A multi-criteria analysis for secondary wood in circular construction: a new entrance building on fortress island Pampus as a case study

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Abstract

The construction sector has a large impact on the environment by greenhouse gas emissions and material extraction leading to air, water and soil pollution. To limit the negative effects on the environment, a change from linear to circular construction practises by reducing, reusing and recycling of materials is required. In this study, a multi-criteria analysis (MCA) was conducted to determine the feasibility of using secondary wood in a case study of a new entrance building on fortress island Pampus. Several scenarios for using secondary wood were tested, i.e. reuse, remanufacturing (walls and ceiling) and repurposing (furniture) to determine the most feasible option from a sustainability, circularity and technical viewpoint. Within the MCA, an LCA was conducted to calculate the environmental impact of secondary wood versus new wood. Expert interviews with wood-processing factories and wood experts as well as literature were used to score secondary and new wood on a set of sustainability, circularity and technical criteria. This study showed that secondary wood reduced environmental impact in most scenarios. In addition, the quality of secondary wood should be similar to new wood. However, high costs and practical issues limited the use of secondary wood for the structure layer whereas these limitations were less prominent for furniture. Therefore, better logistics and circular business models are needed to overcome practical problems and high costs to implement the use of secondary wood in construction.

Foreword

I wrote this thesis as final part of the Environment and Resource master at the Vrije Universiteit in Amsterdam. This research project focused on the construction sector, which has a large negative impact on the environment by material depletion and greenhouse gas emissions. The transition to circular and sustainable practices is an enormous challenge and the Netherlands has developed a transition policy to achieve circular construction by 2050. To contribute to this goal, I studied the possibility to use secondary construction materials to improve circular construction. For this, I used an interesting case study, the fortress island Pampus, that has the ambition to become a sustainable island and envisions the construction of a fully circular new entrance building. I have studied the feasibility to use wood of the current building for construction of this new building using a multi-criteria analysis where I analysed circular, sustainable and technical criteria that are important in construction with wood. I expect this study provides insights for Pampus and the (scientific) community to use secondary wood in construction as well as develop policies and business models to tackle the current barriers in secondary wood application.

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1. Introduction

1.1 Problem statement

Human-induced greenhouse gas emissions (GHG) have increased largely in the last decades, contributing to global warming and climate change. Economic and population growth are the main drivers for GHG emissions, resource depletion and biodiversity loss[2]. In fact, while global population quadrupled in the 20th century, material and energy use grew even faster[3].

The construction industry has a large impact on the environment, and is responsible for 39% of global greenhouse gas (GHG) emissions, mainly due to production and supply of materials, as well as operation of buildings[4]. In addition, the construction industry consumes almost 50% of the total material footprint and extraction of materials also leads to air, water and soil pollution[4]. In the Netherlands, the construction industry is responsible for 50% of national material use, 40% of energy use and 30% of water use [5]. Thus, more efficient use and reuse of materials are needed to limit negative consequences on the environment[6]. This can be achieved by the adoption of a circular economy to reduce, reuse and recycle materials and thereby limit the effect of the construction industry on the environment. However, such practices are far from fully implemented[7].

In this study, the Dutch fortress island Pampus was used as a case study to investigate the construction of a new circular entrance building. The focus was on the reuse possibilities of the current building on the island into the new building to enhance circularity.

1.2 Case study area

Pampus is a man-made fortress island near the city of Amsterdam, build on the sand bank "Pampus" between 1887 and 1895 (Figure 1). Pampus was built as part of a ring of 47 military fortifications, the Stelling van Amsterdam (Defence line of Amsterdam, Figure 2) to protect the city and its area against military operations. Pampus was built in the Zuiderzee (currently the IJmeer) to protect from attacks from the water. The fortress was closed in 1933, and deteriorated over the years. Towards the end of the 1980's and in the 1990's, Pampus was renovated and became a tourist attraction, with about 53,000 visitors in 2018. Currently, all of the Stelling van Amsterdam is an UNESCO World Heritage Site[1,8,9].

During its operations as military fortress, Pampus has always been a self-sufficient island and could support soldiers with food, energy and water with no to limited support from the mainland. Currently, Pampus relies on the main land for clean drinking water and food. The island is not connected to the energy grid, but has installed diesel generators for its energy. Now, Pampus has the vision to be the first Dutch UNESCO World Heritage Site to be become fully self-sufficient, in line with its history, as well as fully sustainable. Pampus envisions a future with on-site renewable energy generation, self-sufficient food production and water purification. Another aspect of the transformation is the realisation of a new, circular and energy neutral (or positive) entrance building[1,9]. For this, the current entrance building will be deconstructed. To remain in line with history and to reduce environmental impact, Pampus has the goal to use materials mainly from the area within the Stelling van Amsterdam (Figure 2).

Figure 1: Pampus fortress (left) and overview of island (right). Pictures derived from Pampus Factsheet[1].

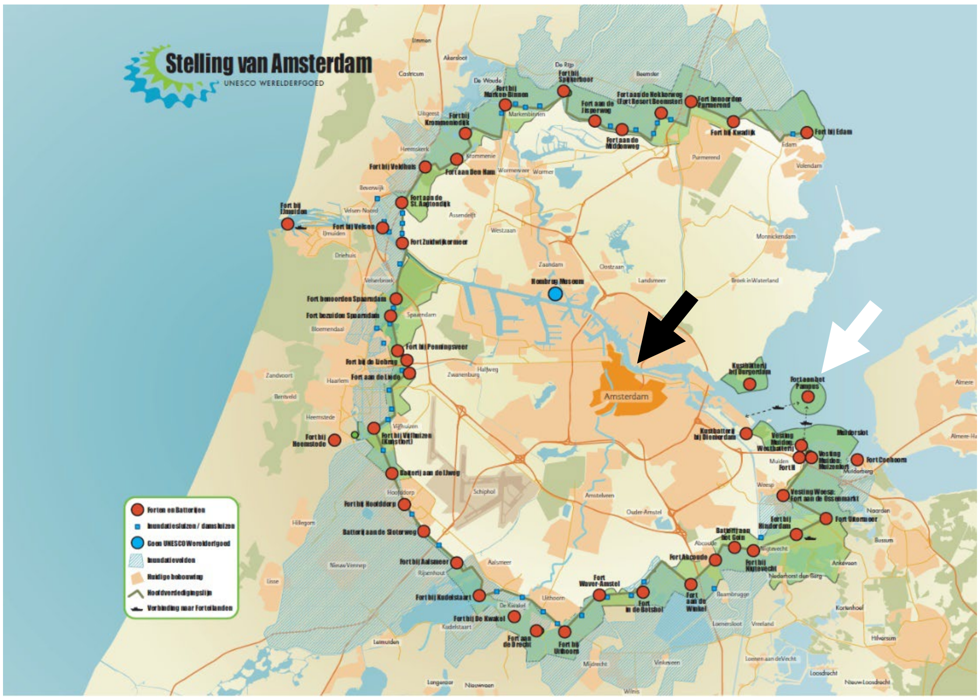


Figure 2: Stelling van Amsterdam. A ring of military fortifications in the area around Amsterdam, the Netherlands (black arrow). Pampus is indicated with white arrow. Map from[10].

2. Theoretical background

2.1 Circular economy and circular construction

The Ellen MacArthur Foundation (EMF) that develops and promotes a transition to a circular economy (CE), defines CE as a non-linear economic model that is restorative by intention, where energy is from renewable sources, toxic chemicals are minimized and eliminated and where waste does not exist. Instead, biological components can re-enter the biosphere safely, while technical components are designed to be reused at the highest possible quality and circulate without entering the biosphere[6]. Design for long life time, maintenance, repair, reuse and recycling are important aspects to reduce virgin material use and waste creation and instead achieve a circular economy[11]. Clearly, a circular system will reduce the impact of human activities on the environment[6]. Despite these advantages, in 2005, the degree of circularity worldwide was low, as only 6% of materials processed were from recycled origin[12]. Specific for the construction industry, in the Netherlands, 95% of construction waste is recycled as road base material and filler material to raise the level of new buildings[13], however, this process leads to lower value of materials and only 3-4% of materials for new buildings are secondary material[14]. To promote circularity, the EU adopted the circular economy action plan in 2015, updated in 2020[15]. In this plan, the EU presents a policy framework to "make sustainable products, services and business models the norm", to reduce waste and establish an internal market for secondary raw materials[15]. In addition, the Netherlands has the goal to have a circular economy by 2050[16], and, more specifically, adopted a policy to transition to circular construction[5]. Together, increased awareness is present to adopt circular approaches in the construction sector, however, implementation is still far from optimal[17].

2.2 Characteristics of circular construction

In the construction sector, it is crucial to take into account circularity in all life cycle stages of buildings, i.e. the project design, material manufacture, construction, operation and end-of-life[17]. Up until now, many published papers focus on only one of these, mainly reducing waste at the end-of-life of a building[17]. However, key to adoption of circular practices is to consider CE already in the design stage of a project. It is crucial to design with the 'design for disassembly and deconstruction' (DfDD) principle by using modular or prefabricated elements to be able to reuse materials easily at the end-of-life of a building[7,17,18]. In addition, careful selection of materials will contribute to circular construction, e.g. secondary and/or bio-based materials[19,20] while considering their possible applications at the end-of-life of the building to prevent waste generation. Also the source and supply chain of materials can have a large impact on the environment in case of material transportation[7]. During construction and a building's use phase, the focus is on minimizing waste generation and energy use, as well as promotion of refurbished/repaired products during maintenance of a building. Careful sorting of waste materials is important to be able to reuse these in another building or product[7]. At the end-of-life of a building, if construction was performed with a DfDD design, most parts of the building should be able to be reused in another cycle, and the remaining waste has to be sorted and screened to reuse or recycle in other applications[7,17,21]. Clearly, many actors are involved and should work together during the full life cycle of a building, e.g. constructors, suppliers, designers as well as government to work towards policies, technological innovation and new business models to promote circular construction[7]. Also research into new circular business models is increasing, e.g. pay-for-service contracts for parts of buildings to improve circular construction[22].

To reduce the environmental impact of the construction sector, biobased construction attracted increased attention in recent years, such as construction with wood. Wood is a renewable source and therefore, construction with wood from well-managed forests, e.g. FSC-certified forests, should prevent excessive logging and nature destruction. In addition, as trees store CO2, construction with wood in general avoids more CO_2 than emission during construction. In fact, construction with wood has a lower environmental impact compared to other building materials[23,24] and has been suggested as a way to mitigate climate change[25]. Although the developments towards more wood- or biobased construction are promising, the wood currently available in the built environment should not be overlooked. As current practices for secondary wood are mainly low-value purposes, such as production of fibreboard, animal bedding or energy generation by incineration, high-value use of secondary wood would maintain high economic value of materials and reduce virgin resource use[26]. Therefore, insight into the reuse possibilities of secondary wood and possible trade-offs between circularity and sustainability are important to improve high-value reuse, policy and legislation and future strategies for the construction sector.

2.3 Circular approach

Despite the clear characteristics of circular buildings/construction, the actual application of circular principles in construction are low. A useful heuristic approach to adopt circular principles is the so-called R-framework. Several R-frameworks have been described, with the most simple one being Reduce, Reuse and Repair as the 3R system to deal with materials and products. More elaborate frameworks include more R's, with the most extensive framework including 10Rs (Figure 3). This framework is a value-retention hierarchy, indicating that the top R's provide most addition to the circular economy and the bottom R's the least. In this study, this framework will be used to consider several purposes of the old building on Pampus.

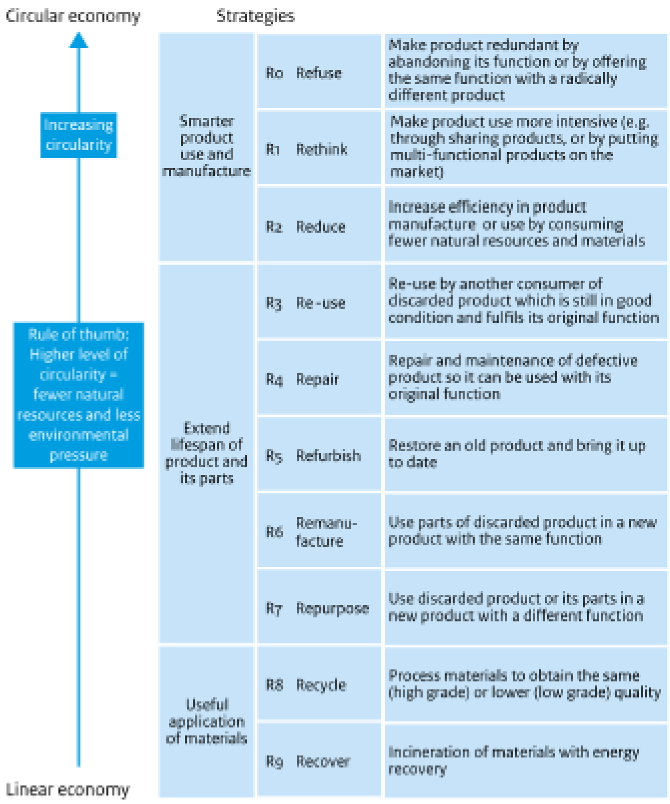


Figure 3: 10R framework[26]

2.4 Barriers and trade-offs of circular construction

Major barriers have been identified globally and in the Netherlands to reach a full circular economy, such as lack of knowledge and skills, as well as a lack of promoting regulations. More specifically for the construction industry, lack of standardized practices for reuse of materials, circular business models and uncertainty of materials supply are among the main barriers[7,14,27,28]. In addition, the use of secondary materials in construction is not wide spread yet due to possible quality and performance issues[29] as well as the availability of low-priced virgin materials[7].

Apart from these barriers, trade-offs between circularity and sustainability have been identified as well. Several studies posit CE as a condition for sustainability, where other studies find trade-offs between these two[11]. Sustainability comprises of three intertwining impact spheres, i.e. environment, economy and society and can be described as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”[30]. In the case of circularity, the energy required to recycle materials may in some cases have a higher environmental impact than extraction of virgin materials[11], thus negatively impacting sustainability. In addition, the availability of secondary materials may be too low due to storage in buildings and products[28] and high costs may be involved in changing to a circular economy, creating negative value[11,28]. Lastly, CE focuses mainly on the environmental sphere but not necessarily integrates the social aspect[11]. Taken together, although CE will likely contribute to sustainability by reducing environmental impact, there may be circumstances where this is not the case and where some aspects of sustainability may be neglected.

3. Research gap

Despite international and national policies, circular construction is not common practice yet due to several barriers as identified above. It is crucial to obtain more practical experience with circular construction, and specifically with the use of secondary materials. Therefore, in this study, Pampus was used as a case study to investigate several scenarios to use secondary wood in the construction of a new entrance building. On Pampus, the current wooden entrance building (from now on called 'old building') will be deconstructed to make space for the new building. Dutch practices are low-value recycling of wood into chipboard, or incineration for energy recovery[31] thus downgrading of the material. However, construction with wood of the old building would be a higher order use as stated within the 10R framework of circular construction (Figure 3) and also fits within Pampus' view to become a sustainable and self-sufficient island.

3.1 Research objectives and research question

In this study, a multi-criteria analysis was performed for three scenarios to use old building's wood in the new entrance building. Each scenario was scored on a set of circularity, sustainability and technical criteria to determine whether the use of secondary wood in the new building is a feasible option compared to the use of new wood. This will provide Pampus with a strategy to deal with the old building, and more general, gain experience with circular construction, and insight in the considerations and trade-offs that are involved in the use of secondary wood in the construction sector.

