IMPACT OF CIRCULAR BUILDING PRODUCTS ON AFFORDABLE HOUSING PROJECTS

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ABSTRACT

The Dutch housing shortage is a problem that should be fixed along with a shift towards a circular economy. Financial and systematic barriers along the way are slowing down the urgent transition. This paper looks into the technological and financial aspects that are involved in circular housing constructions. In addition, the role of government and different stakeholders is discussed. After identifying the conventional building practices and their alternative circular building products, a comparative financial analysis is performed through literature review, market research and Life Cycle Costing (LCC). The layers of structure and skin and their combination was the focus of the study. The result of the analysis showed that prefabrication of LVL modules and their skin can cost as much as conventional precast concrete buildings while having the extra benefits of flexibility, safe and quick construction, healthy interior air, higher-quality products and most importantly less environmental impact.

KEYWORDS: *Affordable housing, Circular, Building products, LCC*

I. INTRODUCTION

1.1. Problem statement

Today, the Netherlands is experiencing a 4.2% shortage in the housing stock, which accounts for 331,000 extra homes (Lijun, 2020). The market not only has to supply for the current shortage, but it also has to meet future demands. It is estimated that the Netherlands should expect 850,000 population growth by 2030 that entails 775,000 additional households needing a place to live in ten years (BPD, 2016). It is getting increasingly harder to find affordable housing, especially for the low and middle-income households (Tasan-Kok & Özogul, 2019). Housing associations (or woningcorporaties) are private non-profit organizations that provide rent regulated social housing to the vulnerable populations in Dutch cities. (Hoekstra, 2013) Housing associations can play a significant role in overcoming the crisis. However, today it takes an average waiting time of 15 years for people to access social housing units in Amsterdam (Tasan-Kok & Özogul, 2019). Until now, the housing stock of the Netherlands consists of 33% of social housing that is the highest rate among European countries (Czischke & van Bortel, 2018).

The Dutch ministry of home affairs is aiming to produce 845,000 homes in the next decade (Nltimes, 2020). For instance, the plan in Amsterdam is to dedicate 40% of the constructions to social housing and to add mid-priced housing for another 40% (Solanki, 2020). Building this large number of dwellings in the current linear building culture will have negative consequences on the environment. The construction industry is the most waste-producing sector compared to agriculture, metal, food and textile industries in the Netherlands (CBS, 2019). In 2012, 25 million tonnes of waste was produced in the construction sector that was three times more than the total household wastes (Schut et al., 2015). The building industry should transition from a linear way of production to a circular economy as soon as possible.

Ellen MacArthur Foundation (2017, para. 1) defines circular economy as "... a systemic approach to economic development designed to benefit businesses, society, and the environment. In contrast to the 'take-make-waste' linear model, a circular economy is regenerative by design and aims to gradually decouple growth from the consumption of finite resources." Constructing circular buildings is an essential step for circular economy and decreasing the burden on the natural reserves of the planet (Kanters, 2020). A study by Braakman et al. (2021) shows that replacing traditional materials of a house with circular products does not affect the cost until reaching the circularity level of 0.49 (when 0 is not circular and 1 is circular). However, gaining higher levels of circularity showed to negatively affect the affordability of the house since some circular products are still scarce and expensive.

It can be an impactful step for the Dutch construction industry if social housing associations replace their current linear practice with circular construction methods. Besides, housing associations often oversee the housing units during the entire lifecycle, therefore the residual value of the products in a circular construction can be a good incentive for them. On the other hand, some of the social housing associations are having financial struggles. They are assigned to make their outdated units more sustainable, and their income from the rent collection is now divided between renovation and building new dwellings (Capital Value, 2019). This might hinder their choice to adopt circular practices in the new constructions. This paper aims to analyse the existing opportunities and barriers in the path of circular affordable housing production.

1.2. Research question

The question that this paper is aiming to answer is how can the use of circular building products by social housing associations impact the costs of the project? Transitioning toward circular products requires a thorough understanding of four fields of technology and design, finances, management, and governance (TUDelft CESBE2x, 2020). Therefore, the following sub-questions are asked:

- How is the current construction method of social housing units and what are the circular alternative construction methods?
- What is the financial impact of choosing circular or conventional building products?
- Who are the stakeholders and what are the relevant laws and policies?

These questions can clarify the alternative circular scenario, so the research question is answered by having the system's entirety in mind. Based on the sub-questions above the contents are divided into Three sections.

II. METHODS

This paper studies the effect of circular building products on housing constructions through qualitative and quantitative strategies. A literature review was done to find the most common structure and skin techniques. Plus, Dutch building product market was analysed to collect circular and prefabricated construction opportunities. The cost of these products was collected from the suppliers and De BouwkostenWijzer. For answering the second sub-question, available literature on building materials cost comparison was studied, and the LCC (Life Cycle Cost) of a few hypothetical cases was compared. Boundaries are defined for the LCC layers and scope to fit in the time frame of the research. The Third question regarding the management and governance was shortly reviewed through literature.

III. TECHNOLOGY AND DESIGN

Dutch housing typologies are classified into two general groups of single and multi-family dwellings. Single-family buildings such as detached, semi-detached and row houses comprise 65% of the housing stock, and the rest are multi-family residences like gallery, porch, and apartment buildings (Geldermans, 2020) (Icibaci, 2019). Multi-family typologies have the largest share of rental homes, and social housing associations primarily own row houses and multi-family buildings (Agentschap Nl, 2011). In this section, current construction of Dutch dwellings is analysed to clarify how circular they currently are and how they can be improved. According to Stewart Brand, site, structure, skin, services, space plan and stuff have different paces for change. The idea of shearing layers indicates that buildings cannot be perceived as permanent objects, and they are subject to alteration over time (Koenig, 2019). For instance, having load bearing interior walls makes it difficult to change the function of buildings in the future. This research focuses on the skin and structure layer of constructions.

3.1. CURRENT CONSTRUCTION PRACTICES

Residential buildings in the Netherlands used to be constructed with timber and brickwork. Since the Second World War, fire risks in cities, the rise in timber prices and the development of multi-family buildings influenced the construction industry to gravitate towards concrete structures. The introduction of cast construction in the 1960s replaced wooden foundations and floors with concrete piles and slabs. Gietbouw (pouring concrete) was initiated in the 1970s, which increased the consumption of concrete considerably (Icibaci, 2019). Concrete makes up more than 80% of the entire mass of Dutch building materials (Arnoldussen et al., 2020). The concrete industry uses 50 to 55% of the produced cement for in-situ pouring and 35 to 40% for prefabricated products (Icibaci, 2019). Not as much as concrete but materials such as brick (4% of building material mass), wood (3%) and iron (4%) are also commonly used (Arnoldussen et al., 2020). Steel construction is mostly utilised for offices or industrial structures (Icibaci, 2019).

The general categories of load distribution in structures are load-bearing external walls, Load-bearing transverse walls and skeletal frames (Konstantinou, 2014). In the Netherlands, the main types of structural systems are called Stapelbouw, Gietbouw, Montagebouw and Skeletbouw (NVJ, n.d.). These systems are sometimes combined and create hybrid forms. Stapelbouw is a traditional method that entails stacking blocks and floor elements on-site and mounting them manually. The combination of cavity walls and prefabricated concrete floors are an evolution of this traditional method that before the war used to be built with timber floors and no cavity walls. On the other hand, Non-traditional methods such as Gietbouw (pouring construction) and Montagebouw (assembling construction) were used for large scale constructions because they are faster and require less workforce. Concrete is the primary material for these buildings. (Icibaci, 2019) Gietbouw uses different kinds of formworks such as tunnel, column and climbing for casting the concrete and shaping the building (NVJ, n.d.). For instance, tunnel-form structures are the most common type of construction used in Dutch residential buildings, and they are usually finished with plaster or brickwork. For Montagebouw, walls and floors are made out of large, prefabricated components, assembled by cranes and attached with dry or wet joints (Icibaci, 2019). Skeletbouw is a frame system of timber, steel or reinforced concrete. Walls in these constructions are not load-bearing (NVJ, n.d.). This system is usually applied to non-residential buildings such as offices (Gerrits, 2008).

Another important layer of the building construction is the skin that wraps around the structural systems that are mentioned before. There is a wide range of building envelope constructions that are generated and influenced by the available materials, building culture and function of the buildings (Konstantinou, 2014). For instance, brick is widely used in Dutch facade design practices (Arnoldussen et al., 2020). Some of the common external brick facades are cavity walls and precast panels. SRB_DUP methods can also be used that provide dry connection of bricks with steel nuts and omit the need for mortar (Icibaci, 2019). Furthermore, the insulation used in new buildings is mostly mineral wool. Some cases use plastic-based options such as polyurethane foam (PUR) or Expanded Polystyrene (EPS) to insulate (Icibaci, 2019). All these materials and practices are deep rooted in the industry and hard to change.

