Low-tech timber design for affordable housing

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Abstract

This research investigates how the notion of low-tech timber construction can contribute to improving the affordability of housing. For this, the two main aspects of affordability and the degree of low-tech have been investigated and made measurable by means of parameters. First of all, by creating a housing cooperative, housing remains accessible to people with low and middle incomes. The amount to be financed and the incentives for the governmental agencies to finance a project can be influenced by the degree of low-tech of a project. The construction method (technical), the use of materials (environmental) and the integration of the local community (social) determine the parameters for the degree of low-tech of a project. Overarching aspects within these parameters are 'simplicity', 'rationality', 'locality' and 'human scale'. The design of an entire project has influence on all the parameters of low-tech. The use of prefabricated universal elements and modules greatly improves the ease of construction, an open structure in the building promotes the future adaptability, and integrating a public function in the project is almost necessary to integrate the local community. The use of light frame timber construction in combination with wood fibre insulation has the highest degree of low-tech of existing timber products.

Keywords: *Timber design, Low-tech, Affordable housing, Housing cooperative,*

I. Introduction

The aim of this paper is to contribute towards solving the housing shortage by improving the quality and quantity of affordable housing as well as towards achieving the Sustainable Development Goals of the UN by efficient use of low-carbon materials. This means that housing development must take place in a sustainable manner. That is why the sustainable development pillars of 'People', 'Planet' and 'Profit' must be in balance. People should have a comfortable, affordable and healthy living environment. The planet requires a reduction of CO_2 emissions and efficient use of resources to be able to survive. The profit is important to make the project realistic and attractive to developers. The pillar 'Profit' will have to be defined differently in order to advocate a stronger focus on the social and environmental aspects of development. In this paper a strong focus lies in the possibilities for low-tech design solutions to realize affordable housing and to make efficient use of materials. In addition, the focus will be on the use of timber design because of the material properties that are positive for all three pillars of sustainable development and for the possibilities for prefab and modular construction. Therefore, the main research question in this paper is 'How can low-tech possibilities for timber design increase the affordability of housing?'. The paper firstly researches the way affordability and the degree of low-tech can be measured, resulting in a range of technical, environmental and social parameters. Secondly, two case studies have been investigated to test the usability of all the parameters and to determine the degree of low-tech and affordability of an entire project on different scales. Thirdly, an elaboration on the technical parameters is done by investigating two case studies on the degree of low-tech of existing timber products.

II. Research

2.1. Theoretical framework

To redefine the sustainable development pillar 'Profit', the research of Wilson and Post (2011) has been inquired. They have explored the phenomena of social businesses, a market-based approach to social value creation. In essence, social businesses combine social and economic goals, where the power of market-based approaches can be pro-actively and deliberately utilized to address widespread social problems. Their primary and integral social mission is often multi-faceted, encompassing a wide range of social impacts and stakeholders, even encompassing environmental issues.

A market-based approach for their social goals is chosen for three distinct interrelated reasons: Firstly, a market-based approach is considered an economically self sustaining and reliable way to reach their social change agenda. Secondly, the market-based approach is aimed at creating self-sufficiency and self-reliance for previously disadvantaged stakeholders to tackle social issues on a larger scale, and even permanently. Thirdly, participation and success in the market is seen as a way to create a powerful influence for social change, because it creates pressure for the traditional entrepreneurs to adjust their practices and approaches in the market. Wilson and Post (2011) also see these social businesses as an act of positive protest, rather than an act of demonstrating and therefore encourage competition. For the capital and governance structures, social businesses tend to remain privately owned and select highly values-aligned investors to enable them to pursue their social goals without conflict of interests, and without the disturbance of actors who only judge an investment solely on financial return.

Thus, a business model where the social (People) and/or environmental (Planet) mission is deeply embedded in the product/service, design, legal and capital structures, strategies, and operational principles of the business, potentially offers a sustainable solution to some of the world's most present social or environmental issues that can compete in the market dynamics. Thereby enabling social and environmental arguments to be more valid in design discussions and decisions.

A concept that might be considered as a social business is that of a housing cooperative. A housing cooperative is a form of collective living, in which the residents form a community with shared responsibility (Gemeente Amsterdam, 2021a). The members jointly (via the housing cooperative) own the building. This means that the residents are responsible for the design, construction and management of their building. The members rent their home from their housing cooperative. As a result, the residents have direct say in the way in which they live together. A housing cooperative is an alternative option between social rent and expensive purchase. It is not the maximum price on the market, but the rental value that determines the value of the property (Gemeente Amsterdam, 2021b). Housing cooperatives cannot sell out and are not profit-oriented. As a result, the homes remain accessible to people with a low and middle income.

