

AN INVESTIGATION OF THE DIFFICULTY OF IMPLEMENTING DESIGN FOR DISASSEMBLY PRINCIPLES IN THE CONSTRUCTION INDUSTRY OF SRI LANKA

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Abstract: Construction materials take up the highest percentage of natural resource consumption while providing a considerable amount of waste. Also, the construction industry is responsible for a substantial percentage of greenhouse gas emissions which cause global warming. Design for disassembly would provide a solution by delivering disassembly measures for a building-components, and materials could be reused keeping them in a closed loop to minimise manufacturing of new construction materials. This paper will discuss the difficulty of implementing principles of design for disassembly in Sri Lanka by considering the expert opinion collected through a questionnaire as quantified qualitative data. Samples will be based on convenience in non-probability sampling method. Findings of the paper express, market demand for reused components and materials is the most challenging barrier for implementing Design for Disassembly in Sri Lanka, following compatibility with commercial market standards. In the local construction sector possibility of implementing design for disassembly is heavily based on the selection of materials and construction system.

Keywords. *Circularity; Design for Disassembly; Industrial metabolism; Material Reuse.*

1. Introduction

Operational energy of a building during its lifetime was previously believed to be much greater than the energy required for construction. Hence, the number of researches has been higher towards that. Several recent studies have shown that the initial energy required in construction is much larger than what we have anticipated previously and sometimes could tremendously exceed the operational energy of a building. Therefore, new research regarding embodied energy in construction and the circularity of materials is convenient. A possible strategy is to reuse and recycle building materials and components to make the most out of them. DfD (Design for Disassembly) is an efficient approach for reducing energy and material consumption in contemporary and future construction. As it is still an emerging concept, there is only a few literature on the subject. In the Sri Lankan context, the concept of DfD is unheard of, and literature on the subject is absent.

1.1. AIMS & OBJECTIVES

This study aims to explore and systemize the principles of design for disassembly, assessing the difficulty of implementing them in the local construction industry and will find the barriers for its implementation.

OBJECTIVE 1: Systemizing and Compiling DfD Design Principles.

OBJECTIVE 2: Assessment of the difficulty of implementing DfD principles in Sri Lanka.

OBJECTIVE 3: Understanding Barriers of DfD implementation.

By evaluating the DfD principle categories, barriers could be narrowed, identified and mitigated when implementing the concept in the future.

2. Literature Review

2.1 INTRODUCTION TO DFD

According to Rios et al. (2015), the definition of Design for Disassembly is as follows, DfD is a method that uses planning and design to make the deconstruction process and procedures easier. Building deconstruction is a method of selective demolition in which elements are removed from a structure in such a way that they may be separated and reused afterwards. Deconstruction could be described as the act of physically separating a product into its pieces or subassembly parts through a systematic technique allowing for the selective separation of reusable, recyclable, non-recyclable, and hazardous subassemblies (Gungor & Gupta, 1999). By recovering building assemblies, they could be used as it is in a different building or the building could be re-erected in a different place if the new context permits.

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With the ability to separate components and materials, they could be reused, or repurposed for a different project. By separating materials, it would help the material recycling process, isolating hazardous or non-recyclable materials and providing high purity for recyclable materials.

DfD in the industry of construction is a significant approach to Construction Ecology as it emphasises the importance of building waste minimization management by integrating Service Life Planning, technological solutions for easy disassembly, and the assessment of building materials and components to keep the materials and components in a loop in an efficient manner. According to Tleuken et al. (2022), if initial design decisions have taken for a building to be disassembled, the environmental impact would be greatly reduced due to the ability to recover over 95% of the embodied energy of construction materials and up to 50% of the entire building's life cycle energy. Hypothetically, if building materials and components have their true native properties in terms of physical dimension, condition, molecular integrity and aesthetics and if they are 100% recovered the cost of materials that went for construction could be recovered completely if even more adjusted to inflation.

Building construction does not normally take future disassembly into consideration, although for a more environmentally conscious society, buildings should be constructed with decoupling, and disassembly systems allowing the disengagement of components or entire structures as required. Although the construction industry still has not embraced the concept of design for disassembly. Buildings are constructed as if they are permanent. Although its expected life span is several decades and the materials they are built from have a life span of several centuries.

2.2 PRINCIPLES OF DFD

Literature related to Design for Disassembly discloses design practices and philosophies that can be divided into two major categories such as 'Flexibility' and 'Connections'. By referring to the literature review DfD guidelines and principles have been divided into 8 categories as follows.