Buildings can be described by the so-called S-model[32] (Figure 4) where a building is divided in 6 layers that represent components/products that have similar life cycles. In this study, focus is on the Structure layer of the building (exterior walls and ceiling) as well as the Stuff layer (furniture, appliances etc). Material focus was wood, as the majority of the old building is constructed of wood.

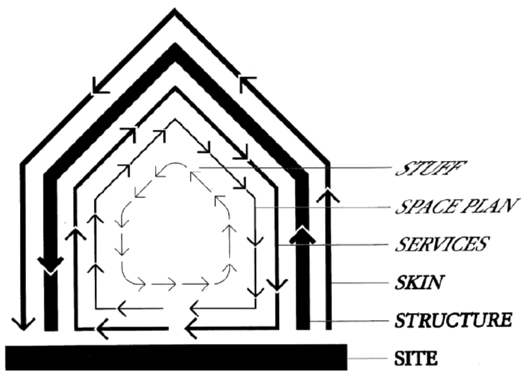


Figure 4: Six layers of a building, according to Brand[32]

3.2 Research question

The research question of this study is as follows:

What is the most feasible scenario, from a circularity, sustainability and technical viewpoint, for the use of the old wooden building in the construction of a circular new entrance building on fortress island Pampus?

3.2.1 Sub-questions

1. *What and how many materials are present in the current the old building on Pampus?*
2. *Is it feasible to use wood of the old building for the structural layer of the new building?*
3. *Is it feasible to use wood of the old building for the stuff layer of the new building?*

4. Methodology

4.1 Multi-criteria analysis

In this study, several criteria for secondary wood use were analyzed using a multi-criteria analysis (MCA). An MCA is a well-established decision support tool to compare different alternative scenarios (Figure 5). In an MCA the researcher can identify, gather, organize and analyse the most important criteria that have to be taken into account for a decision. Criteria do not need to be quantified in monetary terms, but can take different units, including qualitative outcomes[33]. MCAs have been used for construction purposes before[34–36] and as non-monetary criteria such as environmental impact or life span (see 4.1.2 Criteria in MCA) were also important in this study, an MCA was the preferred analysis tool to identify the feasibility of using the old building for construction of the new building on Pampus.

An MCA comprises of different steps, starting with scenario development. In this study, different purposes of the old building's wood were analysed, based on the 10R framework, i.e. Reuse, Remanufacturing and Refurbishing (see 4.1.1 Scenarios in the MCA). The use of new wood was taken as a business as usual scenario. Subsequently, scenarios were scored on a set of circularity, sustainability and technical criteria in the impact assessment step. After scoring, criteria were weighted to quantify the importance of the criteria relative to each other during the valuation & evaluation step. This will show whether use of the old building's wood is more beneficial than new wood. A sensitivity analysis was performed to test the robustness of the data, by varying the main assumptions. An evaluation of the preferred option will follow in the discussion section of this study.

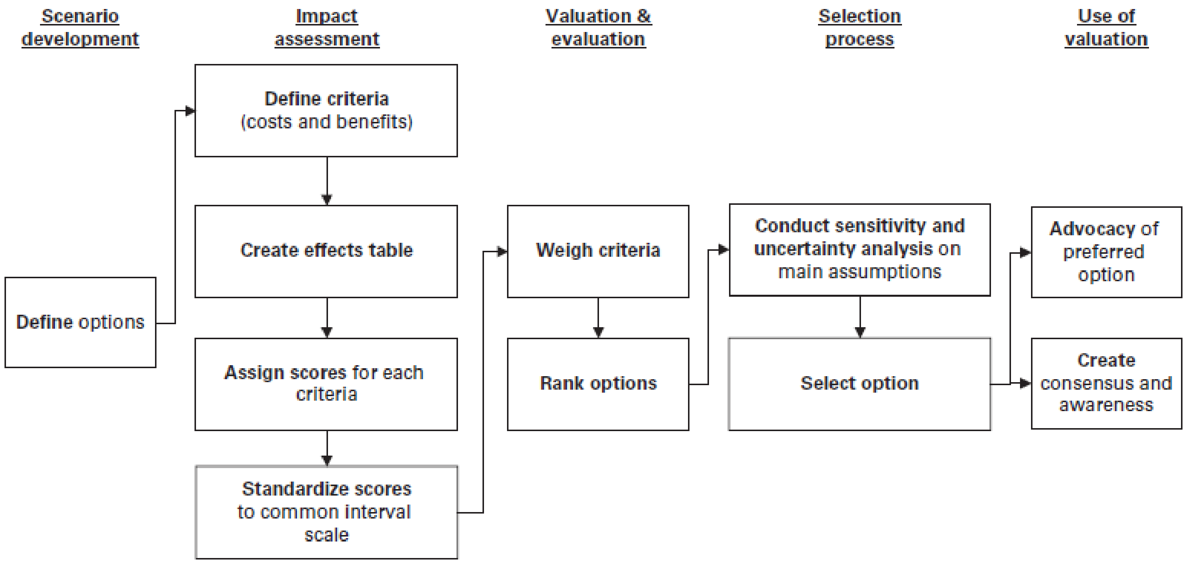


Figure 5: Multi-criteria analysis flowchart. Derived from Brander and Van Beukering, Chapter 7[33]

4.1.1 Scenarios in the MCA

Three scenarios were analysed that were based on the available wood in the old building and the requirements of the new building. The scenarios are placed within the 10R framework.

4.1.1.1 Scenario 1: Reuse of secondary wood as timber frame construction (TFC)

Based on the design of the new building, columns with horizontal beams on top will form the main constructive elements (Supplementary figure 2 & Supplementary figure 3). Walls will be placed between the columns, and to provide strength to the walls, these have to be fixed to vertical wooden beams, thus creating a timber frame construction (TFC). In TFC, vertical beams are placed at 60cm distance apart (Figure 6). Conventionally, beams are layered with thin wooden boards, such as oriented strand boards (OSB), and filled with isolation material in between boards (Figure 7, right). However, in this study, reuse of the old building's interior walls and ceiling were modelled as walls, with the foundation and roof beams as vertical beams. Possible isolation material was not included in this study.

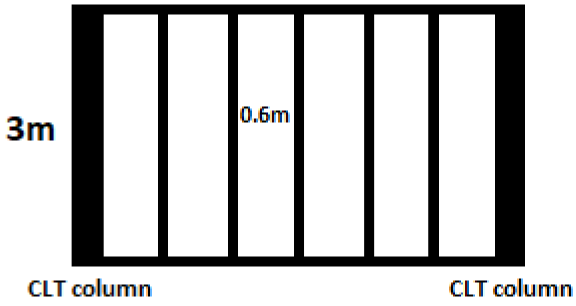


Figure 6: Schematic Timber frame construction (not at scale)

4.1.1.2 Scenario 2: Remanufacturing of secondary wood as cross-laminated timber (CLT)

CLT is made from several layers of wood in alternating directions glued together (Figure 7, left). CLT can be prefabricated, and easily assembled at the construction site and is increasingly used as a biobased option for construction[37]. Using secondary wood for CLT production will be studied in comparison to new CLT. In this study, use of the old building's wood as ceiling in the new building is classified as remanufacturing based the 10R framework (Figure 3) as parts of the ceiling of the old building will be used in the same function in the new building but need remanufacturing.

Figure 7: Left: Cross-laminated timber (CLT) panels (link). Right: Timber frame construction (link)

4.1.1.3 Scenario 3: Refurbishing of secondary wood into furniture

Instead of using the old building's wood for the structure layer of the new building in a timber frame or as CLT, a third option analysed in this study was repurposing the exterior walls of the old building into furniture (both tables and chairs).

4.1.2 Criteria in MCA

Literature review[7,35,38–40] and discussions within the Pampus team formed the basis of this set of criteria (Table 1). Circularity criteria were based on the different life cycle phases of a building[7] whereas sustainability criteria took into account the three spheres of sustainability (environmental, economic and social spheres). Scoring of all criteria was based on experts interviews and literature review (see 4.1.3.3 Expert interviews and 4.1.3.4 Literature review).

Table 1: Criteria in the MCA

Sustainability aspect	Criteria	Indicator	Construction phase
Environment	Reuse possibility	Modular / prefabricated design	Design and end-of-life deconstruction
	Environmental impact	LCA outputs	Material selection
Economical	Financial feasibility	Costs	
Social	Job creation	Social job creation	
	Cultural benefits	Use of local materials	
Technical	Durability	Life span (technical)	
	Practical feasibility	Ease of construction	Building construction and service life
		Safety	
		Maintenance	

<u>Modular/prefabricated design</u>

Important in circular construction is the possibility to reuse or repurpose a product or its materials at the end-of-life. Modular construction will ease the process of taking apart different components of a building. In addition, prefabricated design minimizes material loss, transport load (less emissions and air pollution) as well as waste and noise at the construction site[7].

<u>Environmental impact</u>

Life cycle assessment (LCA) is a common method to calculate environmental impact of a product or process. This can be expressed as global warming potential (GWP) indicating the kg CO2 equivalent (CO2eq) emissions. The GWP of the different scenarios will be calculated resulting in % reductions of secondary wood versus new (9.1 Appendix A).

<u>Costs</u>

The criterium costs is defined as the costs of producing the product (TFC, CLT or furniture) from purchasing to final delivery at the construction site. The costs were not calculated exactly, as the Pampus project was still in an early stage and costs will depend on purchasing/production companies. Therefore, costs of new and secondary wood were scored relative to each other.

<u>Job creation</u>

The social sphere of sustainability was included in this study as the extent to which the scenarios could create non-commercial jobs, e.g. for people with disabilities, a working place for people with poor job opportunities or volunteer jobs.

<u>Local materials</u>

Lower transport distances will contribute to emission reductions. In addition, materials from within the Stelling van Amsterdam will be in line with Pampus' history of self-sufficiency.

<u>Life span</u>

Life span is the expected technical duration of the product (TFC, CLT or furniture).

Ease of construction

In this criterium, the practical easiness of producing the product (TFC, CLT or furniture) was evaluated. This may depend on e.g. the availability of factories and labour time (e.g. to remove nails and dirt from secondary wood).

Maintenance

Ease of product maintenance during its life time was scored for new and secondary wood.

Safety

Safety is a quality criterium for stability of the building/furniture and included as a technical criterium.

4.1.3 Methods and data collection

Within the different steps of the MCA, several methods were used for data collection.

4.1.3.1 Material inventory old building

A material inventory was performed to assess the available secondary materials from the old building. For this, counting and measuring of the constructive elements was performed (such as walls, ceiling).

4.1.3.2 Life cycle assessment

Life cycle assessment (LCA) is a tool to assess the environmental impact of a product/service along the full life cycle, from resource extraction to end-of-life, including reuse/recycle processes (Table 1). LCA has been standardized by the International Standardization Organisation in ISO 14040 & 14044[41,42]. LCA is increasingly applied in circular construction to assess the circularity of a building and decide on the largest environmental impact reduction scenario[43–45]. An LCA consists of several steps as explained below with regard to the current study.

Goal and functional unit

The goal of the LCA in this study is to compare the environmental impact between new wood and secondary wood in different scenarios in construction of the new building. The functional unit of TFC and CLT are $1m^3$. For furniture, the functional unit is one piece of furniture.

Impact categories

In an LCA, data is obtained on quantities of gas emissions (such as CO2) and other substances that are emitted during a product's life cycle. These can be categorized into impact categories, such as global warming potential, ozone depletion potential, eutrophication potential and human toxicity potential[41,42]. In this study, only global warming potential (GWP) was assessed, which is the effect of all greenhouse gases (GHG) on global warming, expressed as CO2equivalent (CO2eq). GWP is commonly used for buildings[46]. In addition, other endpoints such as ozone depletion potential, human toxicity potential, generally follow the same pattern as GWP[47], indicating that GWP is a proxy for most impact categories. For primary wood extraction, however, land use is largely impacted[47], but due to lack of data, this was not included as a separate impact assessment.

System boundaries

All steps from extraction of materials until end-of-life of materials such as disposal or recycling, can be included in an LCA (Table 1, according to EN15978). In this study, the extraction (A1), transport to factory (A2) and production of materials (A3) as well as the transport (A4) of materials to the construction site were included, as the most important difference between the materials is the origin (secondary or new). The construction, maintenance, use, end-of-life and next product system phases were excluded as the impacts of these phases are expected to be the same, since all options are wood and all technical characteristics are assumed to be similar. However, as the end-of life and next product stage have a large impact on circularity principles[7], these steps will be taken into account as criteria in the MCA (criterion 'reuse possibility').

Table 2: Life cycle stages of an LCA

LCA stage	Life cycle stages	Process
A1	Production	Extraction of raw materials
A2		Transport
A3		Production
A4	Construction	Transport
A5		Construction
B1	Use	Commissioning
B2		Maintenance
B3		Renovation/repair
B4		Replacement
B5		Refurbishment
B6		Energy consumption for operation
B7		Water consumption for operation
C1	End of life	Deconstruction/demolition
C2		Transport
C3		Waste recovery
C4		Disposal
D	Next product system	Potential for reuse, recovery and recycling

Life cycle inventory: data collection

During the life cycle inventory (LCI) data on e.g. emissions are gathered. Several methods exist to express the data from the LCI into an impact assessment. Usually, LCI data is obtained from databases (an important construction database is EcoInvent), and expressed in impact assessments (LCIA) such as global warming potential (GWP). In this study, however, access to the databases was not possible due to license restrictions. Therefore, scientific literature and/or Environmental Product Declarations (EPDs) were used. EPDs provide the environmental impact of a product based on LCA calculations, in line with ISO14025. EPDs state GWP, energy and water use as well as several other impact categories for different stages of the product's life cycle.

Stages A1-A3

For A1-A3 of new wood, GWP data was obtained from the EPDs (TFC, CLT, furniture) and scientific papers (furniture) to compare with secondary wood. GWP data for TFC and CLT in scientific literature was very variable. However, for the Dutch market, the two main suppliers of CLT, Derix and De Groot Vroomshoop, provided EPD data (three EPDs in total) of their CLT products and therefore this data was used. For TFC, two EPDs were used, one general Swedish spruce wood and spruce wood from Stora Enso, a supplier of the Netherlands. Spruce wood is the main type of wood for TFC (Expert interview #5, this study). The EPDs of Swedish spruce wood reported GWP split into fossil, biogenic and land use and land use change (LULUC) CO2eq emissions, which is a new procedure according to EN15804+A2 from 2019. Fossil emissions were used in this study as these report the human-induced GHG into the atmosphere whereas biogenic CO2 storage in wood can be considered temporarily when biogenic CO2 is released upon the end of life of a tree/wooden building, thus cancelling out storage and emission[48].

For secondary wood, no emissions were counted for A1 and A2. For A3, it was assumed that a certain amount of sawing is required to be able to use it in the new building. However, data on CO2eq emissions from this procedure were not easily available and will be very factory- and machinery-specific. For TFC, an average of A3 data from EPDs was used (5.2kg CO2eq/m^3) as A3 data was relatively similar between EPDs. As A3 emissions for CLT differed between 4kg CO2eq and 122kg CO2eq/m^3 of CLT between the providers, three different emissions were modelled for secondary wood (4, 50 and 120kg CO2eq/m^3).