One of the biggest obstacles to setting up a housing cooperative is the necessary financing in advance. It is estimated that the financing gap is around 10 to 20% of the required financing after deduction of bank financing (70%), own contribution (5%) and land costs (Gemeente Amsterdam, 2021b). The proposal of the municipality of Amsterdam is that a municipal financing scheme will provide for the financing gap. A condition of this arrangement is that the housing cooperative is obliged to refinance the municipal financing after 15 years. It is expected that during that time sufficient equity capital will have been built up by the housing cooperative, so that municipal financing is no longer necessary. After this period, the housing cooperative can build up capital to invest in its own homes and facilities or to set up a solidarity fund together with other housing cooperatives. This means that the accumulated capital can be used to make new housing cooperatives possible, which means that municipal financing is no longer necessary in the long term.

2.2. Affordable housing

With the idea of a social business and a housing cooperative in mind, affordability of housing is already partially covered. But the amount that needs to be financed and the incentives for the municipality to finance a project are still important factors when talking about affordability of housing. This can be divided into two main aspects that coincide with the classic separation of supply and demand. On the one hand, the affordability of something is determined by the amount that must be sacrificed (demand). On the other hand, the affordability of something depends on the amount of resources available to obtain it (supply).

2.2.1. Demand side of affordability

The amount that must be sacrificed for realizing housing projects can be interpreted as the total costs for the project. The cost items that are the most relevant for a housing cooperative are the planning costs, building costs and operating costs. Within the building costs, the costs for structural work, completion/finishing, transport and fees can be anticipated in particular if the aim is to achieve a self sustaining and local business model.

The costs for fees are closely related to the role of the national, regional and local government in the building industry. Verheul (2017) has researched the institutional void of housing and area transformation in the Netherlands. They argue that inner-city construction and area transformation should be higher on the agenda, whereby collaboration with other policy domains, such as sustainability, energy transition, employment opportunities and quality of life, may offer a solution. Difficult and lengthy procedures, national regulations and local policies create complexities and excessive development costs, making the transformation of existing built-up area very expensive. As a result, major pre-investments are required for area transformation. Therefore, Verheul (2017) argues that the market is currently not capable of realizing the million houses required by 2030 on its own. This means that national, regional and local governments have an important role in relation to the market environment. Governments can break through financial barriers by being part of the market. They can regulate it, provide financial incentives and give direction to market players by formulating and communicating their own plans, visions and propositions for an area without including unnecessarily onerous municipal regulations. For instance, parking standards, the program of requirements and zoning plans can be dealt with more flexibly.

2.2.2. Supply side of affordability

The amount of resources available for realizing housing projects can be interpreted as the available funding. One of the biggest obstacles to setting up a housing cooperative is the necessary financing in advance. It is therefore important that there is enough incentive for government agencies to provide financing.

First of all, there is the condition that the housing cooperative is obliged to refinance the municipal financing after 15 years. In addition to financial reasons, the consideration of government funding may also depend on a coherence of public objectives, such as innovation, sustainability and social objectives (Verheul, 2017). Public investment in housing construction and transformation is then based on a catalyst effect for surrounding areas and other sectors. Besides, the extent to which an area transformation responds to existing infrastructure and urban facilities can be a reason for government funding. If there is a link between housing, accessibility and sustainability, (revolving) government funding may be eligible (Verheul, 2017). Verheul (2017) concludes by stating that targeted, revolving government investments and new instruments can be tested through experiments and pilot projects. By jointly designating areas as living labs, the commitment and learning capacity of parties can be increased. Moreover, by working on knowledge development and knowledge sharing, societal problems can be tackled more efficiently. This also applies to the looming increase in unaffordable houses and underutilized areas.

2.2.3. Parameters affordability

Certain parameters can be derived from this that together provide more insight into how affordability can be defined and measured. The subdivision of these parameters corresponds to that of the affordability concept, as described above. On the one hand, the costs of a project (demand) and on the other hand, the possibilities for financing the project (supply). Subsequently, it is important to assign scoring criteria to these parameters. In order to apply the parameters universally, the scoring criteria will either be based on a certain ratio, on a score in a point-based system, or on reaching a certain level within the parameter. The parameters for affordability and their scoring criteria are shown and explained in appendix 1. These parameters can be put in a rating graph. This creates a tool with which projects can be assessed in terms of affordability, shown in figure 1.