Table 1, Design Criteria (Materiality)

Category	Criterion	Relevant Literature
1. Materiality	Usage of Recycled and Recyclable Materials	Crowther (2001,2003)
	Minimising the number of materials	Crowther (2001,2003)
	Avoiding Hazardous materials	Catalli and Williams (2001); Fletcher, Popovic, and Plank (2000); Sassi (2006); Crowther (2001,2003)
	Usage of non-composite materials	Fletcher, Popovic, and Plank (2000); Berge (1992); Crowther (2001,2003)

Table 2, Design Criteria (Separations of Materials and systems)

Category	Criterion	Relevant Literature
2. Separations of Materials and Systems	Separation of Structure and Skin	Fletcher, Popovic, and Plank (2000); Berge (1992); Crowther (2001,2003)
	Separation of services (MEP systems)	Ciarimbo and Guy (2007); Crowther (1999); Catalli and Williams (2001); Berge (1992); Crowther (2001,2003)
	Separation of Structure and Partitioning	Paterson (2000); Berge (1992); Crowther (2001,2003)

Table 3, Design Criteria (Joinery)

Category	Criterion	Relevant Literature
3. Joinery	Dry Joinery	Fletcher, Popovic, and Plank (2000)
	Mechanical Connections	Ciarimbo and Guy (2007); Crowther (1999); Crowther (2001,2003)
	Exposed Connections	Catalli and Williams (2001); Paterson (2000); Fletcher, Popovic, and Plank (2000)

Table 4, Design Criteria (Simplicity & Uniformity)

Category	Criterion	Relevant Literature
4. Simplicity & Uniformity	Uniform(grid-based) and simple Structural System	Catalli and Williams (2001); Fletcher, Popovic, and Plank (2000); Berge (1992); Sassi (2006); Crowther (2001,2003)
	Simplicity in building Geometry (Form, Scale)	Ciarimbo and Guy (2007); Catalli and Williams (2001); Fletcher, Popovic, and Plank (2000); Berge (1992)
	Minimised number and types of components	Crowther (2001,2003); Sassi (2006)
	Modularity	Crowther (2001,2003)
	Employment of Precast or Pre-Fabricated Structures	Fletcher, Popovic, and Plank (2000)

Table 5, Design Criteria (Handling & Labour Practices)

Category	Criterion	Relevant Literature
5. Labour Practice & Handling	Using simple and orthodox building practices	Paterson (2000); Crowther (2001,2003)
	Using Labour practices that reflect productivity and safety	Ciarimbo and Guy (2007); Crowther (1999); Crowther (2001,2003)
	Handleable Sized components	Crowther (1999); Paterson (2000); Crowther (2001,2003)

Table 6, Design Criteria (Documentation)

Category	Criterion	Relevant Literature
6. Documentation	Providing Materials and components with permanent Identification	Ciarimbo and Guy (2007); Crowther (1999); Catalli and Williams (2001); Paterson (2000); Fletcher, Popovic, and Plank (2000); Sassi (2006); Crowther (2001,2003)
	Disassembly plan	Ciarimbo and Guy (2007); Catalli and Williams (2001); Fletcher, Popovic, and Plank (2000); Sassi (2006); Crowther (2001,2003)

Table 7, Design Criteria (Easy Disassembly)

Category	Criterion	Relevant Literature
7. Easy Disassembly	Providing accessibility for Disassembly-Making the materials with the shortest anticipated lifecycle most accessible	Ciarimbo and Guy (2007); Crowther (1999); Catalli and Williams (2001); Paterson (2000); Sassi (2006); Crowther (2001,2003)
	Concurrent or Parallel Disassembly of components	Crowther (1999); Fletcher, Popovic, and Plank (2000); Sassi (2006); Crowther (2001,2003)
	Providing realistic tolerances to allow for manoeuvring during disassembly	Crowther (2001,2003)

Table 8, Design Criteria (Market & Standardisation)

Category	Criterion	Relevant Literature
8. Standardisation & Market Demand	Compatibility with commercial market standards	Ciarimbo and Guy (2007); Crowther (1999); Paterson (2000)
	Market Demand for reused Components and Materials	Fletcher, Popovic, and Plank (2000)

3. Methodology

3.1. DATA COLLECTION

Expert opinion is collected through a questionnaire to assess the difficulty of implementing DfD in the construction industry of Sri Lanka as well as the difficulty of implementing the concept in the near future. As there are no known practitioners who implemented Design for disassembly in the local context. A considerable number of experts are selected as responders for the questionnaire that are based on their subjective opinions. 90 Experts will be selected based on the convenience sampling method. This sample includes practising and experienced Architects and Structural Engineers. The questionnaire is based on the theoretical survey and 25 principles that are categorised into 8 groups.