3.2. REUSE

As the need for constructing new houses grows, it is crucial to think carefully about the choice of materials. In the circular building industry, using secondary materials is the optimal option but reuse in the building stock that was just described is complex. These dwellings typically were not designed while having the deconstruction phase in mind. The pre-war housing stock, predominantly built with traditional methods, is the main target for harvesting building products currently. These buildings have a high concentration of wood, and they are deconstructed manually. The non-traditional and concrete intense structures form a significant section of the available materials, and their fractions are difficult to deconstruct and transport. Thus, they are reused less often compared to timber products, and they get recycled instead. In the case of brick walls, the reclaimed bricks are not meant to carry loads, and they get to function for aesthetics. The downside is that new bricks tend to be cheaper than reclaimed alternatives. Furthermore, used Mineral wool and EPS are some of the insulations that can be found as secondhand. Plus, sandwich panels are observed to be replaced instead of being repaired (Icibaci, 2019).

It is not usual and frequent in the Dutch housing market to demolish buildings. Between 1995 to 2003 the rate of demolished houses to new constructions was 1 to 7. Demolition typically happens to low-quality and inexpensive houses like the postwar mass housing stock. For example, social housing units are demolished twice as much as private residences (Icibaci, 2019) since the quality of the social sector units is lower. This difference in quality can be because the willingness to customize, repair and modify is higher in ownerships rather than in rental relationships (Geldermans, 2020). The trends also show the expansion of the private sector, which means higher survivability of the houses and less demolition in the future (Icibaci, 2019). Reuse of building products is a critical aspect of circularity, but the building market still needs to use new building products since used materials are not always available. However, the industry should stop using building products without considering their environmental impact, deconstruction and the end-of-life scenario.

3.3. CIRCULAR BUILDINGS AND PRODUCTS

Many design strategies are proposed to enable circularity in a product. Two of the important ones are design for adaptability (DFAD) and design for disassembly (DFD). Such concepts are facilitating the initiation of circularity, but they would have no positive impact if a holistic collaboration of the system does not accompany them. Design for adaptability emphasises on creating structures that allow for alteration of layouts (Mouilek, 2009). By the progression of the circular economy, the old concept of Open Building has revitalised recently. Open Building is a concept defined by John Habraken that has adaptability at its centre. The idea was developed in 1972, and it was a response to the top-down monotonous mass housing after the Second World War. According to Open Building, different layers of the construction would be independent of each other, and the user will have the potential to customise the space plan. The concept also calls for embracing new business models and ownership strategies (Geldermans, 2020). Design for disassembly is a strategy that enables the reuse of building materials through planning the deconstruction in the design phase. There are several aspects to the implementation of DFD such as elaborating materials, documenting deconstruction methods, designing the connections, designing standardised components, detaching non-reusable and non-recyclable parts and paying attention to labour procedures (Rios et al., 2015).

Prefabrication is a practice that can be instrumental in achieving DFD and DFAD. Prefab components have the potential to create high-quality results faster and with lower costs (Smith, 2010). Furthermore, sometimes ordering extra materials, damages in transportation, and lack of experienced workers generates plenty of waste during the on-site construction. Prefabrication can help to plan the process and prevent wastes (Vivian et al., 2006). However, the current practice of prefabrication is focused on the assembly and neglects the deconstruction phase. The IFD-programme in the Netherlands that promotes Industrial, Flexible and Demountable Buildings, has led to more innovations on prefab products but has not become a widespread sustainable practice (Geldermans, 2020). Prefab products can be categorised into groups based on the degree of their completion before being mounted on-site. Therefore, the classes are materials, components, panels, and modules (Smith, 2010). The goal of this section is to collect and recognise a series of prefab products that can be used in circular constructions.

Materials: The basis of a circular design is the choice of materials. Materials that are consumable such as plant-based materials belong to biological cycles. These materials would degrade and return to nature if they are appropriately designed. On the other hand, human-made products that are made out of minerals or synthetic materials should flow within the closed-loop of technical cycles to be reused, remanufactured or recovered (Wautelet, 2018).

Timber is one of the most common biodegradable materials used in the building industry. Trees grow by absorbing CO2 and using the sun's energy, so the carbon content of timber is half of its dry mass. While timber stores the carbon through its production, materials such as concrete and steel emit CO2 to be manufactured (McGar, 2015). Plus, timber has the potential to be easily reused or cascaded. Structural timber products can be optimum sustainable alternatives to the current building practices. Therefore, the products discussed below have timber as their primary material. The building industry has developed many options to boost the natural performance and strength of wood. Engineered wood products are manufactured with a range of soft and hardwoods, and each manufacturing process prepares the wood for a different function. Some of these products are namely plywood, fibreboard (such as MDF), OSB, glue-laminated timber (glulam), cross-laminated timber (CLT), Laminated veneer lumber (LVL), Dowel-laminated timber (DLT), Massiv-Holz-Mauer (MHM or solid wood wall) and Wave-layered timber (WLT). Products such as glulam, CLT, DLT, MHM and WLT can be used to bear structural loads (New Nordic Timber, 2019). Most of these engineered products require some adhesive substance to connect the layers together. The share of the adhesives in the dry weight of products varies from 10% in MDF to 1-2% in laminations. Mostly these glues belong to technical cycles, and even though they have minimal quantities, they better be replaced by binders from biological cycles for a more circular result. Soy, lignin, and furfural adhesives are biobased options that are available but have not yet been used in the industry since their characteristics are different and require more experiments. Plus, some products are designed without any use of glue, but their structural performance is not as high as the glued kinds. (Van der Lugt, 2020). Types such as DLT, MHM and WLT are free of any adhesives that eliminate any concerns about toxicity in the environment.

Components: Beams, columns, frames, or walls are some of the components that are available in wood. This basic element can be shaped linearly or as a slab. The slab options might be more expensive than the framing, but they have better thermal and structural properties (Smith, 2010).

Panels: Panels refer to walls, floor or roof elements that are planer and producing these elements off-site is called panelization. It is recommended to integrate building utilities and cables in the panels so the construction can be finalised quicker. This also makes it easier to upgrade the systems. Light-frame panels and Structural Insulated Panels (SIPs) are two cases of wood-based panelization. Production of light frame panels in a factory can provide a better-quality premade wood framing that is especially profitable in larger-scale projects compared to small scale practices. SIPs are made of EPS or PUR in the middle of two sheets of OSB. These panels have proved to be better at withstanding fire and insulating the buildings compared to wood frames and cavity walls. Some contractors can provide precut SIPs, including doors, windows and finishings (Smith, 2010). MetsaWood also produces wooden panels called Kerto floors or walls that are made of LVL components forming a frame. There are also cladding systems that can be produced as panels. Wooden claddings' durability should be taken care of by choice of rot-resistant woods like redwood and cedar, by addition of natural sealants like oils and waxes or be enhanced chemically through impregnation, stain, or varnish (Smith, 2010).

Modules: Modules are the last level of completion in prefabrication. It is possible to have a structure finished up to 95% until it is moved to the site. The transport of these units can become difficult because of their size. Some companies provide the modules as a flat pack (like panelization) accompanied the instruction for their assembly. Higher levels of prefabrication are likely to reduce the flexibility of the buildings by limiting the transport or plan arrangements. Therefore, architects should be able to find the right balance that benefits their project. Using hybrid systems can also be useful for reaching that optimum result (Smith, 2010). Companies such as Sustainer homes and Finch buildings are specialized at creating timber modules in the Netherlands.

IV. FINANCES

At this section, the cost of conventional building materials and practices is compared to biobased materials accompanied with circular methods such as prefabrication. For understanding the financial feasibility of different construction materials and systems, many papers have been published. First, a review of the available literature from around the world is done. Later in the section, a life-cycle cost analysis (LCC) will be performed to compare biobased and conventional building materials in the Netherlands and their effect on costs.

4.1. LITERATURE REVIEW ON COST COMPARISON

Some papers compare precast concrete construction with the cast in situ options. Holla et al. (2016), a study in India, emphasises that the precast cost savings are only feasible in projects requiring large scale production of components. Another study in Indonesia by Syahrizal et al. (2017) states that precast concrete cost is 33.09% lower than in-place concrete and precast is also built 20% faster.

Another set of papers compare the cost of mass timber solutions with current conventional concrete structures. Some papers present mass timber as affordable solutions, while others show it as costly alternatives. This difference can be due to the studied country, the organisation's role that produced the paper, and the comparison lens. A paper by Fanella (2018), on behalf of a concrete reinforcing steel institute in the U.S., shows CLT wall structures to be 16 to 29% more expensive than cast-in-situ concrete skeletons. Furthermore, Smith et al. (2009), a study in New Zealand, shows that LVL timber costs 6% higher than concrete and steel options. LVL can be used as skeleton structure unlike CLTs.

On the other hand, According to Mallo & Espinoza (2016), a conference paper about the U.S. market, the adoption of CLT reduces the cost of structures by 21.7% depending on the choice of manufacturer. Lower initial cost and faster construction procedures are the reasons behind the cost savings. In that market, the cost of CLT is between $5 and $20 per square feet while the cost of precast concrete is $14 and $40 per square feet. Plus, since timber is lighter than concrete, the foundation can be smaller and therefore cheaper. This paper also mentions that insufficient building codes are limiting the widespread use of CLT products. A study by Forsythe & Forest and Wood Products Australia (2018) compares mass timber solutions with the cast-in-place concrete. This study presents timber frames to cost 13% less and CLT to cost 6% less than cast-in-place concrete. It continues to mention the positive effects of timber on life cycle costs through thermal and acoustic insulation and the possibility of the minimum end of life disposal costs. Forest and Wood Products Australia (2015) specifies the influence of connectors' choice on financial feasibility. Simple brackets are easier to reach and faster to install than hidden plates or dowels. Besides, in case of using hybrid constructions, the components will be obtained from various suppliers that has an adverse effect on affordability (Steelconstruction, n.d.).

