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Article

Reusing Timber Formwork in Building Construction: Testing, Redesign, and Socio-Economic Reflection

Arno Pronk [1], Stijn Brancart [2,*], and Fred Sanders [3]

[1] Faculty of the Built Environment, Eindhoven University of Technology, The Netherlands
[2] Faculty of Architecture and the Built Environment, Delft University of Technology, The Netherlands
[3] CPONH NGO, The Netherlands

* Corresponding author (s.brancart@tudelft.nl)

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Abstract
In 2018, the construction sector was responsible for 39% of the worldwide energy and process-related carbon dioxide emissions (Global Alliance for Buildings and Construction et al., 2019). This is partly due to the embodied carbon, which represents the carbon emissions related to building construction and material production (LETI, 2020). While zero energy buildings and zero energy renovations start to get the operational carbon down, the circular economy aims to do this by closing material loops and stimulating the reuse of discarded materials in building construction (Ellen McArthur Foundation et al., 2015). Although it is not a new phenomenon, material reuse does require a substantially different approach and is at this point not yet common in the building industry. This is especially true for load-bearing components. This article presents a pilot project for the reuse of discarded timber formwork for the construction of the façade and (load-bearing) substructure of a new house. Through this pilot case and by reflecting on a series of similar cases, it studies the remaining challenges for material reuse but also proposes and assesses redesign strategies that will allow upscaling the reuse of timber formwork. The project shows that although waste, material, and money can be saved by using reclaimed materials, it does complicate the design and construction process and, as such, does not necessarily reduce the total project budget. Moreover, for reuse to become a current practice, new design approaches and collaborations will need to be established. Finally, socio-economic factors must be considered to increase the acceptance of reclaimed materials in new building construction.

Keywords
circular economy; circular housing; CO_2 reduction; material reuse; resource efficiency; sustainable architecture

Issue
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1. Introduction

Considering the current climate and sustainability crisis, a lot of focus is put on reducing building-related carbon emissions. This is not surprising, since the building sector is responsible for almost 40% of worldwide energy and process-related CO_2 emissions (Global Alliance for Buildings and Construction et al., 2019). While policy makers and the construction sector are moving increasingly towards the construction of zero energy buildings, another aspect of sustainable construction is slowly reaching the foreground: the embodied carbon. This is the carbon that is emitted during the construction, maintenance, and end-of-life processing of a building and its materials (LETI, 2020). The embodied carbon of buildings has been underrepresented in the sustainability discourse in favour of the more acute need to lower operational carbon. Some studies even suggest that the embodied carbon of buildings is increasing due to higher material consumption in low and zero energy buildings

(Giordano et al., 2017). Others show that embodied carbon is much more related to the types of buildings and the materials that were used (Hoxha et al., 2017). Overall, however, with decreasing operational carbon, the embodied carbon is starting to represent the larger share of the total carbon emissions of buildings (LETI, 2020). Without efficient strategies for reducing it, the construction sector will never be able to effectively and adequately reduce its environmental impact. Reducing the impact of material use in construction cannot be considered separately from the recent developments regarding the circular economy (Ellen McArthur Foundation et al., 2015). Much of this material impact is related to the extraction of virgin resources and the waste management of discarded materials after all. Circular construction aims at closing material loops by reusing or recycling construction materials or by growing the required resources in a biological cycle (Galle et al., 2019). Effective reuse of building materials requires strategies for the repurposing of discarded materials on one hand while transitioning towards a more futureproof construction practice that extends the functional life of new buildings and materials on the other. The latter, which is generally called design for change, aims at facilitating reuse and repurposing of buildings and building elements in the future (Brancart et al., 2017). The former allows an immediate reduction of both waste production and virgin material use, and can, as such, lower embodied carbon instantly (Brütting et al., 2020). This article focuses on direct reuse.

While not yet common practice, material reuse is not a new phenomenon. Many interesting examples have been scattered throughout history, especially at times when material costs where high and labour was much less expensive (Addis, 2012; Fivet & Brütting, 2020). Within the context of the circular economy, the reclamation of building materials during demolition, so-called urban mining, is gradually finding its way into practice (Arora et al., 2020; Koutamanis et al., 2018). Reclaimed bricks, interior doors, and roof and floor tiles start making up a second-hand market, as they are often being sold by demolition companies (Devlieger et al., 2019). Exemplary cases do however show that the use of reclaimed materials requires specific attention and current design approaches often fail to accommodate them (Kawa, 2021). In many cases, the exchange of materials between a demolition site and a construction project will require careful planning. The main challenges for reuse appear to be situated on a social and organisational level (Gorgolewski, 2008). Moreover, unknowns about the material properties often require additional studies or testing (Brütting et al., 2019). As a result, reclaimed materials are often applied in building layers with low-performance criteria where quality assurance is not required or can be more easily done.

This article zooms in on the use of reclaimed timber. It argues that the reuse of building materials and in this case, timber can help substantially lower the embodied carbon levels of buildings. Yet, to increase the uptake of reclaimed building components, some barriers need to be overcome. Therefore, the article first aims to provide a general overview of reuse strategies and current limitations, based on a review of built cases. Secondly, it goes in-depth on one specific challenge: the reuse of discarded timber formwork. The functional lifetime of timber formwork is short compared to its technical life. This currently leads to high amounts of waste and loss of economic value. This article, therefore, studies the reuse potential of formwork in housing construction and investigates redesign strategies to increase it, based on an A-to-Z case study for a new circular house on IJburg Amsterdam, compared to several similar projects. The research focuses on the following two specific questions: What is the load-bearing capacity of the formwork elements? Which connection types will allow more effective reuse?

Specific about the central case study is that one of the building owners is also the project architect and principal investigator of this study. As such, he was actively and positively involved in the material reuse. The other residents, his family, and another family with which they share the house, were less involved. While they acknowledged the value of a circular design and construction approach, they were also concerned about the impact on the building layout and appearance. This kind of resistance is not uncommon. Aside from technological challenges, there are also socio-economic barriers to overcome (Charef et al., 2021). Consumers are used to choosing from extensive catalogues of buildings materials. Moreover, they lack experience with and knowledge about circular products, their advantages and drawbacks. This results in a lack of confidence about the durability, quality, and usability of the products, along with a general resistance to change. Many of the studied cases report such resistance in one or more of the project stakeholders. Yet, open communication but especially the quality of the design and finished project managed to persuade them. In most projects though, the focus remains on the technological solutions, as this type of sustainable construction is still in a more explorative and experimental stage (Schut et al., 2016). While this article does primarily consider the technological barriers to material reuse, it does reflect on the socio-economic aspects that will be required to scale-up circular construction practices.

