Informing Life Cycle Assessments Through Design for Disassembly

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ABSTRACT: What determines the lifespan of building materials? This question can be approached in numerous ways. In this article, we work from the assumption that the least erroneous answer is: the future.
Design for disassembly (DfD) is a way to mitigate the uncertainties of dealing with the future of construction and as a way to relinquish material lifespan from construction lifespan. (Crowther, 1999) DfD is an instrumental part of developing circular economy in architecture where lifespan of materials cannot be defined by the typology or construction type as it facilitates disassembly on various levels of a building. DfD is a strategy often referred to in literature as prompting longer lifespans of materials through reuse and recycling thereby potentially both reducing the need for virgin material resources in construction and prolonging the use of a resource. Simultaneously DfD prompts an architectural understanding of buildings as changeable artifacts, as open-ended entities. By juxtaposing the principles of DfD and LCA, this article forms a critique of the understanding of lifespan represented in conventional LCA. To contextualize this inquiry, two examples of DfD in contemporary construction are analysed, where the specific conditions for disassembly in the façade systems are laid out. The examples are two hybrid building systems in the current Danish building industry which show fundamentally different approaches to disassembly. The two examples and all data from chapter 5 in this article is based on case studies carried out by one of the authors of this article, as a part of an ongoing Ph.D. project anticipating completion in the spring of 2024. The resulting discussion is concerned with the possibility of informing the conventional LCA paradigm by imposing on it, notions of the unpredictable nature of the future, of lifespans, of end-of-life and reuse scenarios, with which DfD is occupied.

KEYWORDS: Design for disassembly, life cycle assessment, circular building principles, facade design

1.0 INTRODUCTION – BUILDING FOR AN UNKNOWN FUTURE

The Brundtland definition of sustainability exhibits an inherent understanding of sustainability as an ideas closely interwoven with a notion of an unknown future, which is very clearly stated in the extensively used quote from the Brundtland report (Keeble1988):

> Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

With this in consideration, the practical and philosophical implications of choosing and planning for a specific future becomes apparently problematic. We know that our actions must not compromise future generations but what does the future need and how do we get there? Many environmental impacts are tied not just to what we do (build) today but equally to how the built environment can adapt or change with the unforeseeable demands of the future. The total environmental impact of buildings depends on past and present decisions and on the multitude of yet unknown variables of the future. As buildings potentially have very long lives, we would have to be able to look far into the future to be accurate in our assessments. This is the apparent embedded weakness in LCA and this article investigates how the unknown future can be addressed otherwise: through design for disassembly.

Product stage			Construction installation stage		Use stage							End of life stage				Beyond the system boundaries
Raw materials	Transport	Manufacturing	Transport	Construction installation stage	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Figure 1: LCA stages that are included in the calculation according to Danish Building Code. Stage D is not included in buildings that are more than 1000 square meters. Source: (Diagram by Pelle Munch Petersen 2019)

Life Cycle Assessment (LCA) is a method for assessing the environmental impacts of a material, product or a service by factoring in the full lifespan from cradle to grave. LCA (as methodologically defined in the Danish building code) work by both establishing the actual and measurable environmental impacts tied to the production of the materials in a construction (Stage A1-A3: Product stage) and by assuming future impacts in the later stages of the materials life (Stage B Use stage, Stage C End-of-life)(Hansen and Hansen 2018). However, the longer the life of a given material, the more variables there are for future scenarios and therefore the more speculative the assessment becomes.

Therefore, we look at how DfD can be used to construct in a way that allows for many different future scenarios to unfold and discuss what consequences DfD can have on LCA DfD allows for better scenarios regarding maintenance, selective non-destructive demolition partially or for the building as a whole. It is a strategy often referred to in literature as prompting longer lifespans of materials through reuse and recycling thereby potentially reducing the need for virgin material resources in construction. Simultaneously DfD prompts an architectural understanding of buildings as changeable artifacts. Designing a building for disassembly is about anticipating the future unknown and possible physical changes of a building. DfD can be incorporated as a design strategy for the ease of taking a building apart instead of destructive demolishing at EOL.