For furniture, EPDs for tables and chairs were limitedly available, but EPDs for chairs and tables from brands Leva (UK) and Ovo (Italy) were used[49–51]. In addition, Web of Science database was searched with search terms such as 'environmental impact', 'furniture', 'wood', 'LCA' and 'life cycle assessment' to obtain GWP data for wooden tables and chairs[52,53]. Only data from Europe were included to be most similar to this study. Most of the available data showed GWP for A1-A3 together and per piece or per kg furniture. Therefore, all suitable data for A1-A3 were first recalculated as emissions per kg furniture which showed a variation between 0.37 - 3.12 kg CO2eq / kg furniture with most data points in the lower numbers[49–53] (Supplementary figure 1). Due to the skewness of data points, the median (0.47kg CO2eq/kg) was subsequently used to multiply with the mass of a table/chair to calculate CO2eq emissions per piece of furniture (4.3kg for a chair, 10.4kg for a table).

No emissions were counted for A1 and A2 for secondary wood and for A3, it was assumed that furniture would be produced on Pampus. Then, only electricity for sawing would cause CO2eq emissions. For this, an average of the capacity of three circle saws was calculated (1133.3W) and two hours of sawing per furniture piece was assumed. Using the conversion factor for kWh grey electricity to CO2eq emissions specific for the Netherlands[54], this resulted in 1.26kg CO2eq emissions per piece of furniture.

Transport (A4)

CO2eq emissions from transport were based on Dutch research into emissions of different vehicles[55]. CO2eq emissions differed depending on the mass transported as well as the type of road traveled (Table 3). For this study, motorway averages in 2020 were used. Based on the weight that had to be transported, 787gCO2eq/km (heavy-duty lorry) or 431gCO2eq/km (medium-duty lorry) was used for new CLT and TFC transport respectively, and light-duty transport for the old building (less material and therefore less weight and emissions) with 168g CO2eq/km. It was assumed that all wood could be transported at once from the factory to Pampus (new CLT or TFC spruce wood) or from Pampus to the factory and back (secondary wood). Google Maps was used to estimate transport distances for the different suppliers. Calculation equation used was:

Total kg CO2eq = (gCO2eq/km * distance (km)) / 1000

Emissions from boat transport to and from Pampus were based on the European Chemical Transport Agency (ECTA) [56] and data in the free online OneClick LCA software (2015) (Table 3). Both emission numbers were comparable and an average was taken. These numbers did not include the mass transported and emission numbers had to be multiplied by the mass of the wood that was transported as follows:

Total kg CO2eq = (gCO2eq/km * distance (km) * ton material) / 1000

Mass of wood was calculated as follows: total m^3 * density of wood. Density of CLT was derived from the EPDs (470kg/m^3 or 491kg/m^3 for Derix and DGV). For the secondary material, 400kg/m^3 was applied, based on the density of spruce wood[57] which is the wood type of the interior of the old building.

Table 3: CO2eq emissions from road and boat transport

Road transport	gCO2eq/km	gCO2eq/t.km
Light duty vehicle	168	n.a.
Medium duty vehicle (10-20 ton)	431	n.a.
Heavy duty vehicle (> 20 ton)	787	n.a.
Boat transport		
Small bulk ship	n.a.	30.5
Inland water ways	n.a.	31
Average boat transport		30.75

gCO2eq/t.km = gram CO2eq per ton kilometer

4.1.3.3 Expert interviews

To determine the possibilities and challenges of using the wood of the old building, wood factories in the Netherlands were selected and asked for their opinion on the MCA criteria (Table 4). Interviews were semi-structured around questions about their experience with secondary wood for CLT/TFC/furniture, practical issues in using secondary wood, costs of secondary wood versus new wood, expected life span, safety and maintenance of secondary wood in comparison with new wood and possibility of modular/prefab design. Performance of secondary wood versus new wood was scored semi-quantitively for each expert using +, -, -/+, and = symbols indicating better, worse, uncertain, or similar performance of secondary versus new wood. A summary of the interviews is provided in 9.4 Appendix D.

Table 4: Expert interviews

Expert interview #	Company	Area
1	New Horizon	General construction with wood
2	EcoScala (CLT and TFC)	
3	Derix	CLT production
4	De Groot Vroomshoop	
5	Houtbouw 't Zand	TFC production
6	Anonymous*	
7	Herso	Furniture production
8	Meubelmakerij Kruizinga	
9	Fiction Factory	

* Company preferred not to be mentioned by name

4.1.3.4 Literature review

In addition to expert interviews, literature was searched with Web of Science to support expert interview data for quality criteria such as life span, maintenance and safety of secondary wood. Key words used were ‘secondary wood construction’, ‘secondary timber construction’, ‘reuse timber construction’, ‘reuse wood construction’, ‘quality secondary wood construction’. In addition, suitable references in identified articles were included as well.

4.1.4 MCA data analysis

In the MCA, the three different scenarios were scored in a range of 1 – 5 based on the data obtained in the LCA, expert interviews and literature review, and weighed based on discussions with Pampus management (9.1 Appendix A). Scoring of new wood was 3 (business-as-usual scenario), and use of secondary materials was scored relative to new wood. The higher the score, the better the scenario was from a circular, sustainable or technical viewpoint.

Within each scenario, the use of secondary wood was scored relative to new wood, as it was not possible to directly compare the scenarios for secondary wood only. This is because different quantities of wood are needed for the different scenarios (e.g. walls, or furniture) and only a limited quantity of wood is available in the old building. This means that when secondary wood is used for a certain scenario, another scenario will require new wood. Additionally, costs and CO2eq emissions for walls and ceiling (TFC and CLT scenarios) will be much higher compared to furniture due to larger wood quantities needed. Therefore, secondary wood was compared with new wood in the scenarios to find out in which scenario the largest benefits (e.g. costs or CO2eq savings) could be achieved. However, some (textual) comparison between the scenarios will be performed based on the quantities of wood available (5.3 Comparing MCAs).

5. Results

5.1 Results of data collection

5.1.1 Material inventory of the old building

The old building was constructed in a modular way from wooden panels, Red Cedar wood for exterior walls and spruce wood for interior walls and ceiling (Table 5). Spruce wooden beams were present as foundation and on the roof. Based on this inventory and the design of the new building (Supplementary figure 2 & Supplementary figure 3), the three scenarios were developed.

In scenario 1, direct reuse of interior walls and ceiling, as well as foundation and roof beams as TFC was investigated, as TFC is commonly made from spruce wood.

In scenario 2, remanufacturing of the spruce interior walls and ceiling into the new building's CLT ceiling was studied as CLT is certified to be produced with spruce and pine wood only (expert interview #3).

In scenario 3, refurbishing of the Red Cedar wood of the exterior walls was investigated for furniture manufacturing, as this type of wood can be used for outdoor and indoor purposes without wood treatment. Spruce wood, as is present as interior walls of the old building, is a commonly used wood type as well, but would need additional (chemical) treatment to be used outdoors. In addition, including spruce wood will likely result in an amount of furniture that exceeds the actual required furniture quantity, thus being an unrealistic option for Pampus. Nevertheless, follow-up research on the feasibility to use spruce wood for furniture may be performed.

Table 5: Material inventory old building

What	Material	Quantity	Size	Application in new building
Outer walls	Red Cedar wood	155m2 / 3.1m3	Boards of variable lengths; 13.5cm width. Wood panels consisted of 7 boards together	Scenario 3: Refurbishing into furniture
Interior walls	Spruce wood	280m2 / 5.6m3		Scenario 1: Reuse as TFC Scenario 2: Remanufacturing as CLT
Ceiling	Spruce wood	390 m2 / 7.8m3		
Foundation beams	Spruce wood	42 beams / 12.2m2	Beams: 14.5m x 0.1m x 0.2m	Scenario 1: Reuse as TFC
Roof beams	Spruce wood	24 beams / 12.2m2	Beams: 25.5m x 0.1m x 0.2m	

Abbreviations: CLT = cross-laminated timber; TFC = timber frame construction.

5.1.2 Life cycle assessment

In this section, the LCA results per scenario are presented.

5.1.2.1 Scenario 1: Reuse of secondary wood as TFC

As the exact amounts of TFC needed in the new building were not clear yet, in this scenario, a range of wood quantities were modelled (Supplementary table 3).

Comparing secondary wood in the old building with the same amount of new wood shows a reduction of 563 and 1035 kg CO2eq (74% and 84%) compared to new wood from Stora Enso and Swedish Spruce respectively (Figure 8A). Likely, more wood is required for the walls, and the old building's wood has to be supplemented with new wood. This showed that a reduction of 62% (632kg CO2eq) could still be achieved (Figure 8B). If all wood required can be obtained from secondary sources, 757 kg CO2eq (76%)

can be avoided (Figure 8B). Transport emissions differed depending on the supplier but was about 37-45% of total emissions for secondary wood (old building or other sources).

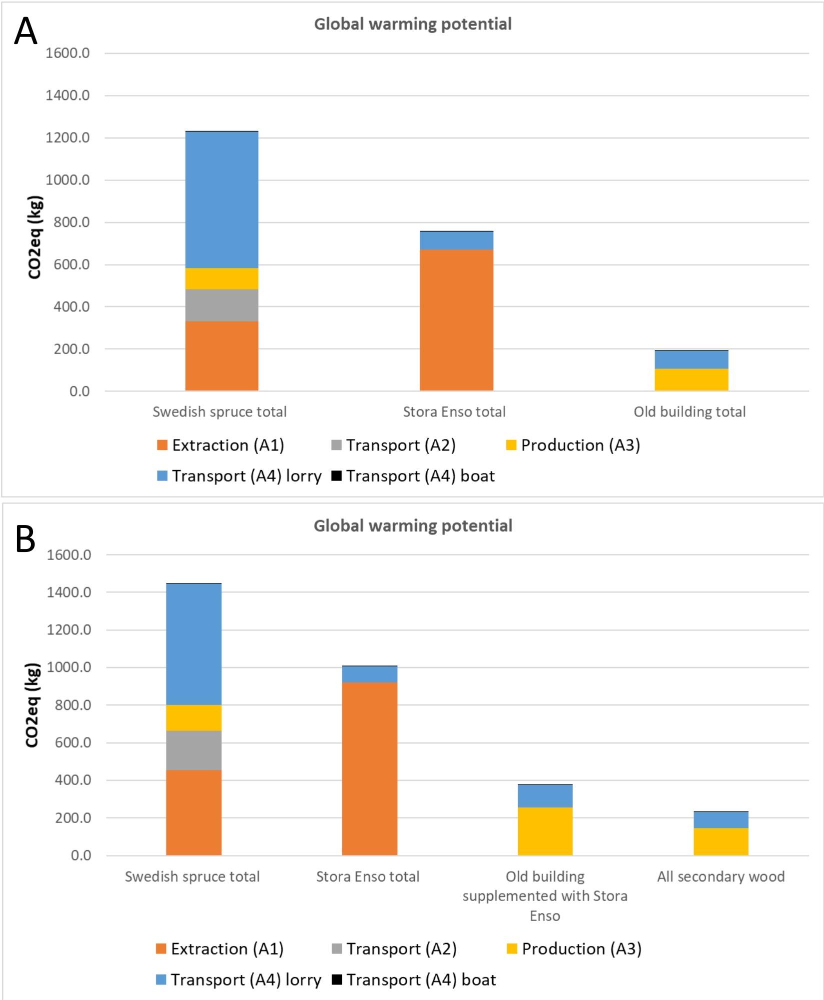


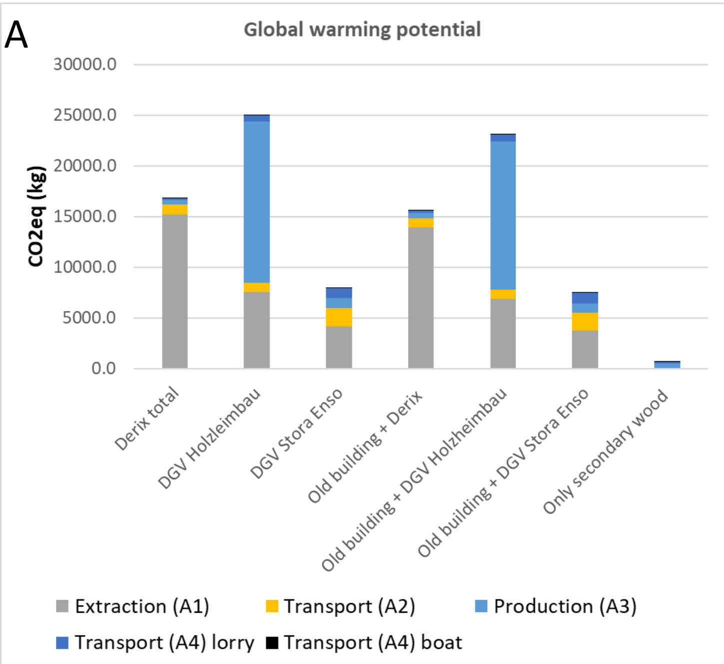
Figure 8: CO2eq emissions of TFC use (A1-A4). A: only old building's wood vs new (20.3m^3); B: Old building's wood supplemented with 4.5m^3 new wood (Stora Enso) vs all new (Stora Enso) or all secondary (27.9m^3 total); Note: CO2eq emissions of Stora Enso are a sum of A1-A3 together as separate values per phase were not reported.

As the CO2eq emissions for A3 of secondary wood are uncertain, several emissions were modelled indicating that with emissions from approximately 35kg CO2eq/m^3, secondary wood use had higher total CO2eq emissions compared to new wood (from Stora Enso; not shown).

5.1.2.2 Scenario 2: Remanufacturing of secondary wood as CLT

It was assumed for the LCA that the old building's wood can be processed to wooden panels with the same thickness and physical characteristics as new CLT. As insufficient spruce wood was present in the old building to produce CLT for the new building, new CLT has to be added. An additional hypothetical scenario was modeled, assuming that sufficient secondary wood can be obtained from within the Stelling van Amsterdam. This allows to study the CO2eq savings if only secondary wood could be used. All requirements and assumptions for the different scenarios are in Supplementary table 4.

Specific emission data for secondary wood processing (A3) were lacking in literature or very variable. However, A3 emissions from the three EPDs for new CLT were all modeled for A3 of secondary wood from the old building. As these emissions were in a large range, results were different depending on the emissions in the A3 phase (Figure 9). When CO2eq emissions in the production phase (A3) are low, the CO2eq emissions were reduced with 1263kg (7.5%), 1895 (7.6%) or 464kg (5.9%) CO2eq compared with new wood from Derix, DGV Holzleimbau and DGV Stora Enso respectively (Figure 9A). If production emissions in A3 are medium or high, the differences between secondary and new wood diminished and new wood from Stora Enso even has lower CO2eq emissions compared to using the old building supplemented with new wood (Figure 9B, C). However, if all wood can be sourced locally from deconstruction sites and/or construction marketplaces, environmental impact will be substantially lower when production emissions are low (saving 7,200 – 24,200kg CO2eq, 91-97% reduction) or medium (1,200 – 18,000kg CO2eq, 15-73% reduction) depending on the supplier of new CLT (Figure 9A, B). Again, high production emissions diminished these savings and was only beneficial compared to DGV Holzleimbau (Figure 9C). Transport emissions (A4) were relatively low compared to A1-A3 for all scenarios modelled (1-3% of A1-A4), except for 'secondary wood only' where transport accounted for 25% of emissions in the case of low A3 emissions (Figure 9A), and secondary wood supplemented with DGV Stora Enso (around 13%) due to the longer transport distance from Austria. Clearly, the main contributors to emissions are from extraction to production and specific for a certain supplier/factory. Emissions differences between production sites in the A3 phase will determine the ultimate environmental impact of using CLT (new or secondary) in construction.



