et al., 2020; Denis et al., 2018; Akinade et al., 2017b). It explores BIM for incrementally constructing a new reality for integrated design approaches by embedding DfD analysis as part of the design process.

Very few alternatives to research this area exist. Although principles of DfD are known, the implementation of these principles as part of integrated design approaches is still embryonic. Cases for observation in the construction sector are rare and tend to focus on temporary buildings or infrastructure projects. The gap of at least fifty years between designing and disassembling prevents observation and case-study research. Since DfD, as part of an integrated design method, cannot be observed and assessed, the only plausible option left is to conduct research through intervention. Thus, Design Science Research (DSR) was defined as the research strategy.

DSR is recommended when the phenomenon cannot be observed through traditional research (Hevner et al., 2007). The research design was based on the DSR Framework proposed by Vaishnavi and Kuechler (2015), which involves loops of iterations between proposing a solution and evaluating it. Figure 3 illustrates the research design process and an overview of the data collection methods used.

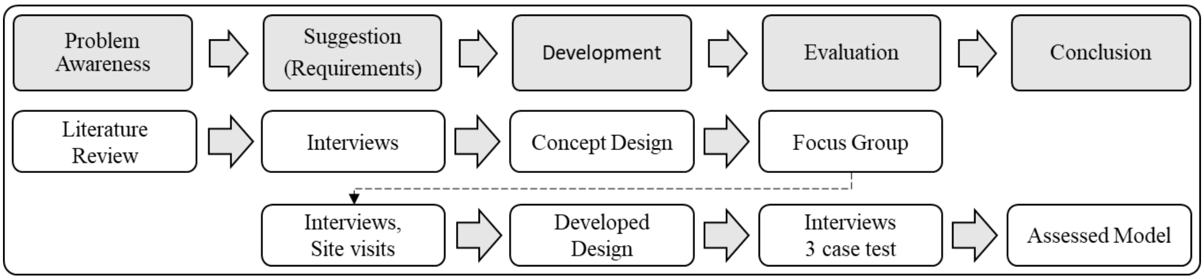


Figure 3. Research design and data collection overview

The initial literature review was focused on the decommissioning process of buildings and DfD and BIM-supported decision-making principles. Subsequently, interviews were conducted to elicit DfD requirements. Five UK professionals with varying levels of experience of DfD or projects where DfD is relevant were interviewed. These included one professional from the automotive sector, one manager from a nuclear power station undergoing a regeneration (decommissioning) process, one professional working for a demolition waste management organization, one architect involved in the design of a to be disassembled World Cup stadium and one project director leading a major UK Hospital development project, worth approximately £560 million, containing two temporary high rise decant buildings requiring disassembly.

A conceptual proposition for the integrated DfD information model was developed and discussed through a focus group involving five academics conducting research related to BIM, waste management, design and construction. Subsequently, four site visits (two factories of prefabricated concrete elements, one specialized in steel structure and one in timber and their ongoing projects, including two warehouses, two supermarkets, one commercial office building and the expansion of one football stadium) were conducted. Also, twelve interviews with professionals involved in these projects (designers, architects, civil and production engineers, and contractors) and a documental analyses of project briefs and memorials were conducted. The final integrated DfD information model was developed and assessed through interviews, three test cases, and nine interviews with four engineers and five academics.

3.1 Design

3.1.1 Classification System

Materials and elements widely used in construction were selected to establish an 'element disassembly classification system'. The classification aimed to explore BIM resources, the software's possibilities and test its application, taking into consideration the fact that buildings have a wide variety of elements, differing from project to project. It is not the purpose of this research to dictate a classification of disassembly for each construction element. Instead, it explores the criteria that can be used to facilitate decision-making throughout the development of a project while enabling building disassembly.

The chosen materials within the disassembly classification system are standard. As explained in Mattaraia, Martins and Fabricio (2016), material choices directly influence disassembly. Table 1 presents the materials used in this research organized into three parts: structure, external envelope and internal partitions following the Brazilian National Standards Organization (ABNT) NBR 15575: 2013. These were classified according to their disassembly level, weighted mean, and disassembly characteristics. The characteristics were investigated previously by the author (Mattaraia, 2013) and are further explained below.

