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Designing for Deconstruction—The Related Factors

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Abstract: Buildings are stationary, complex edifices which come in a variety of sizes and shapes of comparatively low value goods. Their building materials are not readily reused or recycled as can not be easily separated and utilized without further processing. This reprocessing takes place at almost every step of a material cycle and requires energy inputs, where together with energy come the carbon dioxide emissions that make up the vast majority of greenhouse gas emissions the main cause of global warming. If components and materials are recovered from a building for reuse, the additional inputs are eliminated and it is easier to adapt or change the building to meet evolving functions over its lifetime. Treating the buildings efficiently at the end of their service life can hold significant economic and environmental value. However, the value that can be extracted is very much dependent on how the buildings have been designed and built. This is the role of Design for Deconstruction (DfD), the intentional design of buildings in order to make them easily deconstructable and reuse their intact building materials and components in other building. Due to the perception of designers that buildings are static constructions the DfD is not widely used and only a limited number of buildings are fully deconstructable. This paper looks at the DfD process and identifies the four key categories involved in the process. These categories play an important role in the construction industry to become more sustainable, smarter and resourceful, by maximizing the reuse potential of DfD process.

Key words: Reuse, DfD, sustainable built environment, construction industry.

1. Introduction

Global trends and challenges have been the determinants of the increase in global demand for resources since the beginning of the 20th century. Over the past two centuries countries around the world have experienced structural economic change by moving from biomass-based agrarian societies to urban industrial economies based on fossil fuels and coal [1]. The construction industry and the built environment are the world's largest consumer of raw materials and generator of waste in the world and in Europe [2, 3]. Currently, 40% of the world's raw materials are used in the construction of buildings which they account for an average of 41% of the world's energy use and are attributable for 30% of global greenhouse gas emissions [4, 5]. In Europe**,** the building sector accounts for 38% of the total waste production, 40% of the carbon dioxide (CO_2) emissions and 50% of all-natural resources used with in construction [6-9]. Evolving demographic trends and societal changes will fundamentally change the demand for resources and building materials many of which are becoming scarcer and harder to extract. Nowadays natural resources are consumed at a faster rate than their natural regeneration with construction industry to consume yearly about 50% more natural resources than only 30 years ago. Global demand for resources and building materials and related pressures on the environment are steadily increasing and their consumption will increase at three times the rate produced by 2050. Looking ahead, the world's population is expected to increase by approximately one third by 2050, from 7.7 billion currently to 9.7 billion [10]. World economic output is projected to triple in the period 2010-2050 [11] while middle class may increase from 3.2 billion in 2016 to 5.2 billion in 2028 becoming a majority of the global population for the first time ever [12], adding to existing demand for homes and services, is putting unprecedented pressure on natural resources. Continued global competition for

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virgin resources and supply chain disruptions create uncertainty and contribute to material price volatility, thereby increasing their costs. Extracting basic raw materials becomes more difficult and costly as governments around the world adopt stricter environmental policies to protect fragile ecosystems and sustainable extraction of key raw materials. The built environment is under increasing pressure to minimize its impact. These have warned industry leaders and governments and policy makers to the necessity of rethinking the models attached to materials and energy use.

The traditional linear "take, make, dispose" economic model, which relies on large quantities of low-cost, easily accessible materials and energy across borders, has been at the heart of industrial development and has generated an unprecedented level of growth (Fig. 1). However, this linear economic model is not a sustainable model and many believe that has reached its limits as discarding building materials rather than reusing them will continue to require extraction of huge quantities of new materials with the associated impacts on our ecosystems.

It is needed a new mental model that clearly envisions these "wastes" as valuable resources harvested from existing buildings and used to build new ones. The diagram in Fig. 2 illustrates the dynamics of deconstruction within the waste stream [13] in the formation of this new model.

Deconstruction is an alternative strategy to demolition that involves dismantling, disassembly, recovery and partial or whole removal of building materials in order to maximize the reuse potential of its components. By applying the deconstruction process, the unsustainable nature of the traditional waste management process can be altered. The main reason that makes the reuse of construction materials prohibitive is the design of the buildings which does not allow the easy recovery of its materials. This is the task of Design for Deconstruction (DfD) to define those principles that will allow the easy, fast, intact and economical separation of building materials in order to be reused or recycling. DfD could make a significant contribution to the conservation of raw materials. DfD is the means to facilitate deconstruction through design and planning.

Deconstruction combines the recovery of both quality and quantity of reusable and recyclable materials. The re-use of materials can serve a broad set of goals including the development of closed loop material cycles. It also improves the economics for manufacturers for innovative approaches such as products as "services" that are leased over time, or material take-back.