The difference between these papers' outcome shows room to optimise timber construction's financial feasibility through design, improving codes and increasing their availability. According to email contact with the company Solid Timber, the key to creating affordable and circular buildings is to consider it as a goal from the very early stages. Prefabrication is known as a cost-saving solution that also needs to be decided early on. According to Bertram et al. (2019), modular constructions are likely to finalise 20 to 50% earlier and 20% less costly than conventional practice. The document also adds that manufacture of the modules can take place alongside the on-site foundation work. Besides, modular units can eliminate a multitude of subcontractors involved in the building process, therefore diminishing the extra margin fees integrated into their quotes. Lopez & Froese (2016) has compared the effects of SIP panel constructions with prefabricated modules for a single-family home and SIP building was 11% more expensive than the moduled construction. However, the cost of manufacturing and transport was similar, and the cost savings were due to less required labour and faster construction. Realising these cost savings relates to many factors such as accessibility of the off-site factory, repetition and design complexity, and experts' availability.

4.2. LCC

After learning about the previous studies on comparative cost analysis, an LCC is performed on 12 models of structure, five types of skins and 16 cases that show a combination of different structures and skins forming a 10x10m space in the middle of an apartment (Appendix 5). The circular products are picked from Cirkelstad's online product catalogue. LCC can consider all the costs throughout the life cycle phases of a building: the initial phase, the construction phase, operational phase, and end of life phase (Braakman et al., 2021). It is also useful to assign a goal, stakeholder, scope, and a period for the costs (TUDelft CESBE2x, 2020). Here the goal is a comparison to find the most affordable combination, the stakeholder is the social housing associations, and the scope is the entire cycle except for some of the omitted costs. The LCC is done for a period of 70 years. The material costs are gathered from contact with different suppliers, companies and De BouwkostenWijzer series. Based on the LCC analysis, skeleton structures have the lowest cost and DLT floors and walls have the highest cost among the structure systems. DLT components (The most circular) are the most expensive because they are less widespread than CLT or LVL. The low cost of skeleton structures is always compensated by the high cost of their infill skin. Buildings with skeleton structures can function as open buildings; however, interior load-bearing walls are used dominantly in the residential sector that limits the flexibility.

Table 1 The LCC results of 12 cases of structure and skin combinations

Cases		Structure	Structure LCC	Skin	Skin LCC	Total LCC
Concrete	Case 1	Cast in place concrete	46266.31	Traditional brick wall and insulation	7464.28	53730.60
	Case 2	Precast concrete walls and floors	22274.22	Traditional brick wall and insulation	7464.28	29738.51
	Case 3	Precast skeleton	15508.79	Traditional brick wall and insulation and concrete wall	27859.49	43368.29
	Case 4	Precast floors and sandwich wall	35873.12	Precast sandwich wall	0	35873.12
Hybrid	Case 5	Precast skeleton	15508.79	Insulation wood fibre and cladding and infill	33710.25	49219.05
	Case 6	Precast concrete walls and floors	22274.22	Insulation wood fibre and timber cladding	9323.80	31598.03
Biobased	Case 7	CLT walls and floors	40983.35	Insulation wood fibre and timber cladding	9323.80	50307.16
	Case 8	DLT walls and floors	65033.23	Insulation wood fibre and timber cladding	9323.80	74357.04
	Case 9	Glulam skeleton	3931.61	Insulation wood fibre and cladding and infill	33710.25	37641.87
	Case 10	Kerto floor and CLT walls	32451.20	Insulation wood fibre and timber cladding	9323.80	41775.00
	Case 11	Kerto floor and SIP walls	31865.89	Wooden cladding	8129.32	39995.21
	Case 12	Kerto floors and walls	30109.97	Insulation wood fibre and timber cladding	9323.80	39433.78
	Case 13	CLT modules (finch buildings)	34026.93	Insulation wood fibre and timber cladding	9323.80	43350.73
	Case 14	LVL modules (Sustainer homes)	25759.73	Insulation wood fibre and timber cladding	9323.80	35083.53
	Case 15	CLT modules with skin	38757.53	Prefabricated	0	38757.53
	Case 16	LVL modules with skin	30490.33	Prefabricated	0	30490.33

Based on this LCC analysis, the skeletons have higher ultimate prices. Comparing the precast wall and floor systems (Case 2) with precast skeleton structures (Case 3) shows that the skeleton building is 28.7% more expensive than the building with precast walls. In precast wall systems, the structure operates two jobs of dividing and bearing the load, but in skeleton buildings, each of those tasks requires a separate set of materials. Furthermore, if the non-load-bearing concrete walls of case 3 are replaced by Kerto timber walls (Case 5), a hybrid system is created that is even more costly. However, the glulam skeleton building with Kerto skin (case 9) costs 20% less than precast skeleton option and costs 15% more than the precast wall and floor system (Case 2). Therefore, there is an opportunity to make affordable skeleton buildings out of timber instead of hybrid or precast skeletons (Appendix, figure 15).

Apart from skeletons, according to the LCC result, cast-in-place concrete buildings are more expensive than precast options. CLT walls and floors, despite being better CO2 storages, are more expensive than SIPs and Kerto. By comparing the details of the precast concrete case and Kerto walls and floors (case 12) (the most affordable biobased option), it has appeared that the LCC of Ketro is 24% higher than the precast concrete case. The effect of residual value in the LCC is very minimal. To gain that residual value plenty of costs goes to dismantling the components with care. Thus, the cost of dismantling is cancelling out the effect of residual value (Appendix, figure 17). Meanwhile, calculating the debris cost of concrete shows 125 Euro NPV (Net Present Value) cost for 52 cubic meters of concrete. This is only 2.5 euro per tonne of concrete. Plus, dismantling concrete for recycling or dumping does not need any careful considerations, and it is cheaper than disassembly for reuse. This is why debris costs are not included in the calculations. It is a problem that the cost of dumping concrete is so low, and the government should consider increasing it to help the circular transition. In conclusion, if the assembly and disassembly of Kerto elements are done more efficiently and quickly, the LCC will be decreased considerably. Now it is useful to investigate the LCC of prefabricated LVL modules that are a way to speed up assembly and disassembly.

The prefabricated LVL modules (Case 14) result in a Life cycle cost that is 11% lower than the Kerto floors and walls (Case 12). By prefabricating the cladding of the modules together with the structure, the construction time further decreases, and the LCC becomes 22% less than case 12. Reduction of construction and dismantling costs prove to be effective in bringing the life cycle cost of biobased buildings (prefabricated cladded LVL modules) to the same range of precast concrete (Appendix, figure 18). Hence, Pursuing prefabrication can be a good solution for the affordability gap between biobased and conventional building materials. It is also possible to have these prefab modules shape a skeleton structure that enables flexibility of use in the life cycle.

V. MANAGEMENT AND GOVERNANCE

The private and non-profit associations for social housing work with local governments and other stakeholders to supply affordable and good quality homes for the tenants. They are responsible for following national laws and regulations and answering to society's needs (Aedes, 2016). The choice of biobased and prefabricated products is not only a financial concern. For instance, wood's natural character provides a healthy environment that does not emit chemical vapours (Dalton, 2017). Besides, off-site fabrication creates higher-quality products with less disturbance and traffic for the neighbourhood, and it prepares a safer construction site for the workers (Chris, 2016). The circular transition can be beneficial for inhabitants and society in many aspects. Therefore, it is suggested to extend the WOZ Immovable Property tax to include sustainability criteria. Buildings can have circularity labels similar to existing energy labels, and if they rank lower, they would have to pay higher taxes. Initiation of these policies can help speed up the transition (Schut et al., 2015).

VI. CONCLUSION

The Netherlands must aim for overcoming the housing shortage with constructing circular buildings, but financial barriers are slowing down the process along with the solidified linear building culture. This paper explained how the use of circular building products by social housing associations could impact the project's costs. Social housing associations are assumed as primary stakeholders. They have the perfect industry position to make a difference since they stay in touch with the buildings throughout the entire lifecycle. Looking into different lenses of technology, finances, management, and governance helped the paper view the whole system, but the main focus was on the relationship between the choice of technologies and the finances. Currently, cast-in-place and precast concrete in the form of load-bearing walls are the most common systems in the housing construction and the facades are covered with mineral wool insulations and brickwork. Biobased systems with dry and metal connectors should replace outdated systems that have a high carbon footprint and are incredibly difficult to disassemble.

Prefabrication can be a cost-saving and waste-preventing solution for circular constructions. Engineered timber products such as Glulam, Cross Laminated Timber (CLT), Laminated Veneer Lumber (LVL) and Dowel-Laminated Timber (DLT) were the material of focus in this paper. CLTs and DLTs can turn into walls and slab components, and Glulam and LVLs are suitable to form columns and beams. A higher level of prefabrication after components are panels. Panels such as Kerto walls and floors, Structural Insulated Panels (SIPs) and wooden frames can include extra functions of insulating, opening and cladding in their prefabrication. Lastly, the modules are considered the highest level of prefabrication. These circular products' financial implication is assessed in the paper by the cost comparison literature review and an LCC analysis.