2.0 RESEARCH QUESTION AND METHOD

What is the relation between LCA and DfD regarding lifespan of materials? How does their respective governing logic showcase different approaches to the understanding of the potential life of building materials?
To contextualise this inquiry, first the governing logic of LCA in construction is analysed and secondly two examples of DfD in contemporary construction are pinpointed, where the specific conditions for disassembly in the building systems are laid out. The examples are two hybrid building systems in the current Danish building industry: WoodStock and LCT. The two examples show different approaches to the processes of assembly and disassembly of the building envelope, which are influential on the possibility of separating the lifespan of buildings from the lifespan of its materials. Lastly the two different takes on the future life of materials are discussed in relation to LCA.

3.0 PROBLEMATISATION OF THE CONCEPT OF LIFESPAN IN LCA

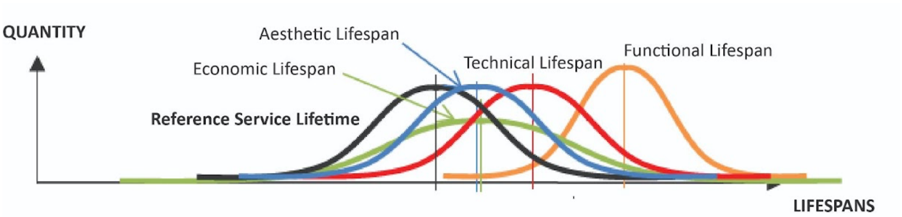


Figure 2: Different competing lifespans. Source: (Original diagram by Aagaard et al., translated by Pelle Munch Petersen 2019)

3.1 The role of lifespans in life cycle assessments

The lifespan of materials in LCA is commonly defined by recommendations that are compromises between different hypothetical competing lifetimes. These lifetimes are referred to as (Aagaard et al., 2013):

- Technical lifespan
- Functional lifespan
- Economical lifespan
- Aesthetic lifespan

The resulting lifespan of any given material is in reality defined by a complex interplay of many potential lifespans. The defining lifespan is the shortest of the possible lifespans. In construction, building materials work in connection with other materials and therefore the lifespans of all materials in a given construction should be investigated collectively. Especially in cases where materials are connected in non-reversible ways. Here the material with the shortest lifespan will be the defining lifespan.
A lifespan that is not addressed adequately is *political lifespan* as political motivated demolition is common but impossible to predict. The politically motivated demolition can be motivated by a wish to mitigate ghettos, make way for new development etc. As such, to say anything about the future life of buildings and the lifespan of material is difficult. In many it is defined by other factors than the material itself. Rather the joining, the context, political climate and more define the lifespan.

3.2 Lack of general knowledge on the lifespans of buildings

In a Danish context the research and documentation of building lifetime material use is very limited. Energy use of buildings is calculated and measured in all construction as it represents a running cost. As such operational energy is accounted for but the embedded impacts of materials are so far not considered accurately. The only register in Denmark that monitors the material use and life of buildings is called 'Building and Dwelling Register' [BBR] (Bygnings- *og* boligregister*, BBR*, n.d.).

However this register is flawed, and inconsistent as it is the owner's responsibility to update and register changes in construction, technology, and use. Doing this requires technical knowhow and can be difficult for common building owners. Furthermore, not all owners are aware of their responsibility to update and maintain the register.

Consequently, looking into the Danish situation of building life and material lifetime there is not enough data. The BBR is incomplete as registration of typical upgrades and maintenance are not required. Therefore, it is extremely difficult to predict the life of a building material based on retrospective analysis of building data. When doing so anyway the calculation becomes quite hypothetical and LCA must be considered hypothetical if not unrealistic.

3.3 What determines the lifespan and end-of-life of building materials?

It is virtually impossible to predict with precision the lifetime impacts and *End of Life (EoL) scenario* of a specific building or building material. The shorter the technical lifespan a material has - the higher the accuracy of the assessed lifetime impacts - as it can be done with some empirical precision. If we for instance know that the sealant/resin in the spacer in a three-layered-glazed window glass will last no more than 25 years - then we can know with some accuracy that it will not last longer than that. Meanwhile, only very few materials and components in construction have such short technical lifespan. Often the material with the shortest lifespan will determine the “Reference Service Lifespan” (RSL) (the estimated lifespan of a material). For instance, the economical lifespan will be the defining parameter, if it is cheaper to discard the material and buy new - or discard the building and build a new one. And, if the nail with which a panel is mounted lasts a shorter time than the panel, the lifespan of the panel might be defined by the nail. As such the construction as a whole also defines the lifespan of a material.