For the time being, Designing for Deconstruction is not without its challenges as it carries an additional level of responsibility and requires significant effort from all parties involved in the construction process due to lack of regulation and uncertainty about the quality and quantity of materials used. Another impediment to consider when designing for deconstruction is disconnect between decisions made at the design stage of a building and those that may be made several decades later when the building reaches the end of its life.

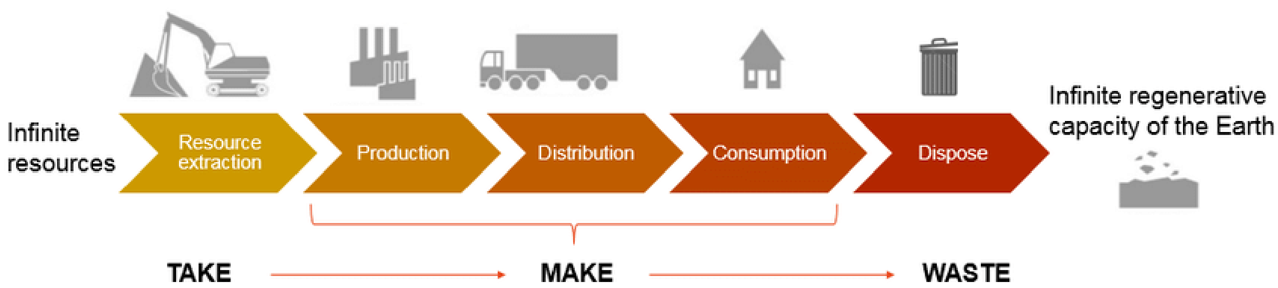

Fig. 1 Economic model take-make-waste.

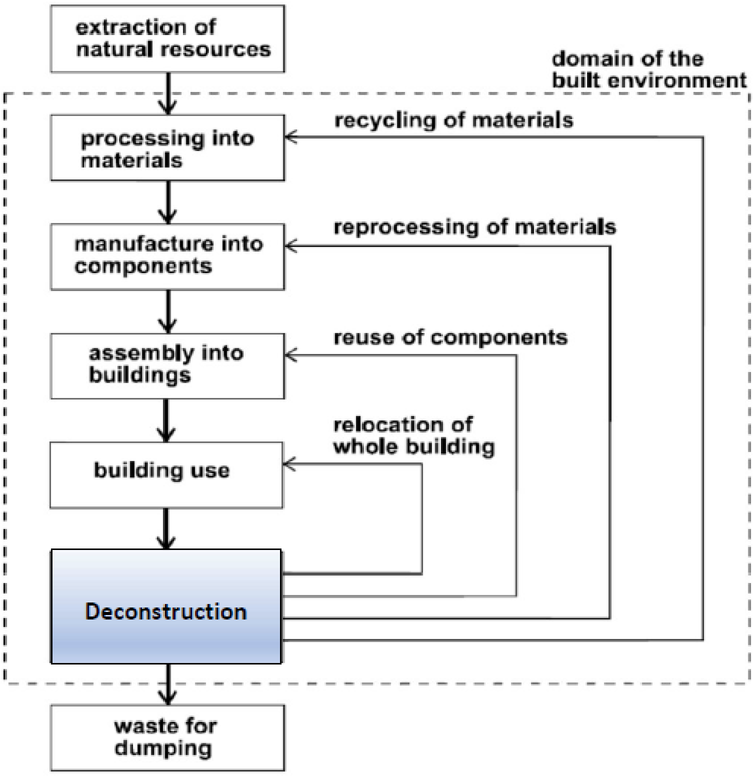

Fig. 2 Variations of deconstruction within the waste stream [13].

2. Designing for Deconstruction

In a world where many natural resources are becoming scarce it is important to consider alternatives that aim to close the material loop. This involves increasing reuse, so reliance is shifted towards materials that have already been extracted to fulfil demand. However, fragmented supply chains and "old fashioned design strategies" are currently preventing wide scale reuse. DfD is about designing buildings with the intent to manage their end-of life scenario more efficiently and to close the construction components loops. All the life-cycle stages of a building are optimized during the DfD in order to maximize the recovery of the building components for reuse and to ensure that the subsequent stages of remodeling, repair and adaptability are conducted efficiently [14-17]. Designing structures that are easier to adapt permits a structure or building and/or its environment to fit or suit new conditions and therefore lengthens the lifetime of the structure offering economic and environmental benefits. Moreover, if a structure is DfD can accommodate easier changes in use, size or performance significantly reducing the speed and cost of changes. However, even though DfD has demonstrated environmental, social, and economic benefits, limited amount of buildings designed and built today are designed for deconstruction as DfD is a challenging and usually more expensive process than the conventional design process [14, 17-22]. Having looked at the deconstruction of existing buildings it can be seen that deconstruction of most structures would be much easier if it had been considered at the design stage and therefore inherently designed into the building. Also, from the design phase, certain strategies and principles should be adopted in order to make the deconstruction process more efficient and profitable. Implementing these appropriate strategies will maximize the disassembly of reusable materials. In this study four categories are discussed to be of major importance for the DfD process: material, design, human and policy/legislation and are discussed in the following sections along with their associated factors.