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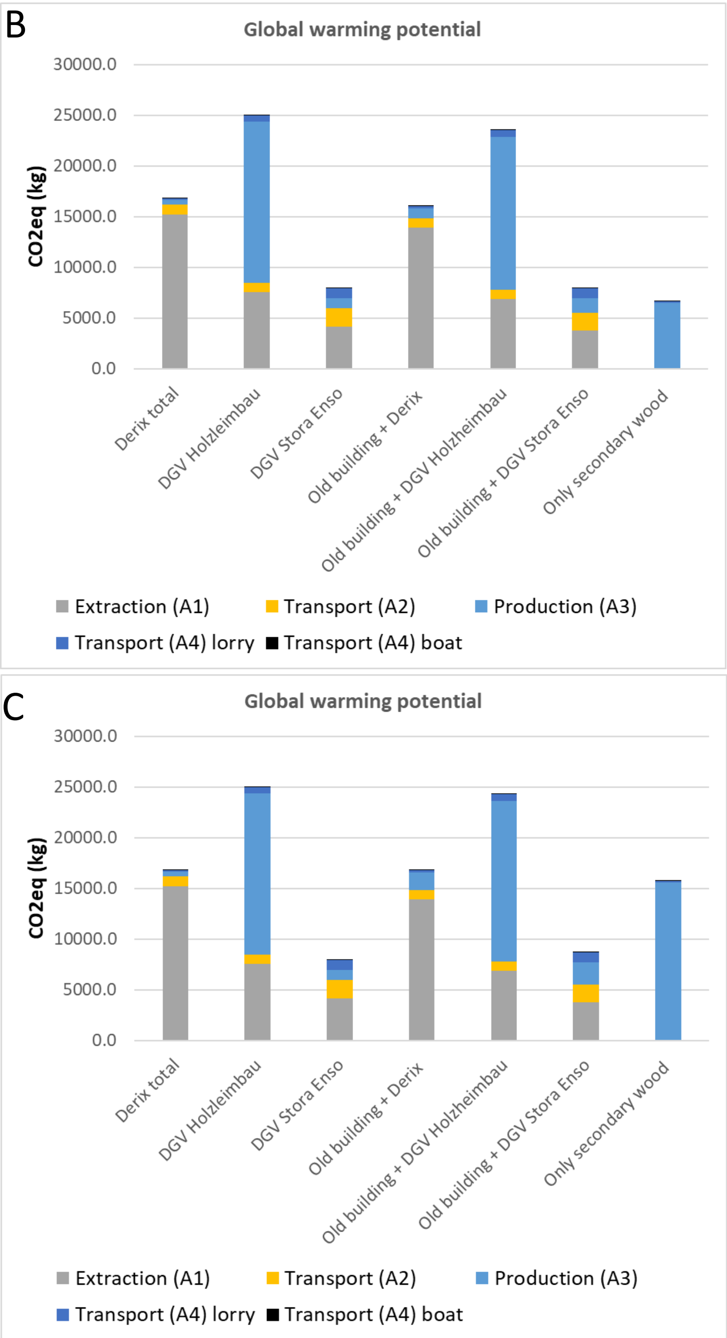


Figure 9: CO2eq emissions of CLT use (A1-A4) modelled with low (4kg; A), medium (50kg; B) and high (120kg; C) CO2eq emissions in production phase (A3) for secondary wood. Abbreviation: DGV = De Groot Vroomshoop

5.1.2.3 Scenario 3: Refurbishing of secondary wood into furniture

Based on the availability of Red Cedar wood, 25 tables and 100 chairs can be produced with standard dimensions (see all assumptions in Supplementary table 5).

A reduction of CO2eq emissions of 18kg (93%, chair) and 21kg (94%, table) can be reached by producing furniture of secondary wood on the island itself. The largest part of newly produced furniture is in the transport (Figure 10), due to the fact that for one piece of furniture, full transport emissions of a van are allocated to one piece. However, calculating emissions for all pieces of furniture (Figure 11) showed that transport is only a small part of total emissions (5%) as the emissions are spread over all furniture pieces. In this case, total emissions can be reduced by 43% and 77% for chairs and tables separately, and 54% (187kg) for all tables and chairs together (from 345kg CO2eq (new) to 158 kgCO2eq (secondary) for all furniture pieces). If more furniture is needed, the exact emissions will differ, but clearly using secondary wood is environmentally beneficial.

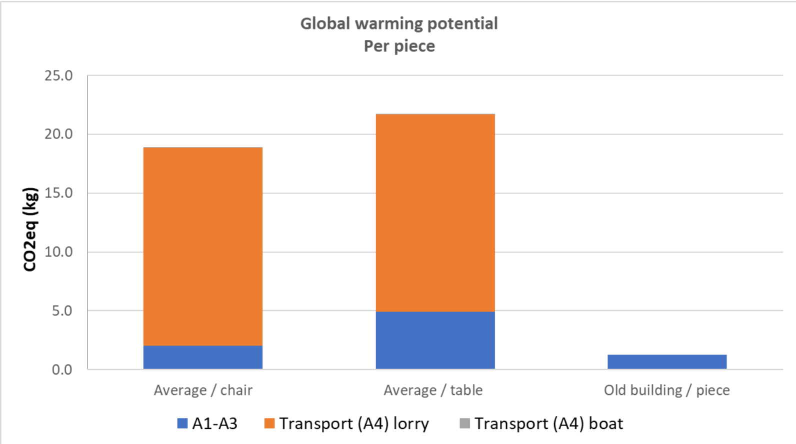


Figure 10: CO2eq emissions (kg) per piece of furniture

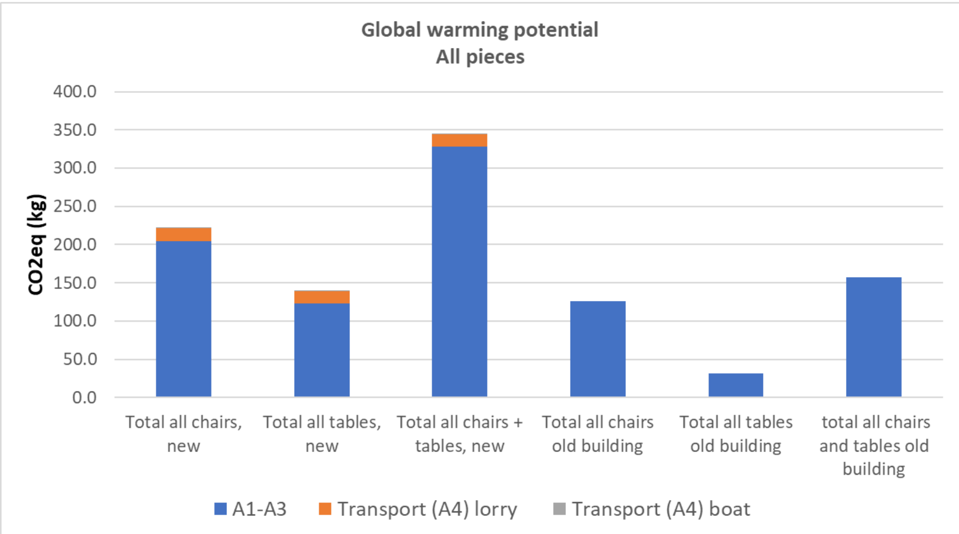


Figure 11: CO2eq (kg) emissions for all chairs and tables

5.1.3 Expert interviews

In this section, for each scenario, the results of expert interviews are presented per scenario and criterium. An extensive text summary can be found in the supplement (9.4 Appendix D). Environmental impact was not discussed with experts as this was calculated using an LCA. The same applies for social job creation and the use of local materials, as these criteria were scored based on the author's insight. During the interviews, some criteria from the tables were not explicitly mentioned and could not be scored (indicated with n.d., not discussed). In general, when experts talked about 'quality' of wood, this was interpreted to include the life span, safety and maintenance criteria, also when not explicitly mentioned. This could reliably be interpreted in this way as all experts indicated that secondary wood had similar quality as new wood and no quality differences are expected when wood is checked and certified. Thus, these three criteria are expected to be the same for secondary and new wood.

5.1.3.1 Scenario 1: Reuse of secondary wood as TFC

In general, all experts indicated the same quality (life span, safety and maintenance) of secondary wood and new wood. However, costs are mostly expected to be much higher due to removal of e.g.

nails, glue and paint before reuse is possible. This also reduces the ease of construction as well as the option to prefabricate, which is commonly performed for new wood (Table 6).

Table 6: Results expert interviews scenario 1

Criteria	Expert #1	Expert #2	Expert #5	Expert #6
Modular / prefabricated design	n.d.	-	n.d.	-
Costs	=	-	-	-
Life span (technical)	=	=	=	=
Ease of construction	n.d.	n.d.	-	-
Safety	=	=	=	=
Maintenance	=	=	=	=

Abbreviations and symbols: n.d.: not discussed; = secondary and new wood are similar; - secondary wood scores less than new wood; -/+ uncertain whether secondary wood scores better or worse than new wood; + secondary wood scores better than new wood.

5.1.3.2: Scenario 2: Remanufacturing of secondary wood as CLT

In the case of CLT, all experts indicated that currently, secondary wood is not used for CLT, and would be very impractical and include high costs. Therefore, scoring of several criteria could not be performed because the use of secondary wood for CLT was only hypothetical (Table 7).

Table 7: Results expert interviews scenario 2

Criteria	Expert #2	Expert #3	Expert #4
Modular / prefabricated design	n.d.	n.d.	n.d.
Costs	n.d.	-/+	-
Life span (technical)	=	=	n.d.
Ease of construction	-	-	-
Safety	n.d.	n.d	n.d.
Maintenance	n.d.	n.d.	n.d.

Abbreviations and symbols: n.d.: not discussed; = secondary and new wood are similar; - secondary wood scores less than new wood; -/+ uncertain whether secondary wood scores better or worse than new wood; + secondary wood scores better than new wood.

5.1.3.3 Scenario 3: Refurbishing of secondary wood into furniture

In general, all experts indicated that furniture made from secondary wood has the same life span as new wood, as long as you select the good wood. Costs will depend mainly on the salary costs as secondary wood needs selection, removal of nails, screws etc., which makes it less easier to use. Criteria ‘safety’ and ‘maintenance’ were less relevant for furniture compared to the use of secondary wood in constructive elements such as TFC and CLT, and were not much discussed (Table 8).

Table 8: Results expert interviews scenario 3

Criteria	Expert #7	Expert #8	Expert #9
Modular / prefabricated design	=	=	=
Costs	+	-/+	-
Life span (technical)	=	=	=
Ease of construction	-	-	-
Safety	n.d.	n.d	n.d.
Maintenance	=	n.d.	n.d.

Abbreviations and symbols: n.d.: not discussed; = secondary and new wood are similar; - secondary wood scores less than new wood; -/+ uncertain whether secondary wood scores better or worse than new wood; + secondary wood scores better than new wood.

5.1.4 Literature review

Literature was searched to score criteria in the MCA in addition to expert interviews. The main focus was on articles that discussed quality of secondary wood. Although limitedly available, in general, the use of secondary wood is possible after careful checking for damage, mechanical strength and fungal/bacterial infestation (Table 9).

Table 9: Results literature review

Author	Summary
Akanbi 2017[58]	Mathematical modelling showed that ~65% of timber from buildings can be reused
Rose 2018[59]	Laboratory experiments indicated that secondary timber could be used for CLT production
Höglmeier 2013[60]	26% of construction wood is applicable for reuse (German case study)
Börjesson 2000[24]	Possibility to reuse structural timber and non-structural wooden floors, doors, window frames, stairs. Reuse not always possible when wood is damaged or chemically treated
Whittaker 2019[61]	Timber holds great potential for reuse, if free from fungal/bacterial infestation, preservatives and other damage
Cavalli 2016[62]	Mechanical properties of secondary timber and wood poles remain similar to new wood
Van den Briel[31]	There is currently limited reuse of waste wood from construction in the Netherlands, mainly from beams, floors and doors. Sorting of good-quality wood is time-consuming and costly
Kránitz 2016[63]	Ageing of wood has some impact on mechanical properties of wood

5.2 MCA analysis

For all scenarios, MCA criteria were scored and weighted based on LCA input, expert interviews and literature review as indicated in Appendix 9.1.

5.2.1. Scenario 1: Reuse of secondary wood as TFC

Scoring of all criteria (Table 10) resulted in a higher total score of new wood for TFC production (Figure 12). In general, technically it is possible to produce correct-sized beams for TFC with secondary wood (expert interviews #1, 2, 5, 6) and secondary wood quality (indicated with life span, maintenance and safety) will be similar to new wood, due to the certification process that is required for construction wood. However, it is not common practice yet and the wood will need to be cleaned and inspected, which is more time-consuming thus scoring lower on 'Ease of construction', 'costs' and the 'modular/prefab design' criteria. Together, these criteria influenced the higher total scoring for new wood, despite the lower environmental impact of secondary wood.

Table 10: Scoring of criteria for scenario 1

Criteria		Models -->	new	Secondary from old building	Secondary old building + new	Secondary only
Environment	Reuse possibility	Modular / prefabricated design	3	1	1	1
	Environmental impact	CO2eq emissions change	3	4.49	4.25	4.54
Economical	Financial feasibility	Costs	3	1	1	1
Social	Job creation	Social job creation	3	3	3	3
	Cultural benefits	Use of local materials	3	5	5	5
Technical	Durability	Life span	3	3	3	3
	Practical feasibility	Ease of construction	3	1	1	1
		Safety	3	3	3	3
		Maintenance	3	3	3	3

