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DESIGN FOR DISASSEMBLY IN HOUSING: THE NEED TO ADAPT LCA TO SHEARING LAYERS

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ABSTRACT

The current lack of sustainable and affordable housing is a global issue which has reached a crisis point. Traditional construction approaches used to solve sustainability issues in housing are often in tension with affordability, where the achieving one of these two aims is often to the detriment to the other. The application of Design for Disassembly (DfD) in combination with Industrialised Construction (IC) can simultaneously provide environmentally and economically sustainable solutions to these ongoing housing challenges. However, the application of DfD and the planning of varying lifespans for different building components raises issues with the conventional Whole Building Life Cycle Assessment (LCA) methodology, which is used to quantify environmental impacts of the construction.

This paper covers three theoretical objectives: (1) to provide an overview of DfD and IC and how these can be combined to provide resource efficient, affordable housing (2) examine how the Shearing Layers concept can extend the building lifespan and better ensure a sustainable End-of-Life, and (3) a preliminary outline proposal as to how the Whole Building LCA methodology, based on existing standards, can be adapted to align with the Shearing Layers. These objectives will be achieved through a literature review, covering the theoretical principles of DfD and the key ISO standards related to LCA. Based on the literature and applied theory, a preliminary aggregated LCA methodology is proposed that will be further developed and tested using case studies in future investigations by the author.

The result of the discussion reveals potential conflict between construction in practice and applying Shearing Layers and the adapted Whole Building LCA and the need for further investigation to establish the number of years assumed for each layer of the LCA. Whilst inventory data for materials and processes follow conventional practices, it is the proposed organisation of information into layers illustrates to designers the need to design housing for disassembly to remove and replace building components.

KEYWORDS

Sustainable housing; Design for Disassembly (DfD); Life Cycle Assessment (LCA); Circular Economy (CE); shearing layers.

1. INTRODUCTION

A key issue to address the challenges of the climate and housing crises is resource inefficiency, construction not only accounts for nearly 40% of global energy-related CO2 emissions (UN 2017); over a third of all EU waste is generated by construction and demolition (European Commission 2020a). Additionally, advancements in energy efficiency have exposed the urgent need to reduce the extraction of raw materials and embodied carbon to achieve net zero by 2050 (European Commission 2020b; LETI 2020; Gervasio and Dimova 2018). In tandem, there is not only a lack of social and affordable housing, 'affordable housing' is becoming increasingly unaffordable (Housing Europe 2021).

To address these challenges, the industry must move away from the linear "take-make-waste" model that has underpinned development to a Circular Economy (CE) approach, decoupling growth from the consumption of finite resources (The Ellen Macarthur Foundation 2015). Circular housing systems can potentially improve affordability whilst simultaneously improving environmental sustainability.

These circular goals can be achieved through DfD in combination with Industrialised Construction (IC), also known as Modern Methods of Construction (MMC). IC is a broad term encompassing the systematic and controlled production of buildings. It is increasingly associated with industry 4.0 and merging with ICTs such as BIM to support an integrated project team and document information for all building life-cycle stages. Both IC and CE principles consider buildings as a product rather than a one-off prototype. These two schools of thought intersect in practice through DfD where demountable standardised elements are easily adapted, reused, repaired, recycled, or relocated. Long-term cost savings are possible through circularity and the closing of material loops, with the added benefit of sheltering businesses from resource price fluctuations (European Commission 2020b). Although designing for circularity through DfD requires an increase in initial capital investment, this can be overcompensated with a reduction in future costs over the whole building lifecycle (Braakman, Bhochhibhoya, and de Graaf 2021).

Life Cycle Assessment (LCA) is a methodology and decision-supporting tool commonly used by industry professionals and scholars to measure and compare the environmental impacts of buildings. It is important to use a reliable Whole Building LCA methodology that is aligned with sustainable construction practices such as DfD, not only to appropriately measure and reduce the environmental impact of housing, but crucially to be able to define sustainability targets at the policy level. Therefore, the aim of this paper is to propose the first steps towards adapting and improving the conventional Whole Building LCA methodology, for application to housing built using DfD.