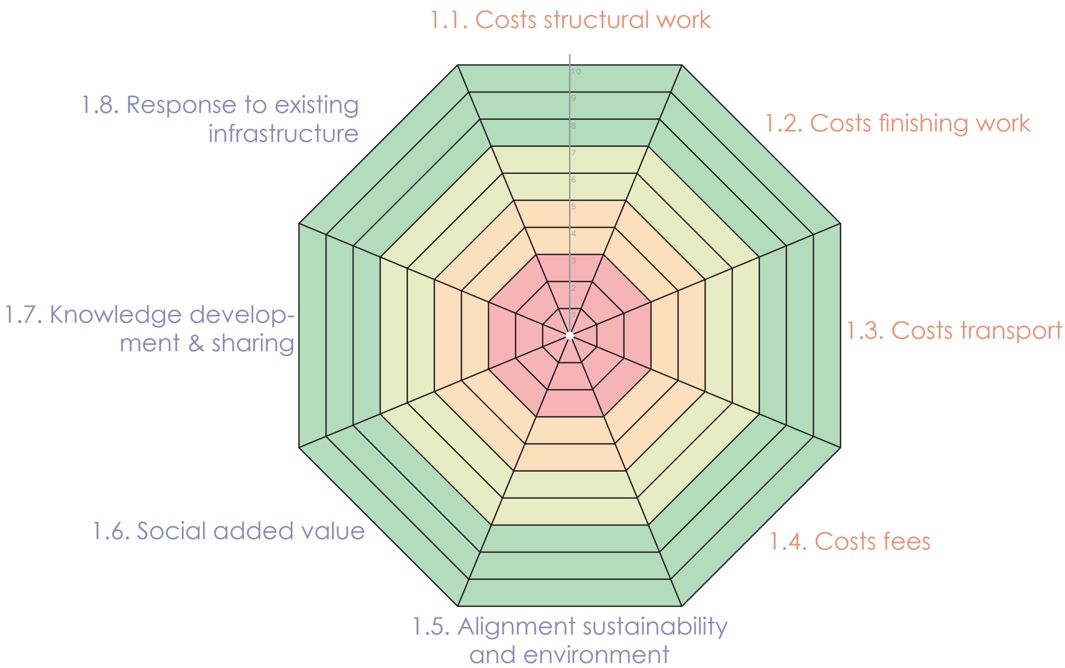

Figure 1. Rating graph affordability.

2.3. Low-tech

The notion of low-tech is very broad and can be found in a wide range of fields. To get a better understanding of the concept of low-tech and how it can be beneficial for the sustainable development of affordable housing, definitions from inside and outside the field of architecture will be investigated. From this a set of parameters will be determined to be able to measure the degree of low-tech in existing and future projects.

2.3.1. Low-tech definitions inside the field of architecture

Fowles (2021) is part of the architectural studio Feilden Fowles, which is heavily concerned with the notion of low-tech design. They define the term as follows: “Low-tech seeks to re-balance the relationship between buildings and technology. It is about leanness, fewer components, a preference for natural, low-embodied carbon materials, reduced reliance on technology and mechanical servicing, robustness and flexibility – in essence, simplicity. (…) Low-tech approaches must combine intuitive design (…) with the accurate and empirical processes of iterative design, digital modelling and measurement.” (Fowles, 2021). Their studio implements multiple fabric first approaches that try to maximise the performance of building materials and components before the implementation of mechanical technology to make a building energy-efficient. Fowles (2020) describes the following fabric first approaches: A careful selection of low-embodied carbon materials, fewer materials used well, passive environmental control for air, heat, cooling, light and humidity, and the use of local materials and methods. The desired outcomes from these fabric first approaches are determined by Fowles (2020) as follows: Carbon sequestration, ease of construction, future adaptability, reuse at the end of life, resilience, low maintenance and investment in the local economy. This results in practical applications such as the implementation of universal elements, easy to dismantle joints, simple, lean constructions, showing of craftsmanship, a local approach and the expression of tectonics and material properties.

These approaches, desired outcomes, and applications define the implications of the notion of low-tech in the field of architecture very well. The approach of using local materials and methods encourages the use of a local supply chain with a cascading use of the material.

2.3.2. Low-tech definitions outside the field of architecture

To get an even better understanding of the notion of low-tech, definitions and approaches of low-tech outside the field of architecture have been investigated.