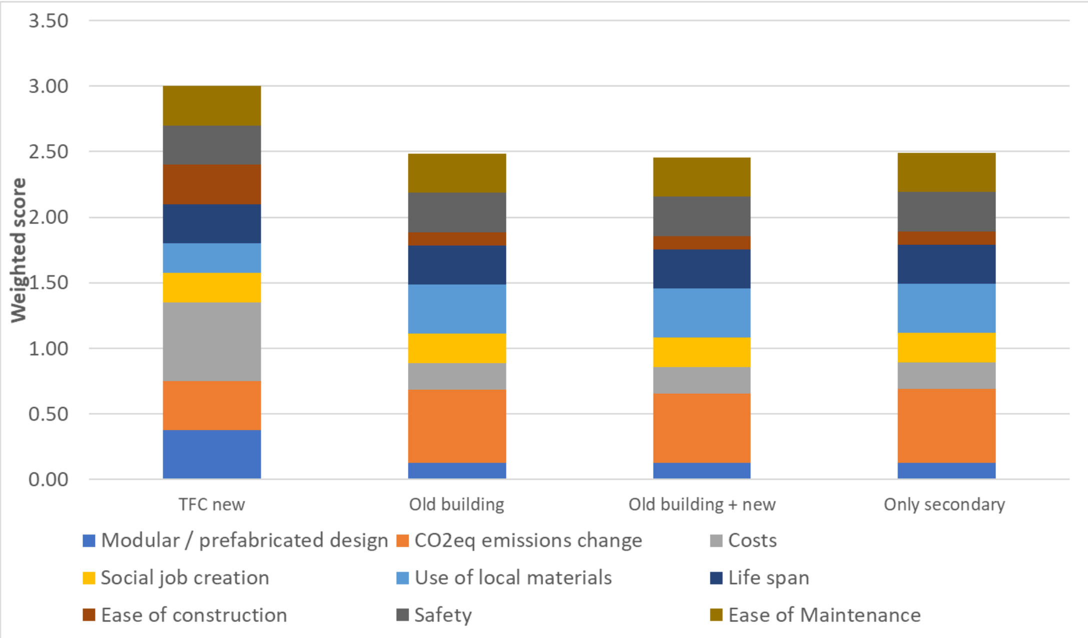
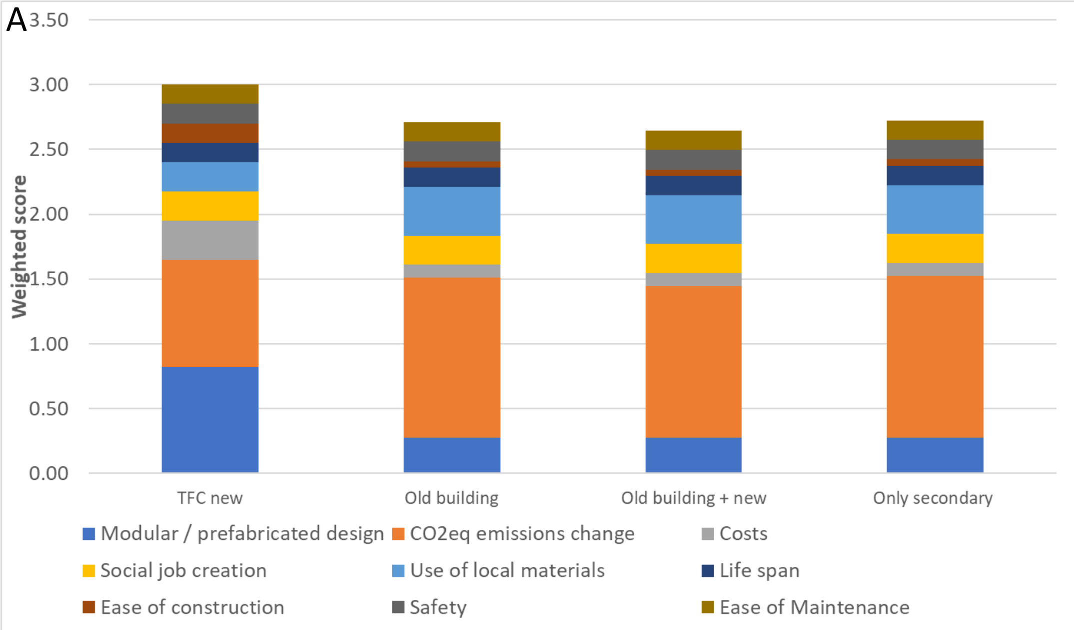


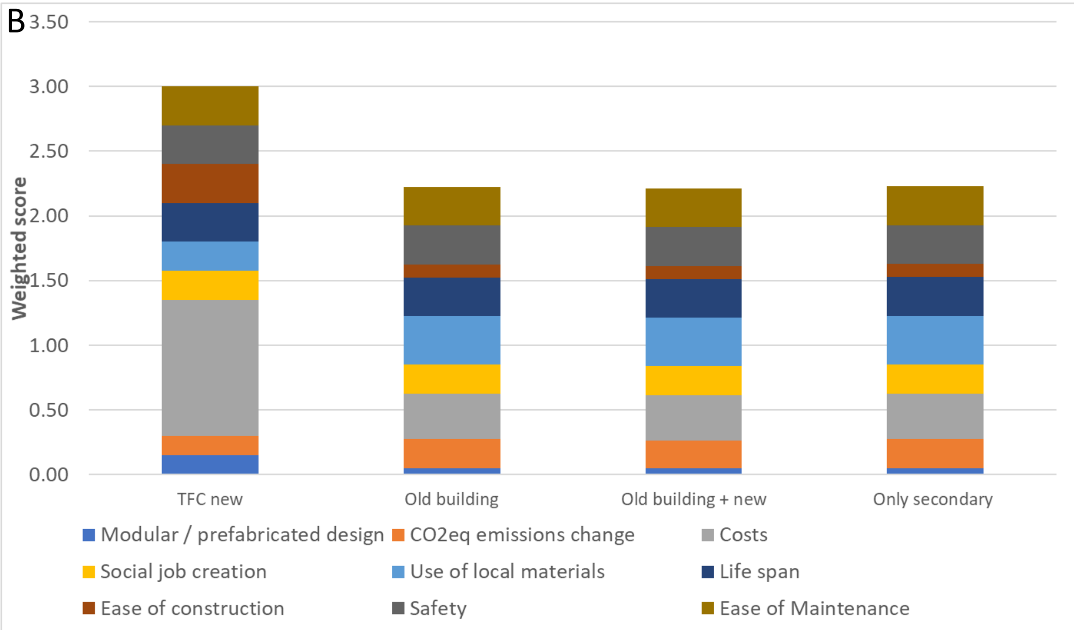
Figure 12: MCA output TFC. From left to right: new wood, old building's wood (20.3m^3), old building supplemented with new wood (27.9m$^{3;}$ new from Stora Enso), secondary wood only (27.9m^3). CO2eq emission reduction based on comparison with new wood from Stora Enso, as this is a leading supplier for the Netherlands.

5.2.1.1 Sensitivity analysis

Weighing of the different criteria was changed to determine the importance of criteria and effect on the most ideal situation (Supplementary table 2). Two extreme scenarios were modelled: one where costs and technical aspects for reusing secondary wood were weighed lower and environmental impact higher as well as the other way around. Indeed, when environmental impact has a larger weight, secondary wood scores higher, but still lower than new wood, whereas when economical and practical considerations are weighted more, secondary wood scores even lower (Figure 13, A and B respectively). However, as the new wood scenario remained the option with the higher score, the data were not highly influenced by a different weighing, indicating data robustness.

Costs and ease of construction largely influenced the higher scoring for new wood. Assuming costs and ease of construction are challenges that can be overcome in a project, these criteria were set at 0%, with other criteria weighing equally. This showed that secondary wood use scored higher than new wood mainly due to environmental impact reduction, although the differences between new and secondary wood were small (Figure 13C).





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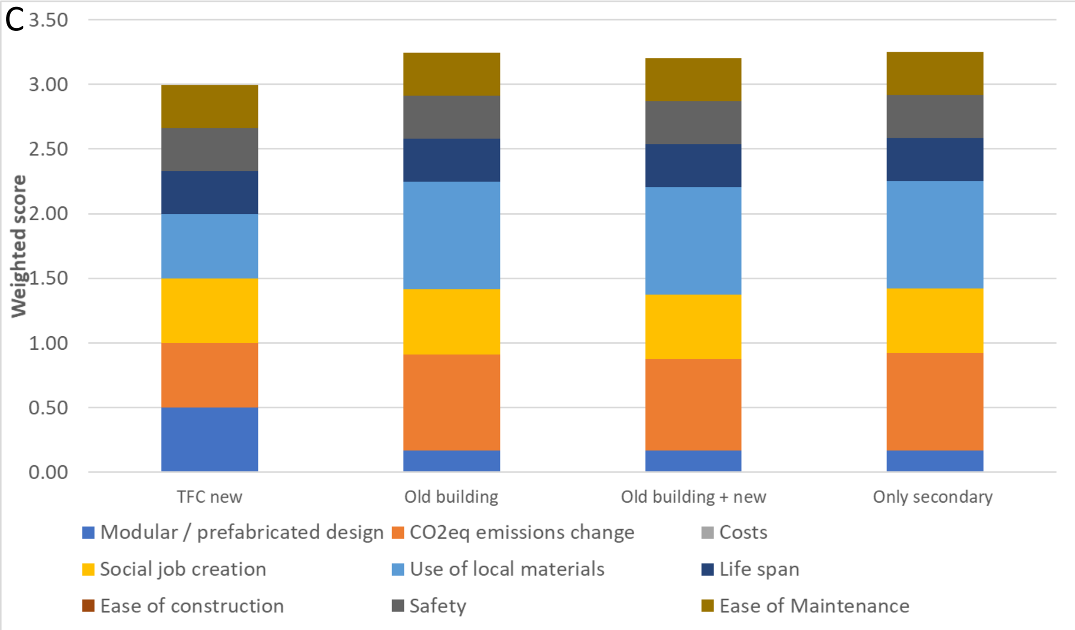


Figure 13: Sensitivity analysis TFC. A: Environmental factors weigh most. B: Economic and Technical aspects weigh most. C: Excluding costs and ease of construction from MCA.

5.2.2. Scenario 2: : Remanufacturing of secondary wood as CLT

Scoring of all criteria (Table 11) resulted in a higher total score for new wood for CLT production (Figure 14) mainly due to higher costs and lower ease of construction of secondary wood. Experts #2-4 and Rose et al.[64] indicated that although secondary wood when qualified and certified in theory could be used for CLT production with the same characteristics and strength, this is not done yet due to practical issues. Factories are not designed to process wood from customers, as this would halt the process and therefore being time consuming and costly. In addition, certification of secondary wood will also be time consuming.

Table 11: Scoring of criteria for scenario 2

Criteria		**Models -->**	**New**	**New + secondary**	**Secondary only**
Environment	**Reuse possibility**	Modular / prefabricated design	3	1	1
	Environmental impact	CO2eq emissions change	3	3.15	4.92
Economical	**Financial feasibility**	Costs	3	1	1
Social	**Job creation**	Social job creation	3	3	3
	Cultural benefits	Use of local materials	3	4	5
Technical	**Durability**	Life span	3	3	3
	Practical feasibility	Ease of construction	3	1	1
		Safety	3	3	3
		Maintenance	3	3	3

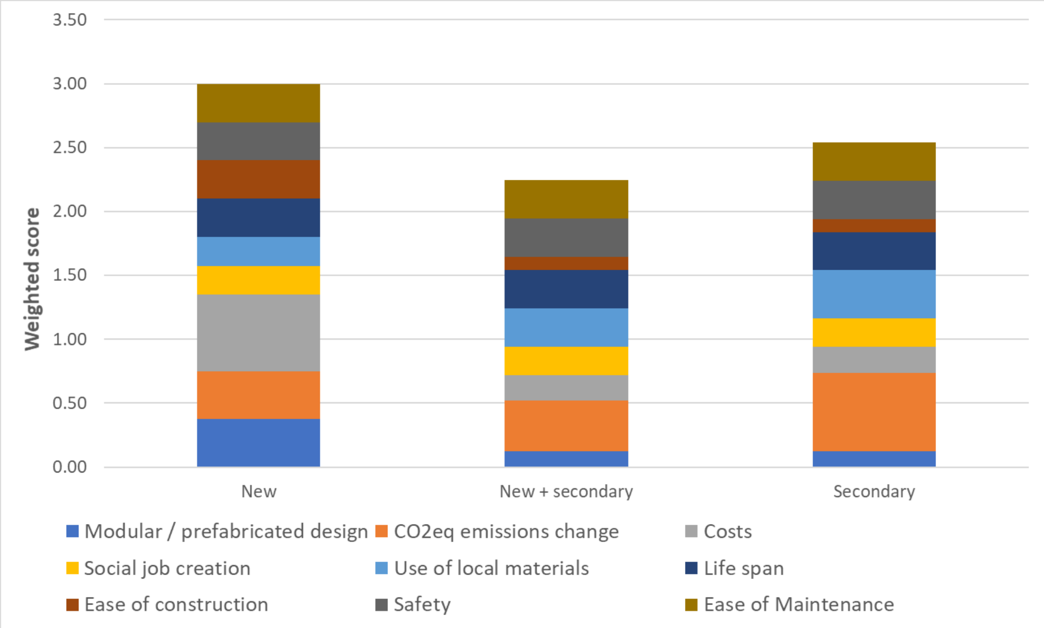


Figure 14: MCA output CLT. From left to right: new wood, old building supplemented with new wood (New + secondary) and secondary wood only. For environmental impact, low A3 CO2eq emissions for secondary wood were used.

5.2.2.1 Sensitivity analysis

Similar to the TFC scenario, two extreme weighing options were tested showing that changing the weighing factors to more environment-heavy or more cost/technical-heavy still showed new CLT as the highest option, indicating robustness of the data (Supplementary figure 4).

5.2.3 Scenario 3: Refurbishing of secondary wood into furniture

Scoring of all criteria (Table 12) resulted in a higher total score of secondary wood for furniture production compared to new furniture (Figure 15). The main contributors to this score were the reduction in kg CO2eq emissions, the option to include the social sphere of sustainability by job creation on Pampus and the use of materials from within the Stelling van Amsterdam. The only criterion scoring lower is the ease of construction. Indeed, removing all nails from secondary wood and cleaning the wood from sand and other dirt, makes construction with secondary wood more time-consuming and therefore less easy (expert interview #8, 9). Expert interviews (#7, 8, 9) indicated that the costs will depend on the price for new wood, and the salary of furniture maker. As the ease of construction scores lower, these costs may be higher than using new wood/furniture. However, as this scenario assumes production on Pampus with volunteers, the costs will be lower. Life span, maintenance and safety are not different between new and secondary wood (expert interviews (#7, 8, 9). In addition, modular/prefabricated design is applicable for both new and secondary wood and no difference is expected.

Table 12: Scoring of criteria for scenario 3

Criteria		Models -->	new	secondary
Environment	Reuse possibility	Modular / prefabricated design	3	3
	Environmental impact	CO2eq emissions change	3	4.09
Economical	Financial feasibility	Costs	3	5
Social	Job creation	Social job creation	3	5
	Cultural benefits	Use of local materials	3	5
Technical	Durability	Life span	3	3
	Practical feasibility	Ease of construction	3	1
		Safety	3	3
		Maintenance	3	3

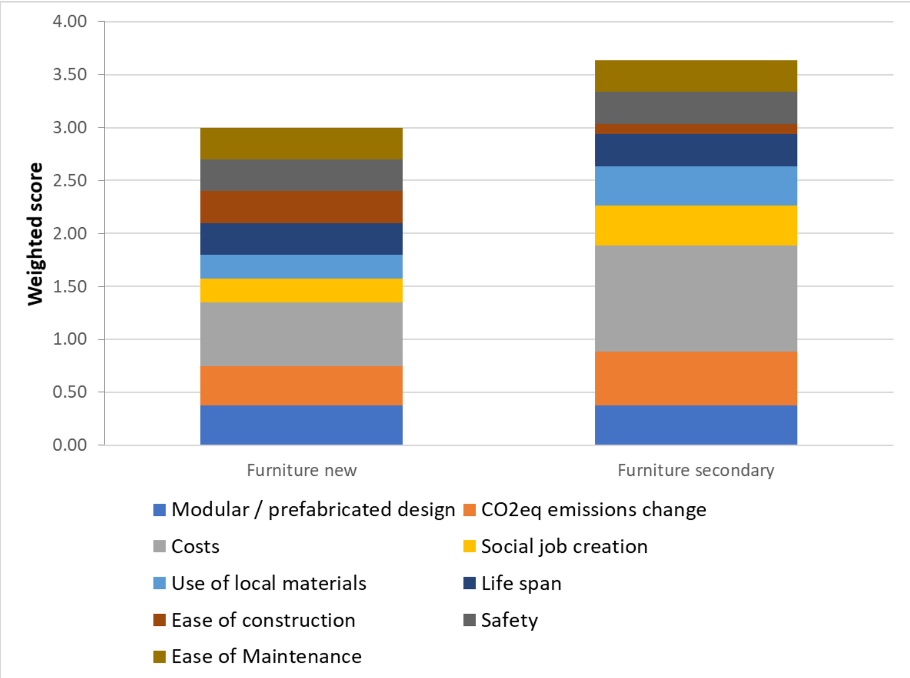


Figure 15: MCA results of furniture made from new or secondary wood

5.2.3.1 Sensitivity analysis

Weighing of the different criteria was changed similarly to the TFC and CLT scenario. For both extremes, secondary wood remained the preferred option (Supplementary figure 5) indicating data robustness.