2. DESIGN FOR DISASSEMBLY IN HOUSING

2.1.Design for Disassembly (DfD)

In the Architecture Engineering and Construction (AEC) industry, Design for Disassembly - also referred to as Design for Deconstruction – is the design and planning of the future disassembly (or deconstruction) of a building, in addition to its assembly (Cruz Rios and Grau 2019). DfD can reduce embodied carbon across the building stages and is considered the "ultimate cradle-to-cradle cycle strategy" (Smith, 2010, p.222). Economic value can be maximised whilst simultaneously minimising environmental impacts in line with CE principles. This is achieved through the recovery of building materials based on the 3Rs principle (reduce, reuse, recycle). Benefits also include increased flexibility and adaptability, optimised maintenance, retention of heritage, and the possibility to easily relocate an entire building (Rios, Chong, and Grau 2015).

Although significant research in applying DfD to construction and housing began in the early 2000s (Smith 2010) the concept is not new, it has been used by nomadic groups throughout history and well-known structures include the Native American Tipi (Fig.1), Mongolian Yurt (Fig.2), and Bedouin tents or "Buryuut Hajar" (Fig.3). Disassembly is also integral to exhibition pavilions, entertainment structures, military facilities and refugee shelters assembled for rapid deployment and temporary use (Guy and Ciarimboli 2008). Such examples provide valuable knowledge for the application of DfD to permanent housing; notable Research and Development (R&D) projects include Cellophane House by KieranTimberlake (2008) and European project Buildings as Material Banks (BAMB 2020).

DfD is dependent on design principles including standardised and interchangeable components and connections, dry construction methods with mechanical connections as opposed to chemical bonding, designing with safety and accessibility in mind, and documentation of materials and methods for disassembly (Guy and Ciarimboli 2008; Crowther 2005; Morgan, Architects, and Stevenson 2005). The deconstruction plan is key to this process and should be developed during the design phase (Tingley 2012; Jensen and Sommer 2019). Designing for disassembly goes against construction conventions and requires the collaboration of multiple stakeholders, such as a deconstruction manager after the use stage (Charef and Lu 2021).

2.2. DfD in combination with IC: A kit-of-parts

DfD in housing can be implemented on a small scale using conventional construction techniques, the use of human-scale components or 'sub-assemblies' are ideal in application to modest self-build projects such as the open source WikiHouse project (TED Talks 2013). However, the benefits of DfD can be scaled-up when paired with Industrialised Construction (IC). Through economies of scale DfD in combination with IC can provide social and affordable housing on a mass-scale: reducing construction time, improving build quality, and reducing costs. Production of industrialised housing can take place in factories either off-site or in temporary on-site hubs. It is expected that a significant proportion of housing in the coming decades across Europe will be built in such factories, and sustainable homes will be mass-customised from range of prefabricated standard elements (McKinsey 2020).

This form of housing production can provide user-oriented housing through a 'kit-of-parts' or catalogue of large standard prefabricated elements such as the roof, structure, and wall panels to name a few (Fig.4). A first step in applying DfD to industrially produced housing would be to ensure each element from the kit-of-parts is designed to be assembled as well as disassembled, with the possibility of re-assembly.

Figure 1. [left] Native American Tipi. Source: https://hearthworks.co.uk/history-of-traditional-tipis
Figure 2. [centre] Mongolian Yurt. Source: http://loc.gov/pictures/resource/ppmsca.14742/
Figure 3. [right] Bedouin Buryuut Hajar. Source: https://www.loc.gov/resource/cph.3b22258/

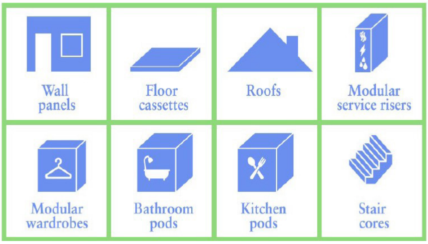

Figure 4. Industrialising housing with a kit-of-parts: Source: Author's own image

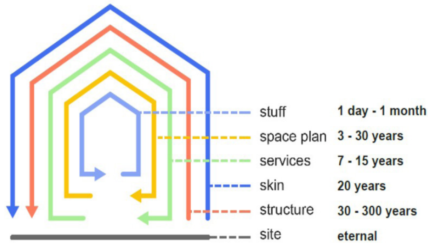

Figure 5. Shearing Layers diagram adapted by author. Source: Author's own image based on Brand (1994)

2.3. Shearing Layers and the Six S's

DfD principles aim to extend the building lifespan for as long as possible to increase material longevity, as advocated by the Ellen McArthur Foundation (2015). Therefore, resource efficiency of residential buildings should be maximised through dismantling and recycling housing at the end of the service life, in addition to maintaining, repairing, and replacing components during the use phase. A building comprises of different components with varying lifespans that should be accounted for, to extend the lifespan of an entire house or apartment block.