1. Materiality
2. Separation of Materials and systems
3. Reversible Joinery
4. Simplicity and Uniformity
5. Labour Practice and handling
6. Documentation
7. Convenient Disassembly
8. Standardisation and market demand

3.2. DATA ANALYSIS & INTERPRETATION

Data to be analysed as content analysis, Content will be grouped into different categories based on observations. A Likert scale is used to provide a quantified value on a five-increment linear scale. Assessment of difficulty is based on a Likert scale as, very easy, easy, Moderately Difficult, Difficult & Very Difficult. Responses to the questionnaire are then added together and calculated as a percentage of difficulty of implementing them. A higher percentage means it is more difficult to implement and vice versa. Then the difficulty of implementing each principal group is calculated as a percentage. By referring to the difficulty value major barriers for implementing design for disassembly in Sri Lanka could be identified.

Table 9, Difficulty Percentages in Linear Scale

Likert Scale Increment	Difficulty	Difficulty Percentage
1	Very Easy	20%
2	Easy	40%
3	Moderate	60%
4	Difficult	80%
5	Very Difficult	100%

3.2.1. Formula for Assessing Difficulty of an Individual Principle

$$DP_i = \frac{\sum_{i=1}^n R_i}{n} \times 20\%$$

$$\sum_{i=1}^n R_i = R_1 + R_2 + \dots + R_n$$

DP_i = Difficulty Percentage of a DfD principle
 R_i = Response value for a principle (1-5)
 n = Total number of responses

(1)

3.2.2. Formula for Assessing Difficulty of an Individual principle group

$$DP_G = \frac{DP_1 + DP_2 + \dots + DP_N}{N} \quad \begin{array}{l} DP_G = \text{Difficulty Percentage of a DfD principle group} \\ DP_i = \text{Difficulty percentage of a DfD principle} \\ N = \text{Total number of principles in a group} \end{array} \quad (2)$$

4. Data Analysis

Among the sample of 90 experts, 36 have responded to the given questionnaire. The data collected is analysed as a percentage of difficulty of each principle, principle group and ultimately as a comparison of principal groups. The following bar graphs visually represent the collected data, categorised into principle groups.

4.1. INDIVIDUAL PRINCIPLE GROUP ANALYSIS

4.1.1. Materiality

According to the experts, minimising the number of materials is the most difficult principle to implement in the materiality category as different systems of buildings will require different properties and characteristics therefore several different materials have been used in any building, although it will convolute the material recovery process. The usage of recycled and recyclable materials has the second most difficulty. Although in the Sri Lankan context usage of recycled or recyclable materials is rare. This indicates there could be other reasons that prevent recyclable material usage such as a client's influence, or lack of awareness considering the benefits of using recyclable or recycled materials. Another aspect would be the discrimination of used materials and higher demand for the brand-new materials. With the current local technology, some materials could not be considered as recyclable materials as material recyclability is still at a primal state. Including reinforced cement concrete, aggregates, and masonry work. Avoiding composite and hazardous materials seems to be not considerably difficult. Hazardous materials like asbestos are used widely in the construction industry of Sri Lanka, although experts find it the least difficult.

