Modularity in Design for Disassembly (DfD): Exploring the Strategy for a Better Sustainable Architecture

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Abstract. This paper explores the idea of modularity as one of the important design strategies that potentially creates a circular and more sustainable architecture. Modularity is a common design strategy used to generate form, create spatial efficiency, support mass production and prefabricated design, particularly in modern architecture. However, its contribution to sustainability is rarely discussed. This paper utilises Design for Disassembly (DfD) as a framework to investigate the potential of modularity in design, speculating that such design aspects can potentially minimize waste and improve efficiency in the systematic assembly and disassembly of building components. This paper employs two architectural projects designed with DfD approach as study cases, the Loblolly House and Cellophane House in the USA. The data are taken from works of literature and online secondary sources. The particular building components are mapped based on categories, such as building layers or joints and analysed based on its modular characteristics. The study reveals that the application of modules in particular building layers and separable joints with further use of the division-subdivision operation are significant design strategies found in each case. Such strategies provide better flexibility and interchangeability of building components during the assembly-disassembly process, proven by the calculation of construction waste. These findings arguably expand the discussion of modularity and encourage further study of modular design for a better sustainable architecture.

Keywords: Design for Disassembly, design strategy, modularity, sustainable architecture

1. Introduction

This paper explores modularity as one of the important design strategies that potentially creates a circular and more sustainable architecture. It aims to develop a discussion about how modularity can contribute to sustainability, mainly through the systematic reuse of building material and producing less waste [1], [2]. The idea of modularity has been discussed as a strategy for generating form, creating spatial efficiency, producing mass design, remarkably in the era of modern architecture [3]–[5]. Modularity grows as the technology advances, focusing on the material and construction as prefabricated systems [5], [6]. However, the idea of modularity as a design strategy that contributes to sustainability is rarely discussed [1], [5].

Sustainability as a principle has been widely discussed regarding its role in supporting architectural practice to be more responsible [7]. In the meantime, the discussion of sustainable architecture focuses more on the building performance such as energy efficiency [8], zero run-offs [9], usage of green or high-tech technology and material, or biomimicry as a form of aesthetic [10], which pays attention mainly to the building during its operation. Such discussions of sustainability provide limited recognition
to the design approach as a system [1], [5], [7], or way of thinking [6], excluding the continuous process - from the conception of the building until it ends operating and disassembled. This paper believes that the after-life of a building should also be planned to prevent building demolition in order to create a more circular architecture.

Design for Disassembly (DfD), also known as Design for Deconstruction [1], [2], [11], is employed in this paper as one of the approaches in sustainable architecture that orients itself in the design process and manufacture for the possible reuse of building materials and producing minimum material waste [11], [12]. Through the idea of systematic assembly and disassembly, the design of building attempts to design building components in an efficient manner, which operates based on materials, building layers [13], [14], and separable joints [15]. In the development of DfD, the idea of modularity is utilized to expand the efficiency of building material and provide better predictability of time, cost, and energy through the flexible and interchangeable building components. Therefore, DfD, as a framework, is used to investigate the potential of modularity in design, speculating that such design aspects can minimize building waste and extend material life [1], [7].

This paper is structured to study the application of modularity as a design strategy that potentially contributes to sustainability. Started with exploring the idea of modularity and its application in the DfD context then continues with identifying the pattern of modularity in two study cases. The particular building components with modular characteristics are mapped based on their position in building layers or joints. These categories are analyzed based on its modular characteristics to look further for building components' flexibility and interchangeability. Such a method is used to find the significance of modularity as a strategy for designing sustainable architecture.

2. Literature Review: Exploring Modularity in Design for Disassembly

In exploring the modularity based on the DfD context, it is essential to understand the basic ideas of DfD—the systematic assembly and disassembly of building components. The word "disassembly" in the context of DfD refers to "systematic disassembly", where the order of the disassembly process is the reverse of the sequence of the assembly process [2]. This approach focuses on how the manufacturing and the sequential disassembly processes occur in a building, allowing a circular life cycle of building material. By doing so, the building components can be regulated as systematic as possible (Fig 1). Further, at the end of building life [1], [2], [11], more building components can be reused directly and produce less waste.