5.3 Comparing MCAs

The results above indicate that repurposing the old building's wood into furniture scores higher on a set of circularity/sustainability/technical criteria compared to new wood. For both CLT and TFC, new wood scores higher than secondary wood mainly due to practical problems and higher costs. As CLT is practically impossible (expert interview #2), only the furniture and TFC scenarios remain viable options, although with limitations, especially for TFC.

Based on the available wood in the old building, Red Cedar wood can be used for 25 tables and 100 chairs, leaving spruce beams and wood panels to cover part of the wood required for the TFC. Based on CO_2eq emissions of new wood from Stora Enso, in total around 780 kg CO_2eq emissions can be avoided if both the TFC and furniture scenarios are executed (Table 13, in blue the total scenario).

Table 13: Absolute and relative CO2eq emissions of different MCAs

	Total kg CO2eq new wood (Stora Enso)	**Avoided kg CO2eq with secondary wood**	**% reduction**
TFC spruce wood	760 - 1000	560 - 630	62 - 76
Furniture	344	187	54
Total TFC + Furniture	1100 - 1344	747 - 817	56 - 74

6. Discussion

The goal of this study was to investigate the most feasible option, from a circularity, sustainability and technical viewpoint, for using secondary wood in construction. By applying this goal to case study Pampus, the use of secondary wood for TFC, CLT and furniture could avoid CO2eq emission, but costs and practical issues limited secondary wood for CLT and TFC, whereas these limitations were less prominent for furniture.

In this section, first a methodological discussion of the MCA and the data collection methods will be conducted, followed by answering the research question.

6.1 MCA

6.1.1 Choice of criteria

To obtain more insight in high-value reuse of wood, an MCA was used in this study to investigate several scenarios for secondary wood use on Pampus. MCAs have been used in the construction sector before to determine sustainable construction options and materials[34–36,40] and used to define the MCA criteria in this study to cover the three sustainability spheres (environment, economic and social) as well as circularity principles[7,34–36,38–40].

Nevertheless, these studies indicated criteria that were not included in this study. For example, energy efficiency of building materials and waste are commonly mentioned[7,34,35,40]. However, as only wood was considered, the energy efficiency is expected to be the same for both new and secondary wood. For waste, due to the early phase of the construction (design phase), it was not possible to assess this. It is well possible that waste generation is larger when using secondary wood for TFC or CLT due to inefficiencies in the processing, however, for furniture, this may be less due to the smaller size of the objects compared to TFC and CLT. Taken together, the selection of criteria for this study was most suitable to the early phase of the case but more criteria should be included in the MCA to support the decision-making if the construction process on Pampus will be in an advanced phase. In addition, as most of the criteria in this study are not project-specific, these criteria can easily be used by other construction projects to determine the preferred option in material origin or type and pinpoint the barriers towards sustainable and circular construction practices.

6.1.2 Data reliability

Data obtained in LCA, expert interviews and literature review were used to model the MCA. This section evaluates the data collection methods, data availability and confidence.

6.1.2.1 LCA

LCA system boundaries

In this study, only A1-A4 were included as the main difference was the origin of the wood (new or secondary). The construction and use phase of the building or furniture are expected to give similar results as new and secondary wood have similar features with regard to mass, strength, thermal characteristics and the building's energy use. Stages end-of-life (C) and the next product system (D) are the cause of a lot of debate on how to allocate burdens and credits of recycling or reuse to a product system[44,65–67]. However, as this study indicated that wood can be reused several times, the C and D stages are likely to be similar for new and secondary wood. In addition, for the structure layer, it is expected that the ceiling and walls will last long and any future reuse applications are uncertain due to e.g. changes in techniques or preferences[68].

However, to obtain a more comprehensive representation of the environmental impact of new wood, the environmental impact of disposal of the old building (walls, ceiling or furniture) could have been included. Several scenarios can be depicted for disposal, such as recycling into lower grade purposes or incineration with energy recovery. Vice versa, the avoided environmental impact of new wood could have been included in the impact calculations of secondary wood. However, these complicated analyses were beyond the scope of this study. In addition, even if environmental impact changes for new or secondary wood, it may not change the final results much as the MCA results are a weighted average of many criteria.

Future studies may investigate the environmental impact for new and secondary wood over the full building's or furniture's life cycle on Pampus. Nevertheless, the main difference in the life cycle of the new building on Pampus (either Structure layer or Stuff layer) is in the origin of the wood, new or secondary, where secondary wood avoids emissions in A1 and A2, which has been taken into account in this study. Taking a broader perspective, although exact impact numbers are difficult due to methodological issues, reduction of virgin resource use and extension of a product's life will help to reduce the impact on the environment and contribute to a circular economy[6].

LCA data availability and data confidence

LCAs have been extensively used in the construction sector to measure the impact of buildings and materials on the environment[69]. In this study, access to commonly used databases for LCA calculations, such as EcoInvent, was not possible. However, the use of EPDs for new wood is a suitable alternative, as these are LCA-based declarations containing the aggregated data presented into the impact categories. In addition, it has been shown for a set of construction materials that EPD data, especially GWP, does not differ much from generic data in databases, and such a simplified report can be used[70]. In addition, the data for new CLT was product-specific data from suppliers that supply the Dutch market. Data for the spruce wood for TFC was also derived from relevant suppliers for the Netherlands. Although this wood was not such a specific product as CLT, the emissions included sawing into different dimensions, both beams and boards. Exact emissions for the Pampus case may differ if custom-made sizes are required, and needs to be investigated in a later stage of the Pampus project.

Data availability for A3 of secondary wood into CLT or TFC was lacking. In this phase, processing of wood is very project- and factory specific. If access to background databases would have been possible, more generic information on electricity use may have been available to estimate A3. Another study in the US obtained such information through surveys at deconstruction facilities[71]. However, for this study, that was not possible but different CO2eq emissions were modelled to obtain a range of total emissions for using secondary wood. Nevertheless, also for new CLT, the A3 emissions differed substantially between suppliers, likely due to different types of energy used (grey vs green), the amount of material processed in the factory as well as potential methodological differences in the underlying LCA of the EPDs[72]. Thus, this makes it not only difficult to compare EPDs[72], but also difficult to use these numbers for secondary wood in the current study. In addition, expert interviews all indicated that processing of secondary wood for reuse is less efficient, which may result in higher emissions in A3 compared to new wood. Moreover, the assumed 20% waste of secondary material was not included in the impact assessment. Waste wood can have different purposes (e.g. incineration with energy recovery), but it would have been too complicated for this study to include all of these purposes. Nevertheless, as a range of emissions in A3 was modelled for secondary CLT and TFC to take into account the uncertainties, the use of secondary wood was environmentally beneficial under certain circumstances, especially because A1 and A2 did not have any emissions. More specific information on electricity use for processing secondary wood may be possible when the Pampus project is in an advanced stage and factory-specific data may be available.

For furniture, many suppliers can deliver furniture and only limited number of EPDs were available. In addition, literature data were scarce, showing data for furniture made only partly from wood, or from different geographical regions which affects e.g. energy type used[72]. More LCAs of furniture would help increase insight in environmental impact of furniture. Nevertheless, the available data from Europe did not vary largely and thus a reliable estimation could be made for new furniture[49–53]. The data for secondary furniture is only based on electricity use and its conversion to CO2eq emissions for sawing[54], as it was assumed that all activities would be performed on Pampus itself. However, not included in the impact are the nails or glue needed for furniture manufacturing, due to lack of data. However, a study found that glue had neglectable impact, whereas iron parts (e.g. nails) had much higher impact[73]. This suggests using glue is better from an environmental perspective, however from a circular perspective nails/screws may be better to allow easier disassembly at the end of life. Ideally, secondary nails/screws are therefore used. Also excluded is the possible disposal of the current (also wooden) furniture on Pampus; disposal into incineration or low-grade recycling would negatively influence the reduced impact by using the old building's wood for new furniture. Although exact calculations on the impact of disposal are outside the scope of this study, careful consideration by the management of Pampus on the purpose of the current furniture or the actual execution of the 'furniture scenario' is needed.

Taken together, LCA data so far is either very product-specific or quite general and more research is needed to fill the gap of using secondary materials, including wood, in construction. This would allow better calculations of secondary material use and may promote its use in the construction sector.

LCA impact categories

In this study, only CO2eq emissions were reported. However, many more impact categories can be specified, and could be found in the EPDs. However, in the context of this study, GWP was sufficient to determine the environmental impact of secondary wood. In addition, other impact categories were shown to follow the same pattern as GWP[47], except for land use and land use change (LULUC), which is impacted by forestry. However, only recently, CO2eq emissions from LULUC have to be reported and more information is needed on how to include this[74]. Nevertheless, the use of secondary wood has no impact on LULUC, making reuse a preferred option from the LULUC perspective. In future studies, other impact categories should be included to allow a more comprehensive comparison of the environmental impact of secondary and new wood.

LCA and circularity

With regard to circularity, LCA has several limitations. CE principles such as reuse or recycling are challenging to address in an LCA, as discussed above. Several suggestions have been described to overcome these problems, as well as development of other CE metrics, both LCA and non-LCA based[44,45,75]. Although useful alternatives have been proposed, so far no new method has been standardized. Nevertheless, despite its shortcomings, in a review of a large set of CE indicators and frameworks, LCA and LCA-based measures appeared to include most of the circularity goals including resource use, recycling and reuse (although with methodological limitations) and life span[45]. Also, the goal of this study was not to assess the circularity of the full building but assess environmental impact of the use of secondary wood as one of the criteria to include in the MCA. In fact, integrating LCA in an MCA has been performed before in several research areas, and is a robust approach to evaluate environmental issues[39]. Taken together, LCA was a suitable and sufficient tool to analyse environmental impact of new and secondary wood in this study and a useful addition to the MCA.

6.1.2.2 Expert interviews and literature review

Expert interviews and literature review were used to assess several of the economic and technical criteria. In general, consensus was present among experts about the possibilities to reuse wood in construction although with practical and financial limitations. This was in line with the (limited) literature, stating that upon inspection, wood without damage can be reused, although this is time-consuming and costly[24,31,58–63]. Thus, scoring of criteria in the MCA could reliably be performed.

6.2 Secondary wood in construction, the way forward?

Biobased construction has been proposed as a way to reduce the environmental impact of the construction sector[25] and reuse of currently available wood from the built environment can reduce resource depletion. So far, the use of secondary materials in construction is limited, due to possible quality and performance issues[29] as well as the availability of low-priced virgin materials[7]. However, the circumstances determining whether secondary wood is preferred over new wood are not entirely clear and possible trade-offs between circularity and sustainability[11,28] need to be investigated to improve high-value reuse, policy and legislation for the construction sector. This study filled in this knowledge gap by combining environmental impact calculations with other criteria that are important in circularity, sustainability and technical performance to determine the feasibility of secondary wood use in construction. Below, the results are discussed per building layer.

6.2.1 Secondary wood for the Structure layer

6.2.1.1 Environmental impact of secondary wood

The current literature on secondary wood use in construction is limited. Previously, some studies have been performed to recycle wood waste into wood panels, such as medium density fibreboard (MDF) or other wood or mixed wood products[76–78]. With respect to greenhouse gas emissions from wood reuse, both lower and higher emissions have been reported[71,79], depending on the methodology choices for the LCA or the type of wood. In the current study, the environmental impact in general was lower for secondary wood compared to new wood, but this depended on the material availability and processing emissions in LCA phase A3. Indeed, material availability in the old building to produce TFC or CLT was likely not sufficient. However, if hypothetically all required wood could be sourced from within the area of Pampus, and processing of the wood was similar to new wood, CO2eq emissions could be avoided, about 600 kg for TFC and 7000-24,000kg for CLT (secondary wood only). Although currently, CLT from secondary wood is not a viable option, it was shown in laboratory experiments that it is technically feasible to make CLT from secondary wood that was sourced from construction and demolition sites in the UK[59]. Thus, if CLT would be made from secondary wood, this study indicates that it can avoid much more CO2eq compared to TFC, due to the higher wood area needed for CLT panels. The avoided CO2eq emissions for TFC may not be as large as CLT, also other (polluting) emissions, into soil and water, as well as land use change from forestry will be avoided. A broader impact assessment including more impact categories will likely show larger environmental benefits of secondary wood.

A negative impact of recycling/reuse practices has been reported due to transport of materials[80]. In this study, the impact of transport of total CO2eq emissions was limited, mainly due to the assumption that all wood could be transported at once. Clearly, if this would not be possible, or when a factory with a long distance (such as Swedish spruce) would be chosen the impact may be larger. Careful selection of supplier/factory is important to limit CO2eq emissions.

Taken together, this and previous studies indicate that potential savings in CO2eq emissions are project-specific and site-specific depending on the material availability, processing required and transport distances involved. Thus, calculating the (expected) environmental impact is crucial for each construction project to determine the lowest impact option for secondary materials[81].

6.1.1.2 Economic, social and technical impact of secondary wood

Not only environmental impact determines whether secondary wood is preferred over new wood. Technical quality of wood is important in construction, and expert interviews in this study indicated that secondary wood quality would be similar to new wood, in line with previous studies indicating reusability of wood[24,58]. Thus, the findings in this study contradicted the uncertainties of lower quality voiced before[29]. Prerequisite, however, was that wood needed to be free from fungal/bacterial contamination, and certain treatments, thus, wood sorting is required. Although not investigated here, it may be possible to include the social sphere of sustainability by creating social work places to sort, inspect and clean secondary wood for reuse[31] leading to job creation when progressing towards a circular economy.

The main factors influencing preference of new over secondary wood were costs, modular/prefab design and ease of construction. A higher score for cultural benefit (material from within the Stelling) or lower environmental impact could not reverse these three criteria, and the data showed to be stable despite different weighing factors in the sensitivity analyses. In a previous review on recycling and reuse practices of construction and demolition waste[81], some authors found higher costs for reprocessing secondary wood, whereas others did not. Clearly, the exact costs will be project-specific and also depend on the price of new materials. However, as it is not common practice in the Netherlands to construct with secondary wood, to do so, would be inefficient and reduce prefabrication possibilities and may therefore lead to higher costs. Indeed, only when costs and ease of construction were excluded in the analysis of TFC, secondary wood outweighed new wood. However, the difference was small, mainly due to the reduced prefabrication possibilities of secondary wood. This could only be overcome if better logistics for secondary wood processing would exist (see Recommendations).

6.1.2 Secondary wood for the Stuff layer

As furniture production was assumed to be performed on the island, much less CO2eq will be emitted. This will lower the environmental impact compared to new furniture, in line with a previous study showing reduced environmental impact by using secondary wood for wardrobe manufacturing[82]. Other studies on furniture did not test the effect of secondary wood, but compared new wood to other materials[52,53,73,83]. More studies may be performed to get a better understanding of the environmental impact of secondary wood for furniture manufacturing, especially when furniture will be produced in factories as this may increase CO2eq emissions compared to the current study due to transport of furniture. Nevertheless, this study convincingly showed that secondary wood outweighed new wood under different weighing conditions, not only for the environmental but also most of the other criteria when produced on the island itself. This makes secondary wood a good option to consider for furniture manufacturing. In addition, refurbishing has clear advantages for the social sphere of sustainability that could easily be incorporated here to create a workspace for e.g. people with poorer job opportunities[31]. It also adds to Pampus' ambition to become self-sufficient, as likely sufficient wood is available for all required furniture. In addition, as for TFC and CLT, no quality issues are to be expected from secondary wood, whereas ease of construction is not likely to be problematic due to the smaller size of furniture compared to TFC and CLT.