2. Building With Waste: Reclaimed Timber for Façades and Load-Bearing Construction

To better understand and position the pilot project that is presented in the following sections, this article first drafts a more general framework by reflecting on a series of representative cases. These cases focus on the application of reclaimed timber products in façades and load-bearing structures. Figure 1 shows the nine selected cases. Although they all share similarities as well as

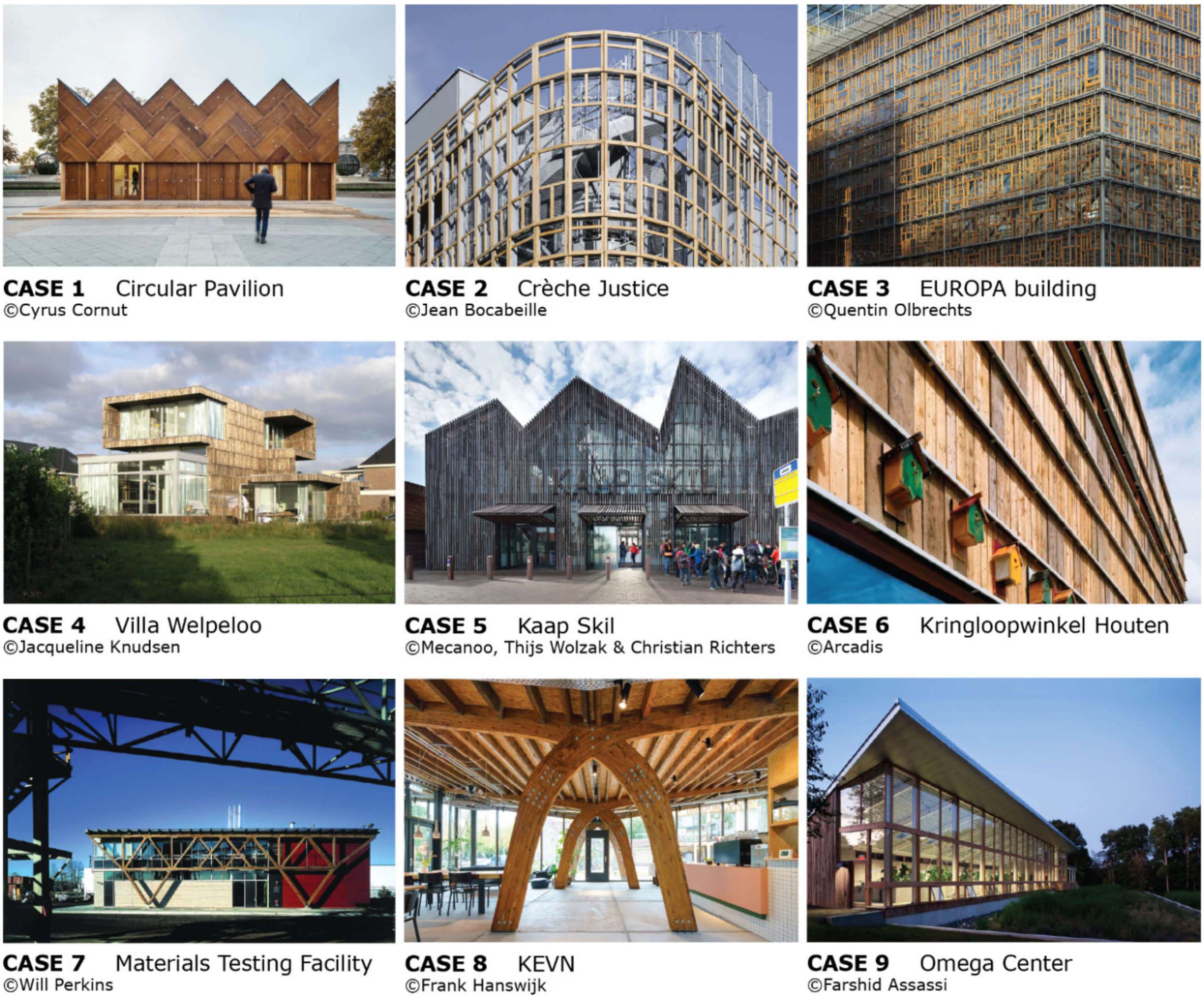


Figure 1. The nine selected project cases.

feature some unique characteristics, they can be roughly divided into three groups. Cases 1 to 3 represent the reuse of reclaimed building products like doors and window frames in new façades. The EUROPA building is the only of these cases in which the reclaimed elements—in this case, window frames—were reapplied for the same function. Cases 4 to 6 all include façades that were clad with reclaimed materials from outside the building industry: from damaged cable reels over hardwood sheet piling to used transport pallets. Cases 7 to 9 finally represent the category of buildings in which reclaimed timber is used as part of the load-bearing structure. Such cases are of particular interest in the scope of the presented pilot project. They are however far less common and underreported in (scientific) literature.

Table 1 summarises the most relevant project information and lessons learned. These were gathered from existing literature (including scientific articles, new articles, and interviews with designers or building owners). While each project is characterised by a distinct approach, it is possible to draw some general conclusions. Based on the variety of cases, it is reasonable to assume that these conclusions can be generalised, though it is also clear that many of the studied aspects should be considered case by case. The analysis focuses on four aspects: motivation, process, application, and cost.

In most cases, sustainability aspects like waste savings and a reduction of the embodied energy provided the main motivation for the application of reclaimed timber. The choice for material reuse was generally part of much broader sustainability ambitions related to energy performance, circularity and, in the case of the Omega Centre, even regenerative design. Yet, in all cases, the designers or building owners point towards the improvement of the project's overall architectural quality as one of the main advantages of material reuse. The reclaimed materials were made highly visible and often have a prominent position in the project, even in cases like KEVN and the Materials Testing Facility, where they are part of the load-bearing structure. In some projects, the origin of the materials plays a role in the design concept. This is especially clear in the case of Kaap Skil, where maritime sheet piling was used in the façade of a maritime museum, but also in the EUROPA building, with its façade consisting of reclaimed window frames from all EU member states.

The prominent position of the reclaimed timber in the architectural concept warrants an equally prominent position in the design and construction process. The limited availability and often small volumes of reclaimed materials, logistic considerations regarding transportation and stocking, and the many unknowns related to material properties and quality assurance require specific actions. These differ fundamentally from the conventional approach, in which new building products are often selected at a later stage or the end of the process. In many of the presented cases, the design team, therefore, collaborated with reuse experts. Two lessons

Table 1. An overview of the basic project info and most important lessons learned.

Case	Reuse	Lessons Learned	References
Circular Pavilion Paris (FR), 2015 Encore Heureux Architects	Interior doors as façade cladding	The final design had to be adapted to the exact sizes of the door panels	Valenzuela (2015) and Kawa (2021)
Crèche Justice Paris (FR), 2020 BFV architects with Bellastock	Interior door (frames) as façade cladding	Material changed for final design based on unsuitable performance	Myers (2020) and Kawa (2021)
EUROPA building Brussels (BE), 2017 Samyn & Partners	Window frames from different EU countries	A double façade guarantees adequate energy performance, a mathematical system defines the seemingly random pattern of the differently sized frames	Wright (2017)
Villa Welpeloo Enschede (NL), 2009 Superuse Studios	Timber from cable reels as façade cladding	The design of the façade is based on the size limitations of the reclaimed timber pieces	Superuse Studios (2009) and Kawa (2021)
Kaap Skil Texel (NL), 2011 Mecanoo architecten with Pieters Bouwtechniek	Hardwood sheet piling as façade cladding	Use of maritime wood enforced architectural concept for maritime museum, contractor attracted based on involvement in demolition project	Opalis (n.d.) and Mecanoo (n.d.)
Kringloopwinkel Houten Houten (NL), 2012 Arcadis	Transport pallet wood as façade cladding	Reuse of pallet wood resulted in considerable savings, the design and outlook of the façade are defined by a large variety of timber pieces	DGBC (2020)
Materials Testing Facility Vancouver (CA), 1999 Busby + Associates Architects with Fast & Epp Partners	Timber trusses, glulam beams as floor decking	Underestimation of glulam's strength, reclaimed timber a lot cheaper, strong involvement of partners, scepticism of users turned to appreciation of result	Public Architecture (2011) and Brütting et al. (2019)
KEVN Eindhoven (NL), 2020 Superuse Studios	Timber frames	The frames were cut to make purlins from the same timber, the entire pavilion can be disassembled for another reuse	Superuse Studios (2020)
Omega Center New York (USA), 2009 BNIM Architects with Planet Reuse	90% of total timber use, including frames, panels, doors, beams	Specifications should be flexible to allow changing material choices based on availability, the involvement of a reuse broker helps maintain a tighter schedule, reclaimed timber is considerably cheaper than new FSC timber	Public Architecture (2011)

were drawn from almost every project: It is important to prepare for material reuse early in the design process and the design and construction team need to be sufficiently flexible to deal with and adapt to the many unknowns. Additionally, it appears that strong collaborations, as well as open communication, were key in making the reuse work.