The classification of disassembly varies between 0 and 1, the closer to 1, the greater the possibility of disassembly and reuse. Also, a weight between 1 and 3 was stipulated to calculate the building's final disassembly classification. Weights were attributed with a basis on material function and the potential damage it can cause to other materials during the disassembly process. For example, structural elements have been attributed to 1 whereas internal partitions and external envelope, 3. Building envelope elements have an intermediate weight of 2 because they can cause damage to partitions, but rarely to the structure. The weights were presented to four engineers and five academic experts for internal validation.

Table 1. Disassembly Classification

(Materials and elements	Classification (0 a 1)	Weight (weighted mean)	Characteristics
Main Structure			
On-site pre-cast concrete	0.1	1	Chemical bonds It requires heavy equipment. Difficult to handle, transportation and store – High cost, labour and time – is usually demolished. It can be recycled, but for other uses. It cannot be reused in the original function.
Pre-cast prestressed concrete elements	0.3	1	Some connections can be broken. Parts are produced considering transportation and storage. They can break during disassembly. Equipment used for assembly can be used for disassembly. Most connections are chemical. It can be recycled, but for other uses. They are hardly reused.

Welded metal	0.6	1	Prefabricated elements facilitate transportation and storage. Equipment used for assembly can be used for disassembly. – Resists disassembly. Welded connection makes it difficult to separate the parts and can cause damage. It can be recycled. It can be reused, but it is not usual.
Bolted metal	0.8	1	Prefabricated elements facilitate transport and storage. Equipment used for assembly can be used for disassembly. – Resists disassembly. Screw connection facilitates the separation of parts and reduces damage. It can be recycled. It can be reused.
Timber	1.0	1	Prefabricated elements facilitate transportation and storage. Equipment used for assembly can be used for disassembly. – Resists disassembly. Mechanical connections through parts or fittings facilitate the separation of the elements reduces damage – Can be recycled. It can be reused. It is a sustainable material, provided it is certified and without chemical additives harmful to the environment.
External Envelope			
Glass	0.3	2	Fragile - attention when disassembling. In storage and transportation require careful handling. It is usually discarded when there are demolitions and renovations. It is not usually reused.
Hollow block masonry	2.4	2	It does not resist disassembly. It is usually broken, removed, and discarded. It can be recycled but not reused.
Clay brick masonry	0.8	2	Depending on the model and the mortar used, they can facilitate or hinder the process. It is a small material that can be removed with few tools and manually. It is easy to transport and store. It can be reused in the same way as the original use.
Pre-cast concrete elements	0.8	2	Resistant and fitted elements – Resist disassembly. It can be reused after disassembly. It can also be recycled.
Internal Partitions			
Dry wall	0.2	3	Chemical bonds It does not resist disassembly. It is not reused or recycled.
Glass Partition	0.3	3	Fragile - attention when disassembling. In storage and transportation require careful handling. It is usually discarded when there are demolitions and renovations. It is not usually reused.
Hollow block masonry	0,4	3	It does not resist disassembly. It is usually broken, removed, and discarded. It can be recycled but not reused.

Clay brick masonry	0.8	3	Depending on the model and the mortar used, they can facilitate or hinder the process. It is a small material that can be removed with few tools and manually. It is easy to transport and store. It can be reused in the same way as the original use.

3.1.2 Materials Characterization

In the following, the descriptive material characterization is presented according to Mattaraia (2013).

3.1.2.1 Main Structure

The following structural systems were considered: on-site concrete, pre-cast concrete, steel, and timber structure.

On-site concrete (disassembly classification 0.1): structures have a low potential for disassembly, as they have chemical connections and require heavy equipment, and are both difficult to handle while disassembling and difficult to transport when disassembled. Often, the only option is demolition due to high costs arising from the volume of work and time required for effective dismantling.

Pre-cast concrete structure (disassembly classification 0.3): is simpler to disassemble compared to on-site concrete. It allows for fitting points and connections that can be undone. Also, the parts are produced taking into account transportation and storage during assembly, which contributes to disassembly. However, there is a risk of breakage during disassembly, and it has chemical bonds. Slabs are manufactured and assembled on-site, but it requires grouting, preventing future separation and disassembly without damaging the parts. However, other elements, such as pillars, can be disassembled without further damage.

Steel structures (disassembly classification 0.6 for welded structures and 0.8 for bolted ones). Assembly considerations contribute to disassembly. Transportation, storage, and equipment for assembly are beneficial for disassembly. It has a significant recycling potential, and it is durable. However, there are risks of corrosion. Elements are challenging to disassemble when welded. Bolted structures increased the potential for disassembly and reassembly.