Precast concrete showed to be less expensive than cast-in-place. Depending on the availability of CLT, the purchasing cost of this material differs in every context. Timber buildings are not common in the Netherlands, and the LCC shows concrete products to be at least 20% cheaper than circular products. Even considering the residual value could not prove the affordability of biobased options since the dismantling costs would neutralise their effect. At the same time destructing and dumping concrete at the end of life is very cheap. Increasing the dumping cost, material purchasing tax of concrete or property tax can balance LCC calculations. Besides, prefabrication can reduce construction costs, marginal sub-contractor costs and dismantling costs. They also create safe and organised construction sites. However, they are only profitable if repetition is high in the design. Ultimately prefabricated LVL modules showed to have the same LCC as precast concrete. These modules can also form skeleton structures that enable open buildings. Therefore, investing in the prefabrication industry by social housing associations can be the boost that circular and biobased products need.

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APPENDIX

Appendix 1: Formulas (Braakman et al., 2021):

This section explains the details of the performed LCC. The initial phase contains the cost of purchasing the products; this study uses product prices that do not include taxes or transportation costs. The construction phase covers the labour and equipment cost, and the operational phase is about the cost of replacing and the maintenance. This study considers the replacements needed based on the lifespan of each product but excludes the maintenance costs. Lastly, the end of life phase (EoL) usually entails dismantling, logistic and residual value. Whether the products are dismantled for reuse, remanufacture, or recycling, the degree of attention to damage is different. Dismantling cost is calculated concerning the construction cost; 90% of the construction cost for product reuse, 75% for remanufacturing and 15% for recycling. The cost of logistics is not used in this LCC. Residual value is about the cost of the product's disposal or the revenue made from selling the second-hand products (Braakman et al., 2021). Except for purchasing and construction costs that are in the present time all the other costs happen in the future. The value of money is influenced over time by inflation and interest rates so the future costs should be calculated by the Net Present Value formula (TUDelft CESBE2x, 2020). Figure 1 is a good overview on the different costs that are used in the LCC.

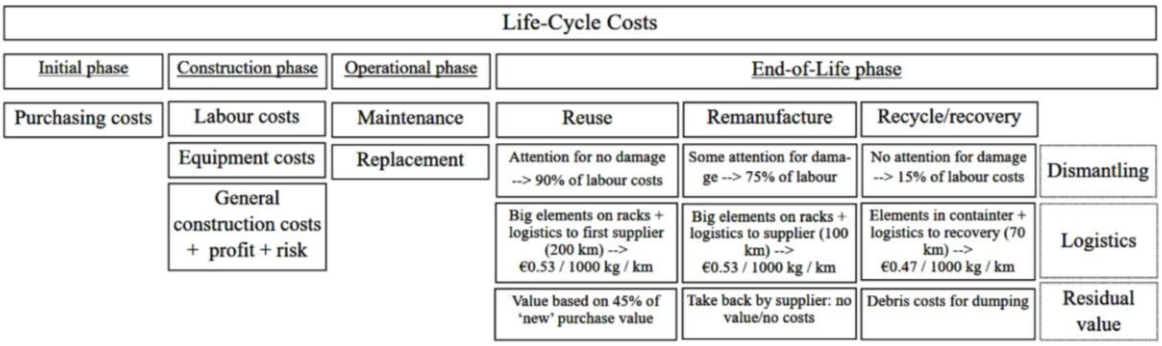

Figure 1 Cost breakdown structure of LCC. Source: Braakman et al., 2021

The LCC calculations are not made to properly track the end-of-life scenario of materials and they are focused on the iterations in a certain period. However, the iterations of use should go on as long as possible in a circular economy.

LCC = Initial phase + Construction phase + Operational phase + EoL phase

Initial phase = Purchasing costs
Construction phase = Labour and equipment costs
Operational phase = Maintenance costs + Replacement costs
EoL phase = Dismantling costs + Logistic costs - Residual value

$LCC = C0 + \Sigma Ct / (1+i-j-k)^t$

C0 = initial costs (initial and construction phase)
Ct = present value of all recurring costs (operational and EoL cost) at year t
t = year of cash flow
i = discount rate: 3%
j = inflation rate: 1.81%
k = escalation rate of materials: −0.43% for timber and −0.12% for concrete products (Mack, 2012)

Dismantling costs= (0.9 for reuse, 0.75 for remanufacturing, 0.15 for recycle) x Purchasing cost/ $(1+i-j)^t$

For recycle: Residual value= - Mass per tonne x Debris cost for each material / $(1+i-j-k)^t$
or
For reuse: Residual value= 0.45 x Purchasing costs / $(1+i-j-k)^t$

Example: total debris cost for the structure of case 1:
Debris cost for concrete: 2.5 Euro per tonne
-(2400 kg/m3 x 57 m3) / (1000 kg/tonne) x (2.5 euro per tonne)= -342
$-342/ (1+0.03-0.0181-(-0.0012))^{70} = -137.5194197$
This number is so small and it does not affect the comparison very much so residual value is only calculated for the biobased products that can be reused easily.

This formula is only used when a product's lifespan is shorter than 70 years (LCC period):

Replacement costs= Purchasing costs/$(1+i-j-k)^t$ + (construction costs/$(1+i-j)^t$)) + Dismantling costs + Debris costs

The list below shows the lifespan of the relevant materials. It is noteworthy that the longer lasting wooden cladding is also more expensive.

Table 2 Lifespan of materials

Material	Lifespan (years)	Reference
Concrete	50-100	Keulemans, 2016
CLT	60 - 700	SmartStruct, 2012
Rockwool	70	Rockwool, 2020
Brick	100	Brick architecture, 2017
PS insulation	50	PlasticsEurope, n.d.
Wood fibre insulation	70	Cademartori, 2019
Spruce Wood cladding	25-35	Abbeytimber, 2020
Fraké Wooden cladding	50	Platowood, n.d.

Appendix 2: The prices used in the LCC is from the table 3 and 4 bellow. The dimension of the products is chosen based on the 10x10m room and a rule of thumb document (Gerrits, 2008).

Table 3 Cost of the conventional building products

Current construction	Info	Unit	Rate (Euro)	Reference
Structural component				
Cast in situation concrete wall	0.2x2.5xL	Lm	206.99	Archidat bouwkosten, 2018
Cast in situation concrete floor	0.2x2.5xL	Lm	264.99	Archidat bouwkosten, 2018
Cast in situation concrete floor	0.3x2.5xL	Lm	264.99	Archidat bouwkosten, 2018
Precast hollow core concrete floor	Thickness= 0.2 m	m2	44	Archidat bouwkosten, 2018
Precast concrete wall	Thickness= 0.15 m	m2	55	Archidat bouwkosten, 2018
Precast concrete beam	0.3x0.2x3 m	Piece	526.79	Archidat bouwkosten, 2018
Precast concrete column	0.2x0.2x3 m	Piece	445.74	Archidat bouwkosten, 2018
Skin components				
Insulation rockwool	R=4.55	m2	17	Archidat bouwkosten website, 2020
Brick wall		m2	81.5	Archidat bouwkosten, 2018
Brick slips		m2	48.28	Max4home, 2020
panels				
Prefab Insulated façade panels with brick slips	R=1.38		156.29	Archidat bouwkosten, 2018
Precast sandwich panel with brick slips	Thickness= 0.27 m	m2	211.29	Calculated

Table 4 Cost of the Circular building products

Circular products	Info	Unit	Rate (Euro)	Reference
Structural components				
CLT floors	Thickness= 0.2 m	m2	105	Solid timber, 2020
CLT walls	Thickness=0.15 m	m2	95	Solid timber, 2020
Nur-holz Floor (DLT)		m3	1000	Brightforest, 2020
Nur-holz Wall (DLT)		m3	1000	Brightforest, 2020
Wood I Beam	0.058x0.36x10	Piece	80	Metsa wood, 2020
Multiplex	Thickness= 0.018 m	m2	46.4	Archidat bouwkosten, 2018
Glulam beam		m3	600	Solid timber
Glulam column		m3	600	Solid timber
Metal connectors	10 to 15% of the components' costs.			Solid timber, 2020
Skin components				
Insulation hemp	R=4	m2	24	groenebouwmaterialen
Insulation wood fibre	R=4.5	m2	21.33	groenebouwmaterialen
Insulation wood fibre rigid	R=0.75	m2	14.8	groenebouwmaterialen

Spruce wooden cladding		m2	35-45	Platowood
Fraké Wooden cladding		m2	60-70	Platowood
Poplar wooden cladding		m2	75-85	Platowood
Pretty plastic		m2	89	Pretty plastic
Panels				
Kerto ripa	Thickness= 0.2 m	m2	75	Metsa wood, 2020
SIP wall	Thickness=0.2 m	m2	90	Ecosip, 2015
Module				
LVL Module (Sustainer homes)	3.5 x 5 x 3.35 m	piece	Can't publish	Sustainer homes, 2020

Appendix 3: Assumptions about construction costs

Construction cost cannot be calculated as straightforward as price per square meter or cubic meter since it depends on how the construction process is planned, the size of the elements, or what type of connection is used. Therefore, the real-life examples stated in the following sources helped find an approximate relation between construction cost and material purchasing cost. Based on Chan, T. & Aibinu (2012) in constructing a conventional cast-in-place building, 50% of the cost is for materials, 45% for Labour and 5% for other activities. This ratio makes the labour cost to be approximately 90% of material costs for cast in situ structures. According to Seagate Structures' comparison chart (n.d.), CLT construction takes 35% of the time spent on a cast in place method. Plus, a presentation by WoodWorks titled Mass Timber Construction: Products, Performance and Design (2019) states that CLT buildings are constructed two times faster than precast concrete buildings. Furthermore, prefabricated modules can take up to 50% less time to be mounted compared to panels (Bertram et al., 2019), and their construction can also cost 50% less (Lopez & Froese, 2016). Based on the preceding papers, each construction's purchasing price was multiplied by 0.9 for cast in place structures, by 0.9x0.35=0.315 for CLT buildings, 0.9x0.35x2=0.63 for Precast concrete and by 0.9x0.35x0.5=0.1575 for prefabricated modules. DLT material is mounted similar to CLT products, but it is much more expensive; therefore, the construction cost is assumed to be the same as a CLT building.