The selected cases all feature reclaimed timber in façade and load-bearing applications. In most cases, the materials were applied for functions different from their initial use. Even more so, several of the reclaimed materials originally weren't building products at all. In almost all cases the materials first had to be processed to be sized, protected, and installed properly for their new function. Thanks to its great workability, this is relatively simple when using timber. While reclaimed materials are getting more and more common for the cladding of façades, it is more difficult to find cases of reclaimed load-bearing structures. This is most likely due to the required performance levels and associated risks. These structural requirements often ask for creative solutions. The timber trusses in the Materials Testing Facility for example were recomposed from the most qualitative pieces of the reclaimed truss elements. Due to unknowns about the structural integrity of the glulam beams, the design and engineering team decided to apply them as floor decking, thus overdimensioning the structure but also avoiding having to rely on the strength of the glue (Public Architecture, 2011).

A final important aspect is the cost. It is difficult to provide a general conclusion or even make a meaningful comparison between the cases for this. After all, the available budgets for the different projects differed largely as well as the origin of the reclaimed materials and the technical complexity related to their reuse. While the thrift shop in Houten was realised with a small budget (one million euros for 1392 m^2), shipping window frames from all over Europe has undoubtedly only increased the total project cost of the EUROPA building. In general, savings can be made with respect to the actual material cost. In most cases, these materials would have been discarded as waste after all. Yet, the logistics and additional work hours often increase considerably. In many cases, an additional partner had to be added to the team or contractors and engineers needed to be involved earlier and more intensively. Moreover, temporary storage, transportation, and, in some cases, prototyping and testing, ramp up the budget. As such, it is not possible to say that material reuse will automatically result in a reduction of the project cost.

In most of these cases, the end user was not heavily involved in the building design and material selection. Out of the nine projects, only Villa Welpeloo (case 4) was realised on behalf of the actual end user. The residents and building owners, a young couple, had the express wish to build a sustainable home by integrating as many aspects of circular design as possible. They commissioned a young architectural firm and together they achieved 60% reuse of existing materials. This required making some concessions, but these were acceptable seen as the circular design was one of the initial requirements. The other cases mainly concern public buildings and, as such, the end user was not intensively involved in the construction process and circular design choices. Moreover, cases like the EUROPA building, using a mix of different reclaimed window frames, or Kaap Skil, using maritime wood in a maritime museum, show that reclaimed materials are still mostly used in "eye-catching" applications. As such, they underline the potential added value of circular design. This does however avoid owners or end users having to make concessions in terms of expected interior appearance or supposed quality of materials that often hinder the application of reclaimed materials.

The reference projects show that qualitive material reuse can be achieved, but the exceptionality of the buildings also shows that it remains a niche and the use of reclaimed building materials has not yet become commonplace in more everyday construction. While the availability of used materials appears to be increasing, their reuse is not yet established, partly because the recycling of materials such as aluminium, glass, and concrete granulates has already been perfected (Rijksdienst voor Ondernemend Nederland, 2021; Sanders & van Timmeren, 2018). Although the costs of circular material and product use outweigh those of other materials in the long term, it appears that the initial additional cost is insufficiently quality-enhancing to convince customers, home or building owners. This has a negative impact on the uptake of used materials, for example in the construction sector in the Netherlands (Oostra, 2020).

3. The IJburg Villa of Reused Wood as Central Case Study

This article focuses on a central case study, a residential villa in Amsterdam, the Netherlands. The project was realised in 2017 and is a pilot project for the application of reclaimed timber formwork in new building construction. This case is of particular interest as it reuses the timber formwork for load-bearing elements. Thanks to mechanical testing, performed by the authors, the case provides insight into the capacity of the formwork and its reuse potential for different building elements. The presented method can be adapted to study the reuse potential of other load-bearing building products. In this case, the discarded plywood formwork was applied both in the outer walls and the floor, as part of the (load-bearing) structure. Figure 2 shows design drawings of the building, pictures of the building during construction, and pictures of after its realisation. As large quantities of plywood formwork are discarded regularly, there is a clear potential for its reuse, even on a larger scale. The goal of this pilot project was to study the feasibility of formwork reuse, especially for structural applications.