Timber structures (disassembly classification 1.0): were included in this framework due to increases in use worldwide. Timber is a flexible and renewable material. It is considered sustainable if certified. It is joined through bolts or small joints. Fitted structures that do not require bolts or joints. Parts are prefabricated, and the assembly process is considered during design. This aspect facilitates transportation, also contributing to disassembly. Timber structures with mechanical connections or fittings are flexible and long-lasting, thus allowing reuse.

3.1.2.2 External Envelope

The following building envelope systems were considered: glass (curtain wall), masonry and pre-cast concrete elements. These are often related to the adopted structural system (e.g., masonry and on-site concrete, glass and steel and pre-cast panels and prefabricated concrete), but there are no set rules.

Glass – of various types, e.g., laminated, strengthened and security - (disassembly classification 0.3): a fragile material that requires great care when disassembling. Its assembly, storage and transportation are considered during the design and manufacturing processes, thus contributing to disassembly. However, its fragility often leads to breakages followed by disposal. Health and safety risks must also be considered. Frames are often made of timber, PVC or metal and can be disassembled, although reuse is limited.

Masonry – clay brick (disassembly classification 0.8): solid clay bricks are widely used worldwide. Numerous variables, such as the type of brick, the laying process, whether exposed, rendered, varnished, or painted, can impact the classification. Also impacting is the type of connection (often mortar). It is resistant, and its small dimensions contribute to its disassembly, storage, and transport. However, it requires careful handling and time to be disassembled correctly. Reuse is possible, although the costs are often prohibitive.

Masonry – hollow blocks (disassembly classification 0.4): as above. However, hollow clay or cement blocks are not as resistant and tend to break on disassembly.

Pre-cast concrete panels (disassembly classification 0.8): as any prefabricated element, assembly is planned from inception, thus facilitating disassembly and reassembly. Often, it can be disassembled, stored, and transported without being damaged. Panels are often fitted, thus facilitating disassembly. Silicone can be used as an adhesive, but its removal does not impact the disassembly process.

3.1.2.3 Internal Partitions

The following were considered: dry-wall partitions, glass partitions, masonry made of clay brick or hollow clay or cement block.

Dry-wall partitions (disassembly classification 0.2): Often, the structure is made of low-grade timber or metal clad with plasterboards. Plasterboards are joined with adhesive tape and subsequently plastered, skimmed, and painted. Dry walls are usually demolished because the system is fragile, not prone to disassembly, and potentially toxic.

Glass partitions (disassembly classification 0.3): often demolished due to low adaptability levels (e.g., strengthened, or laminated glass cannot be cut). Although glass is not a toxic material, it is fragile and requires careful handling.

Masonry – hollow blocks (disassembly classification 0.4): were (but no longer are) widely used in low rise residential buildings. Its characteristics are presented above.

Masonry – clay bricks (disassembly classification 0.8): were (but no longer are) widely used in low rise residential buildings. Its characteristics are presented above.

3.1.3 Establishing Weighted Mean

For obtaining a general disassembly rating of a building, it is necessary to assess the mean value of the various materials and elements used. Because some building elements are more easily disassembled than others, it is necessary to consider a weighted average. The main characteristics used for the classification of overall building disassembly were derived from Crowther (2005) as follows:

1. *Connections*: the type of connection between parts can impair the disassembly process. For example, if there are fitted parts, it is possible to disassemble without damage, whereas parts with chemical bonds can hardly be separated without damage.

2. *Resistance to Disassembly and Reassembly:* the material must be resistant during disassembly to be better used and reused; several materials are not resistant and need to be recycled or disposed.

3. *Layers*: buildings are constructed in layers, such as structure, envelope, mechanical and electrical systems. The greater access to elements, the easier is the disassembling process without damages to the element being disassembled or adjacent ones.

4. *Scale*: the scaling of the elements is essential to schedule their removal and reuse because the fewer tools, people, and time it takes to disassemble, the more chances the elements will have to be reused.

5. *Standardization*: disassembly is more efficient if elements and materials are standardized. This is because the same tools and labour can be used.

6. *Storage and Transportation*: As with assembly, storage and transport are essential for reusing materials. For example, large and very large elements hinder transportation and storage. As such, they are unlikely to be reused.

7. *Manufacturing Process*: maintaining information about the manufacturing process of building elements is essential before proceeding to disassembly and reassembly.