The skin layer mostly included wood fibre insulation, Rockwool, brick and wooden claddings. The mounting process of wood fibre and Rockwool insulation is similar; therefore, it would not significantly impact the comparative analysis. The construction cost of brick walls is estimated based on Nalumansi & Mwesige (2011) that shows a mason can complete 3.48 square meter of wall per day. This number is an average of works below and above the window level. The construction cost of wood claddings is based on an Australian website's mentioned cost and exchanged to the Euro currency, which is 49.55 euro per square meter (Serviceseeking, 2019).

Appendix 4: Comparing concrete and timber’s environmental impact

Table 5 carbon emission and uptake of building materials Source: Ruuska, 2013

Material	Carbon emission (g/kg)	Carbon Uptake (g/kg)
Precast Concrete	121	-
Reinforced Aerated Concrete Block	511	-
Glued laminated timber	109	1730
CLT	362	1611
Wood fibre insulation	243	1240
Wooden cladding	121	1835

Appendix 5: The structures of the 10x10 m Room used for LCC calculations:

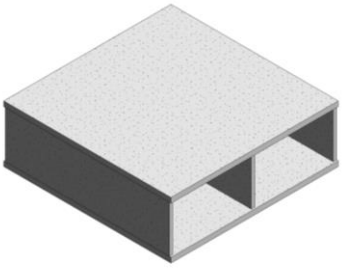

Figure 2 Cast-in-place structure

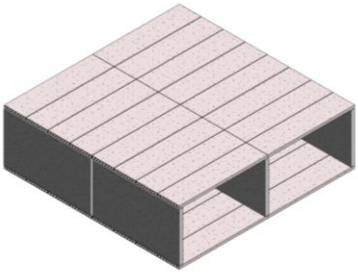

Figure 3 Precast concrete structure

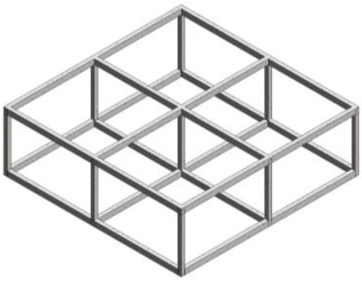

Figure 4 Precast concrete skeleton

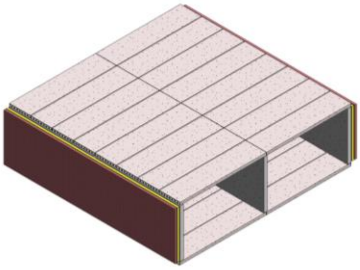

Figure 5 Precast concrete sandwich panels

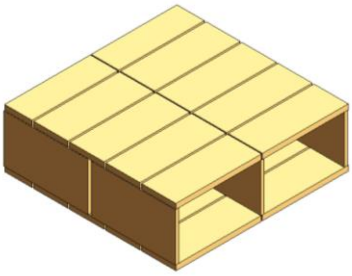

Figure 6 CLT walls and floors

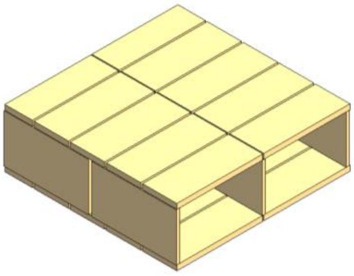

Figure 7 DLT walls and floors

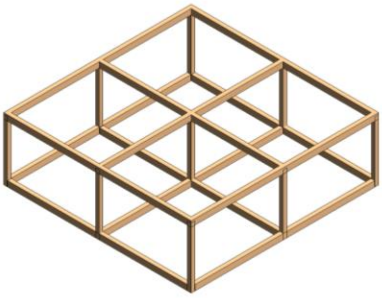

Figure 8 Glulam skeleton

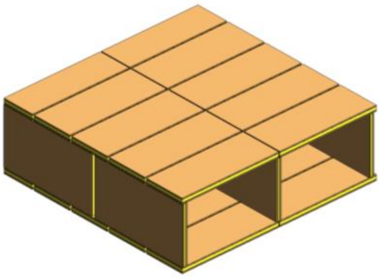

Figure 9 Kerto or SIP floors and walls

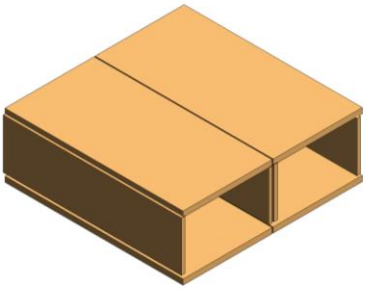

Figure 10 CLT modules

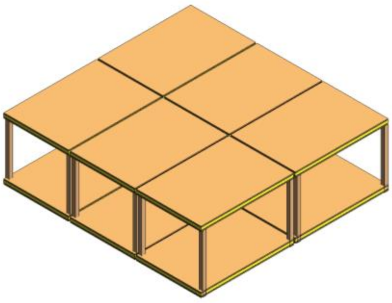

Figure 11 LVL modules

Appendix 6: The result of the LCC calculations is illustrated in the charts bellow. The charts are planned to cluster the comparable types.