Table 1 Material related factors involved in the DfD.

No	Material Related Factor	Principle Reference
1.	Use of durable reusable materials	(Akinade, O.O. et al, [24]); (Guy et al.; [25]); (Sassi P. [26]); (Webster et al [16]); (Crowther P., [27]).
2.	Use as connections nut/bolt that can be easily removed instead of nails and gluing	(Akinade, O.O. et al, [24]); (Jensen G.K., et al., [28]); (Guy et al., [25]); (Crowther P. [27]); (Webster et al., [16]).
3.	Use prefabricated, modular assemblies	(Guy et al., [25]; (Crowther P., [27]); Jaillon L., et al [32].
4.	Avoid composite materials during design specification	(Akinade, O.O. et al, [24]); (Guy et al [25]); (Sassi P. [26]); (Crowther P., [27]); (Jensen G.K., et al., [28]); Webster et al., [16]).
5.	Minimize number of connectors and limit the different types	(Akinade, O.O. et al, [24]); (Tingley, D. D. [29]); (Guy et al., [25]); (Crowther P. [27]); (Webster et al [16]).
6.	Minimize number and types of building components	(Akinade, O.O. et al, [24]); (Tingley, D.D. [29]); (Guy et al., [25]); (Crowther, P. [27]); (Webster et al [16]); (Chini et al [30]).
7.	Avoid toxic and hazardous materials	Akinade, O.O. et al, [24]; (Guy et al., [25]); (Sassi P. [26]); (Crowther P., [27]); (Jensen G.K., et al., [28]); (Tingley, D. D., [29]); Webster et al., [16]).
8.	Use of recyclable materials	(Guy et al [25]); (Crowther P. [27]); (Chini A.R., et al. [30-31])
9.	Avoid materials with secondary finishes, such as coatings which compromise reuse potential	(Akinade, O.O. et al, [24]); (Jensen G.K., et al., [28]); Tingley D.D., [29]); (Guy et al., [25]); (Crowther P. [27]).
10.	Select easily separable materials with reuse potential	(Guy et al., [25]); (Webster M.D., et al., [16]).
11.	Use lightweight materials	(Crowther P., [27])

3. Material Related Factors

DfD of buildings, first revealed in the 1990s [23], aims at resolving the issues of salvaging and repurposing the building materials at the end of their service life. In contrast to the traditional linear material flow, which commences with the extraction of raw materials and ends with the dumping of debris in landfills, DfD envisions a closed cycle of resource use and reuse. DfD aims at creating buildings to reduce virgin materials consumption and waste in their construction, refurbishment and demolition, to extend building lives in situ, and to construct buildings that are “material banks” of future building materials. Selecting the right materials, connections, and components for DfD is probably the most important design aspect for the design team for achieving a high degree of DfD. Additionally, when material choices are made issues such as reuse, recycle and disposal associated to material and components should be examined very thoroughly before deciding whether the material is durable enough for reuse in its current form or if the material is not to be reused, it should be easily recycled. Table 1 shows the most crucial materials related factors involved in the DfD Process.

4. Design Related Factors

There are various design rules that should be followed in order to enhance deconstructability of buildings as mentioned in Table 2. These rules help to maximize the flexibility of designs, thereby enhancing the whole or partial building deconstruction and re-location or reuse its component without reprocessing.

Designing for deconstruction requires an in-depth conceptual and theoretical exploration of the make-up of building systems using both holistic and systemic approach. This is to capture the complexity and multiplicity of the makeup of buildings as well as interactions among building elements. The idea underscores the theory of building layers where parts of buildings are organized into subsystems known as layers. Building in layers also allows for consideration of different life spans of materials, and therefore considers the importance of access to these individual layers so that components on higher layers could be altered or replaced without affecting lower layers. Building layers make DfD technically possible because layers' interfaces become points of deconstruction.

Table 2 Design related factors for DfD.