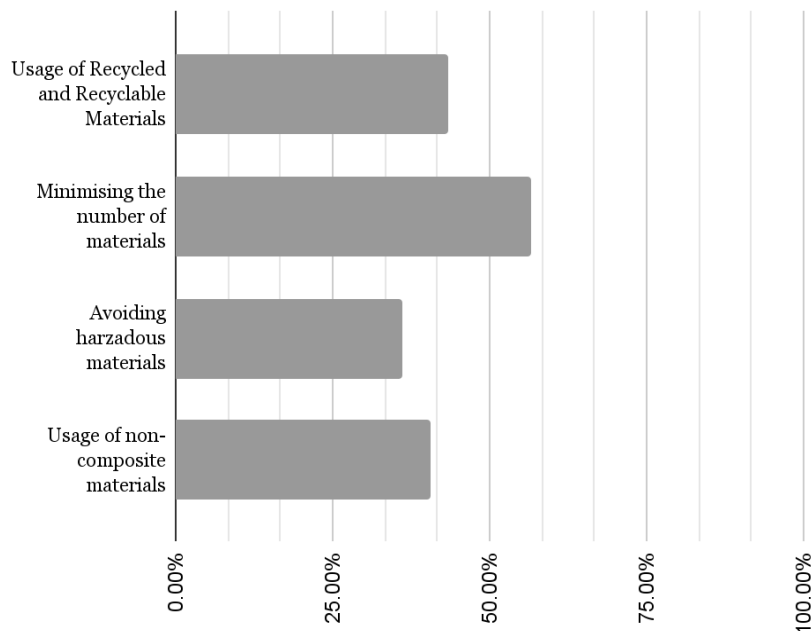


Figure 1: Difficulty of implementing Materiality DfD principles

4.1.2. Separation of Materials and Systems

Research data finds separation of services as the principle with the highest difficulty, separation of structure and skin as the next and separation of structure and partitioning as the least difficult. In the general construction practice of Sri Lanka, structure, skin, partitioning and services are embedded together. This decision could be taken considering aesthetic purposes, concealing and minimising details and clutter to make simple geometry and forms. Some buildings are designed with open plans and little to no partitioning even in Sri Lanka. Therefore, experts find it to be the least difficult principle to implement. Separation of the structure and skin is also common in Sri Lankan construction practices. Generally, less expensive materials are used for skin and partitioning locally.

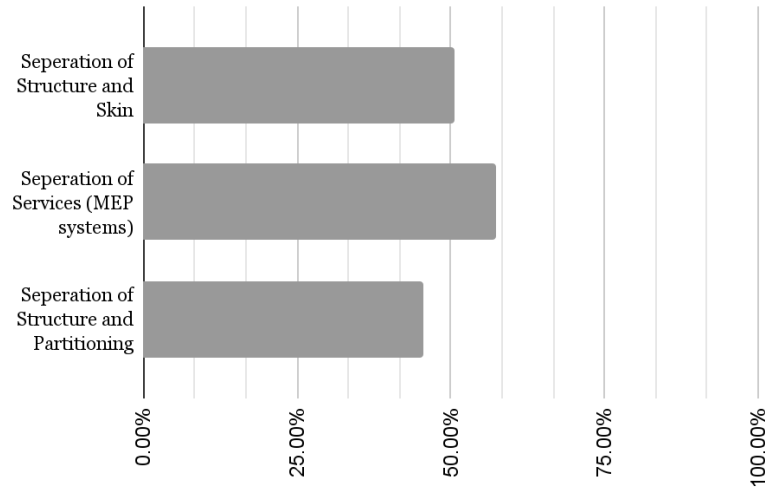


Figure 2: Difficulty of implementing Separation of Material and systems DfD principles

4.1.3. Joinery

Considering the Joinery, experts convey dry joinery to be the least difficult DfD principle to implement. Most of the joineries in local buildings are wet joineries as local construction is mainly done out of concrete and brick. In the local practice when reinforced cement concrete is used, it is used by pouring concrete into a formwork in site. Although this would be a sequential process, each assembly including columns, beams, slabs and walls are chemically bonded with each other. After that, it would be impossible to disassemble and has to be demolished. Although, when alternative materials are used experts find implementing mechanical connections the most difficult one next to exposed connections. When considering local material usage where dry joineries could be used, mechanical connections are not used all the time. Sometimes joineries are welded and non-reversible.

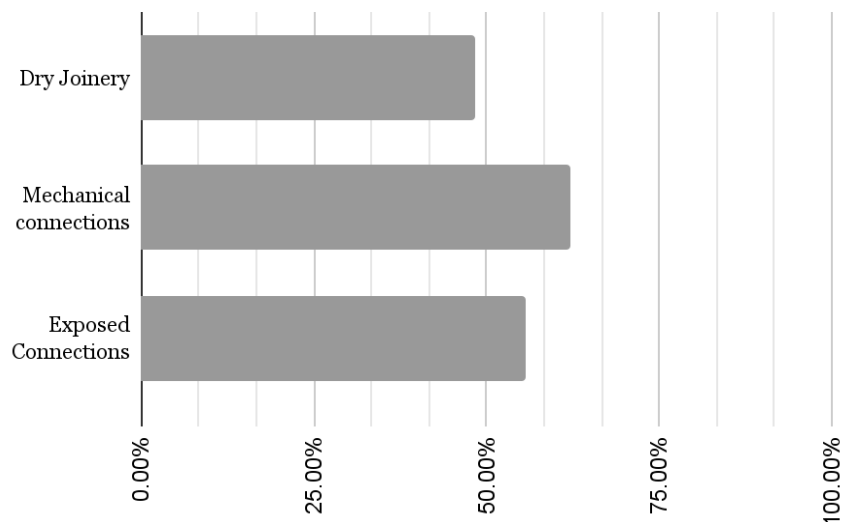


Figure 3: Difficulty of implementing joinery DfD principles

4.1.4. Simplicity and Uniformity

Considering the expert opinion Employment of precast and prefabricated structure is extremely difficult. Next to modular structures. Precast systems and modular structures are still a novel concept in Sri Lanka, perhaps due to higher expense or difficulty of transporting and handling. Besides, local construction workers are unfamiliar with these practices.