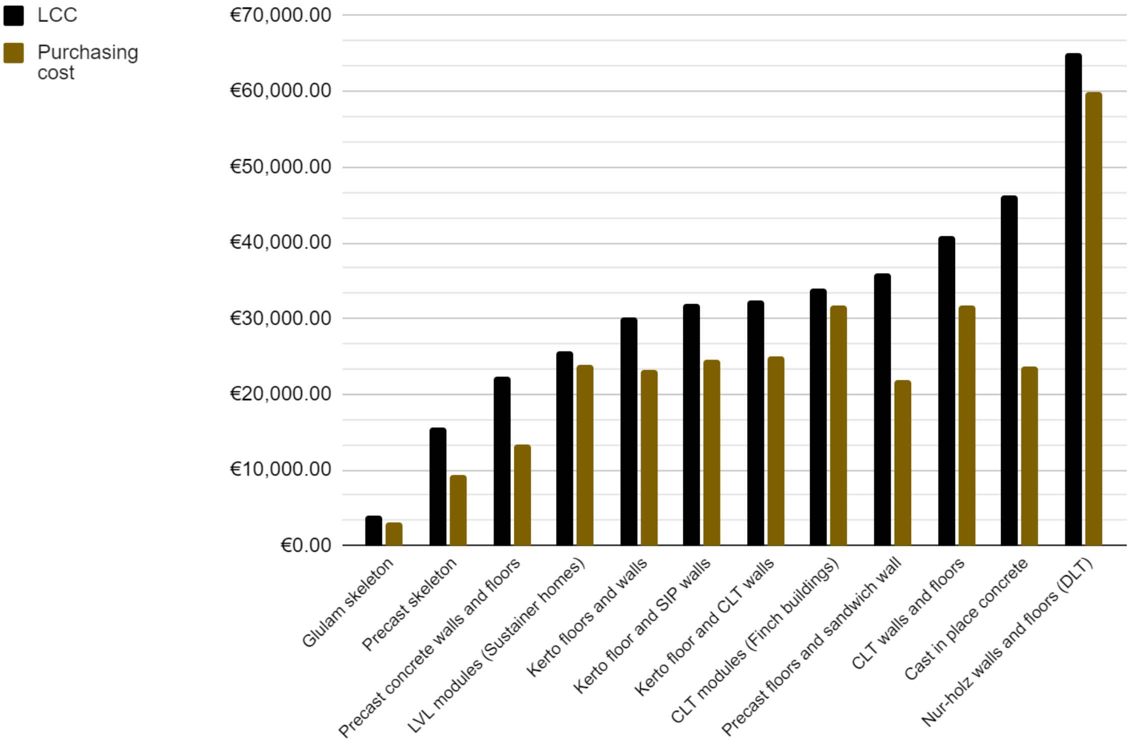

Figure 12 Comparing the prices of different structures

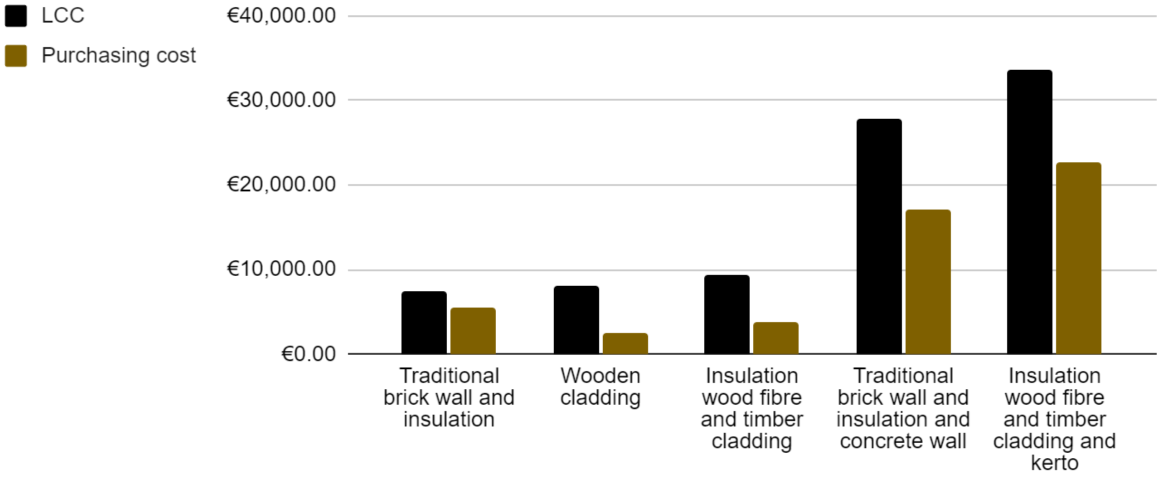

Figure 13 Comparing the prices of different skins

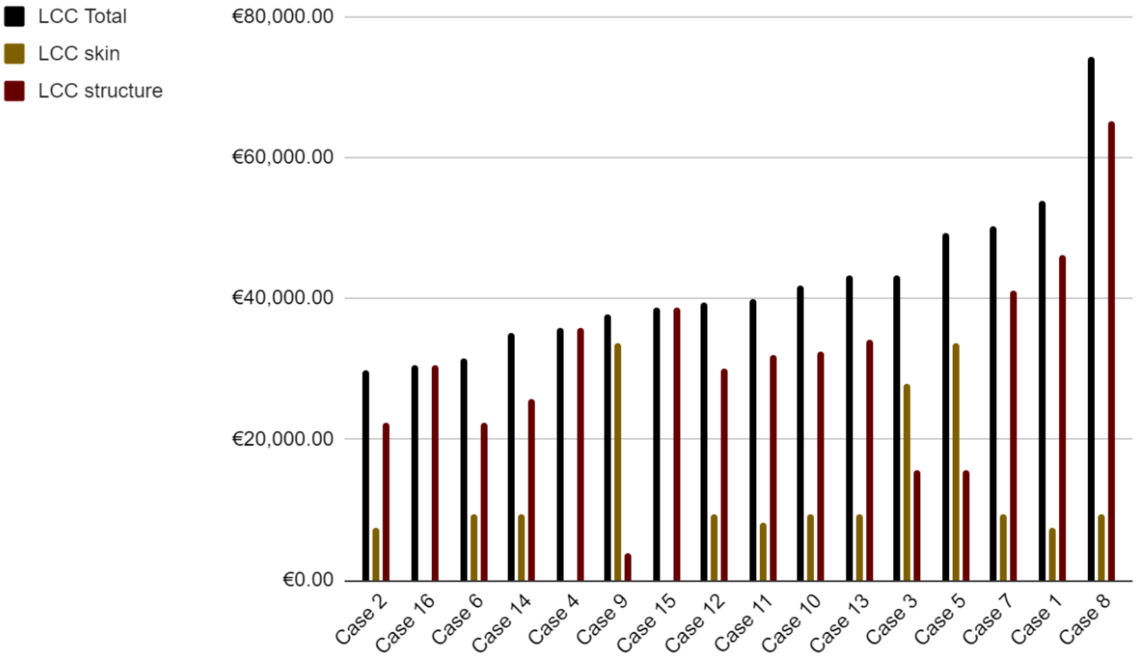

Figure 14 Comparing the LCC of all the cases

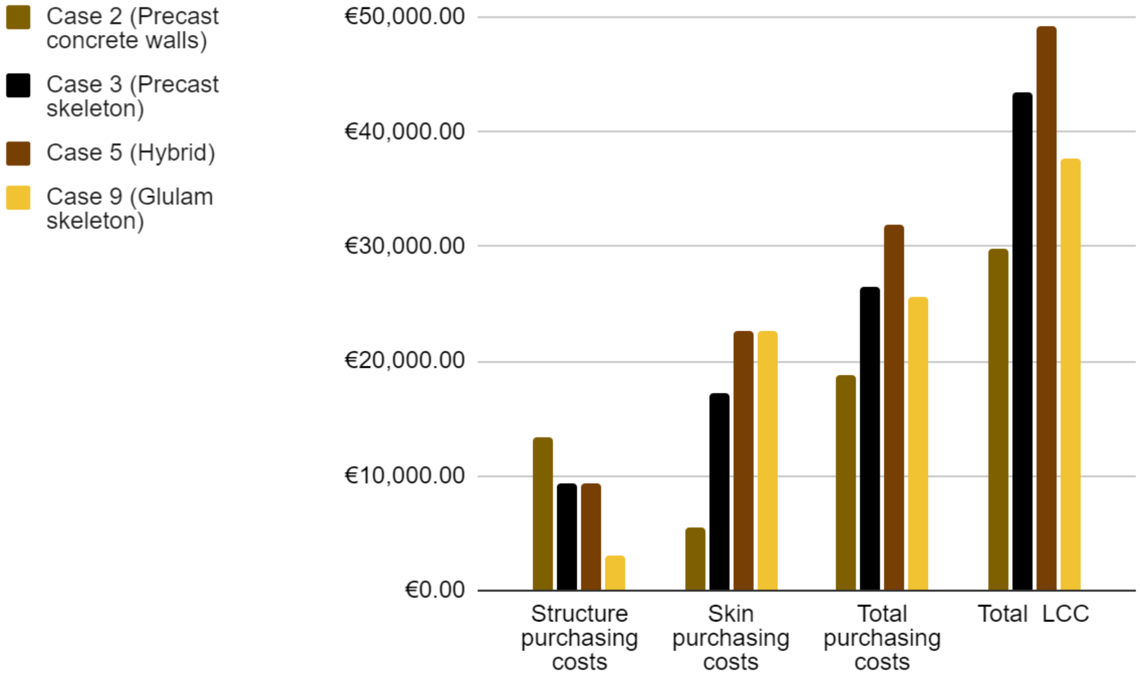

Figure 15 Comparing the skeleton constructions

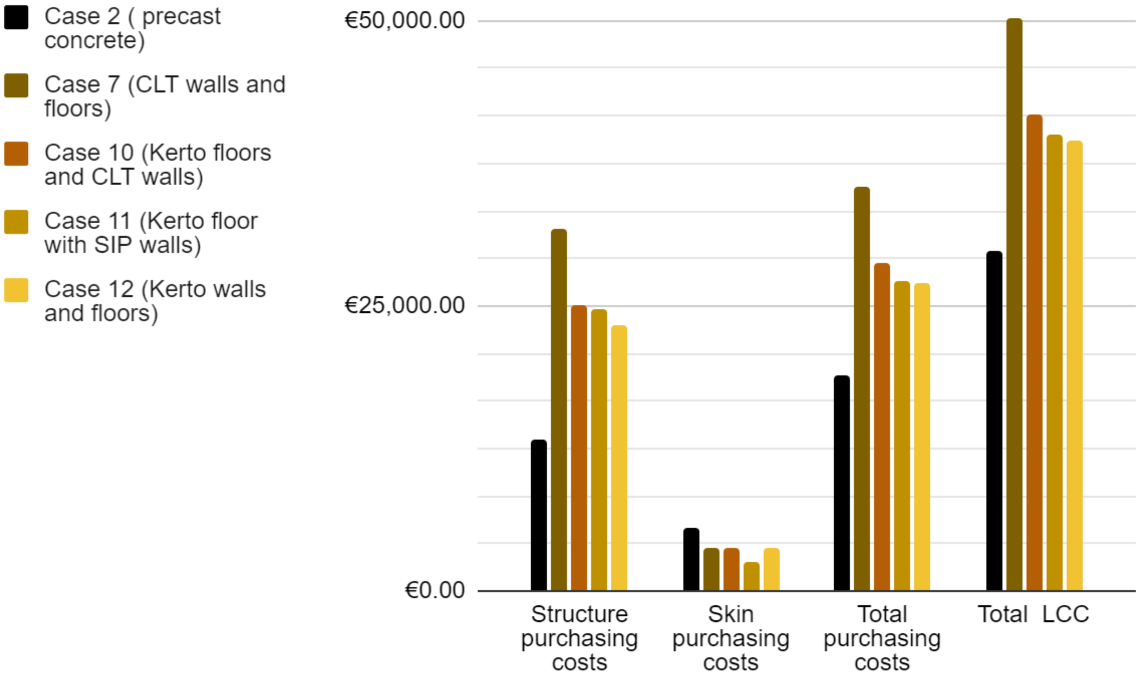

Figure 16 Comparing the wall and floor construction systems

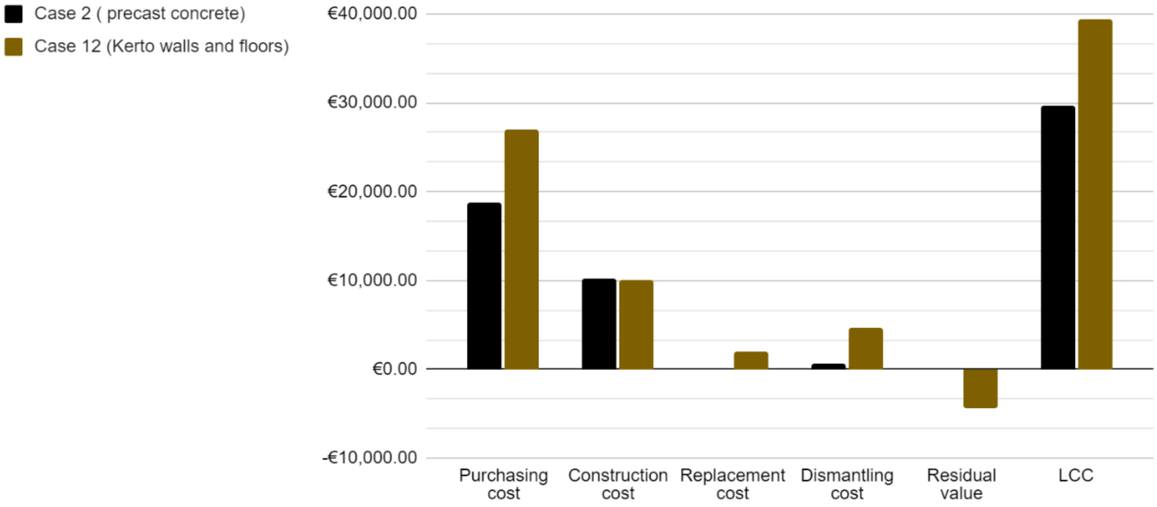

Figure 17 Comparing the details of LCC for Kerto and precast concrete

The LVL was chosen for this comparison since it was cheaper than CLT products:

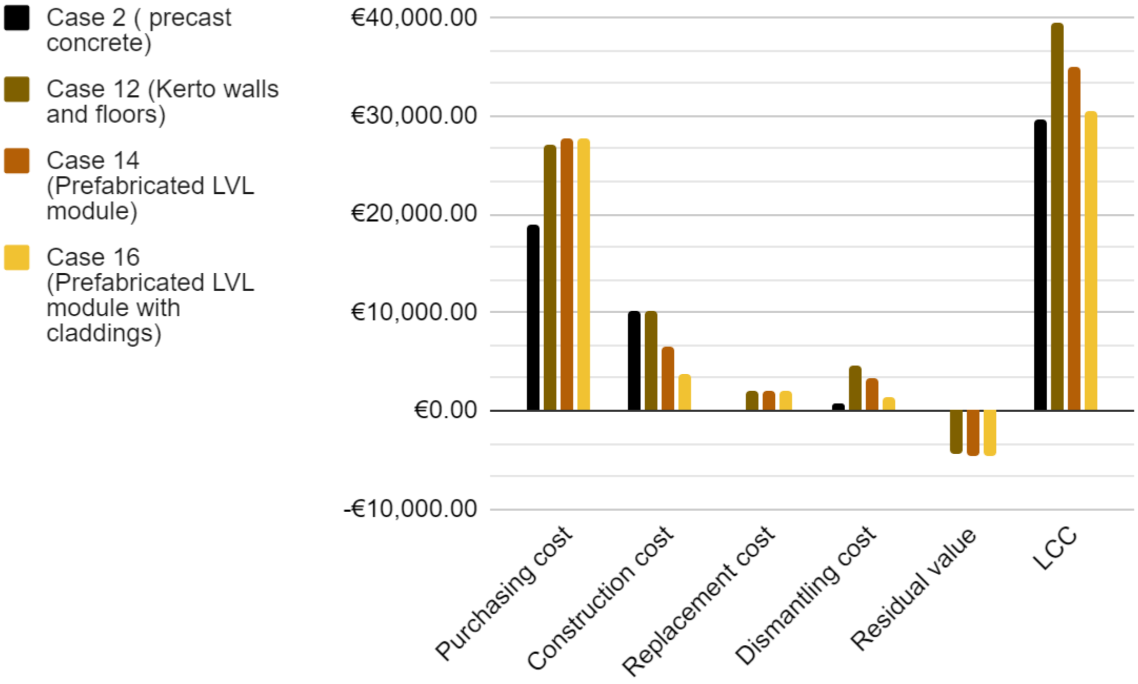

Figure 18 Comparing the LVL systems, Kerto and Precast concrete

Appendix 7:

Table 6 Calculating purchasing costs

Case 1: concrete					
Structure: Cast in situ	Info	Quantity	Per unit	Rate (Euro)	Amount (Euro)
Cast in situation concrete wall	0.2x2.5xL	34.1	Lm	206.99	7058.359
Cast in situation concrete floor	0.2x2.5xL	80	Lm	206.99	16559.2
Structure					23617.559
Skin: Brick full					
insulation rockwool	R=4.55	56	m2	17	952
brick wall		56	m2	81.5	4564
Skin					5516
Total initial cost					29133.559

Case 2: concrete					
Structure: Precast walls	Info	Quantity	Per unit	Rate (Euro)	Amount
Precast concrete wall	Thickness= 0.15 m	82.32	m2	55	4527.6
Precast hollow core concrete floor	Thickness= 0.2 m	200	m2	44	8800
Structure					13327.6
Skin: Brick full					
insulation rockwool	R=4.55	56	m2	17	952
brick wall		56	m2	81.5	4564
Skin					5516
Total initial cost					18843.6

Case 3: concrete					
Structure: Precast skeleton	Info	Quantity	Per unit	Rate (Euro)	Amount
Precast concrete beam	0.3x0.2x3 m	10	Piece	526.79	5267.9
Precast concrete column	0.2x0.2x3 m	9	Piece	445.74	4011.66
Structure					9279.56
Skin: non-load bearing concrete and brick					
Precast hollow core concrete floor	Thickness= 0.2 m	200	m2	44	8800
Precast concrete wall	Thickness= 0.15 m	51.52	m2	55	2833.6
insulation rockwool	R=4.55	56	m2	17	952
brick wall		56	m2	81.5	4564
Skin					17149.6
Total initial cost					26429.16

Case 4: Concrete					