In the book How Buildings Learn: What Happens After They're Built, Brand (1994) organised these varying lifespans into six categories with the Shearing Layers concept. The concept built upon the work of Duffy (1992), who Brand quoted to substantiate the theory which views buildings as "a set of components that evolve in different timescales". The six S's include the 'site', 'skin' (façade), 'structure', 'services', 'space plan' (internal layout) and 'stuff' (furniture and appliances) (Fig. 5).

Breaking down the building concept into separate layers facilitates planning for the replacement of parts to close material loops whilst the building is inhabited, in addition to the planned reuse and recycling of building elements at the end of the building lifetime. The structure is shown as the longest lasting built element (potentially up to 300 years according to Brand) and hence more permanent, in contrast to the space-plan which is subject to adapt with lifestyle changes, such as adult children leaving the family home or the need to work from home. How these six layers are connected to each other is crucial to enable the removal of building elements, "[o]therwise the slow systems block the flow of the quick ones, and the quick ones tear up the slow ones with their constant change" (Brand 1994).

R&D projects piloting DfD in housing increasingly incorporate Brand's Shearing Layers model to account for their varying lifespans (Acharya, Boyd, and Finch 2020; Crowther 2005). The application of Shearing Layers to a kit-of-parts for housing should consider the varying lifespans of each component, categorising these into the separate building layers. Potential difficulties lie in elements that combine the structure with the skin, which could include both roof and external walls when using a panelised system (highlighted in red in figure.6). To ensure the Shearing Layers are adhered to, independent load bearing structures such as portal frames would mitigate the issue of separating the outer layer, or the thermal envelope.

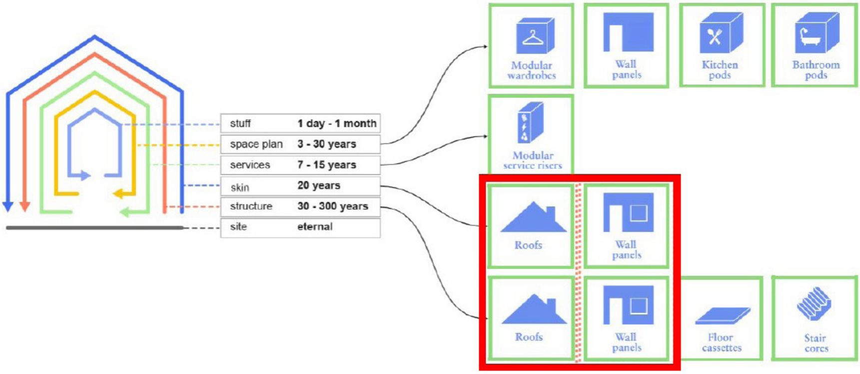

Figure 6. Shearing Layers applied to a kit-of-parts. Source: Author's own image

3. LIFE CYCLE ASSESSMENT (LCA)

3.1. An overview of LCA

Life Cycle Assessment (LCA) is a standardised method to comprehensively quantify all emissions and resources involved in the production of goods and services, providing information on the environmental and health impacts, in addition to resource depletion (European Commission 2010). LCA serves as an analytical tool that can be used to compare products, accounting for all input and output flows related to the entire life cycle, from raw material acquisition, manufacture, use and maintenance (whilst the home is occupied), to the deconstruction and beyond EoL phase (T. Sartori et al. 2021).
LCA was originally used to assess small scale products as opposed to buildings; according to Guinée et al. (2011) one of the first studies was carried out by the Midwest Research Institute (MRI) for The Coca Cola Company in 1969 to compare different beverage containers. The LCA methodology was applied to buildings decades later in the 1990s and is also referred to as a Whole Building LCA (BRE 2018).

A Whole Building LCA is an increasingly core component of Green Building assessments such as carried out by BREEAM, which incorporated LCA into their credit system following demand for transparency from the construction industry (T. Sartori et al. 2021). The inclusion of quantitative methods such as LCA supports the move towards a performance-based rather than descriptive approach to measuring sustainability. This is promoted by leading Green Building certification body BREEAM, who in reference to LCA state "you can't manage it if you don't measure it" (BREEAM, 2018).