![Figure 1. Example of systematic assembly disassembly of a modular building component, which implies specific orders of sizes, materials, and construction techniques (source: author's own work, 2020)](image-url)
The building components are designed to be easily assembled and disassembled, and so forth to be reused further as a whole or partial, without degrading the material quality [13]. Based on the works of literature [1], [2], [13], such systematic designed assembly requires two principles that can improve the process of building's assembly; they are (1) layer-based operation in structural elements, the skin of the building, or services, utilization of (2) light-weight materials and (3) separable connectors or joints [5], [11]. The building layer needs to be separated so that each layer can be accessible when it needs to be taken without disturbing or damaging other components [16]. This principle is related to the idea that each layer has a different lifespan [14]; thus, buildings need to be mapped into layers, including site, skin, structure, plans, services, and stuff. However, this separation needs to be supported by the use of separable joints. The use of chemical joints and nails as connectors between elements must be avoided to prevent contamination or damage to the material [13], [16].

Based on early study, those principles are often found using the idea of modularity [12], as modularity offers better predictability and more diverse reuse scenario [17], [18]. The idea of modularity is based on the geometrical classification, which operates as a system arranged in a particular order [5]. It is also defined as elements or components with a basic dimension or technical measurement, which acts as a basis and stands alone. A module becomes a self-contained component of a system but supports the whole system with well-defined connectivity with other components [19]. As implications, such ideas provide a simpler organization, where the number of variations components is reduced to standard components (modules), and the smallest constituent components become the standard of the modular system [20].

Modularity is not merely used in generating form but also in designing more sustainable architecture. If the modularity is applied since the conception phase, the building waste can be more manageable by suggesting the revaluation of the used materials and building components [11]. It can be seen in how it is applied in building construction with prefabricated and fixed material [21], implying a tendency to use less material and less waste [6]. As the modular system allows for prefabrication and mass production, it shortens construction time [5]. Moreover, it also facilitates the re-construction process in different locations [13]. Through the organization of modules, the assembly and disassembly process can be optimized, the efficiency of material and energy usage can be improved, and the circular flow of material can be better regulated [1], [11]. These suggest some role of modularity in creating sustainable architecture.

The idea of modularity is often seen as a limitation for creativity and generating only monotony [5], [22]. However, modularity can enhance the visual of buildings while providing flexibility through the plug and play of modules on-site [23] and variations of the new form [5], [17]. Such variations of form can be achieved by subdivision and differentiation, which offers flexibility and interchangeability through combination and replacement of module and submodule [20], [22] (Fig 2). By creating partial modifications of modules (read: submodule), flexibility occurs without changing the overall designs [20].

Figure 2. Subdivision and differentiation in modularity, allowing flexibility and interchangeability of building components (source: author’s own work based on Salingaros & Tejada (2001), 2020)
The modifications of modules can be made by adding or subtracting modules to create various configurations that can respond to different functions [22]. This form of flexibility has been simulated in Japanese houses where the room size is based on tatami size so that the room will be able to facilitate changes in the tatami module configuration [15]. This systematic form-making operation to produce new forms on a smaller scale as applied in Japanese house practice is an example of subdivision operation. Subdivision operation can create module variations that can still be correlated with other modules [22] (Fig 3).

![Figure 3](image)

**Figure 3.** Learning the interchangeability and flexibility of tatami’s module and the room size in Japanese house (source: author’s own work, 2020)

The variations of modules that occur due to subdivision and differentiation also have restrictions. Even the modules support the potential for reuse on a more diverse scale [12], the variations of modules depend greatly on the building systems – frame, planar or panel, or volumetric or room, especially in modern construction [5]. These systems become the guidelines for the combination of building components, which determine the building's design. A common example is the interchangeability between building materials and combined in varied sizes (Fig 2). The frame becomes the most flexible for variations, while the volumetric module has less flexibility to be combined [5]. However, such condition does not limit the possibility of having a hybrid combination as an open system or exchanges between frame, planar, or panel [5], [6], as long the structural consideration is maintained.

By applying modularity, the disassembly process can be simplified so that the steps towards reuse and recycling can be more manageable. Flexibility facilitates partial modifications for future need, as the interchangeability increases the potential for component reuse and recycling [18]. As a design strategy, the application of modularity requires careful planning of the connection between modules to support the effectiveness of reuse and recycling processes [18]. Therefore, in the next section, the application of modularity will be further studied based on the materials, building layers, and separable connectors, including the patterns of module variations and the combinations.