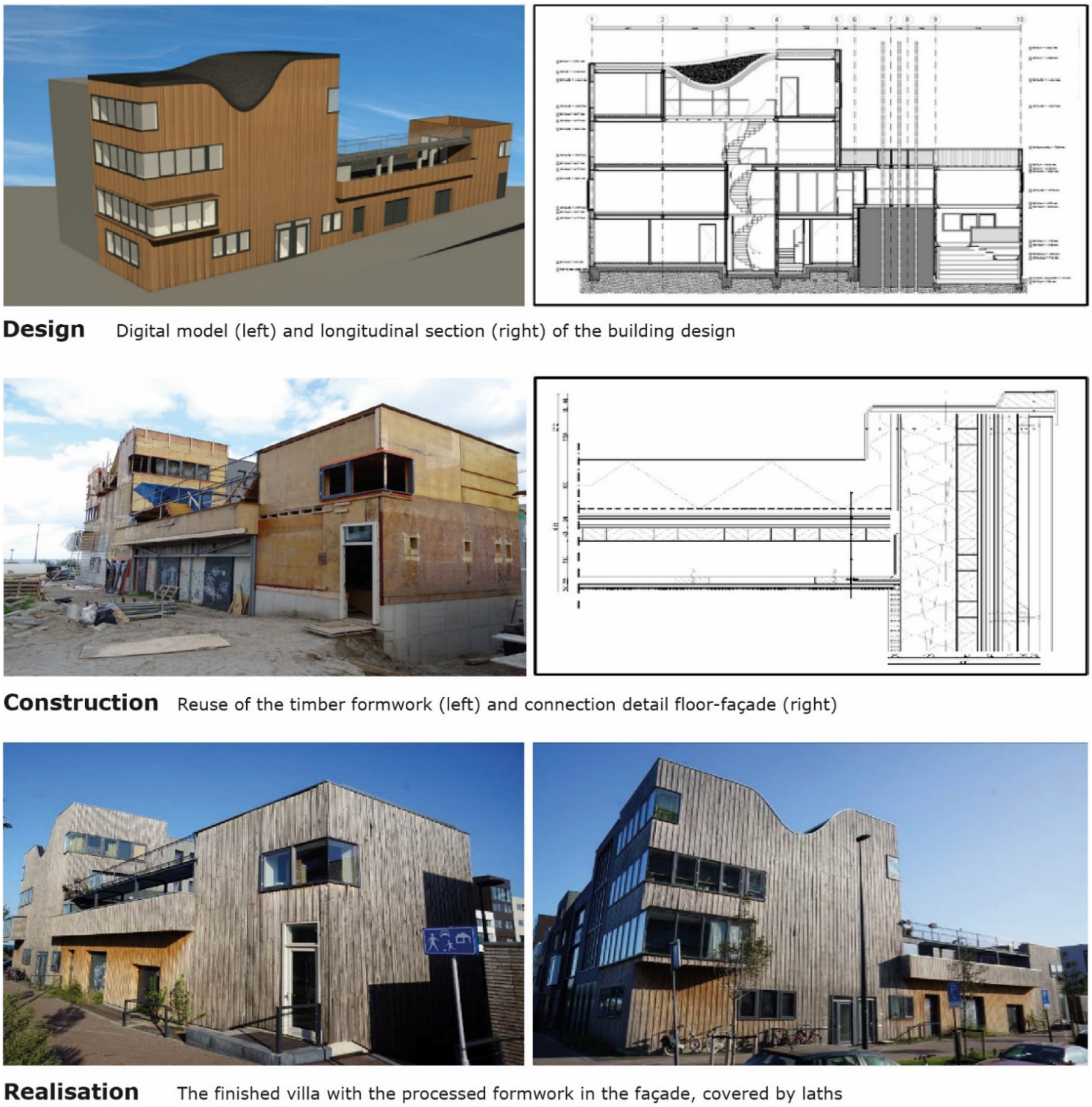


Figure 2. Design, construction, and realisation of the villa with reused wood.

The irregularities in the formwork make it less suited for visible finishing layers. Their high thickness of up to 17 centimetres, however, makes them well suited for load-bearing walls or floors.

At the construction site, the panels were put together to form a four-layer shell of walls and floors. The façades at the end have a load-bearing function. Between these façades, the floors are supported by steel trusses. A steel beam is required at various locations to bridge the dimensional differences of the plates. The wooden floors disappear under insulation material and a cast floor. On the outside, the house is finished with vertical wooden laths. Little of the wooden formwork elements is visible in the final stage. By the time the house was finished, no traces were left of the origin of the reclaimed materials.

4. The Timber Formwork

The purpose of this project is to investigate the reuse and recycling potential of old formwork elements. The CO_2 emission and energy consumption will be 522 kg CO_2 for every cubic meter of plywood based on research by Ashby (2013), Hill et al. (2018), and Danielson (2014). The CO_2 emission factors of the materials are based on processing, manufacturing, energy conception, and transportation. The reuse of this material will result in a considerable reduction of the carbon footprint. This article looks at different opportunities based on the reuse of old formwork of a Dutch concrete contractor specialized in concrete production. A lot of timber formwork is produced every day, but its reuse is limited. The maximum amount of use cycles (as formwork) is determined by the flatness of the shelf and the project characteristics and could rise to a maximum of seven times. Therefore, it is good to look at new opportunities for old formwork that cannot be used anymore. The formwork elements are designed without making any structural calculations. The goal is to make formwork elements with a completely flat and smooth surface in a cost-efficient way. When they are discarded, the elements are taken apart and stored until they are pulverized (see Figure 3).

4.1. Composition of the Formwork Elements

As shown in Figure 3, the formwork elements consist of pine beams that are connected perpendicularly to other, load-bearing pine beams using timber screws. The beams are covered with plywood and lacquered to keep the timber dry. A PVAC glue connects the plywood to the beams. The shelf is fixed with additional staples. Due to the irreversible connection of all these layers, the formwork cannot be disassembled after being discarded.

4.2. Types of Formwork Elements

There are two types of formwork elements (see Figure 4):

1. The A-series consists of formwork elements with full cross sections on large scale.
2. The B-series consists of formwork elements on sample scale. Within this B-series, two types are provided: (a) the BB-series, consisting of a full cross-section sample, and (b) a BZ-series consisting of just the shelf, without a connected beam.

Figure 5 presents the characteristics of series A, B, and BZ.

5. The Mechanical Properties of Timber Formwork

As no structural analysis or mechanical testing is performed during the development of the timber formwork, information about the mechanical behaviour is lacking. For the application of the formwork in the construction of the villa, it was, therefore, important to perform a series of mechanical tests and evaluate the derived properties. This section presents the results of this testing, performed by the authors. Based on this, it reflects on the role and importance of testing procedures and barriers to overcome.

5.1. Bending Test

The samples of the A-series were tested with a 3- and 4-point bending test. The 3-point bending test is carried out to determine the maximum concentrated load. The samples are positioned on two supports with a span of 1800 mm. An equally distributed line load is increased

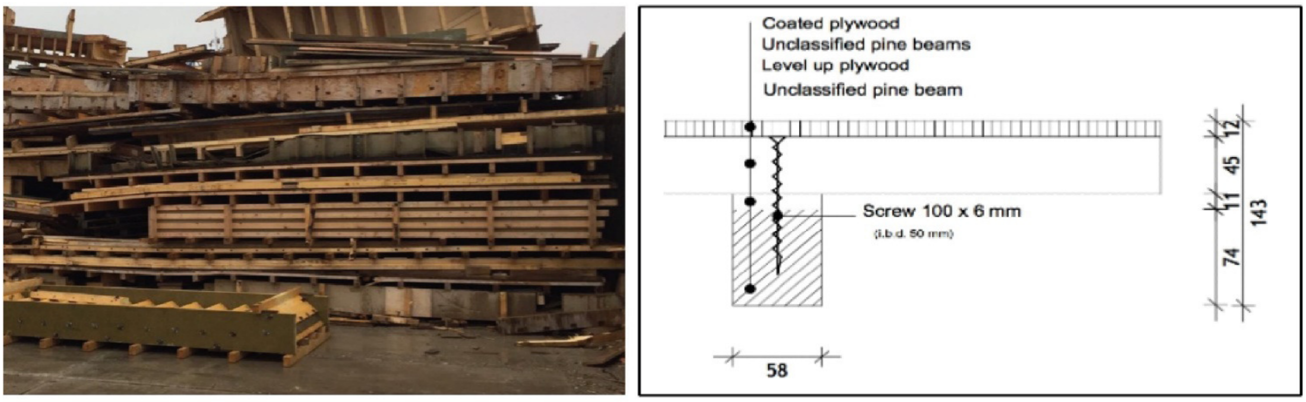
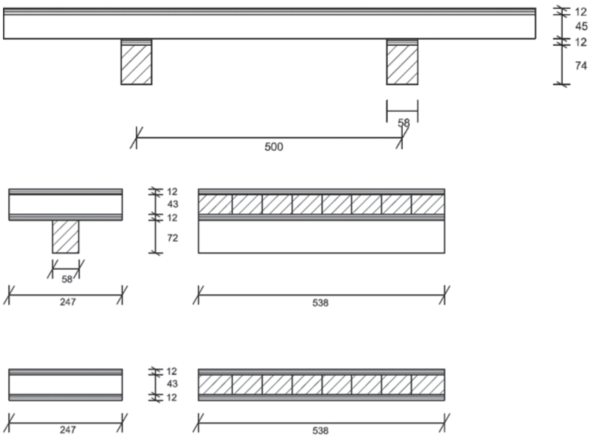


Figure 3. The basis material of old formwork at the depot (left) and its construction (right).

Figure 4. The two types of formwork elements: A-series (left) consists of formwork elements with full cross sections, B-series (right) consists of formwork elements on sample scale.