3.4 A fixed future or an open-ended future?

LCA does not necessarily take into account the possible implications of the possibility to reuse or recycle materials after End-of-life. LCA does not promote a Circular Economy for this reason. This coincides with the intellectual conflict between the architectural strategy of DfD and the logic of LCA. As will be showcased later in this article the primary aim of DfD is to facilitate reuse and recycling and thereby prolonging lifespans of building materials and buildings. During the last year the Danish building code has defined the environmental loads of reused materials (in stage A) in two completely opposite ways showing how difficult the notion of reuse is: First reused materials should be calculated with the full impact as a new produced material and from 2024 the same reused material has zero loads in the LCA calculation (Bolig og planstyrelsen, n.d.). None of which can be an accurate description as reuse represents environmental loads but far less than new production.

Secondly EOL scenarios are based on what happens to materials today when they are discarded. That means that all development is put to a hold in a fixed understanding of the future that only reflects practice today. The only exception to this is the operational energy (stage B6) that can be calculated with a *dynamic energy mix.* Here LCA is anticipating the development in energy-mix based on development so far and the politically decided future for Danish energy production.

4.0 ‘DESIGN FOR DISASSEMBLY’ AS A STRATEGY FOR PROLONGING LIFESPANS

Acknowledging that the future is unknown leads to questioning the hypothetical and linear and fixed nature of LCA scenarios possible in phase B and C. Architectural design can be a way of dealing with the uncertainties of the future, by designing for many possible futures instead of one specific. Design for Disassembly as an architectural design strategy focuses on allowing the disassembly of buildings or parts of buildings. DfD facilitates structural and spatial flexibility, where physical changes can be done in a non-destructive way and makes way for understanding buildings and structures as changeable artifacts. DfD was conceptualized in the product industry in the 1990’s, has slowly migrated into architectural theory and is by now quite well described in literature as a technical strategy. (Sassi 2002) (Brand 1995) (Addis & Schouten 2004) (Nordby 2009) (Munch-Petersen 2019) However, it is still not a common working concept within the building industry in Denmark. DfD as a strategic position towards construction originated in the product industry and is slowly being incorporated in the building industry within a larger paradigm focusing on design for sustainability, which is one of the most complex and ambitious design concepts, having sustainability as the end objective (Kauschen 2014). DfD is found to be a sub-strategy to several of these more complex design strategies, which makes it interesting to explore. (Guy et al. 2008)

Designing buildings or parts of buildings for disassembly facilitates reuse and recycling on material, element, component and building level, by relinquishing material lifespan from construction lifespan (and the other way around) (Crowther, 1999). As such DfD arguably challenges the temporal aspects of the LCA model – more precisely the fixed notions of lifespans and EOL-scenarios – by purposefully facilitating reuse and recycling on various levels. Reuse and recycling prolong the lifespan of that which is reused or recycled, thereby complicating the assessment of its lifecycle. DfD works in favour of a circular material economy, whereas the LCA model favours a linear material economy for making precise assessments as the assessments depend on the given EOL-scenario.

However, DfD and LCA are not to be understood as opposition ideas. They converge on the topic of environmental impacts. Where DfD enables a prolonging of the lifespan of building components and their materials by reuse and recycling, which in turn can lower negative environmental impacts, LCA is used to assess environmental impacts from cradle to grave of a building or component. This is where DfD challenges conventional models of LCA; by making possible (low impact) EOL-scenarios and increasing the potentials of LCA stage D (‘Benefits and loads beyond system boundary’) usually describing potentials of reuse, recovery, and recycling. This article presents two different cases of DfD in façade construction to investigate DfD in practice and how this relates to LCA stage C and D.