In the field of energy production the term low-tech is used to indicate forms of human-driven power (Living Web Farms, 2018) as well as for the use of scrap and other leftover materials (OpenSourceLowTech, 2019).

An example of the use of the term low-tech in the food production can be found in mushroom farms. Here the term stands for depending on human power rather than on electricity. The mushroom growing process of GroCycle (2019) is an easy, visual process utilising mostly human labour. The only electricity used is in the mushroom fruiting room, where an autumn environment is being simulated by controlling the light, humidity and air in the room.

Low-tech is also used in refugee camps to share knowledge to the people. Low-tech lab (2019) has experimented in a refugee camp in Greece to share knowledge of accessing basic resources such as energy, water and food by implementing solutions that people can make themselves with the available technology and materials. By letting the refugees come up with their own solutions, they help them to be independent and self sufficient. Besides, the activities help to create a community feeling. In this field the notion of low-tech has a large social aspect.

De Chatelperron (2015) used the term low-tech in the field of shipbuilding. He defines it as follows: Technology transferred to the basic human needs: access to water, energy and food. On which you can build or repair anywhere in the world. His goal was to create a small ecosystem that is self sufficient. De Chatelperron (2015) concludes that sharing of knowledge from different experts and collaborative research are crucial to be able to reach that goal.

From these definitions and interpretations of the term low-tech common aspects and similarities with the field of architecture can be found. A recurring aspect of low-tech is the use of locally available technologies and resources. The technologies are mostly human scale and can be made and maintained by the users themselves. Often there is also a social aspect to the notion of low-tech by sharing of knowledge within a community and from different experts. This helps to make people independent, self sufficient and creates a community feeling.

2.3.3. Parameters low-tech

Certain parameters can be derived from this that together provide more insight into how low-tech can be defined and measured. These parameters encapsulate the needs of all three pillars of sustainable development, while there is a heavy focus on the environmental and social aspects of low-tech. Overarching aspects within these parameters are ‘simplicity’, ‘rationality’, ‘locality’ and ‘human scale’. The parameters for low-tech and their scoring criteria are shown and explained in appendix 1. These parameters can also be put in a rating graph. This creates a tool with which projects can be assessed in terms of low-tech, shown in figure 2.

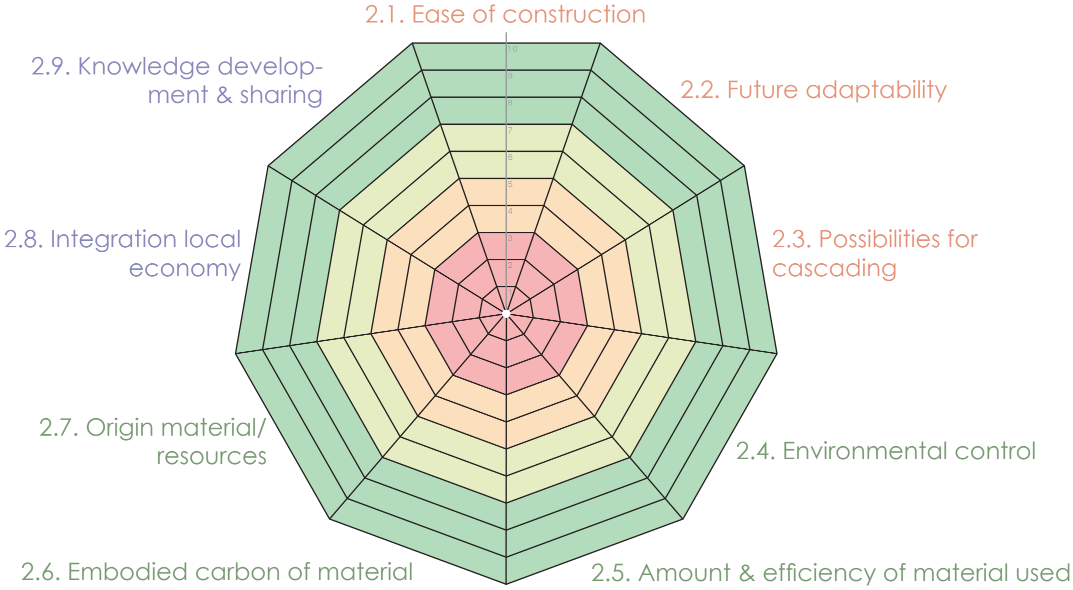

Figure 2. Rating graph low-tech.