Property	Average	Average deviation
Length	1899 mm	0 mm
Width	998 mm	6.82 mm
Total height	153 mm	0 mm
Shelf height	60 mm	0 mm
Area of holes	926 mm2	718 mm2
No. of filled holes	18	14.4

Property	Average	Average deviation
Length	538 mm	0 mm
Width	248 mm	2.53 mm
Moisture content beam	15%	2.11%
Moisture content shelf	18%	3.40%
Mass	6.3 kg	0.18 kg

Property	Average	Average deviation
Length	538 mm	0 mm
Width	246 mm	2.83 mm
Moisture content shelf	23.0%	2.95%
Mass	5.2 kg	0.04 kg

Figure 5. The test samples represent different types of formwork, varying in shape and size. From top to bottom: The A-series consists of nine samples, each derived from one big shelf; the B-series consists of seven samples, each derived from one big shelf; final the BZ-series consists of six samples, each derived from one big shelf.

with 4 kN per minute. The results are expressed by force-deformation graphs (Figures 6 and 7). All samples show a significantly higher strength than required for residential floors.

Further on, the needed force for a deformation of 7,2 mm is in the range between the minimum and maximum calculated estimated force values of 2,28 kN < F < 25,7 kN. Therefore, it can be concluded that the load-bearing part does not only consist of the lower beam, but the elements are also not fully connected.

The 4-point bending test was carried out (see Figure 7), in addition to the 3-point bending test, on the samples of the A-series. A 3-point bending test indicates the maximum concentrated load of the sample. The place of failure will take place close to the middle of the span, where the maximum bending moment occurs. A 4-point bending test, however, is preferred because failure in this case occurs at the weakest spot. The cause of this is that in the area between the loads, the bending moment remains constant and the shear force is equal to zero. The load capacity of the formwork elements is compared to the requirement according to the Dutch Building Act, which states a minimum concentrated residential floor capacity of 3 kN. The allowed deformation equals L/250 = 7,2 mm. The samples in this experiment are not loaded to failure like in the 3-point bending test. This test stopped when the deformation was a bit over 7,2 mm because strength characteristics were already

Sample	Ultimate load (kN)
A1D	25.4[1]
A3D	24.5
A4D	25.6
A6D	27.3
Average	**25.8**
Deviation	**1.0**

Sample	Needed force for maximum deformation (kN)
A1D	10.3[2]
A3D	11.6
A4D	11.6
A6D	12.3
Average	**11.8**
Deviation	**0.3**

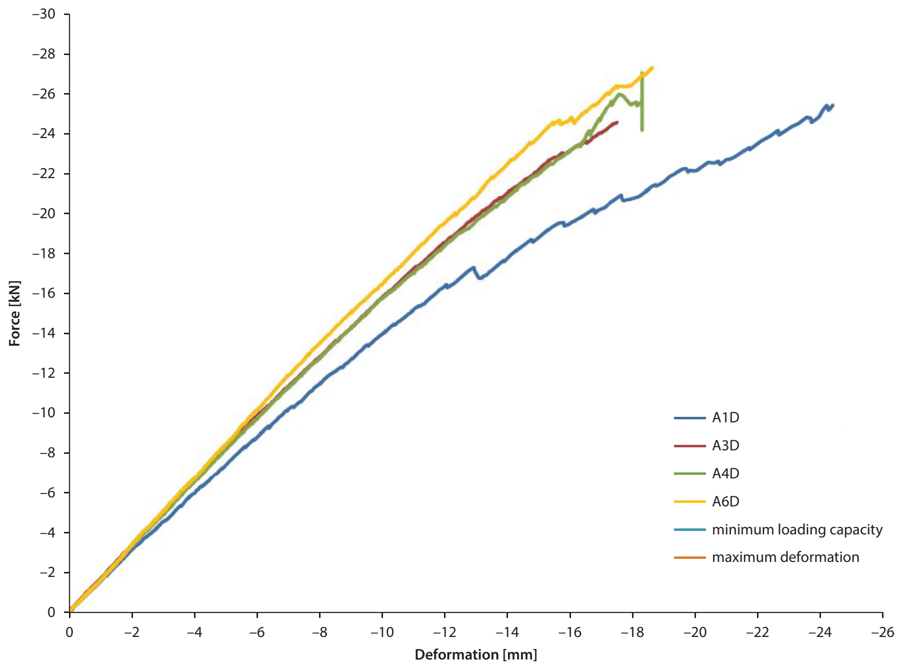


Figure 6. Ultimate load (left), deformation (centre), and required force for maximum deformation (right) based on a 3-point bending test.

Sample	Needed force for maximum deformation (kN)
A2D	18.7
A7D	17.0
A8D	17.5
A9D*	13.7[3]
Average	**17.7**
Deviation	**0,6**

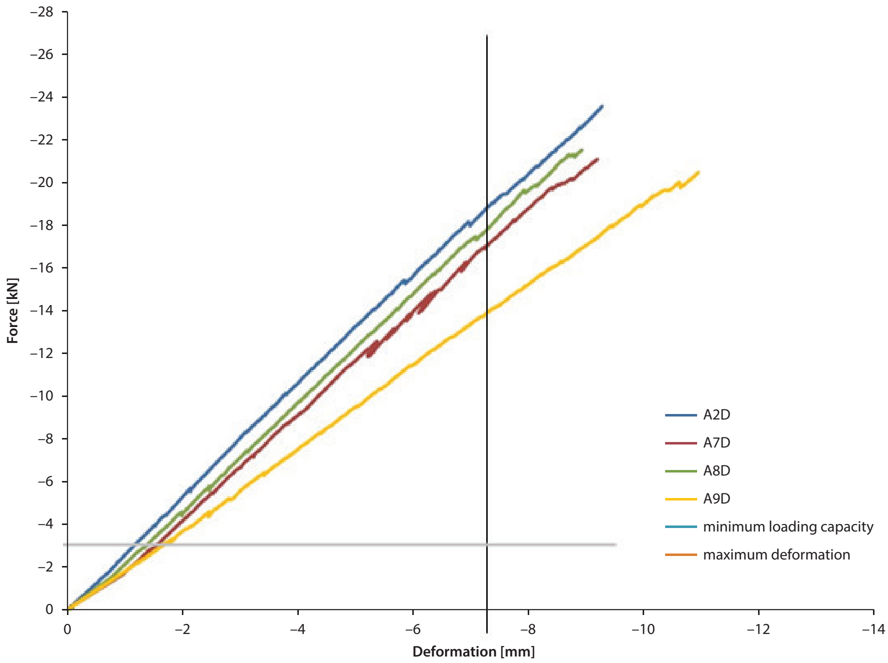


Figure 7. Deformation (left) and force for maximum deformation (right) based on a 4-point bending test of A-series samples.

known. The graphs reaffirm that all elements meet the requirements for structural use.

Using the moduli of elasticity of the beam and the shelf (determined in Sections 5.2 and 5.3, respectively), the maximum span can be calculated. The uniformly distributed load for a residential floor equals 2,5 kN/m^2. The maximum deflection of a residential floor is L/250, according to the Dutch building code NEN-EN 1995–1-1. Using this information, the maximum span can be calculated as 3,07 m.

5.2. E-Modulus of Spruce

The formwork consists of different parts like beams of unclassified spruce and plywood. To measure the e-modulus of the different parts several tests have been performed. For the spruce, an axial compression test was done. To make an indication of the compressive stress, the strength is assumed to be around the strength of the lowest class: C14. With this assumed strength, the expected load can be calculated, to have a good indication of the result:

$$F = \sigma \times A = 14 \times 45 \times 74 = 47 \text{ kN}$$

Based on the section of the spruce (C14) it is assumed that the applied force will be 47 kN and the modulus of elasticity will be 7000 N/mm^2. The three samples of the C-series have been loaded in compression. First, the samples had to be prepared for the dimensions to be following the Eurocode. Therefore, the samples were sawn to 45 × 74 × 270 mm. These samples were loaded axially parallel to the grain, so the direction of the grain in the samples is equal to the longitudinal axis (270 mm).