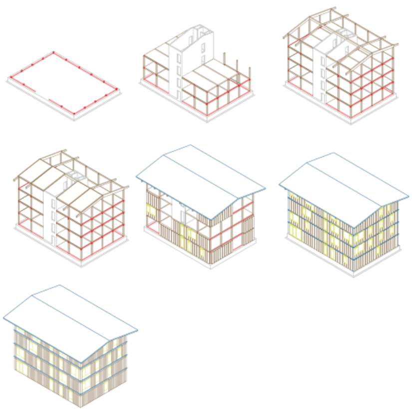
5.0 ANALYSIS OF DFD IN TWO EXAMPLES OF BUILDING SYSTEMS

The concept of disassembly is concrete and tangible; that which is assembled should be able to be disassembled. Assembly details and choice of materials for a building can facilitate - or stand in the way of easy disassembly. However, it is still not a common working concept within the building industry in Denmark.

In this chapter two examples of DfD in contemporary construction in Denmark are pinpointed, where the specific conditions for disassembly of the façade systems are laid out. Both examples are multistorey hybrid building systems for residential purposes. All information and data in this chapter is based on case studies carried out by one of the authors, as a part of a Ph.D. dissertation anticipating completion in the spring of 2024.

The two building systems, WoodStock by the architectural office Tegnestuen Vandkunsten & LifeCycle Tower by CREE GmbH, are examples of two different approaches to DfD in the current Danish building industry. The building systems in question are both hybrid constructions, where concrete, steel and wooden elements make up the structural - load bearing - parts of the buildings. Hybrid construction as a term covers basically the structural part of a building which is composed of more than one type of building material. The DfD strategy presented accounts only for the facades, as they are non-loadbearing and as such are considered having great potential for disassembly. By a qualitative analysis of how possible future disassembly of the façade in the two cases would be done, the static and dynamic conditions of the two building systems becomes evident along with their future circular potentials. As the focus of the analysis is solely on the facades, this article will not consider the parts of the two building systems which apparently present great challenges for disassembly. Examples of these parts are the reinforced concrete structures, the composite wooden-concrete floor slabs, and the concrete foundation. As the objective of this article is to analyse the practical and concrete disassembly of façade systems through the construction drawings of connections, to discuss the role of facilitating reuse and repurposing in the LCA model, the inquiry will not go into the objective of the disassembly or how the dismantled part would be reused or repurposed. Whether the disassembly happens because of the need for modernizing the building or other scenarios, the focus of this article is specifically on the assembly type and way of disassembly of the described façade system.

So, in the following we investigate two different approaches to DfD as a strategy for construction facilitating potential change according to new demands by disassembly for reuse or recycling of materials.



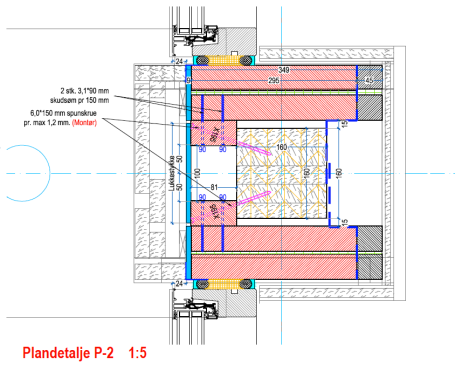


Figure 3, 4 and 5: Fig.3 Photograph showing dwellings on Lisbjerg Bakke. Source: (Line Kjær Frederiksen 2024) **Fig.4:** Illustration of some of the steps in the building process as accounted for in the educational handbook *Anvendt Byggeteknik i Dansk Arkitektur.* Source: (Leimand et al. 2018). **Fig.5:** Construction detail that shows the paper doll concept of assembly and disassembly. Source: (Tegnestuen Vandkunsten A/S 2017)

5.1 WoodStock - Tegnestuen Vandkunsten A/S

The hybrid building system WoodStock is developed by the Danish architectural firm, Tegnestuen Vandkunsten in collaboration with MOE Consulting Engineers and carried out in the residential housing Lisbjerg Bakke in Aarhus, Denmark. Lisbjerg Bakke consists of six multi-story dwellings of 3 to 4 floors with a total of 40 housing units. The project was finished in 2018 and was the first Danish multi-story public housing using load-bearing wooden structures in contemporary construction industry. The project team used LCA's to assess global warming potential of the building materials' environmental impact as a part of their design process, as the client opted to get a DGNB-certification. The buildings were awarded DGNB Gold in 2020.