No	Design Related Factor	Principle Reference
1.	Design building so elements are layered according to anticipated life span	(Tingley D.D., [29]); (Jensen G.K., et al [28]); (Crowther, P. [27]); (Brand, S. [33]).
2.	Use a standard structural grid	(Akinade, O.O. et al, [24]); (Tingley D.D., [29]); (Crowther, P. [27]);
3.	Design for maximum flexibility that it allows the functions to change in the future and preserve the building as a whole	(Akinade, O.O. et al, [24]); (Tingley D.D., [29]); (Crowther, P. [27]); (Jensen G.K., et al [28]); (Chini A.R., et al [30]); (Morgan et al., [34]).
4.	Ensure there is an integrated set of Information, documentation about used materials, and deconstruction method (and as-built drawings) that needs to be stored	(Iacovidou, E. et al [35]); (Tingley D. D., [29]); (Sassi P. [26]); (Guy B. et al., [25]); (Crowther, P. [27]); (Morgan et al., [34]); (Addis W., et al., [36]);
5.	Develop and design a deconstruction plan during the design process	(Tingley D.D., [29]); (Jensen G.K., et al [28]); (Guy et al., [25]); Webster M.D. et al., [16]); (Crowther, P. [27]); Morgan C., et al. [34]); (Chini A.R.,et al., [30])
6.	Provide identification of component and material types using labelling, bar code, RFID	(Iacovidou, E.; et al [35]); (Tingley D.D., [29]); (Guy B. et al., [25]); (Crowther, P. [27]); Webster M.D., et al., [16]); Chini A.R., et al., [30]).
7.	Identify the design life of different elements.	(Addis W. et al., [36]); (Guy B. et al., [25]); (Morgan C. et al., [34]); (Brand S., [33]).
8.	Use prefabrication and mass production where possible	(Akinade, O.O. et al, [24]); (Jensen G.K. et al., [28]); (Jaillon L et al., [32]); Crowther, P. [27]);
9.	Design joints that are accessible and durable	(Jensen G.K. et al., [28]); (Tingley D.D. [29]); (Guy B et al., [25]); (Sassi P. [26]); (Crowther, P. [27]);
10.	Ensure access to building components	(Sassi P. [26]); Morgan C. et al., [34])

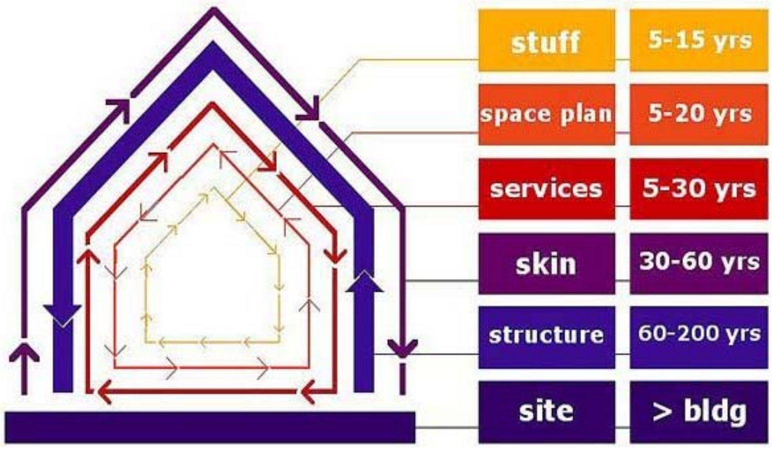

Fig. 3 Brand's 6 S's from *How Buildings Learn*.

The layer concept known as the 6 S's, introduced by Brand [33] highlights six building layers which are site, structure, skin, services, space plan and "stuff"; with the "stuff" being most frequently altered and the structure considered the most permanent of the layers, as shown in Fig. 3.

5. Human Related Factors

A variety of stakeholders are involved in any construction project. Major stakeholders are design teams, clients, contractors and site workers, engaged at different stage and time of the project's life cycle.

Design teams involved from the beginning of the project and play a crucial role on the deconstructionability and reusability of the building while contractors and site works are involved in later stages and their main task is to construct and/or deconstruct the building according to the instructions of the design teams. Therefore, it is important to develop a common understanding and a high level of commitment among all stakeholders to foster harmonious working relationship.

This means the team to have clear, accurate and good understanding of all the issues influencing the partial and whole deconstruction and reuse of the building. Deconstruction is a tedious, labour intensive, systematic process compared to demolition. Because deconstruction is a labour-intensive activity, labour issues, occupational health safety issues require special attention. Deconstruction does not require specialized site workers. Site workers with basic skillsets, professionally trained to avoid poor craftmanship and poor work ethics are well suited to carry out the deconstruction work. In Table 3 are shown the human related factors involved in the DfD process.