3.2. Key standard ISO 14040:2006

The ISO 14040 series provides a standardised global framework for practitioners and scholars alike to conduct a Whole Building LCA. The series provides the basic outline for an LCA methodology with four distinct analytical phases:

1. the goal and scope definition phase,
2. the inventory analysis phase to estimate quantities of materials, products, and processes,
3. the impact assessment phase, and
4. the interpretation phase.

The first phase 'goal and scope definition' sets the depth and breadth of the LCA, phase two involves a Life Cycle Inventory (LCI) that encompasses the input/output data, phase three is the Life Cycle Impact Assessment (LCIA) whereby additional information is used to assess the LCI results, and the last phase is interpretation of the LCI and/or LCIA results which are then summarised and discussed (ISO 2006).

3.3. Key standard EN 15978:2011

An important addition to the international standards was the publication of EN 15978 under CEN/TC 350, which supports the decision-making process and provides more specific guidance for the calculation methods. This should include all building related construction products, processes, and services used over the life cycle of the building (CEN 2011). The standard provides a framework which breaks down the life cycle into four main phases (A-D): 'A' Product and Construction stages, 'B' In-use stage, 'C' EoL, and 'D' Beyond building life cycle. Within each phase are several numbered sub-phases or 'modules'.

The inclusion, or exclusion, of these stages delineate what is known as the system boundaries of the assessment. A summary of the building stages and their associated system boundaries can be understood as the following: cradle-to-gate (modules A1-A3), cradle-to-site (modules A1-A5), cradle-to-grave (modules A1-C4), or cradle-to-cradle (modules A1-D). A cradle-to-cradle Whole Building LCA supports a circular approach to housing and is increasingly incorporated into Green Building assessments (BREEAM 2022; USGBC 2022). This is crucial when designing a circular building system as the reuse, recovery, and recycling potential must be pre-planned to better safeguard the sustainable EoL, which would take place beyond the lifetime of the original project team. A cradle-to-cradle Whole Building LCA could therefore be used to promote circular economy principles in housing through DfD practices.

Product phase			Construction phase		Use phase							End-of-Life phase				Benefits & Loads
A1 - A3			A4 - A5		B1 - B7							C1 - C4				D
A1 - Raw material supply	A2 - Transport to manufacturing plant	A3 - Manufacturing & fabrication	A4 - Transport to project site	A5 - Construction & installation process	B1 - Use	B2 - Maintenance	B3 - Repair	B4 - Replacement	B5 - Refurbishment	B6 - Operational energy use	B7 - Operational water use	C1 - Deconstruction/demolition	C2 - Transport to disposal facility	C3 - Waste processing for reuse, recovery or recycling	C4 - Disposal	D - Re-use, recovery, recycling potential

Figure 7. Building life cycle phases and modules. Source: Author's own image based on EN 15978

3.4. LCA and life span consideration

LCAs assume a service life span for buildings of different uses, including residential buildings; within academia and industry the number of years considered to conduct a Whole building LCA are not consistent (Grant, Ries, and Kibert 2014). A study by Sartori et al. (2008) reviewed 60 case studies from nine countries, revealing common practice was to assume a 30 to 50-year life span to perform a Whole Building LCA. More recently, another academic study by Hossain and Ng (2018) confirms this may still be an accepted norm; within a sample of 36 LCA studies the majority assumed a 41–50-year life span and only 4% assumed a life span greater than 80-years.

There are several ISO standards related to service life planning, such as ISO 15686-5:2017(en) (ISO 2017), however there is no prescriptive number of years detailed. Within Europe, Eurocode EN 1990:2002+A1 specifies a 50-year life span for the structural system of a building. This period has been used by the Joint Research Centre (JRC) of the European Commission as the predicted life span for Whole Building LCAs (Gervasio and Dimova 2018).

Similarly, there is a lack of consensus amongst industry professionals for the length of a building's life span. Whole Building LCAs by BREEAM use a default calculation period of 60-years (BREEAM 2018); the 'Green Guide' by BRE (the parent company of BREEAM) loosely bases the 60-year period on ISO 15686 in addition to guidelines by BPG (1999), BLP (2000), and CIBSE (2000) amongst others.

Another issue – and a source of major conflict with DfD principles and CE goals – is the conventional Whole Building LCA assumes one length of time to assess the impacts of the entire building.