Minimising the number and types of components follow next. Grid-based structural systems are widely employed in the current construction practices of Sri Lanka. Therefore, it is the least difficult one to implement. Simplicity in building geometry has the next to least difficulty. Most often commercial buildings consist of a simple building form and have a bigger scale, typically built as multi story, low to high-rise buildings. Although, for residential buildings, building form varies often, as it is not regulated by the governing bodies and follows a different and wide range of architectural styles.

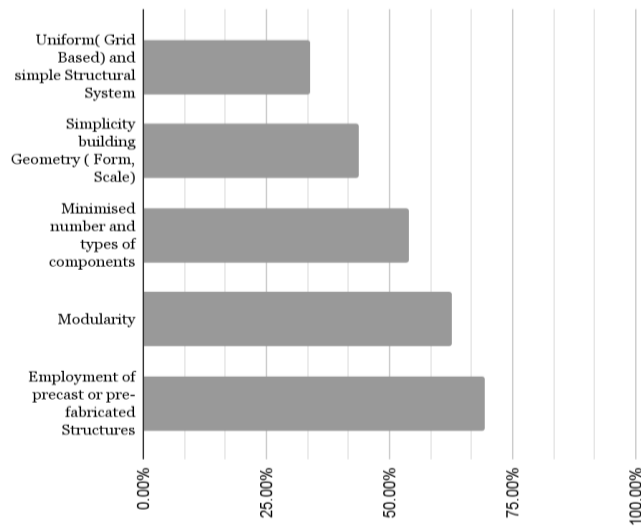


Figure 4: Difficulty of implementing Simplicity and Uniformity DfD principles

4.1.5. Handling and Labour Practice

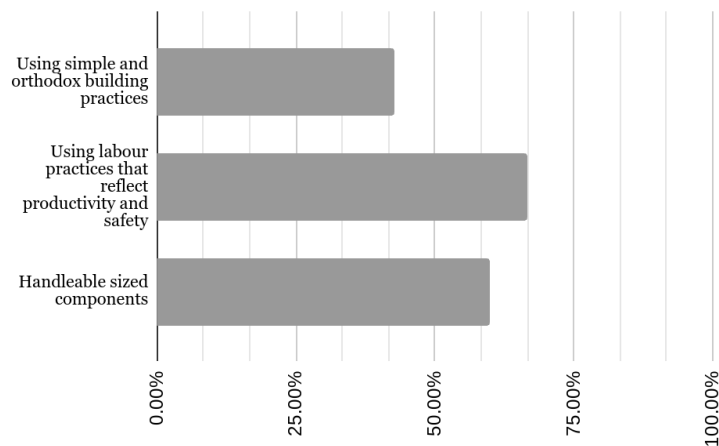


Figure 5: Difficulty of implementing Handling and Labour Practice DfD principles

Using orthodox building practices is the least difficult principle to implement. Although considering the local materiality and construction system, unorthodox construction methods and systems are required for buildings to be disassembled as materials demand. Handleable-sized components have the next difficulty. Using labour practices that reflect productivity and safety has the highest difficulty. In Sri Lanka, generally labour practices are not considered when designing buildings to be safer or as a reflection of craftsmanship.

4.1.6. Documentation

Considering the documentation, experts find they are easier to implement. Disassembly plan being the least difficult following permanent identification for materials perhaps documentation principle implementation are at designer's hands. The disassembly plan could be provided by designers as a document consisting of instructions for disassembly as they seem the most efficient, including the order of disassembly, tool usage, disassembly bill of materials etc.