5.2 Building process

The steps show the load bearing structure consisting of cast concrete foundation and concrete element staircase, the glulam post and beam structure is built around the staircase one floor at a time. As a gesture of thinking ahead, the steel bracket connections in the post and beam structure are prepared for mounting balconies, if a future need arises. The beams shown in red are steel beams, which are chosen with the intent of keeping a low construction height for the floor slabs. The floor slabs are prefabricated cross laminated timber elements, which are then added a layer of 9 cm concrete cast on-site, one floor at a time, to give a composite effect for the slabs to comply with requirements for acoustics, fire, and structural stability. Followingly, the glulam roof purlin and trusses are mounted.

The roof structure is finished by mounting prefab insulated elements between the trusses and is covered with metal sheeting. A few places in the facade, CLT-elements are mounted in between two glulam columns for structural stability. Prefab insulated facade elements are mounted on the glulam columns and on the concrete staircase. This is done starting on the top floor working down. The elements vary in design (one or two windows and/or a door, or no openings at all) depending on placement in the facade.
The horizontal zinc flashings are mounted for each floor, preventing water from penetrating the facade and lastly the facade cladding of spruce boards is mounted.
In the construction process only, lifts were used and no scaffolding as there was no need for a covered construction site.

5.3 Disassembly process

Focusing on the building envelope façade, the disassembly process of the WoodStock building system is analogous to the concept of a paper doll; a basic figure dressed or clad in a way where the cladding can be removed one layer at a time. From the construction detail above it is visible how the disassembly process would be in case of future needs for changes. For example, if balconies were to be mounted, it would be necessary to access the steel brackets in which the glulam columns are fixed. This would be done manually by unscrewing the spruce board cladding, then unscrewing the substructure of wooden slats, then removing the small strip of fiber cement and mineral insulation, which is closing the gap between the façade elements and the columns. At this point, the steel brackets and bolts are accessible for mounting balconies. At this point, the 6,0x150mm screws are accessible as well. The screws are accessible from the outside of the façade elements, which means that the entire façade element can be unscrewed from the columns and removed in one piece. Further disassembly of the façade elements would most likely happen off-site or on the ground at least.

This process of disassembly facilitates removal of several layers of the façade or entire façade elements without affecting the basic figure of the paper doll. The disassembly of the façade can be done independent of the building process. A kind of autonomous approach to disassembly becomes possible.

Figure 6, 7 and 8: Fig. 6 Visualisation of the student housing and café on Østerbrogade 190. Source (Vilhelm Lauritzen Architects, CREE Building 2018) **Fig. 7:** Detail that shows the montage of the façade elements, glulam beams and hybrid floor slabs. Source: (CREE Building 2018) **Fig. 8:** Two vertical sections construction drawings (to the left); the first showing the connection type using long screws. Source: (CREE Building 2018)

5.4 LifeCycle Tower - CREE GmbH

LCT is a hybrid building system property of CREE (an abbreviation of Creative Resource & Energy Efficiency) which was born from the Austrian construction company, Rhomberg Group. Several multi story buildings have been built using the LCT hybrid building system. The first building was LCT One in Dornbirn by Herman Kaufmann Architekten from 2012, is an 8-storey building. Most recently in Copenhagen, Denmark, a 6-storey residential building with a café on ground floor is in the making by a project team consisting of CREE Denmark (licensed CREE partner), Vilhelm Lauritzen Architects, and MOE Consulting Engineers. The building on Østerbrogade 190 has yet to be realized. Nonetheless it is interesting as a case given the high degree of information which is available on the building system.

The CREE building system constitutes the superstructure and the building envelope. The design and choice of materials for the rest of the building is up to the project design team. With regards to working with LCA's, CREE does preliminary LCA's to help early design decision making and therefore mainly look at the LCA stages of A1-A3, at times including A4 if known. Other than that, CREE uses LCA for comparing the building system against other more conventional constructions on a structure-to-structure level (Tim Steffinger, Elif Istanbulluoglu, email to author, June 22, 2022) Depending on parameters like design, location, footprint and more, the embodied carbon of a CREE structure changes, which means that comparisons to e.g., conventional concrete or steel construction, needs to be done singularly on the specific constructions to be precise and useful.