In practice, building lifetimes vary considerably from case to case, even amongst residential buildings; the seemingly arbitrary 50- or 60-year life span is markedly low as the vast majority of housing remains in use over multiple generations.

4. ADPAPTING THE LCA METHODOLOGY

4.1. Proposed aggregated methodology

The issue of an inconsistent predicted building life span becomes redundant when applying LCA to analyse the environmental impacts of housing designed for disassembly. To incorporate CE and the benefits of DfD, the conventional Whole Building LCA presents major shortcomings which must be addressed by adapting the widely accepted methodology. Whilst the incompatibility of DfD with a Whole Building LCA remains unresolved, an increasing number of scholars are contributing to this issue (Joensuu et al. 2022; de Wolf, Hoxha, and Fivet 2020).

This study proposes the application of the Shearing Layers concept to the Whole Building LCA through the aggregation of six separate LCAs, these could comprise of large building components that adhere to the separate Shearing Layers. The methodology would align with the key ISO standards discussed (ISO 14040 and ISO 15978) amongst others, whilst incorporating building information related to kit-of-parts elements commonly used by industrialised house builders. For each layer, the aggregated methodology would assume a life span equal to the upper-range value provided by the Shearing Layers concept. For example, the structure, which according to Brand has a potential lifespan of 30-300 years, would assume a 300-year lifespan. Once the LCAs have been aggregated, the lifespan for the Whole Building LCA would assume the same lifespan as the structure, as once this fails, the whole building would need to be disassembled.

One could argue that separating a residential building into six layers is rather general, in the context of this study and in anticipation of application to future studies, a more granular approach would be too time-consuming and may not yield significantly improved results. Furthermore, the broader aim of the study is to impact the Whole Building LCA methodology adopted in industry, which would be more difficult to achieve with a high level of complexity and more time-consuming process.

4.2. Supporting analytical tools

Analysis of materials and processes will be performed using the ecoinvent Life Cycle Inventory (LCI) database, a mature database integrated into the SimaPro application. Ecoinvent is a globally recognised LCI data source provided by a Swiss not-for-profit association and therefore contains data specific to the Swiss construction industry. The proposed methodology will account for this through adapting input data to a general European origin (rather than Swiss-specific), to support the comparison of future case studies from different European countries.

4.3. Applying Shearing Layers to case studies

The following section provides some detail as to how Brand's six Shearing Layers will relate to built elements in the future case studies. The 'site' layer will be considered eternal, though remediation practices (excavation and landfilling) will be calculated. The 'structure' layer will encompass the foundation and load-bearing elements (including columns, beams, and floor slabs and stair cores) and will assume a 300-year life span. The 'skin' layer (external façade including windows and doors) will consider a 20-year life span. The 'services' layer (modular risers containing HVAC, plumbing, lifts, fire sprinkler systems, and communication and electrical wiring) will assume a 15-year life span. The 'space plan' layer (interior walls, ceilings, floors, and doors) will be calculated with a 30-year life span. Lastly, the 'stuff' layer (furniture such as chairs, desks, and appliances) will not be included in the Whole Building LCA as these are not fixed building elements and are subject to a considerable amount of change. The proposed methodology assumes the upper limit of the time provided by Brand for the expected life span of each layer as previously shown in figure.5. However, it should be noted there is a lack of qualitative data to substantiate the exact number of years that should be adopted for each layer. Therefore, the proposed length of time for each layer for the proposed methodology will be reassessed and further developed.

5. CONCLUSIONS

This paper provided the background to DfD in housing and how in combination with industrialised construction methods can be used to provide sustainable social and affordable housing. Although these building methods and strategies are not common practice, there is growing research and several pilot projects, suggesting this may be used more widely to provide sustainable housing solutions.

It was argued that the current Whole Building LCA methodology does not provide designers and policymakers with a true reflection of the building performance of DfD buildings, on which to base housing-related decisions; this unsuitably assumes the same life span for the whole building. This should instead consider the impacts of separate components and their associated lifespans, aligned to Brand's Shearing Layers concept.

The first steps towards adapting the conventional Whole Building LCA were outlined, to be based on existing standards and that would comprise of aggregated LCAs of prefabricated components from a kit-of-parts. Lastly, this paper anticipates the potential conflicts that may arise in applying the adapted LCA to existing projects due to difficulties in separating layers, particularly where panelised systems are used. This research will be further developed and applied to case studies in future work by the author.

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