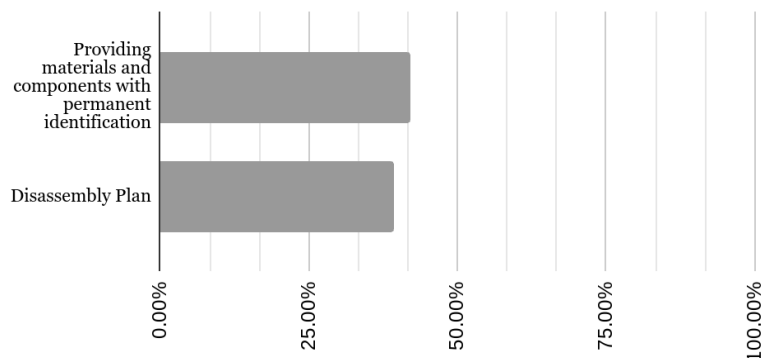


Figure 6: Difficulty of implementing Documentation DfD principles

4.1.7. Easy Disassembly

Questionnaire finds Providing realistic tolerances to allow manoeuvring during disassembly to be the highest difficult principle to implement, next to concurrent or parallel disassembly of components. Providing accessibility of disassembly has the least difficulty. In current Sri Lankan construction practice, means of disassembly are rarely given often because of the material and construction system selection for the construction. Even when disassembly methods are provided, tolerances have not been incorporated which will make the disassembly process considerably difficult and inefficient.

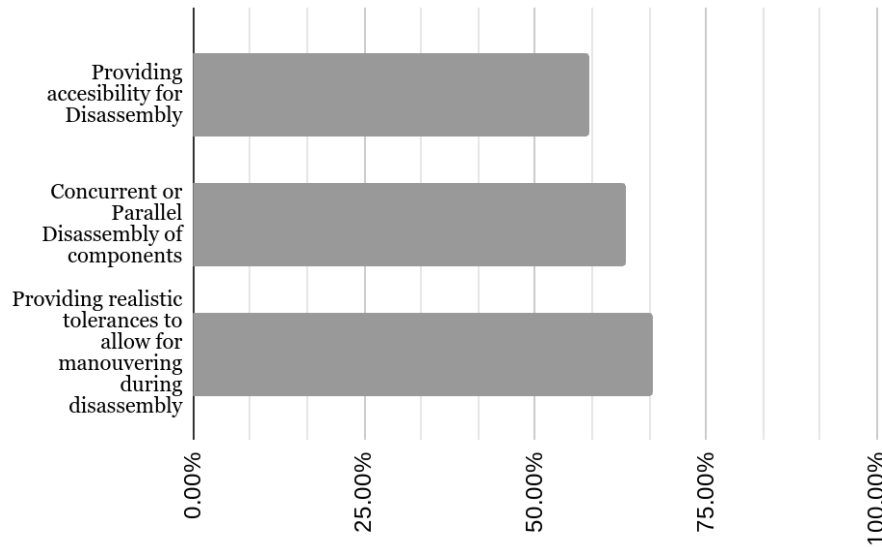


Figure 7: Difficulty of implementing Easy Disassembly DfD principles

4.1.8. Market & Standardisation

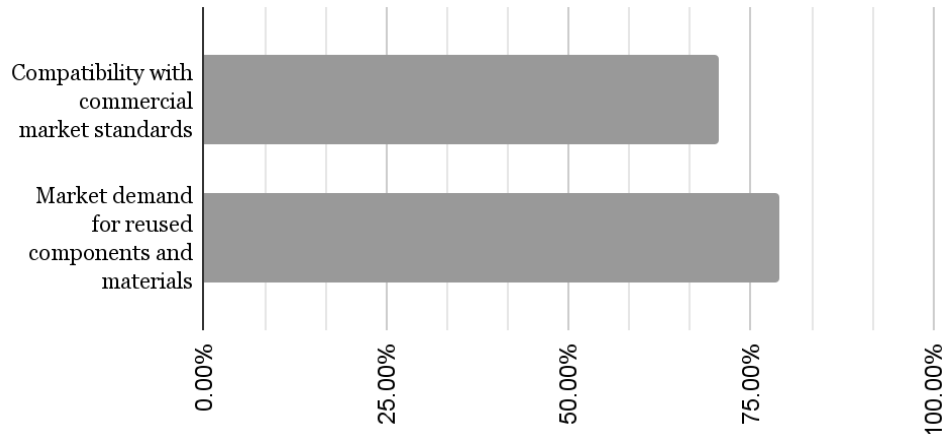


Figure 8: Difficulty of implementing Market & Standardisation DfD principles

According to experts DfD principles in Market & Standardisation are extremely difficult to implement. Market demand for reused components and materials has the principle with the highest difficulty as it is not directly under designers' or stakeholders' control. Although the difficulty of implementing this principle could be reduced over time as DfD is more widely spread in the local context. Compatibility with commercial market standards has a higher difficulty as well, because the Sri Lankan construction industry is not very standardised.