6.1.3 Trade-offs

It has been postulated that there may be trade-offs between circularity and sustainability[11,28], due to possible high energy use for recycling. However in this study, such trade-offs were not identified, but trade-offs between circularity and practical issues, as circular construction was hampered by practical limitations, especially for the Structure layer. This in in line with earlier studies indicating such gaps in the transition to a circular economy[7]. Thus, if these limitations can be solved, secondary wood is both environmentally and technically a good option in the construction sector to reduce its environmental impact.

7. Conclusion

In conclusion, from a circular, sustainable and technical viewpoint it is feasible to use secondary wood for construction, with the least practical limitations for lower-value purposes (refurbishing into furniture), whereas high-value use (Reuse, or Remanufacturing) was hampered by costs and practical issues of non-existing logistics to bring secondary wood back on the market. Nevertheless, this study confirms that although virgin wood is already a low-impact construction material compared to other construction materials[23,24], using secondary wood in construction can avoid CO2eq emissions of logging, transport to factories and processing, with the largest savings for the Structure layer. The insights into the trade-offs between circular, sustainable construction and actual implementation allow for developing legislation and logistics to promote secondary wood use in construction at the highest value possible. This will enhance circular construction practises and reduce the environmental impact of this sector.

8. Recommendations

8.1 Recommendations for Pampus

The MCA results indicated that repurposing the old building's wood into furniture would be the most optimal option, as reuse as TFC or remanufacturing as CLT did not outweigh new material, despite being higher on the 10R ladder and the larger absolute savings in CO2eq emissions. It will help if a more detailed understanding is available about the quantities of wood needed, as well as the processing time, factory and accompanying costs. This will allow Pampus to use the MCA in the current study as a template to reconsider its options. Then, Pampus stakeholders and management could discuss whether to set an example and accept the challenge to overcome the practical barriers of reusing wood as TFC. As Reuse is higher up in the 10R framework, the reuse of interior walls and ceiling into TFC would be more circular than the other scenarios, lead to larger CO2eq emission savings compared to furniture and have a better practical feasibility compared to CLT production. If it will be decided not to reuse the wood as TFC, reuse options can be sought within the area of Pampus to allow high-value use of secondary wood before refurbishing into e.g. furniture.

8.2 General recommendations

In general, to reach a circular economy and more specific a circular construction sector as set out by Dutch legislation, several recommendations can be made. The highest R tested was Reuse, but to go a step further, in fact, a better approach would be to renovate buildings, instead of reusing material in new buildings which may be difficult due to material (un)availability and practical limitations. As I do not want to include another R into the already extensive 10R framework, renovating could be seen as part of Reduce (only materials needed for renovating, not for a full new design) or even Rethink (add elements to a building to be able to use a building more intensively). Thus renovating could help increase circularity (Figure 3). In the case of Pampus, however, this was not possible as it is a UNESCO World Heritage site and legislation prevented renovation in a way that the building would satisfy new criteria such as the possibility to have more visitors. Apart from renovation, a 'design-follows-material' principle could be part of the top three R's of the 10R framework, a principle where the required materials for construction are not based on the design (as was the case in this study), but the design is based on the availability of secondary materials. This would make reuse much easier and reduce the processing energy of available materials. This requires another way of thinking, based on material scarcity. However, as the world's resources are not infinite, the current construction practices that assume infinite material availability, will not hold. Thus, mainly a behavioural change is needed[84].

Based on the current study, it is recommended to have better material recovery routes to have more secondary material available, which was a limitation detected in this study. In addition, circular construction-promoting policies and new business models, including extender producer responsibility (EPR), would lower the costs of reuse and promote circular construction[7]. EPR makes producers responsible for taking back their product at the end-of-life, and may enhance the efficiency of factories to reprocess materials for reuse[85]. EPR is not new, but already embedded in certain EU legislation on e.g. batteries[86]. Currently, in the Netherlands several companies are working to make reuse possible, such as Urban Mining, Madaster and Repurpose, that 'harvest' secondary building materials on construction sites, register all materials in a building online for future reuse and scout for secondary construction materials, respectively.

Taken together, collaboration of many actors involved in construction from design until the end-of-life of a building as well as government policies are needed to transform the construction sector towards a sustainable and circular sector. Although a lot of work is required, increased awareness, initiatives and research in this area are promising and may pave the way towards circular construction practices.

9. Appendix

9.1 Appendix A

Scoring and weighing of criteria

Criteria were scored with a number between 1 and 5 (Supplementary table 1), where the value 3 represents the scenario of new wood (business as usual) or no change between secondary and new wood. In the case of Environmental impact, a score was calculated as a continuous number between 1 and 5, based on the % CO2eq reduction were 1 represent ≥ 100% more CO2eq emissions (less sustainable than business as usual) and 5 ≤ 100% less CO2eq emissions (more sustainable than business as usual)[87].

Standard weighing was applied as follows (Supplementary table 2): 25% for Environmental, 20% for Economic, 15% for Social and 40% for Technical criteria. The weighing factors for each of the indicators within the four groups were equal to add up to 100%.

Supplementary table 1: Scoring characteristics of MCA criteria

Criteria	Scoring and explanation
Modular/prefabricated design	1: Less modular/prefab design possible for secondary compared to new 3: Similar modular/prefab design possible secondary and new 5: More modular/prefab design possible for secondary compared to new
Environmental impact (LCA)	1: 100% more CO2eq emissions 2: 50% more CO2eq emissions 3: 0% change 4: 50% less CO2eq emissions 5 100% less CO2eq emissions
Costs	1: Lower costs secondary material compared to new material 3: Similar costs secondary and new material 5: Higher costs for secondary material compared to new material
Social job creation	1: Less job creation secondary material compared to new material 3: Similar job creation secondary and new materials 5: More job creation secondary material compared to new material
Use of local materials	1: Less use of local materials secondary material compared to new material 3: Similar use of local materials new and secondary material 5: More use of local materials secondary compared to new
Life span	1: Lower life span secondary materials compared to new 3: Similar life span secondary and new materials 5: Higher life span secondary materials compared to new materials
Ease of construction	1: Less easy construction, more handwork/custom-made production needed 3: Similar ease of construction new and secondary materials 5: More easy construction, less handwork/more machinated production for secondary materials compared to new
Safety	1: Lower safety secondary compared to new materials 3: Similar safety secondary and new materials 5: Higher safety secondary compared to new materials
Ease of maintenance	1: Less easy to maintain compared to new materials 3: Maintenance similar between new and secondary materials 5: More easy to maintain compared to new materials

Supplementary table 2: Weighing of criteria. Three percentages are indicated for the Sustainability aspects indicating standard, high environment weighing and low environment weighing conditions (the latter two for sensitivity analyses).

Sustainability aspect (weighing %)	**Criteria**	**Indicator (weighing %)**
Environment (25%; 55%; 10%)	Reuse possibility	Modular / prefabricated design (50%)
	Environmental impact	LCA outputs (50%)
Economical (20%; 10%; 35%)	Financial feasibility	Costs (100%)
Social (15%; 15%; 15%)	Job creation	Social job creation (50%)
	Cultural benefits	Use of local materials (50%)
Technical (40%; 20%; 40%)	Durability	Life span (technical) (25%)
	Practical feasibility	Ease of construction (25%)
		Safety (25%)
		Maintenance (25%)

9.2 Appendix B

Scenarios modelled in LCA/MCA

Supplementary table 3: Scenarios for timber frame construction

Model #	**Product**	**Supplier**	**Assumptions**	**Data sources**
1	New spruce wood	Stora Enso	- Beams: 20cm (thickness) x 10cm (width) x 3m (length) - Walls: 2cm (thickness) x 3m (height), 127m (length). - Origin: Europe (usually Scandinavia, Eastern Europe or Russia) - A4 transport: 1500 km Swedish spruce; 200km Stora Enso - kgCO2eq emissions of A1-A4 - Quantities modelled: * 20.3m3 (12.7m^3 beams + 7.62m^3 single layer walls) * 27.9m3 (12.7m^3 beams and 15.2m^3 double layer walls (to allow for isolation in between walls)	- A1-A3 based on EPDs[88,89] - A4 based on Dutch transport emissions[55] - Weight of wood based on EPDs for new wood and https://opslagco2inhout.nl/en/motivatie for secondary wood
2		Swedish spruce		
3	Secondary wood	Old building's beams, interior walls and ceiling	- Good quality spruce wood (24.4m^3 beams, 13.4m^3 walls in total) - Processing to timber frame in Dutch factory with maximum transport distance of 200 km return trip - All material can be transported at once to factory for processing - 20% material loss due to processing/sawing - kgCO2eq emission of A3 and A4 only - Boat transport 2x for Pampus wood, 1x for other secondary wood	
4	Secondary wood + model 1	Old building supplemented with new wood	- As model 3, but supplemented with 4.5m^3 new wood for the walls from Stora Enso	
5	Secondary wood	Old building + secondary wood from local suppliers	- As model 3, but old building's wood supplemented with secondary wood from within the Defence line - Total of 20.3 and 27.9m^3 calculated	

Supplementary table 4: Scenarios for CLT in LCA

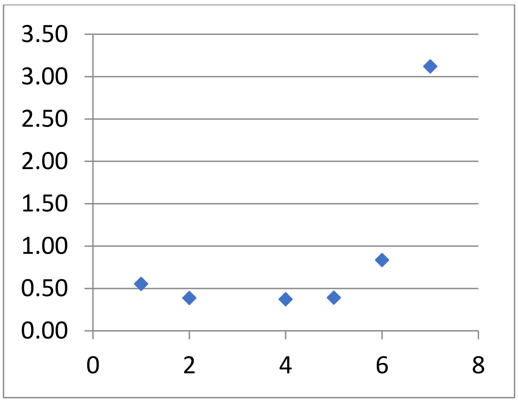
Model #	Product	Supplier	Assumptions	Data sources
1	New CLT	Derix	- 650m^2 wood panels with 20cm thickness (130m^3) - Transport distances lorry: Derix 200km (Niederkürchten, GE), DGV Holzleimbau 800km (Aichach, GE), DGV Stora Enso 1200km (Bad St. Leonhard, Austria)	- A1-A3 based on EPDs[90–92] - A4 based on Dutch transport emissions[55] - Weight of wood based on EPDs for new wood and https://opslagco2inhout.nl/en/motivatie for secondary wood
2		De Groot Vroomshoop (DGV) Holzleimbau		
3		DGV Stora Enso		
4	Secondary wood + model 1	Old building supplemented with new material	- Good quality wood from old building (670m^2, 13.4m^3 in total, 2cm thickness) - Old building wood processed to 20cm thickness boards to be the same as new (67m^2 total) - 20% material loss due to processing (53.6m^2 and 10.7m^3 total) - Add up with 596.5m^2 (119.3m^3) new CLT (supplier Derix) - For old building's wood, kgCO2eq emission of A3 and A4 only - Transport distance lorry: 400km (to Derix factory and back)	
5	Secondary wood + model 2	Old building supplemented with new material	As 4, but using DGV Holzleimbau as supplier for new material	
6	Secondary wood + model 3	Old building supplemented with new material	As 4, but using DGV Stora Enso as supplier for new material	
7	Secondary wood only	Old building supplemented with local secondary wood	- Assumed sufficient secondary wood from within the Stelling van Amsterdam (130m^3) - All material can be transported at once to factory for processing - Good quality wood - Boat transport 2x for Pampus wood, 1x for other secondary wood	

Supplementary table 5: Scenarios for furniture

Model #	Product	Supplier	Assumptions	Data sources
1	New tables/chairs	Dutch supplier	- Dutch supplier assumed, maximum distance 100km - Total of 25 tables and 100 chairs calculated - Dimensions chairs and tables as below	- A1-A3 based on EPDs[49–51] and literature[52,53] - Electricity (kWh) to CO2eq calculations based on www.co2emmissiefactoren.nl
2	Secondary tables/chairs	Old building's wood	- Good quality Red Cedar wood (155m^2 in total) - 20% wood loss due to removal of nails, planing, etc - Hand-made on Pampus - Metal screws/glue not included in LCA - Wood from exterior walls only (thereby also suitable for outdoor furniture) - Size tables: 140 x 90 x 2cm (tabletop), 7 x 7 x 75cm (table legs); 10.4kg - Size chairs: 56 x 60 x 2cm (seating), 56 x 41 x 2cm (back), 46 x 4 x 4cm (legs); 4.3kg - Total of 25 tables and 100 chairs (4 chairs / table) - Capacity circle saws: average (1133 W) of three circle saws (Bosch, DeWALT DWE575K, Hecht 1614) used for kWh and CO2eq emissions	

9.3 Appendix C

Data distribution for CO2eq emissions of furniture



Supplementary figure 1: Variation of kg CO2eq emissions for furniture (wooden tables and chairs). Although one data point is much higher than the other five, data were still Europe-based and relevant to the current study. Therefore, this data point was included in the analysis.

9.4 Appendix D

Summary expert interviews

Supplementary table 6: Overview of expert interviews

Expert interview #	Company	Area
1	New Horizon	General construction with wood
2	EcoScala (CLT and TFC)	
3	Derix	CLT production
4	De Groot Vroomshoop	
5	Houtbouw 't Zand	TFC production
6	Anonymous*	
7	Herso	Furniture production
8	Meubelmakerij Kruizinga	
9	Fiction Factory	

<u>New Horizon</u>

New Horizon 'harvests' construction materials from buildings that are demolished, and works together with suppliers to bring materials back on the market. For example, secondary wooden beams are supplied by Stiho. The same quality for secondary materials as new materials will be guaranteed. It depends how many nails need to be removed, or how mixed materials are, but in general, most of the construction materials can be reused, and quality is usually not a problem. The costs of secondary and new wood are similar.

<u>Ecoscala</u>

Secondary wood can easily be reused with regard to the technical life span (it is either good quality or rotten). Best is to reuse in the same function, or even better to renovate a building. However, although reuse of materials sounds good, the advantage of prefab of new materials is the large reduction in waste generation on the construction site, which is a large contributor to waste in general. CLT made from secondary wood is practically not feasible, because you would need a special factory to do this. TFC is possible from existing wooden beams. Costs are higher for secondary wood due to removal of nails, glue and paint.

<u>Derix</u>

Red cedar wood is not suitable for CLT, as it is not strong enough (should be at least C24 strenght). CLT is made from spruce, pine, larch and douglas wood and is certified by the European Technical Assessment specifying the wood types that can be used. Secondary wood is possible, but it needs sorting, drying, sawing and upgrading to ensure it complies with the quality norms. However, despite people asking for it, secondary wood has not been used so far. The costs are unclear, currently, the costs of new wood are high, so it may be profitable to use secondary wood.

The life span of secondary wood is the same as new wood. CLT is applied indoors and the life span is the same with secondary wood.

<u>De Groot Vroomshoop</u>

Secondary wood is possible, theoretically, but in practice, this will be difficult due to financial and practical reasons. There need to be extra steps such as sorting of the wood, ensure clean wood, transport to factory (outside of the Netherlands) and inefficiency in production (secondary wood cannot enter the production process immediately). This will bring extra costs as there is no profitable business model for secondary wood. Therefore, their advice is to use secondary wood as it is, without any sawing.

Houtbouw ‘t Zand

In the Netherlands and Ireland, TFC is often made prefab, in contrast to other countries. Reuse of wooden beams as TFC is possible, but not done very often because the logistics are lacking. Nails need to be removed, certifying has to be done and the costs are 3-4x higher than new wood. For non-load bearing wood, reuse is easier. Usually it is recycled low-grade, into animal bedding, shredded, or for cardboard/paper industry. Life span and safety of secondary wood are the same as new wood, after checking and certification.