8. *Recycling*: some materials cannot be reused because they are toxic or have a particular composition. Others are prone to damage during disassembly or have low value and prohibitive disassembly time and costs. For these, recycling (if possible is recommended).

9. *Reuse*: some materials are resistant during disassembly and can be reused in the same way, such as bolted metal structures that can be reused if elements of precisely the exact dimensions are considered in the design of a new or refurbishment project. (Note: these must be approved by the regulator before use).

10. *Adaptation*: materials that are resistant during disassembly and can be adapted to new uses (e.g., timber elements can be reused in different ways).

Figure 4 represents a summary of the critical characteristics considered for the development of the classification of disassembly. These have been grouped according to technical, production and goals of the disassembly process.

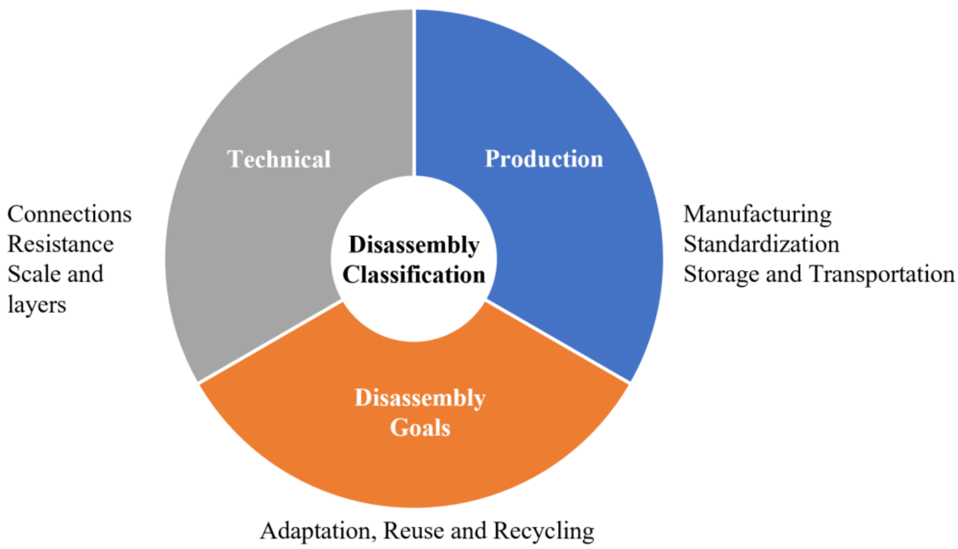


Figure 4. Characteristics that must be considered in the classification of disassembly.

Tables 2, 3 and 4 show the characteristics of the materials and their connections. The tables were developed based on the data gathered through interviews, site visits to the works, factories, and literature review. Within this article, only the most common materials and construction systems used in Brazil were analyzed.

Table 2. Characteristics of structural elements

Structural Solutions	Mechanical connection	Resistance to disassembly	Standardization	Storage and transportation	Scale	Manufacture	Layers	Recycling	Reuse	Adaptation	**Classification**
On-site pre-cast concrete								X			**0.1**
Pre-cast concrete			X			X		X			**0.3**
Welded metal		X	X	X		X	X	X			**0.6**
Bolted metal	X	X	X	X		X	X	X	X		**0.8**
Timber	X	X	X	X	X	X	X	X	X	X	**1.0**

Table 3. Characteristics of external envelopes

External Envelope Solutions	Mechanical connection	Resistance to disassembly	Standardization	Storage and transportation	Scale	Manufacture	Layers	Recycling	Reuse	Adaptation	**Classification**
Glass					X	X		X			**0.3**
Masonry - hollow block			X		X	X		X			**0.4**
Masonry - brick		X	X	X	X	X		X	X	X	**0,8**
Pre-cast concrete	X	X	X	X	X	X	X	X			**0,8**

Table 4. Characteristics of internal partitions

Internal Partitions Solutions	Mechanical connection	Resistance to disassembly	Standardization	Storage and transportation	Scale	Manufacture	Layers	Recycling	Reuse	Adaptation	**Classification**
Dry-Wall					X	X					**0.2**

Glass					X	X		X			**0.3**
Masonry - hollow block			X		X	X		X			**0.4**
Masonry - brick		X	X	X	X	X		X	X	X	**0.8**