Structure: Precast skeleton	Info	Quantity	Per unit	Rate (Euro)	Amount
Precast hollow core concrete floor	Thickness= 0.2 m	200	m2	44	8800
Precast concrete wall	Thickness= 0.15 m	27.44	m2	55	1509.2
Precast sandwich panel with brick slips	Thickness= 0.27 m	54.88	m2	211.29	11595.5952
Structure					21904.7952
Skin					0
Total initial cost					21904.7952

Case 5: Hybrid					
Structure: Precast skeleton	Info	Quantity	Per unit	Rate (Euro)	Amount
Precast concrete beam	0.3x0.2x3 m	10	Piece	526.79	5267.9
Precast concrete column	0.2x0.2x3 m	9	Piece	445.74	4011.66
Structure					9279.56
Skin: Kerto and wood cladding					
Kerto ripa floor and walls	Thickness= 0.2 m	251.52	m2	75	18864
Insulation wood fibre	R=4.5	56	m2	21.33	1194.48
Spruce wooden cladding		56	m2	45	2520
Skin					22578.48
Total initial cost					31858.04

Case 6: Hybrid					
Structure: Precast skeleton	Info	Quantity	Per unit	Rate (Euro)	Amount
Precast concrete wall	Thickness= 0.15 m	82.32	m2	55	4527.6
Precast hollow core concrete floor	Thickness= 0.2 m	200	m2	44	8800
Structure					13327.6
Skin: Insulation and wood cladding					
Insulation wood fibre	R=4.5	56	m2	21.33	1194.48
Spruce wooden cladding		56	m2	45	2520
Skin					3714.48
Total initial cost					17042.08

Case 7: Biobased					
Structure: CLT walls and floors	Info	Quantity	Per unit	Rate (Euro)	Amount
CLT floors	Thickness= 0.2 m	200	m2	105	21000
CLT walls	Thickness=0.15 m	82.32	m2	95	7820.4
Fasteners for structure	10% of the cost				2882.04
Structure					31702.44
Skin: Insulation and wood cladding					
Insulation wood fibre	R=4.5	56	m2	21.33	1194.48
Spruce wooden cladding		56	m2	45	2520
Skin					3714.48
Total initial cost					35416.92

Case 8: Biobased					
Structure: DLT walls and floors	Info	Quantity	Per unit	Rate (Euro)	Amount
Nur-holz Floor (DLT)	Thickness= 0.2 m	40	m3	1000	40000
Nur-holz Wall (DLT)	Thickness=0.15 m	16.464	m3	1000	16464
Fasteners for structure	Same as CLT				3403.4
Structure					59867.4
Skin: Insulation and wood cladding					
Insulation wood fibre	R=4.5	56	m2	21.33	1194.48
Spruce wooden cladding		56	m2	45	2520
Skin					3714.48
Total initial cost					63581.88