5.5 Building process

As the CREE building system can adapt to specific needs, there are multiple solutions to the load bearing structure (glulam columns, hybrid ribbed slabs, a stiffening concrete core or wall panels and steel middle girders, where necessary). The following describes the most generic solutions and the design choices specific for Østerbrogade 190.The unitized superstructure relies on standardized industrial prefabrication. The building process of the LCT-system begins when the foundation is laid. Given the 6 stories of the planned building on Østerbrogade 190, the LCT structure is fixed to the concrete foundation. First the concrete element staircase is erected and then the deck is built around it, by assembling one floor at a time. Then prefabricated non-loadbearing façade elements and the load-bearing glulam columns are mounted as one element, by lifting it in place so that the bottom of the columns is fixed onto a round metal bar. This connection is then cast with a cement-based mortar. The prefabricated hybrid floor slabs (made of reinforced concrete cast together with glulam beams resulting in a composite effect) are then hoisted onto the metal rod on the top of the columns. With this procedure only cranes are needed, and an entire floor can be closed off in one day as described the CREE Planning Manual. The roof construction on Østerbrogade 190 is not specified, but it will be a flat roof.

There is no defined standard for the mounting of the façade cladding on the CREE structure, but it can be done both on- or off-site. Preferably off-site as a part of the prefabrication of the facade elements, as it reduces the working hours on-site. Either way, the substructure of the cladding is affixed to the studs of the timber framework of the facade elements using long screws. On Østerbrogade 190 the cladding is not yet chosen, but anodized aluminium is suggested.

As CREE does not themselves carry out any manufacturing, the company relies on local manufacturers to produce building components. The prefabrication process can be adjusted to fit the production line of the specific manufacturer, as the details can be altered in relation to special requirements of manufacturers. Most manufacturers use their standard production line for prefabricating the CREE facade elements, optionally adding a workstation for attaching the timber framed walls to the glulam columns.

5.6 Disassembly process

There are several solutions to multiple construction details in the LCT building system. With regards to the façade elements, two connections are possible. One is fixing the façade element to the column with long inclined and horizontal screws through the studs of the timber frame. The other solution, which is used in the first project with LTC, is using large steel brackets. It has not been possible to verify which method will be used at Østerbrogade 190, so for this analysis, the assembly with long screws is used as an example.

The timber frame facade element is assembled and insulated before it is fastened to the glulam beams with long screws through the timber frame studs. The element is closed off by screwing a fibre cement board into the timber frame, which means that you would have to remove the facade cladding, the substructure, and the fibre cement board before accessing the screws for unscrewing the element from the columns. Still, it would be necessary to cut the fibre cement and OSB boards to remove the element horizontally, because of the groove and tongue-like interlocking of the top and bottom of the elements. This is the case for both types of connections (brackets and screws) of the elements to the columns.

In both examples, the assembly process is like that of LEGO, where the prefab elements + columns interlock vertically. The disassembly of the building would therefore have to begin from the top by demounting first the roof and then one floor at the time, by first separating stiff connections and secondly lifting elements. Like LEGO, you cannot take out a LEGO block in the middle of a structure – you must take the LEGO structure apart top-down. As such, the process of disassembly would be the reversed version of the assembly process.

6.0 DISCUSSION; HOW CAN DFD INFORM THE NOTION OF LIFESPAN IN LCA

6.1 The two building systems

The two cases: two seemingly similar hybrid building systems, are examples of different ways of working with DfD. Removal of the façade cladding is in both cases possible to do at all times of the building's life. The 'LEGO' concept found in CREE and the paper doll concept found in WoodStock points to two different perspectives on lifespans; With the paper doll concept of DfD, it is possible to separate the materials' lifespans from that of the building. With the LEGO concept this is not possible.

In the case of the LCT, the connection of the façade columns and floor slabs are not mechanical, and as there is a groove and tongue effect of the façade elements (which according to the building system preferably are mounted on the facades' columns and assembled as one element) when mounted on top of each other, one floor at a time, the façade elements will in effect become quite difficult to separate individually from the rest of the structure. This indicates that the disassembly of the individual façade elements will have to happen in a reverse linear sequence of assembly and thereby will require disassembly of the elements above a given façade element in order to remove it. Or instead, a disassembly causing slight destruction of materials where potential cutting is needed. However, if the disassembly of the structure is carried out in reverse order of assembly, the façade elements could be handled in a non-destructive manner and potentially be reused as an element or undergo disassembly into its constituent materials.