Finally, the overall building classification calculation is performed according to Equation 1. CD represents the classification of disassembly multiplied by the weighted average value, divided by the number of elements (or quantity in m²). A simple formula was developed to classify disassembly into practice and analyze the developed application possibilities. However, as the table becomes more complex, the formula can also be more specific, if it follows the same principles discussed throughout the article.

$$\frac{\textit{CD x weighted mean}}{\textit{Number of elements (or quantity in } m^2\textit{)}}$$

Equation 1. Overall building disassembly classification

4 EVALUATION AND DISCUSSION

4.1 Parameters inserted in BIM models.

A project was developed to classify disassembly into practice and analyze the possibilities of assessing a building's disassembly. A 3D model was created in the Revit 2019 software to explore various BIM resources and insert the classification system. It was a prototype to see how the Project for Disassembly can be improved when combined with BIM.

The testing project developed was a shed consisting of beams, pillars and walls made of pre-cast elements of reinforced and prestressed concrete. The selection of these building elements was informed by data gathered through site visits, interviews, and documented analyses. This decision was driven by a need for simplicity and scope to assess a variety of models to explore the tool being proposed to classify disassembly and a better understanding of the relationship between the elements within the model. Three conceptual digital models (sheds) were created for testing the classification system with the same built area: the first was a prefabricated concrete structure, with an external envelope made of concrete panels and internal partitions made of hollow blocks (Figure 5, Tables 5 and 6). The second was a steel structure, with an external envelope made of hollow clay blocks and internal dry-wall partitions (Figure 6, Tables 7 and 8). The third consisted of a timber structure, with an external envelope made of clay bricks and internal glass partitions (Figure 7, Tables 9 and 10).

The models were created within a Revit template to generate tables with information on the number of elements, materials, classification of disassembly and tags on important points to be considered in the project of disassembly. Issues such as weight and life expectancy, among others were also fundamental for disassembly. However, this study focused on the quantity of materials used, how the connections between them would be and the possibility of disassembly. The red highlighted cells represent the non–fulfilment of some specific requirements, such as the impossibility of mechanical connections, as well as the use of chemical connections, such as mortar.

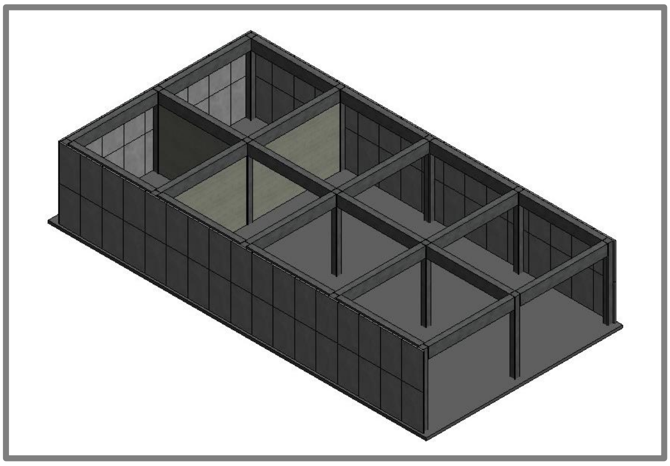


Figure 5. Conceptual model 1

Table 5. Table of units for the classification of disassembly

A	B	C	D	E	F	G	H
counter	family and type	classification of disassembly	weight	weighted average	ligação mecânica	mechanical connection	hand tools
15	precast rectangular column	0.3	1	0.3	☑	☐	☐
86	concrete panel	0.8	2	1.6	☑	☑	☐
22	precast rectangular beam	0.3	1	0.3	☑	☐	☐
123							

Table 6. Table with m² for the classification of disassembly

A	B	C	D	E	F	G	H	I
Count	Area	Family and Type	classification of disassembly	weighted mean	weighted average	Mechanical Conne	resists disassembly	hand tools
1	17 m²	Basic Wall: Genérico	0.4	3	1.2	☐	☐	☑
1	16 m²	Basic Wall: Genérico	0.4	3	1.2	☐	☐	☑
1	17 m²	Basic Wall: Genérico	0.4	3	1.2	☑	☑	☑
3								