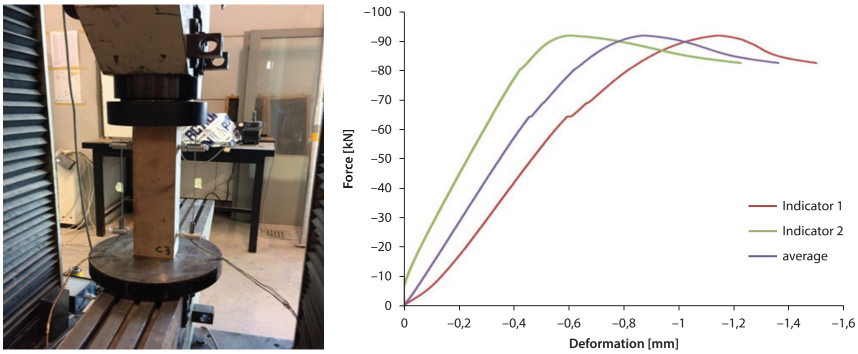
The deformation, due to axial loading, is measured by two LVDTs. Therefore, it is possible to determine if buckling occurs. The deformation is measured over a length of 2L/3 which equals 180 mm. The fixed points of the deformation indicators are placed L/6 = 45 from the top and 45 mm from the bottom, and these positions are determined following the Eurocode. This test is executed with a bench press, which is controlled by deformation, so the deformation is constantly increased over time. The speed of the deformation is equal to 0,5 mm/min. Figure 8 shows the results of the test. Based on these experiments the e-modulus of the spruce is calculated with Hooke's law.

Based on the linear parts in the graphic, the average modulus of elasticity is 7425 N/mm2. This is a plausible answer because the modulus of elasticity of spruce is 7000 N/mm^2 on average.

5.3. E-Modulus of the Shelf

The modulus of elasticity of the shelf is derived through a 4-point bending test with a span of 480 mm. The test is executed with a bench press with a 2,0 mm/min deformation. The results of the four experiments are represented in Figure 9.

In general, this study uses a more statistical approach to determine the load-bearing capacity of the formwork. Such a study provides insight into the overall performance of the formwork, which was entirely lacking. The advantage, in this case, is that large quantities of formwork with similar load-bearing capacity become available for reuse every day. Moreover, since the functional life of the components is short, ageing of the material will be limited. Defects are similar and can therefore be generalised in combination with visual inspection. This is not the case for other types of reuse. Urban mining often leads to small batches of materials that have been



Sample	Ultimate load (kN)	Strength (N/mm²)
C1	91.8	27.6
C2	75.6	22.7
C3	90.9	27.3

Sample	E [N/mm²]
C1	7760.2
C2	5809.3
C3	8704.5
Average	**7424.7**

Figure 8. Results of the compression test of the spruce samples.

loaded under different conditions for long periods of time. This requires a more individual assessment (including damage detection of all individual components) and as such remains an important barrier to the reuse of load-bearing components. It is a subject for further research.

6. Reuse Potential and Component Redesign

Based on the case study research on timber reuse and the analysis of the mechanical behaviour of the formwork samples, this section discusses the reuse potential of timber formwork for new construction and studies different redesign strategies that improve the potential for selective dismantling.

6.1. Reuse Potential

The formwork elements have high strength and stiffness. This could be useful for structural applications like floor systems, façades, roofs, and structural walls. In these cases, the timber would be covered and would not be visible in the finished project.

6.1.1. Structural Residential/Utility Floors

The first possible application of the formwork elements is using them as structural floor elements. The minimum loading capacity, according to the Dutch building regulations, should be 1,75 kN/m^2 for residential use and 2,5 kN/m^2 to 5,0 kN/m^2 for utility use. Based on the testing results, the formwork elements are capable of resisting these live loads.

6.1.2. Façades and Roofs

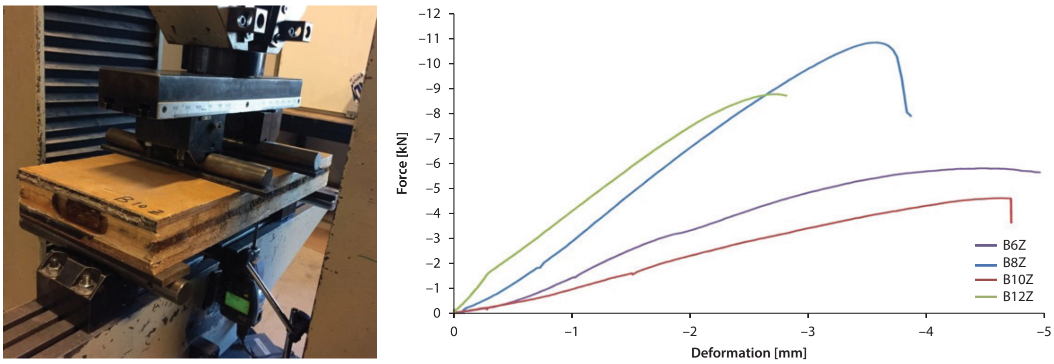
Another application for the formwork elements is using them as façade elements or roof elements. Façade elements will be used as finishing panels and will not support the main structure. When using the elements as load-bearing façades or roofs, it is important to take live loads like snow and wind into account. These forces could be as large as 2,12 kN/m^2, depending on the height and location of the structure.

6.1.3. (Structural) Inner Walls

Formwork elements could be useful as structural inner walls because they have a high strength and stiffness capacity. The space in-between the load-bearing beams, underneath the shelf, could be used for sound and heat insulation. By adding these insulation panels, the elements will meet the requirements of the Dutch building regulations.

6.2. Component Redesign

Now, the formwork elements have a lot of different connectors, which are making the adaptability complex.



Sample	E [N/mm²]
B6Z	578.0
B8Z	1211.2
B10Z	402.2
B12Z	1135.2

Figure 9. Force-deformation graphs resulting from the 4-point bending test of the shelf samples.

The formwork elements can be reused within the production process of the concrete contractor by changing the conventional connections into demountable connections. Nine alternative connections are discussed to find better solutions with low cost, longer lifetime and adaptability:

1. Glue
2. Timber dowels
3. Fixation
4. L-connection
5. Z-connection
6. Bottom magnets
7. Top magnets
8. Vacuum connections
9. Hoisting frame

6.2.1. Material Costs

Figure 10 and Table 2 compare the material cost of the nine options by listing all required materials and estimating their cost. All values are given for one element of 0,5 by 1,8m and are later expressed per m^2. These total costs are again split up into total connection costs and total fixed costs. Since the total fixed costs are the same for all options, it is easier to compare the total connection costs. The analysis considers the cost per time unit, considering the difference in lifespan between the shelf and beam elements. The total lifetime of the beam is assumed to be seven uses.

6.2.2. Factors of Cost and Revenues

The costs of the options for reuse are also partly determined by production costs because certain acts require more man-hours than others. The production costs of these specific methods are based on assumptions. The conventional method has a time factor of 1. Other methods are compared with the conventional method. Table 2 shows the labour costs.