A different scenario becomes evident in the case of WoodStock. Individual parts of the façade cladding can be unscrewed from the wooden strips, revealing where to unscrew the individual façade elements from the wooden structural façade columns. Individual façade elements can be disassembled from the structural framing without affecting the other façade elements.

Regarding potentials and disadvantages in both cases it is quite easy to change the façade cladding, which makes possible many future surface expressions. Regarding the disassembly of the façade elements from the load bearing structure, in the case of LCT the facade elements are not designed for disassembly from the load bearing structure, as is this case in WoodStock.

6.2 'LEGO' and or 'Paper doll' regarding LCA

The 'LEGO' and the 'Paper doll' showcase the potential in material reuse (by means of DfD) and open doors for many future scenarios and by doing so undermine the linear fixed logic of LCA and the premise of all stages except for stage A. Stage A is already done when the building is erected and as such it's impacts belong to the past. But the rest (stage B, C and D) has not happened yet and as such both systems showcase possibilities for different lives and for materials reuse that extends the life of the building, they are part of.
For experienced practitioners of LCA it is commonly understood that LCA is merely a scenario-based calculation tool and not a realistic prediction of what will happen. But as the tool promotes an understanding of predictability of construction lifespan, chances are that the benefits of DfD will never be employed by LCA practice as we cannot calculate the potential gains. The number of possible outcomes is simply too great.

How to best deal with the temporal aspects of construction? As established the consensus today, represented in LCA, is that the future is best dealt with through calculation of impacts now and over time regardless of the limitation this logic entails. In this article, we argue that this can lead to inaccurate assumptions of best practice. The future is unknown and therefore a different approach to impacts over time is necessary. DfD represents an approach where instead of insisting on fitting the unknown nature of the future into a quantitative normative calculation model (LCA) it transfers the problem into an array of design solutions that allows for many possible future scenarios. This challenges the foundation of the linear temporal understanding represented in common LCA. Making it possible that the technical lifespan of the material in fact becomes the RSL by separating the life of the material from the life of the building.

Stage D is commonly 'outside system boundary' and thus not part of an LCA-calculation. However, in both cases mentioned above a best practice and use of the systems will mean that the benefits of reuse should be able to be transferred from stage D to stage A of the next lifecycle (next building). This would mean that processes in stage C (C3 and C4) become redundant as well. This is especially the case when the technical lifespan is potentially longer than the functional, economical, aesthetical, and political.

We argue that very short-lived material impact (technical lifespan) should be considered in a stage B (use stage) as these materials might have to be changed periodically with new ones. But even more important it is to design short lived materials into composition in accordance with the 'Paper doll' mindset where it can be maintained easily in a non-destructive fashion. A full recalibration of the building envelope is possible, e.g bigger or smaller windows can be applied to accommodate different functional demands. It also makes partial refurbishment possible and thus allow for the building to retain its relevance over time. And if not, at least its materials can live on. The 'LEGO' approach is not as dynamic as the whole building has to be taken apart top-down. This way, in theory, the individual elements can be reused, but the building system does not allow for partial disassembly, which can hinder transformation and maintenance. As such, the most significant difference between the two examples is that the paper doll approach makes it possible to separate the lifespan of the facade elements from the lifespan of the building, which is not possible in the LEGO model.

CONCLUSION

The analysis of LCA showcases a fixed linear approach to time and building material lifespan. LCA deals with scenario-based approaches to the future that in some ways reflect status quo (EOLs) and thus hinders development, and in other ways bases the calculation on inadequate data based on an unknown and unsubstantiated past.

The future is difficult to predict and LCA exemplifies this well. But design does not have such limitations. Design can deal with many futures. As it becomes clear in the case studies design can ensure a separation of the building life and the material life.

In essence LCA and DfD complement each other well. The first is a normative calculation tool and the latter is a design method. LCA works well in establishing impact here and now (stage A) but lacks credibility in dealing with the future. DfD opens for many possible futures to take place and thus compensates for the lacks in LCA. Together LCA and DfD form a solid sustainable design approach.

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