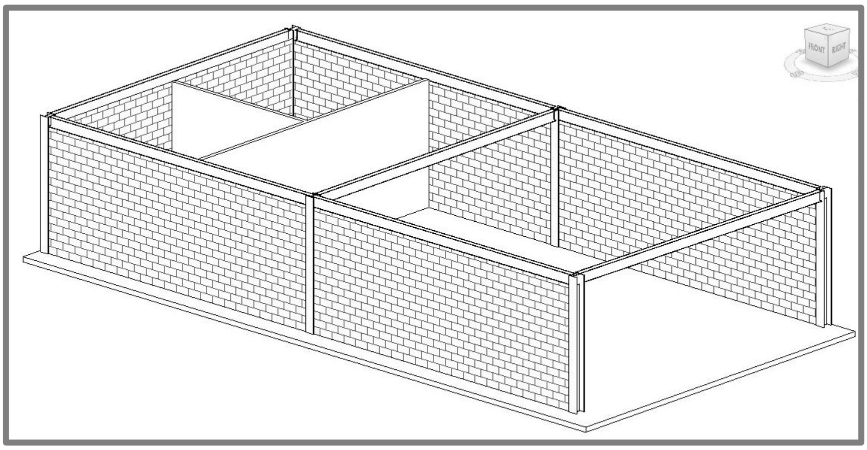


Figure 6. Conceptual model 2

Table 7. Table of units for the classification of disassembly

A	B	C	D	E	F	G	H
Count	Family and Type	Classification for Disassembly	Weight to Average	Weighted Average	Mechanical Connection	Resists Disassembly	Hand tools
7	Beam	0.8	1	0.8	☑	☐	☑
6	Pillar	0.8	1	0.8	☑	☑	☑
13							

Table 8. Table with m² for the classification of disassembly

A	B	C	D	E	F	G	H	I
Count	Area	Family and Type	Classification for Disassembly	Weight to Average	Weighted Average	Mechanical Conne	Resists Disassembly	Hand tools
1	75 m²	Basic Wall: Genéric	0.4	2	0.8	☐	☐	☑
1	37 m²	Basic Wall: Genéric	0.4	2	0.8	☐	☐	☑
1	73 m²	Basic Wall: Genéric	0.4	2	0.8	☐	☐	☑
1	37 m²	Basic Wall: Interior -	0.2	3	0.6	☐	☐	☑
1	37 m²	Basic Wall: Interior -	0.2	3	0.6	☐	☐	☑
1	19 m²	Basic Wall: Interior -	0.2	3	0.6	☐	☐	☑
1	19 m²	Basic Wall: Interior -	0.2	3	0.6	☐	☐	☑
Grand total: 7								

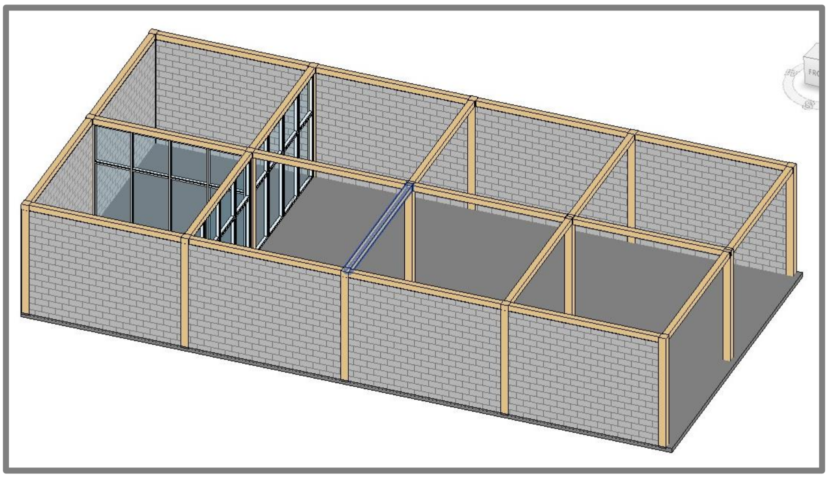


Figure 7. Conceptual model 3

Table 9. Table of units for the classification of disassembly

A	B	C	D	E	F	G	H
Count	family and type	classification of disassembly	weight to avarage	weighted to avera	mechanical connection	resist to disassembly	hand tools
15	Pillar	1	1	1	☑	☑	☑
22	Beam	1	1	1	☑	☑	☑
24	Glass panel	0.3	3	0.9	☐	☐	☑
61							