6. Legislation and Policy Related Factors

Although the construction industry is the most regulated after the pharmaceutical industry, and the benefits of building deconstruction are well known and appreciated among all the stakeholders there are no stringent legislation and policies that place obligation on owners and contractors to adopt DfD in a new building thus making the building deconstructable and reusable at the end of its service life. Governments and policy makers have a major role to play in the formation of the DfD legislation as imbibing building deconstruction in the industry will be difficult unless it is driven by appropriate legislation which should include appropriate policies to ensure wide acceptance and compliance among practitioners.

Additionally, the requirements and terms for building deconstruction and material reuse should also be included and clearly specified in the project contracts. Finally, it should also be mentioned that,

Table 3 Human related factors for DfD.

No	Human Related Factor	Principle Reference
1.	Train all team members on DfD	(Chilton J., [37]); (Addis W., [36]); (Morgan C. et al., [34]); (Chini A.R. et al., [31]); (Tingley D.D., [29]); (Guy B. et al., [25]); (Dorsthorst B. et al., [15]);
2.	The design team needs the right competence, training, and will to work with design for deconstruction	(Akinade, O.O. et al, [24]); (Tingley, D.D., [29]);
3.	Improved education of professionals on design for building deconstruction	(Kanters J., [38]); (Tingley, D.D., [29]); (Akinade, O.O. et al, [24]);
4.	Effective communication on deconstruction needs to other project participants	(Morgan C. et al., [34]); (Kanters J., [38]); (Akinade, O.O. et al, [24]); (Arup et al., [45])
5.	Education and training of builders and designers, waste management facility operators and government procurement staff to raise awareness and change the mindset of waste to one of potential resource.	(Couto A., et at., [39]); Hechier O., et al., [40]); (Leroux K., et al., [41]); Leigh NG et al., [42]); Iacovidou E., et al., [43]);

Table 4 Policy/legislation related factors.

No	Policy / Legislation Related Factor	Principle Reference
1.	DfD should be incorporated in the building codes	(Morgan C. et al., [34]); (Kanters J., [38]); (Rios F.C., [44]);
2.	Legislation to make deconstruction plan compulsory at the planning permission stage	(Morgan C. et al., [34]); (Guy B., et al., [14]);
3.	Government legislation to set targets for material recovery and reuse	(da Rocha, C.G. et al., [46]); (Bradly, G., et al., [47]); (Rodríguez, G., et al., [48]); (Wahlström, M., et al., 49);
4.	Set contractual clauses that will favour building material recovery and reuse in construction projects	(Arup et al [45]); (Wahlström, M., et al., [49])
5.	Award of more credits for building deconstructability in sustainability appraisal	(Ajayi S.O., et al., [51]); Lu W. et al., [52]); Oyedele L.O., et al., [50]); Häkkinen et al., [53]); (Schweber L., [54]);
6.	Legislation must set targets for building deconstruction and must provide supporting legislations and policies to drive such targets	(Ajayi S.O. et al., [51]); Lu W., [52]); (Oyedele S.O. et al., [50])

even though environmental certifications such as BREEAM, LEED, DGNB, GREEN STAR etc., for buildings have become common practice for projects of various types over the last two decades DfD is not prominently featured in their categories and credit system. Table 4 shows the legislation and policy related factors in the DfD Process.

7. Conclusions

The potential of the DfD in the sustainability of the construction industry is widely acknowledged by all stakeholders. Although DfD does not suffice to address the entire sustainability goals, maintains the embodied energy of building materials and components, it decreases the need for new virgin resources and deters the generation of construction and demolition waste. However, due to technical, organizational, political, social, and economic considerations the DfD process is largely unexploited.

This study examines material, design, human and policy/legislation categories involved in the DfD process. These categories are of major importance in the DfD process and were examined along with their associated factors. The key factors of each category must be taken into consideration in each one of the five design stages of the traditional architectural design when designing deconstructable and reusable buildings [25]. The proposed categories could be utilized by designers, architects, design managers, project managers, contractors as guide for planning, designing and constructing building that have the potential to be deconstructed fully or partially. Furthermore, in order to meet the new demanding standards of DfD the skills and the competencies of the architects and the engineers engaged in the DfD process should be enhanced through the relevant sustainability education while demolition and deconstruction contractors and engineers should be brought on board during the early design stages. Finally, the outcomes of this study can assist all stakeholders involved in the construction industry towards achieving the sustainability agenda of the industry.

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