3. **Method: Identifying Modularity in Design for Disassembly**

![Figure 4](image)

**Figure 4.** The study cases: (a) Cellophane House (source: Kieran & Timberlake, 2009) and (b) Lobolly House, USA (source: Kieran & Timberlake, 2008)
This paper employs a case study as a method to identify and explore the application of modularity in DfD. The case study allows the exploration of an issue or problem by using cases within a bounded system [24], in this case, the framework of DfD. Such study allows the exploration through detailed data from documents and reports [24], which in this case the utilization of two architectural projects, the Loblolly House and Cellophane House in the USA, designed with DfD approach by Kieran and Timberlake [17], [21] (Fig 4). The data is collected, reconstructed through drawings, and further analyzed by identifying modular components of the building. The building components are mapped in diagrams and matrix based on the materials, principles of layers, and joints that connect the building components [13], [16]. The identified modules are examined to reveal specific patterns of modularity and further speculate the flexibility and interchangeability aspect of such design, based on the scenarios in reusing building materials, such as (1) whole building reuse or relocation, (2) component reuse or relocation, and (3) material reuse for manufacturing new component [25].

4. Result and Discussion: Modularity in Design for Disassembly

4.1. Patterns of Modularity in Building Components

In exploring the application of modularity in DfD buildings, identifying the building components is important to recognize which building components are repeated and indicated as modules. Based on the previous discussion, buildings designed with the DfD approach are systematically constructed by building elements separated based on build layers and non-hybrid type of joints. Therefore, the search for modularity in DfD is carried out by tracing the form of modularity in particular building components related to the DfD principles.

In Loblolly House and Cellophane House, the building consists of a set of components which are fabricated off-site and assembled on site. Both buildings employ the open system and use mostly prefabricated materials, which can be considered as light-weight, such as steel or metal plane; in lines (frame) and planes system. Both buildings' construction system is similar and claimed to simplify the distribution, assembly, and disassembly processes to be more effective. Both also show that in the practice of DfD, modularity is applied in the form of modular components as DfD building components.

Based on the mapping (Fig 5), the position of modular components in the Loblolly House and the Cellophane house operate based on the building layer [14], even though the module components do not always represent one building layer and vice versa. The modular components used in the Loblolly House and Cellophane House suggest a complex system and act more like a container that organizes several layers while still applying clear separation between layers. It is indicated by the use of several components that integrate several building layers in it, act as a hybrid module [5]. For example, in Loblolly House, the service, floor, and wall layers are combined as cartridge components, while in Cellophane House, a set of walls, services, and floors is organized in the block components.
In line with the DfD principles, both study cases are using modular and separable connectors. The type of connection used at Loblolly and Cellophane House is a standard dry joint. The use of this type of joint is claimed to simplify the disassembly process when the construction can be done only by using simple tools. The analysis found that the use of separable joints is not only at the level of component-component relations but also at the level of connector-connector relation as applied in both study cases (Figure 6). With the use of a non-hybrid connection, the connection can be removed and assembled easily. It creates a presumption that modularity is also applied in the detail part of the buildings, including connectors [2], [25].

Figure 5. The pattern of modularity in Cellophane House (left) and Loblolly House (right) based on building layers (source: author’s own work based on Kieran & Timberlake (2008 & 2009), 2020)

Figure 6. The pattern of modularity on separable connectors in Cellophane House (above) and Loblolly House (below) (source: author’s own work based on Kieran & Timberlake (2008 & 2009), 2020)

4.2. Simulating division and subdivision of modularity
After exploring more about the variation in the modules used, it was found in both cases that there were
several patterns of relationships between the modules. By comparing each module, there is a pattern in which smaller modules can substitute larger modules as the application of the subdivision rules. This pattern is apparent in the correlation between the size of the module, the planar and volumetric modules, allowing several potential alternatives for exchanging modules in the room created (Fig 7).