Table 10. Table with m² for the classification of disassembly

A	B	C	D	E	F	G	H	I
Count	Area	Family and Type	classification of disassembly	weight to avarage	weighted to average	mechanical connection	resist to disassembly	hand tools
1	80 m²	Basic Wall: Genéric	0.8	2	1.6	☐	☑	☑
1	41 m²	Basic Wall: Genéric	0.8	2	1.6	☐	☑	☑
1	80 m²	Basic Wall: Genéric	0.8	2	1.6	☐	☑	☑

Once digitally modelled according to this template, it was possible to insert the disassembly classification for all elements and materials. The table is automatically generated and updated as the project changes, assessing the building’s disassembly more practically and objectively. It also enabled understanding the disassembly classification from the start of the project. Once the digital model had been created, the disassembly parameters were inserted and their respective classifications generated. Thus, it was possible to produce a table to quantify and assess the overall building's classification. All steps of the process and the analysis are kept in a single file (the digital model).

The details of the classification per model are as follows. Conceptual model 1 made of pre-cast concrete structure (CD 0.1), external envelope made of concrete panels (CD 0.8) and internal hollow block partitions (CD 0.4). Conceptual model 2 was made of bolted metal structure (CD 0.8), an external envelope made of clay bricks (CD 0.4) and internal dry-wall partitions (CD 0.2). Moreover, Conceptual model 3 had a timber structural system (CD 1.0), an external envelope made of clay bricks (CD 0.8) and internal glass partitions (CD 0.3). Layers (i.e., structure, envelope, and partitions) were multiplied by their respective weight (i.e., structure solution x 1, the envelope x 2 and internal partitions x 3). As there is no number of elements, the CD is not divided. Thus, the higher the CD, the more viable the disassembly will be.

Figure 8 allows comparing and visualizing the overall results, in addition to checking which layer could be considered to seek better solutions. For example, model 3, even though it has a bolted metal structure, which would facilitate disassembly and reuse, has a glass partition, which is difficult to reuse, as it breaks down during disassembly, in addition to requiring special care in storage and transportation. In addition, plasterboard partitions are also unlikely to be reused and have to comply with special rules for their disposal. Thus, the total disassembly rating of the building is compromised.

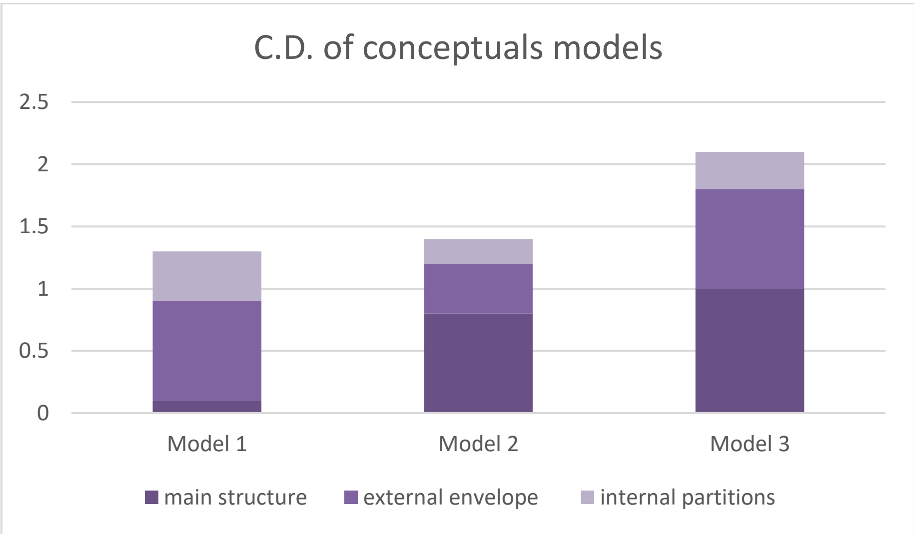


Figure 8 - Classification of general disassembly of buildings

The design process involving disassembly considerations from the beginning to facilitate the analysis and choice of elements that most contribute to it followed the flow shown in Figure 9. Initially, the project's materials and elements are chosen, and their disassembly classification defined; later, the formula was defined. Thus, it was possible to develop the project and the 3D model and then insert the classification into the parameters. A table was generated from this information, which presented the final calculation. Finally, the general classification check and the calculation itself were carried out.