When Considering the opinion of experts about the difficulty of implementing DfD principles in Sri Lanka compared together, creating a market demand for the reused materials and components has the highest difficulty following compatibility with commercial market standards. The third most difficult principle to implement is the employment of pre-casted or pre-fabricated structures. The principle of a grid-based structural system has the least difficulty. The second least difficult principle to implement is avoiding hazardous materials. See Figure 9.

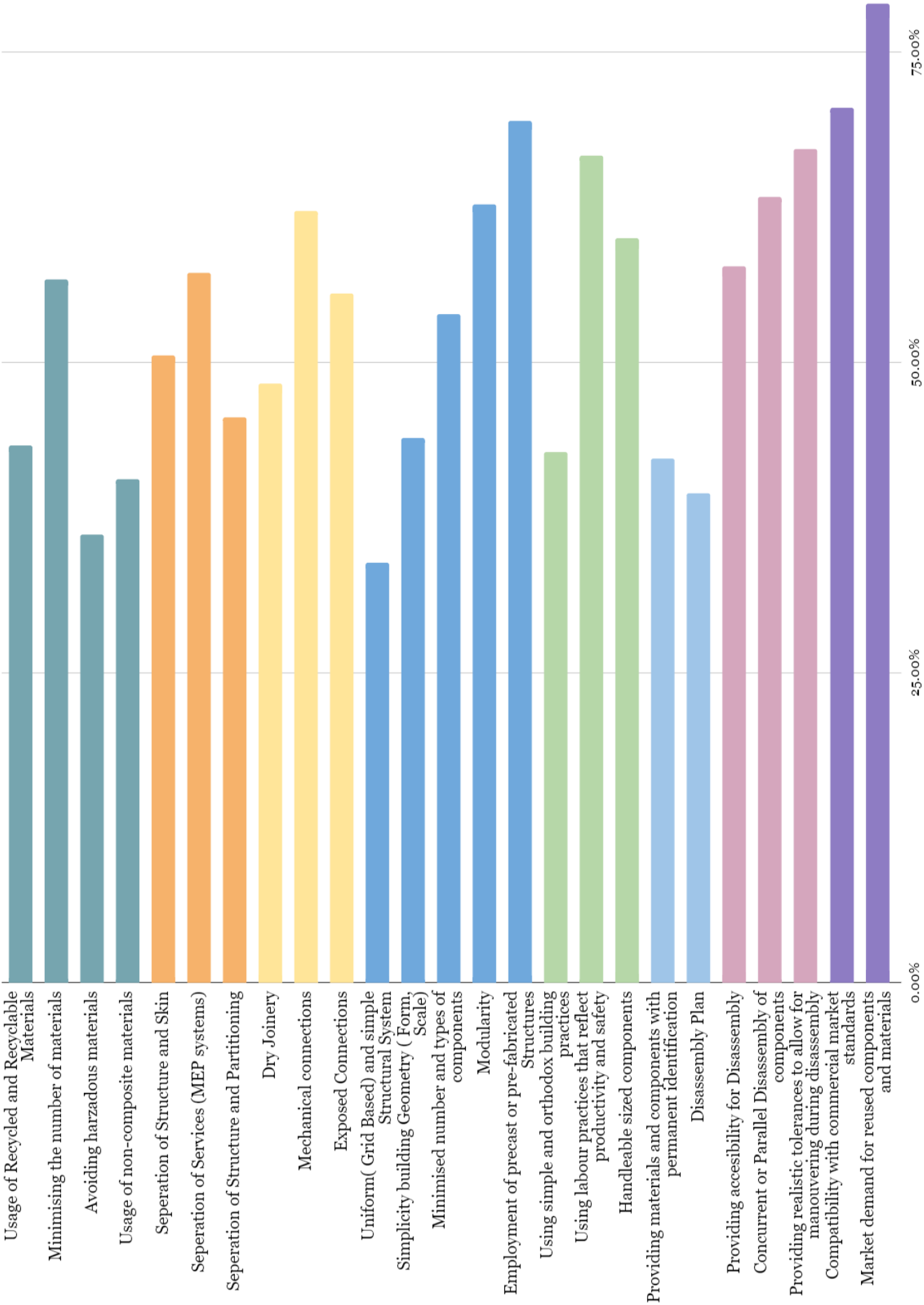


Figure 9: Difficulty of implementing DfD principles

4.2. PRINCIPLE GROUP ANALYSIS

When considering the difficulty of implementing DfD principles put together into groups, Market and standardisation has the highest percentage of difficulty, perhaps due to the lack of control over the principle group from designers' hands after easy disassembly. According to experts, the Documentation principle group is the least difficult one to implement. As it could be directly controlled and designers are able to include these components in their design process. The handling and labour practices principle group has the third highest difficulty. Joinery, simplicity and uniformity, separation of materials and systems, and materiality principle groups have the fifth, fourth, third & second difficulty of implementing consecutively. Although, the current material practice would certainly not support practising Design for Disassembly. This suggests that a simple decision in selecting materials will have a significant impact on the possibility of making a building able to be disassemble