TFC is made from spruce wood, usually it derived from Europe, Scandinavia, Baltic states, Russia.

Sizes of the wooden beams are usually 38mm width, 24-26cm height in walls, and 28-30cm height in roofs to obtain a higher isolation.

Anonymous

TFC is made prefab and easy to disassemble at the end of life. Secondary wood can be used for TFC but it will take longer and reduces the idea of prefab production. Due to the longer time of production, the costs will be higher for secondary wood. In general, the quality, life span of secondary wood is the same as new wood.

Herso

The costs of secondary wood use in furniture production is lower, as there is no purchase of new wood. However, there is the manufacturing costs. The life span of secondary wood is similar to new wood, as long as you take good care of the product. Practically, it is usually easier to use new wood, but new behaviour is needed to change the business. It can take longer to collect enough wood for production, and you have to pay VAT for secondary wood as well, so twice. It would be better if that would not be the case. Modular construction: Herso uses glue, but formaldehyde-free glue, which is better for the environment.

Meubelmakerij (furniture manufacturer) Kruizinga

The costs of secondary wood depend on the price for new wood. It takes extra time to use secondary wood, so the costs mainly depend on the salary of the furniture maker. The life span of secondary wood is the same as new, as long as you select the wood carefully. It is possible to reuse, but screws need to be removed, and dirty wood can damage the machinery. It is important to be careful and select good wood. Type of wood used for furniture is often hard wood as this is easier for detailed furniture manufacturing. Birch wood is good for furniture. Modular manufacturing is possible, only glue the parts that never need to be separated again.

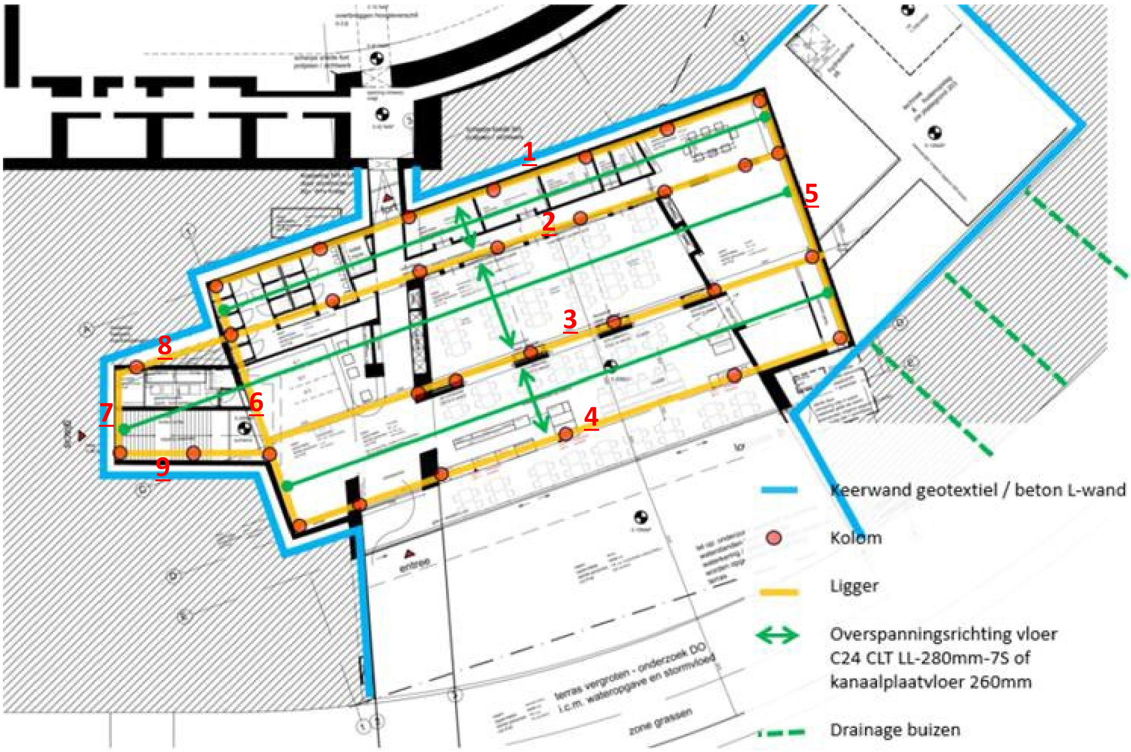
Fiction Factory

The costs of secondary wood are higher due to time consuming task of removing nails etc and therefore high salary costs. The life span of secondary wood is the same as new wood. Suitable wood in the old building are Red Cedar and Spruce. Spruce should be used inside. With respect to modular manufacturing, Ikea is a good example.

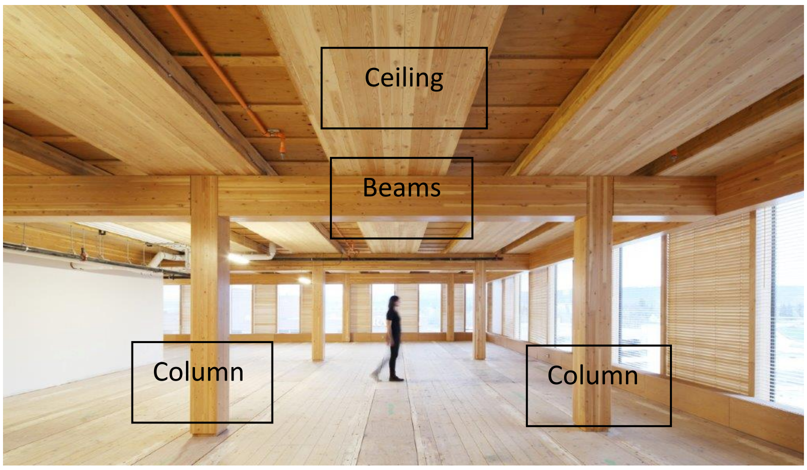
9.5 Appendix E

Design new entrance building on Pampus

The new entrance building on Pampus will be constructed largely underground (Supplementary figure 1) with columns, beams and ceiling made from cross-laminated timber (CLT) as indicated in Supplementary figure 2 (example figure). The total dimensions of the yellow lines # 1, 2, 5, 6, 7, 8, & 9 indicated in Supplementary figure 2 were used to calculate the quantity of TFC needed (approximately). Total length of these walls was 127m, and with 3m height resulted in a total of 381m^2 and 7.6m^3 (0.2m thickness) of wall wood required. Beams for TFC have to be placed every 60cm, which resulted in a total of (127/0.6) = 211 beams required. Dimensions of walls and beams are in Supplementary table 3.



Supplementary figure 2: Design of the new entrance building on Pampus. Blue lines: retaining wall; Red dots: CLT columns; Yellow lines: horizontal CLT beams. Image is copyright protected by Paul de Ruiter Architects and cannot be reproduced without permission[1]

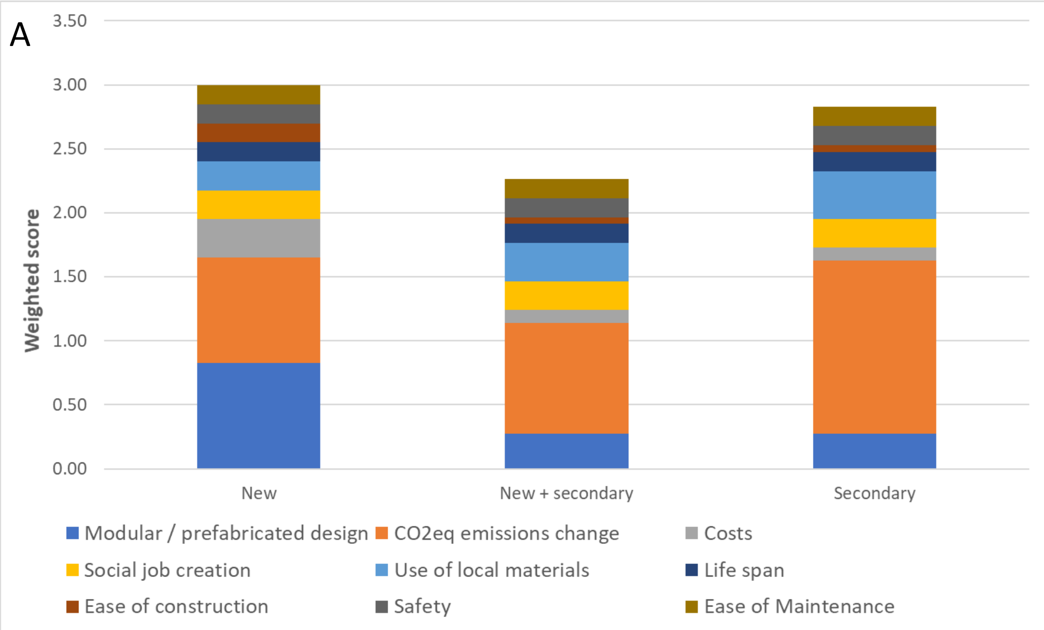


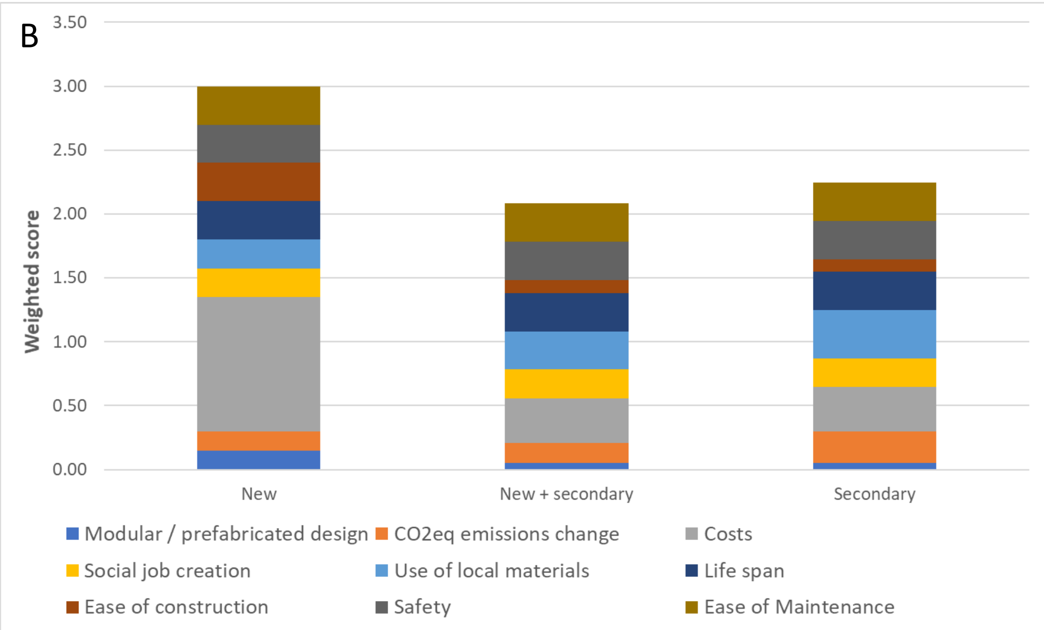
Supplementary figure 3: Example of CLT columns, horizontal beams and ceiling.

9.6 Appendix F

MCA sensitivity analysis

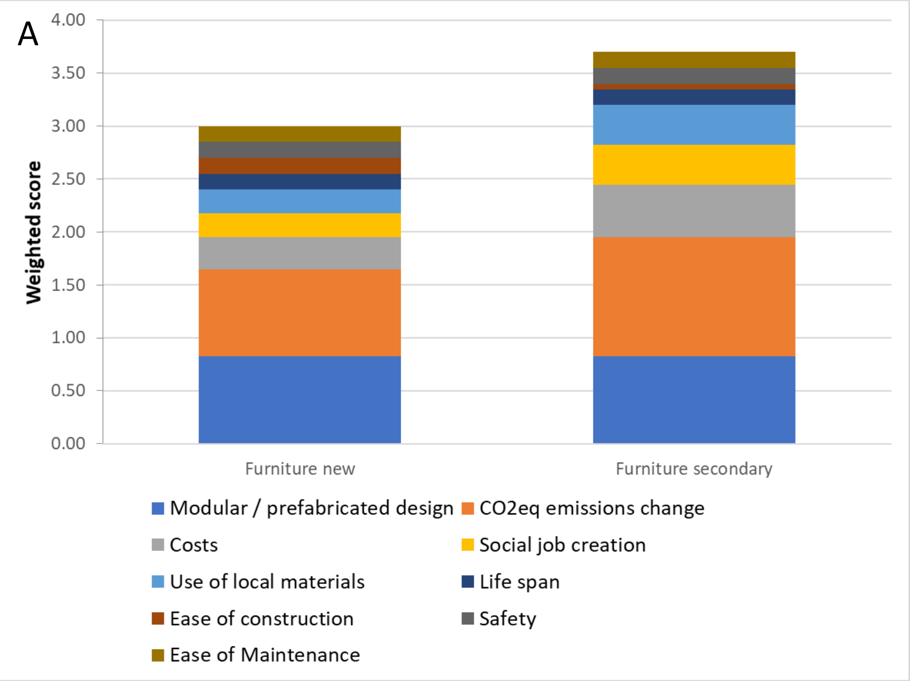
Scenario 2: CLT

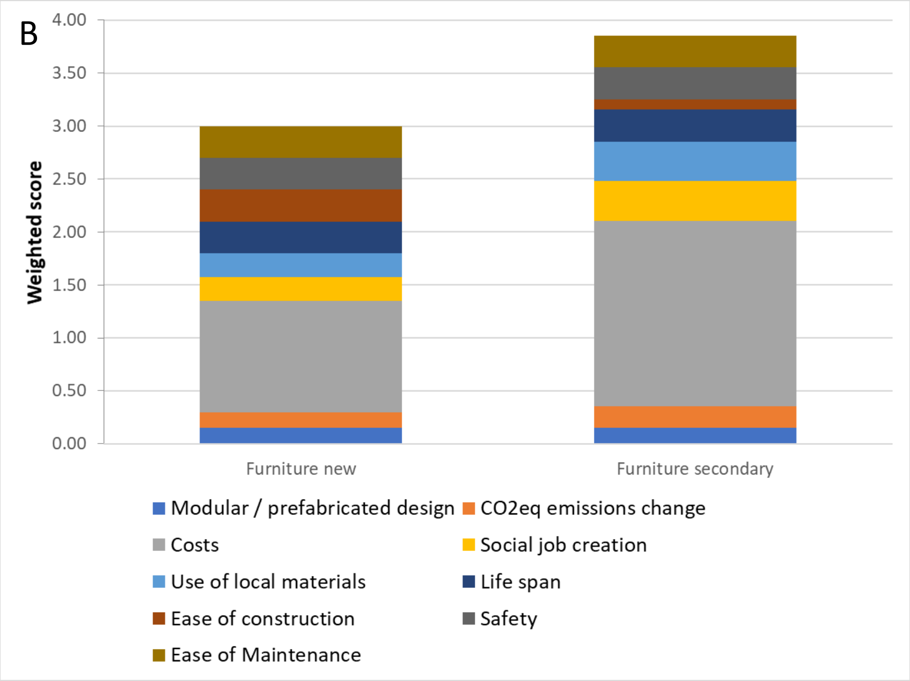




Supplementary figure 4: Sensitivity analysis CLT scenario with environmental-heavy (A) and cost/practical-heavy weighting (B). Low CO_2eq emissions in A3 for secondary wood were used.

Scenario 3: Furniture





Supplementary figure 5: Sensitivity analysis furniture scenario with environmental-heavy (A) and cost/practical-heavy weighting (B).

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