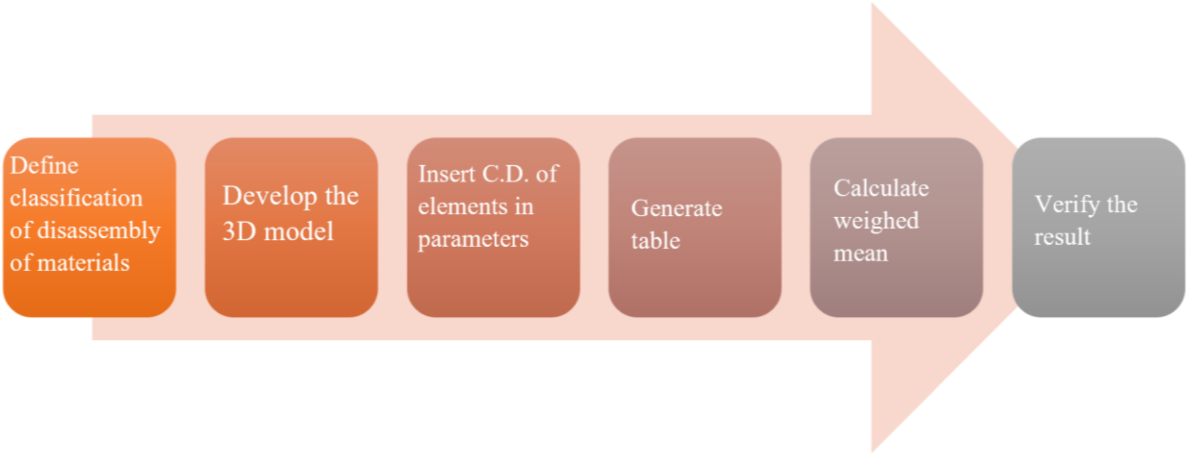


Figure 9. Steps to verify the Classification of Disassembly (CD)

Subsequently, a questionnaire was developed to assess the disassembly classification, which was sent to specialists in adaptations systems with metallic, concrete and wood structures. Those selected were civil engineering academics, specialists in building systems research. The decision to make the assessment through questionnaires was due to the possibility of direct comparison of the results, allowing an objective analysis of the questions. The choice of participants was due to their vast knowledge of structures, so they could share their views concerning the materials chosen to compose the disassembly classification and the construction systems.

Four experts answered the questionnaire who agreed with the proposed disassembly classification and did not report any significant flaws. However, there were suggestions related to adding more materials to the table, such as aggregated and recycled materials, and wood and plastics in the internal vertical partitions. It was not feasible to place composite materials in the table, as their classification would be more complex due to the difficulty of separating the materials, but there is the possibility of the materials being inserted after the individual evaluation, as it is possible to complement the table with several elements. The intention of this work is to initiate the discussion and classification of the elements. To consider the inclusion of the suggested elements into BIM is part of a future research project.

5 CONCLUSION

This research contributes to the knowledge base by suggesting we consider the future disassembly of buildings at the inception of a project, making this process more efficient by combining with BIM to extend the materials' useful life, reduce waste and consume less raw materials. Currently, solid waste disposal, mainly from construction, is a significant concern to everyone aware of the severe consequences of the enormous amount of waste discarded and the tremendous environmental challenges we face.

The classification of disassembly, the design and the 3D model combined can be used as a reference for decision making by addressing issues related to disassembly and reuse and potential environmental impact. However, the proposed solution is not stand-alone. To involve various stakeholders, establish technical standards or even hold organizations responsible for enabling appropriate materials disposal, increasing their reuse and recycling chances is still essential. In its current format, information must still be entered manually, creating additional work prone to error. However, these are minor drawbacks since it is possible to create libraries of objects already containing CD information, thus enabling a more automated process.

This research contributes by generating novel knowledge regarding materials end-of-life suitability for disassembly and reuse. It also presents a solution for incorporating this knowledge into BIM models to inform decision making from project inception. The proposed solution includes a method for classifying disassembly and a data structure for materials and elements characteristics that impact disassembly. This approach was tested and the results validated by a team of experts.

While the results are positive, this work has various limitations that will inform future research. Firstly, the research has only considered a set range of materials. To address this issue, more complex materials should be tested. Secondly, the BIM models used were relatively simple. More research is needed to test more complex buildings containing a more comprehensive range of materials and to understand the Level of Detail (LoD) of the proposed structure. Thirdly, considering that this is the first study of this kind, the input of information was done manually. This approach is prone to error and as such it is a limitation of the work developed that can be addressed in the future. Finally, the materials considered are characteristic of Brazilian construction. Therefore, more research is needed to address other (international) ways of building.

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