Figure 11 estimates the total lifetime cost by combining the material and investment cost and incorporating the ease of use and workability for reuse. Ease of use refers to the expected workability of the connection option. Workable for reuse means that the element can be adapted and reused for different purposes. This includes how easy it is to saw the element. A waste factor estimates the amount of formwork that would still be discarded. In Figure 11, the cost is represented as a ratio of the cost of the conventional elements. The best option is the one with a low value for the material, time and waste factor, and a high value for the ease of use and the workability for reuse. Therefore, only values below one are accepted (green) for the material, time, and waste factor and only values above one for the ease of use and workability for reuse.

				0. Conventional	1. Glueing	2. Timber dowel	3. Connection by fixation	4. L-connection	5. Z-connection	6. Magnet connection (bottom)	7. Magnet connection (top)	8. Vacuum connection	9. Hoisting frame
			Beam length	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	8	8
			Dimensions [m2]	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	4	4
Element	**Price**	**Unit**	**Info**										
Plywood including beams	€ 5.98	/m2	Thickness 12 mm	€ 5.38	€ 5.38	€ 5.38	€ 5.38	€ 5.38	€ 5.38	€ 5.38	5.38	€ 23.92	€ 23.92
Pine timber beams	€ 0.30	/m	74 x 58 m2	€ 0.54	€ 0.54	€ 0.54	€ 0.54	€ 0.54	€ 0.54	€ 0.54	0.54	€ —	€ —
Screws	€ 0.04	/pc	Length 100 mm	€ 1.44	€ —	€ —	€ —	€ —	€ —	€ —	—	€ —	€ —
PVAc glue	€ 2.16	/L	Witte houtlijm	€ 0.16	€ 0.16	€ 0.20	€ 0.16	€ 0.16	€ 0.16	€ 0.16	0.16	€ 0.64	€ 0.64
Screws	€ 0.02	/pc	Length 20 mm	€ —	€ —	€ —	€ —	€ 0.72	€ 0.54	€ 0.09	—	€ —	€ —
L profile	€ 0.70	/m	Aluminium	€ —	€ —	€ —	€ —	€ 2.52	€ 2.52	€ —	—	€ —	€ —
Z profile	€ 0.70	/m	Aluminium	€ —	€ —	€ —	€ —	€ —	€ 2.52	€ —	—	€ —	€ —
Dissolvable glue	€ 86.40	/L	—	€ —	€ 3.00	€ —	€ —	€ —	€ —	€ —	—	€ —	€ —
Magnet	€ 3.37	/pc	25 kg	€ —	€ —	€ —	€ —	€ —	€ —	€ —	6.74	€ —	€ —
Magnet	€ 1.11	/pc	6 kg	€ —	€ —	€ —	€ —	€ —	€ —	€ 2.22	—	€ —	€ —
Timber dowel	€ 0.01	/pc	40 mm	€ —	€ —	€ 0.09	€ —	€ —	€ —	€ —	—	€ —	€ —
Steel strip	€ 1.43	/m	For magnet	€ —	€ —	€ —	€ —	€ —	€ —	€ 2.58	—	€ —	€ —
Vacuum system	€ 80,000.00	/pc	6 systems	€ —	€ —	€ —	€ —	€ —	€ —	€ —	—	€ 480,000.00	€ —
Hoisting system	€ 475.00	/pc	6 systems * 3 pcs	€ —	€ —	€ —	€ —	€ —	€ —	€ —	—	€ —	€ 8,550.00
Hollow tube section	€ 3.83	/m	25x25x2 mm, 2pcs	€ —	€ —	€ —	€ —	€ —	€ —	€ —	7.66	€ —	€ —
Total cost		**/m2**		**€ 8.36**	**€ 10.09**	**€ 6.90**	**€ 6.76**	**€ 10.36**	**€ 12.96**	**€ 12.19**	**€ 22.76**	**€ 120,006.14**	**€ 2,143.64**
Total connection cost		**/m2**		**€ 1.62**	**€ 3.33**	**€ 0.14**	**€ —**	**€ 3.60**	**€ 6.20**	**€ 5.43**	**€ 16.00**	**€ 120,000.00**	**€ 2,137.50**
Total fixed cost		**/m2**		**€ 6.76**	**€ 6.76**	**€ 6.76**	**€ 6.76**	**€ 6.76**	**€ 6.76**	**€ 6.76**	**€ 6.76**	**€ 6.14**	**€ 6.14**
Life span shelf	—			7	7	7	7	7	7	7	7	7	7
Life span beam	—			7	7	7	7	350	490	490	490	28800	21600
ratio	—	—		1	1	1	1	50	70	70	70	4114.285714	3085.714286
Connection cost / life time		**€/m2*times**		**€ 1.62**	**€ 3.33**	**€ 0.14**	**€ —**	**€ 0.07**	**€ 0.09**	**€ 0.08**	**€ 0.23**	**€ 29.17**	**€ 0.69**
Total cost / life time		**€/m2*times**		**€ 8.38**	**€ 10.09**	**€ 6.90**	**€ 6.76**	**€ 6.83**	**€ 6.85**	**€ 6.84**	**€ 6.98**	**€ 35.31**	**€ 6.83**

Figure 10. Material cost of the nine different connection options.

Table 2. Labour cost for the nine connection alternatives.

Connection Option	Time Factor	Explanation
0. Conventional method	1	Reference value. Consisting of screwing secondary beams orthogonal to main beams, gluing shelf to beams, and stapling the shelf
1. Gluing	1.5	Gluing shelf to beams
2. Timber dowel	1	Drilling holes in beam and shelf (200 mm in between distance), attach dowel to beam using glue, attach beam + dowel to shelf using glue
3. Connection by fixation	2	Milling tapered groove in shelf, hammer beam in groove
4. L-connection	1.5	Both profiles need to be screwed on shelf (200 mm in between distance)
5. Z-connection	1.5	2 Z-profiles need to be screwed on shelf and beams, including L-profile, have to be slided in
6. Magnet connection (bottom)	0.5	Steel strip needs to screwed on bottom of shelf
7. Magnet connection (top)	0.5	Steel hollow core beams need to be clamped underneath the shelf
8. Vacuum connection	0.1	Only placing frame on top of shelf
9. Hoisting frame	0.2	Mounting the frame onto the formwork elements

Connection option	Material factor [–]	Time factor [–]	Ease of use	Workable for reuse	Waste factor [–]
0. Conventional method	1	1	1	1	1
1. Gluing	1.20	1.5	1	3	0.3
2. Timber dowel	0.82	1	1	3	0.3
3. Connection by fixation	0.81	2	0.5	2	0.7
4. L-connection	0.82	1.5	2	0.2	0.3
5. Z-connection	0.82	1.5	0.5	0.5	0.35
6. Magnet connection (bottom)	0.82	0.5	3	1	0.5
7. Magnet connection (top)	0.83	0.5	2	2	0.5
8. Vacuum connection	4.21	0.1	3	3	0.2
9. Hoisting frame	0.82	0.2	3	3	0.2

Figure 11. Total costs per lifetime expressed as a ratio of the cost of the conventional formwork system.