Case 9: Biobased					
Structure: glulam skeleton	Info	Quantity	Per unit	Rate (Euro)	Amount
Glulam beam	0.2x0.3	3.6	m3	600	2160
Glulam column	0.2x0.2	1.008	m3	600	604.8
Fasteners for structure	10% of the cost				276.48
Structure					3041.28
Skin: Kerto and wood cladding					
kerto ripa floor and walls	Thickness= 0.2 m	251.52	m2	75	18864
Insulation wood fibre	R=4.5	56	m2	21.33	1194.48
Spruce wooden cladding		56	m2	45	2520
Skin					22578.48
Total initial cost					25619.76

Case 10: Biobased					
Structure: CLT walls and kerto floors	Info	Quantity	Per unit	Rate (Euro)	Amount
CLT walls	Thickness=0.15 m	82.32	m2	95	7820.4
kerto ripa floors	Thickness= 0.2 m	200	m2	75	15000
Fasteners for structure	10% of the cost				2282.04
Structure					25102.44
Skin: Insulation and wood cladding					
Insulation wood fibre	R=4.5	56	m2	21.33	1194.48
Spruce wooden cladding		56	m2	45	2520
Skin					3714.48
Total initial cost					28816.92

Case 11: Biobased					
Structure: SIP walls and kerto floors	Info	Quantity	Per unit	Rate (Euro)	Amount
SIP walls	Thickness=0.2 m	82.32	m2	90	7408.8
kerto ripa floors	Thickness= 0.2 m	200	m2	75	15000
Fasteners for structure	10% of the cost				2240.88
Structure					24649.68
Skin: Only wood cladding					
Spruce wooden cladding		56	m2	45	2520
Skin					2520
Total initial cost					27169.68

Case 12: Biobased					
Structure: Timber frame and kerto floors	Info	Quantity	Per unit	Rate (Euro)	Amount
kerto ripa floor and walls	Thickness= 0.2 m	282.32	m2	75	21174
Fasteners for structure	10% of the cost				2117.4
Structure					23291.4
Skin: Insulation and wood cladding					
Insulation wood fibre	R=4.5	56	m2	21.33	1194.48
Spruce wooden cladding		56	m2	45	2520
Skin					3714.48
Total initial cost					27005.88

Case 13: CLT module (Finch buildings)					
Structure: CLT module	Info	Quantity	Per unit	Rate (Euro)	Amount
CLT wall	Thickness= 0.15 m	82.32	m2	95	7820.4
CLT Floors	Thickness=0.2 m	200	m2	105	21000
Fasteners	10% of the cost				2882.04
CLT module	4.5 x 2.93 x 9.80				
Structure					31702.44
Skin: Insulation and wood cladding					
Insulation wood fibre	R=4.5	56	m2	21.33	1194.48
Spruce wooden cladding		56	m2	45	2520
Skin					3714.48
Total initial cost					35416.92

Case 14: LVL module (sustainer homes)					
Structure: LVL module	Info	Quantity	Per unit	Rate (Euro)	Amount
LVL module	3.5 x 5 x 3.35	6	module	4000	24000
Skin: Insulation and wood cladding					
Insulation wood fibre	R=4.5	56	m2	21.33	1194.48
Spruce wooden cladding		56	m2	45	2520
Total initial cost					27714.48

Case 15: CLT module (Finch buildings) Cladded					
Structure: LVL module	Info	Quantity	Per unit	Rate (Euro)	Amount
Total initial cost					35416.92

Case 16: LVL module (Sustainer homes) Cladded					
Structure: LVL module	Info	Quantity	Per unit	Rate (Euro)	Amount
Total initial cost					27714.48

Appendix 8:

Table 7 LCC calculations

Layer	Type	Initial cost	Construction cost	Lifespan	Replacement cost	Dismantling cost	Residual value	LCC (Euro)
Structure	Cast in place concrete	23617.559	21255.8031	50-100	-	1392.954927		46266.31703
Skin	Rockwool insulation	952		70	-			952
Skin	Traditional brick wall	4564	1828.465116	100	-	119.8246653		6512.289782
current	CASE 1							53730.60681
Structure	Precast concrete walls and floors	13327.6	8396.388	50-100	-	550.2398559		22274.22786
Skin	Rockwool insulation	952	-	70	-	-		952
Skin	Traditional brick wall	4564	1828.465116	100	-	119.8246653		6512.289782
current	CASE 2							29738.51764
Structure	Precast skeleton	9279.56	5846.1228	50-100	-	383.1135206		15508.79632
Skin	non-load bearing concrete	11633.6	7329.168	50-100	-	480.3018088		19443.06981
Skin	Rockwool insulation	952		70	-			952
Skin	Traditional brick wall	4564	1828.465116	100	-	119.8246653		7464.429782
current	CASE 3							43368.29591
Structure	Precast concrete	10309.2	6494.796	50-100	-	425.622972		17229.61897
Skin/Structure	Precast sandwich wall	11595.5952	1521.2736	50	5327.253566	199.3870141		18643.50938
current	CASE 4							35873.12835
Structure	Precast skeleton	9279.56	5846.1228	50-100	-	383.1135206		15508.79632
Skin	Kerto walls	18864	5942.16	60 - more	-	2336.442715	2756.150708	24386.45201
Skin	Insulation wood fibre	1194.48	-	70	-	-		1194.48
Skin	Wooden cladding (Spruce)	2520	2774.8	35	2030.46743	1818.407572	1014.350028	8129.324975
Hybrid	CASE 5							49219.0533

Layer	Type	Initial cost	Construction cost	Lifespan	Replacement cost	Dismantling cost	Residual value	LCC (Euro)
Structure	Precast concrete walls and floors	13327.6	8396.388	50-100	-	550.2398559		22274.22786
Skin	Insulation wood fibre	1194.48		70	-			1194.48
Skin	Wooden cladding (Spruce)	2520	2774.8	35	2030.46743	1818.407572	1014.350028	8129.324975
Hybrid	CASE 6							31598.03283
Structure	CLT walls and floors	31702.44	9986.2686	60 - more	-	3926.576281	4631.928671	40983.35621
Skin	Insulation wood fibre	1194.48		70	-			1194.48
Skin	Wooden cladding (Spruce)	2520	2774.8	35	2030.46743	1818.407572	1014.350028	8129.324975
Biobased	CASE 7							50307.16119
Structure	Nur-holz Floor (DLT) walls and floors	59867.4	9986.2686	60 - more	-	3926.576281	8747.008952	65033.23593
Skin	Insulation wood fibre	1194.48		70	-			1194.48
Skin	Wooden cladding (Spruce)	2520	2774.8	35	2030.46743	1818.407572	1014.350028	8129.324975
Biobased	CASE 8							74357.0409
Structure	Glulam skeleton	3041.28	958.0032	60 - more	-	376.6845048	444.3504042	3931.617301
Skin	Kerto walls and floors	18864	5942.16	60 - more	-	2336.442715	2756.150708	24386.45201
Skin	Insulation wood fibre	1194.48		70	-			1194.48
Skin	Wooden cladding (Spruce)	2520	2774.8	35	2030.46743	1818.407572	1014.350028	8129.324975
Biobased	CASE 9							37641.87428
Structure	Kerto floor and CLT walls	25102.44	7907.2686	60 - more	-	3109.118589	3667.626578	32451.20061
Skin	Insulation wood fibre	1194.48		70	-			1194.48
Skin	Wooden cladding (Spruce)	2520	2774.8	35	2030.46743	1818.407572	1014.350028	8129.324975
Biobased	CASE 10							41775.00559

Layer	Type	Initial cost	Construction cost	Lifespan	Replacement cost	Dismantling cost	Residual value	LCC (Euro)
Structure	Kerto floor and SIP walls	24649.68	7764.6492	60 - more	-	3053.040991	3601.475455	31865.89474
Skin	Wooden cladding (Spruce)	2520	2774.8	35	2030.46743	1818.407572	1014.350028	8129.324975
Biobased	CASE 11							39995.21971
Structure	Kerto floors and walls	23291.4	7336.791	60 - more	-	2884.808198	3403.022084	30109.97711
Skin	Insulation wood fibre	1194.48		70	-			1194.48
Skin	Wooden cladding (Spruce)	2520	2774.8	35	2030.46743	1818.407572	1014.350028	8129.324975
Biobased	CASE 12							39433.78209
Structure	CLT modules (finch buildings)	31702.44	4993.1343	60 - more	-	1963.288141	4631.928671	34026.93377
Skin	Insulation wood fibre	1194.48		70	-			1194.48
Skin	Wooden cladding (Spruce)	2520	2774.8	35	2030.46743	1818.407572	1014.350028	8129.324975
Biobased	CASE 13							43350.73874
Structure	LVL modules (Sustainer homes)	24000	3780	60 - more	-	1486.286714	3506.553063	25759.73365
Skin	Insulation wood fibre	1194.48		70	-			1194.48
Skin	Wooden cladding (Spruce)	2520	2774.8	35	2030.46743	1818.407572	1014.350028	8129.324975
Biobased	CASE 14							35083.53863
Structure with skin	CLT modules (finch buildings)	35416.92	4993.1343	60 - more	2030.46743	1963.288141	5646.278698	38757.53117
Biobased	CASE 15							38757.53117
Structure with skin	LVL modules (Sustainer homes)	27714.48	3780	60 - more	2030.46743	1486.286714	4520.903091	30490.33105
Biobased	CASE 16							30490.33105