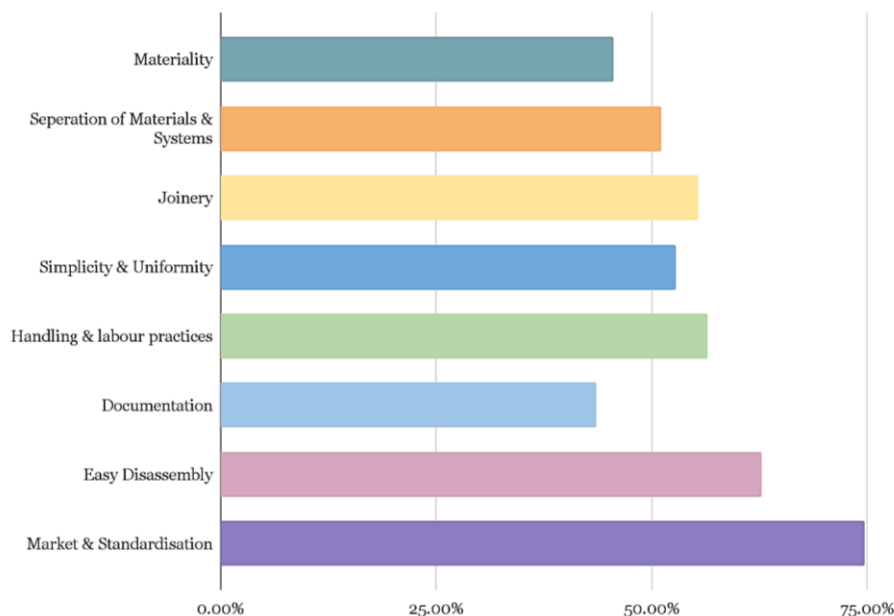


Figure 10: Difficulty of implementing DfD Principle Groups

5. Conclusion

Ability for a building to be disassembled heavily depends on the designer's decisions, including material and construction system selection, design approaches and strategies. Some of the DfD principles are not implemented in Sri Lanka even though experts find them not to be considerably difficult to implement. These principles include the usage of recycled and recyclable materials, separation of structure, partitioning, skin and services. The most difficult principle to implement DfD in Sri Lanka is the market demand for such materials as the local construction industry is not being standardised. Although with time market demand and standardisation would occur if DfD became more and more mainstream. In the Sri Lankan construction industry Reinforced Cement Concrete constructions are done as in-situ wet joinery which makes disassembly impossible. An alternative solution for this would be the employment of precast or modular structures and using dry connections. Nonetheless, using precast or modular construction in the local context is very difficult according to the experts. Which makes using RCC together with DfD strategies extremely difficult. If DfD is required to be implemented using RCC systems more research has to be done focused towards precast and modular construction in Sri Lanka to minimise their costs while improving the efficiency of producing, transporting and assembling of different systems.

Other than the difficulty of implementing DfD principles, two major barriers for the disassembly would be disassembly costs and time. Implementing DfD for construction will increase its first-hand costs while there is no return of investment in the near future. Hypothetically, if materials could be recovered with their native properties and characteristics and if they retain their original value, the total cost for the construction materials could be recovered at the end of the building's service life. Also, when DfD is implemented, buildings could have much longer service life with the ability to easy repair, maintenance and replacement. This will of immense help to the economy in a developing third-world country like Sri Lanka. For implementing DfD some incentive approaches are also required from the governing bodies. Non-standardised dimensions and construction systems would lead to material wastage and higher waste generation as standardising materials, dimensions etc, would encourage implementing DfD furthermore, as compatibility with commercial market standards is improved and increased. It is convenient to shift from profit-driven designs to environmental-driven designs, as global climatic issues are worsening day by day. DfD will provide a significant solution for the matter, and some consider it to be the future of architecture, hence much

more research has to be done about the this novel subject area to make it widespread and implement the concept as soon as possible.

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