Based on the simulation results, the planar and volumetric modules that apply subdivision are strongly correlated and can form more variations in the configuration of a particular space. Since the Loblolly House utilizes planar modules only, the subdivision implies only for generating variations of the room sizes. Meanwhile, Cellophane House uses a combination of planar and volumetric modules and suggest a strong correlation between both types of module, indicating another emphasis on hybrid module [5], [6]. The simulation suggests that the planar and volumetric modules are interchangeable, as they share similar dimensional characteristics. It implies that subdivisions of modules can support the building’s DfD performance, allowing the building’s or components reuse to be more flexible and easily modified, responding to different needs or different sites. Furthermore, it shows that subdivisions support modularity to allow reuse scenarios on a more diverse scale [17], [18].

Figure 7. Modules comparison and the simulation of module’s configuration in Cellophane House (left) and Loblolly House (right)

4.3. Modularity for less waste building

In this section, the components of the buildings are scrutinized to see possible interchangeability in each module, reviewing the potential reuse of building components or materials [12], [18], [25]. Based on the identification of building components on each level, more than 50% of the components of the two case studies are positively interchangeable (Fig 8). The interchangeable components are mostly found in the form of basic components such as structural frame, joints, and also planar elements that form walls and floors. At the Loblolly House, fewer components are interchangeable as the space sizes in loblolly are largely non-modular. Thus, each room requires a component with a specific size to form the space. It shows that planar modules demonstrate better interchangeability compared to the frame or volumetric module, especially in generating room and its size. As a result, the degree of reuse scenario that occurs in both buildings strongly depends on the interchangeability of building components, in particular planar module and connectors.
Furthermore, based on the reuse scenario [25], 100% of the building elements of Loblolly and Cellophane House meet the requirement for building reuse or relocation scenario, as they are supported by the use of separable joints and building layers. The whole building can be relocated to another site without damaging the building components. However, not all of Loblolly and Cellophane House components satisfy the requirement for component reuse and can be assembled in different buildings. Based on the table of component mapping (Fig 8), only 62.5% of the building components of Loblolly House have the potential to be reused for different uses or design, while in Cellophane House is around 67%. This calculation is based on a comparison between the number of differentiated modules that are interchangeable and the number of differentiated modules available. Among all of the components, most of the components that are not reusable are components that require specific requirements such as service block, fixtures, and custom-made elements. The limitation of this study is that both buildings have never been simulated to be disassembled and relocated, so that the calculation above is an estimation.

5. Modularity for a Better Sustainable Architecture
The findings of this study clearly demonstrate that modularity is one of the important design strategies that contribute to more sustainable architecture. Through the inquiry into the application of modules in DfD, we can identify the potential reuse of building components and materials more predictably through its flexible and interchangeable characteristics. This becomes an important knowledge that may shift our perspective in seeing modularity not only for generating form and accelerating building construction but also for producing less waste and extending the life of materials [1], [2], [7]. Through this study, it can be considered possible to design scenarios for building components and material, predicting its after-life to avoid building demolition, as concerned in DfD.

Modularity becomes an important strategy employed in DfD, which informs the architecture more
systematically from the conception until its afterlife. It helps to guide the selection of construction system—frame, planar, or volumetric, for each building layers and also the type of connectors. The application of modules in particular building layers and separable joints, also the division-subdivision pattern applied in the modules, are the significant design strategies found in each case. Hybrid module is apparent in each case, where subdivision operates either in particular building layers—skin and structure and utilization of prefabricated material, increasing the possible and diverse reuse scenario [18], [22].

There are greater possibilities to use the flexible and interchangeable characteristics of modules, which can increase the potential for reuse. Such strategies provide better flexibility and interchangeability of building components during the assembly-disassembly process, as well as a calculation of construction waste. Such strategies create an impact in reducing the number of joint and component variations so that the assembly and disassembly process can be simpler and more efficient. The ease of disassembly process does not only support building reuse or relocation but also facilitates component reuse where the component can be assembled as another building. Given the potential for more diverse reuse scenarios, this could have a significant impact on reducing material waste. Thus, modularity can facilitate life-cycle scenarios on a wider scale. These findings expand the discussion of modularity and encourage further study of modular design for a better sustainable architecture. For this reason, the authors believe that architecture needs further studies about modularity as a strategy related to sustainability to optimize the building cycle and minimize environmental impacts.

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