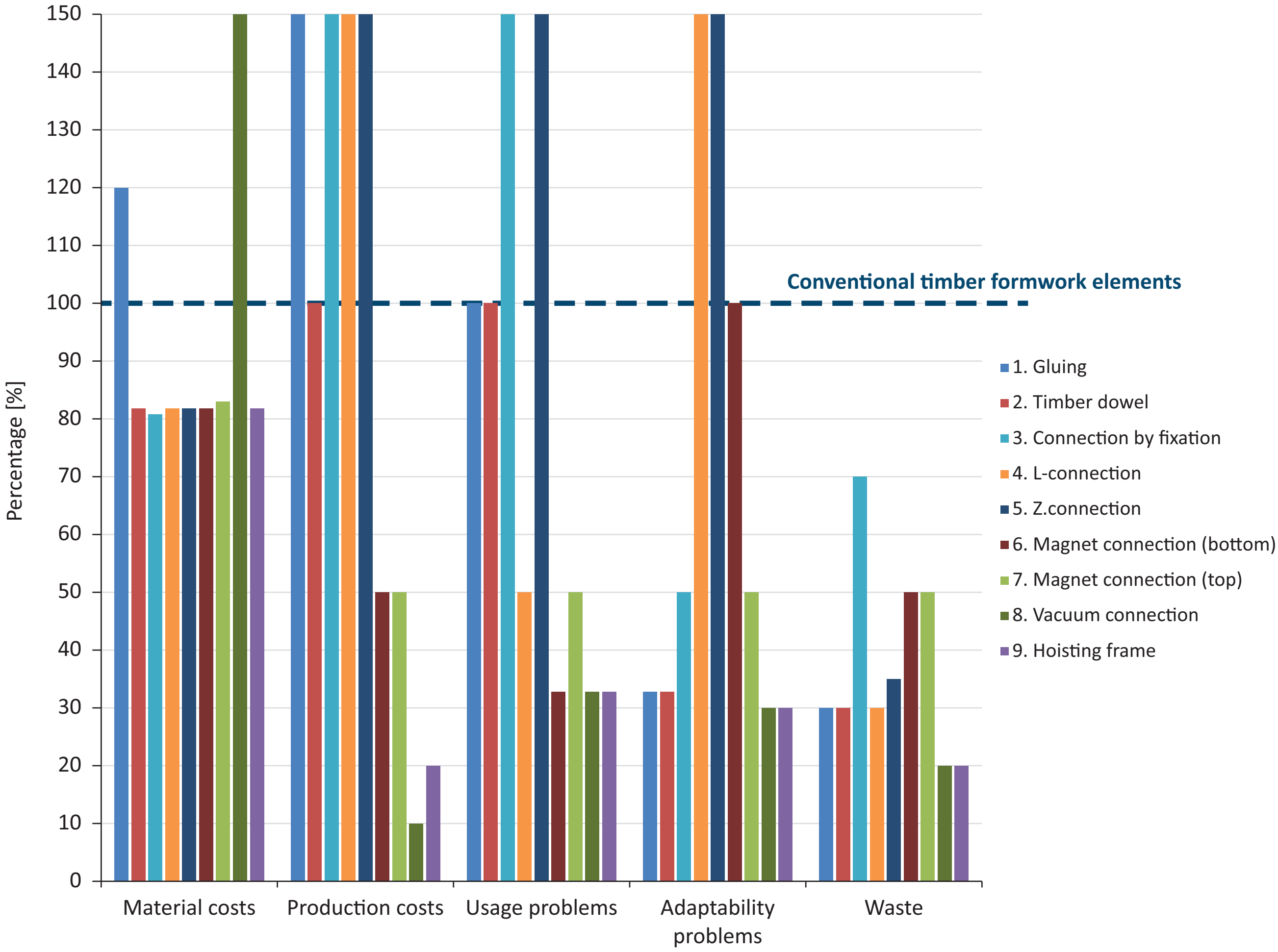


Figure 12. Visualisation of the total cost per lifetime for the different connection alternatives.

The results of Figure 11 are visualized in Figure 12. The dotted line shows the conventional method, being the reference value (100%). All bars lower than 100% are assumed positive.

7. Conclusion

This article is centred around a pilot project that applies reclaimed timber formwork for the construction of a new villa. As these formwork elements are only used a couple of times before being deemed unfit and discarded, they possess a huge potential for repurposing in building construction. While irregularities may make them less suited for visible building layers such as cladding, they do show some promise as part of the (sub)structure. Their thickness and high strength are well suited for solid timber construction. After all, most of the panels are discarded due to excessive seams or markings and not because of a failure in mechanical behaviour. To assess this behaviour, the project entailed the rigorous mechanical testing of the formwork panels, as presented in this article. As no detailed guides or codes exist on the reuse of formwork or even reclaimed timber, the Dutch Building Decree requires such tests. They show that the formwork elements have sufficient (remaining) load-bearing capacity to be applied in different structural applications.

Apart from the considerations about the structural performance of the timber formwork, the pilot project and studied cases provide some conclusions about material reuse. The main lessons are:

- Material reuse (and circular construction in general) requires a systematic and integrated approach.
- This approach should be flexible to adapt to the many unknowns related to material reuse.
- New types of collaborations are required, including the involvement of urban miners or other third parties, but also the more active involvement of contractors and engineers during the early design.
- Knowledge about circular construction and material reuse should be developed by all stakeholders in the value network, but also more horizontally in all layers of the involved companies or organisations.
- There is a need for more uniform definitions, guides, and codes.
- Using reclaimed materials reduces the embodied energy of a building and often saves material costs.

Logistics, planning issues, and additional efforts during the design and construction can, however, complicate the overall process. As such, the overall project budget can, in many cases, not be considerably reduced.

While this article does focus on one specific case study, its main contribution concerns the approach for assessment and redesign of the formwork. Reuse generally comes with a lot of unknowns about the origins and performance of reclaimed building components. This is especially the case for load-bearing products, whose performance ensures safety. This article shows a more statistical approach to reuse based on the availability of large amounts of similar non-building components. This shows a high potential for the repurposing of waste streams. Urban mining and the reuse of building components come with additional challenges. Materials often become available in small batches, making it less economically feasible to perform rigorous testing. Moreover, such components have often been used for long periods of time, sometimes in unknown conditions. This requires more extensive damage detection. Further research on the reuse of building materials can expand on this. Apart from more technological research, it will be important to map and develop solutions for the socio-economic barriers that currently hinder material reuse. Studies conducted in the Netherlands show that despite the increasing availability and large application potential in the construction sector, the use of reclaimed materials has not yet managed to scale up or break through. Financial and socio-cultural factors play an important role in this, such as habituation and the lack of additional comfort to compensate for the higher initial cost. The central case study of the circular house in Amsterdam shows that high percentages of reuse are possible for the construction of new buildings, but also depend on socio-economic factors and in this case the involvement and initiative of the building owner.

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Conflict of Interests

The authors declare no conflict of interests.

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About the Authors

Arno Pronk graduated as an architect from the Faculty of Architecture, TU Delft, in 1994. After his studies, he worked as an architect but also as a design technician. In cooperation with Professor Lichtenberg (Eindhoven University of Technology) he developed and patented the slim line floor system. He has two years of experience as an assistant professor at TU Delft and twenty years at Eindhoven University of Technology, where he realised his PhD research on flexible moulding for fluid architecture.

Stijn Brancart is an assistant professor of structural design at the Department of Architectural Engineering and Technology at TU Delft. After graduating as an architectural engineer in 2013, he finished his PhD research on rapidly and reversibly assembled structural systems in 2018, both at the Vrije Universiteit Brussel. Focusing his work on circular construction, he then went on to work on the Buildings as Materials Banks (BAMB) project and several smaller consultancy projects.

Fred Sanders recently graduated from the Department of Urbanism at TU Delft with his research on bottom-up resident initiatives for creating sustainable cities. He holds an MSc in civil coastal engineering and an MBA from the Erasmus University of Rotterdam. He has twenty years of experience in real estate management and public administration. He is a keynote speaker, journal editor, columnist, and writer of youth novels, promoting sustainable and resilient initiatives.