2.3.4. Influence low-tech on affordability

The parameters of low-tech have a certain influence on the parameters of affordability. They either lower the costs of a project and/or give incentives for funding from government agencies. An overview of the relevant aspects of low-tech and their influence on affordability is shown in figure 3.

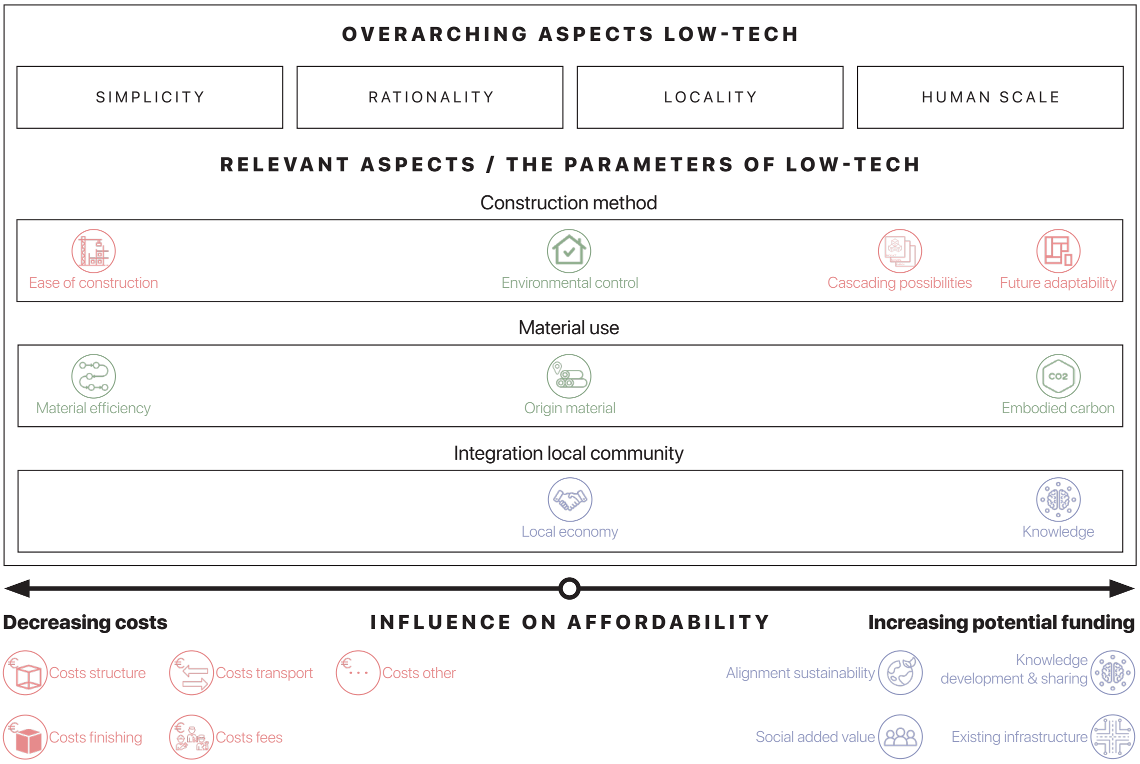

Figure 3. Relevant aspects of low-tech and their influence on affordability.

2.4. Testing parameters on existing timber projects.

After defining the parameters for affordability and low-tech, case studies have been analysed to test the usability of all the technical, environmental, and social parameters. Furthermore the case studies have been analysed to determine the degree of low-tech and affordability of an entire project on different scales. The analyses of the case studies can be found in appendix 2.

2.4.1. Brock Commons _ Acton Ostry architects.

Firstly, the mass timber highrise project 'Brock Commons' has been analysed. The rating graphs of this project are as follows (figures 4&5):

Several conclusions can be drawn from this analysis. First of all, this project excels in the construction method with timber for multi-storey housing. The large-scale application of of prefabricated universal elements for both the timber construction and the facade panels has led to an extremely fast construction time and low construction and failure costs. This fast construction method does make use of steel fastening elements, which means that it scores less in terms of sustainable use of materials. This method has many possibilities in terms of cascading the elements and the material, but the concrete top layer on the CLT floor slabs makes this more difficult. What this project scores very poorly on is the social added value and the alignment with the other objectives in the field of sustainability and the environment. This is because there are few other functions available besides housing. In addition, there is no approach for aspects such as the energy transition, passive control of the indoor climate and strengthening biodiversity. It can also be expected that there would be a greater focus on developing and sharing knowledge about this exceptional way of timber construction as it is part of a university campus.

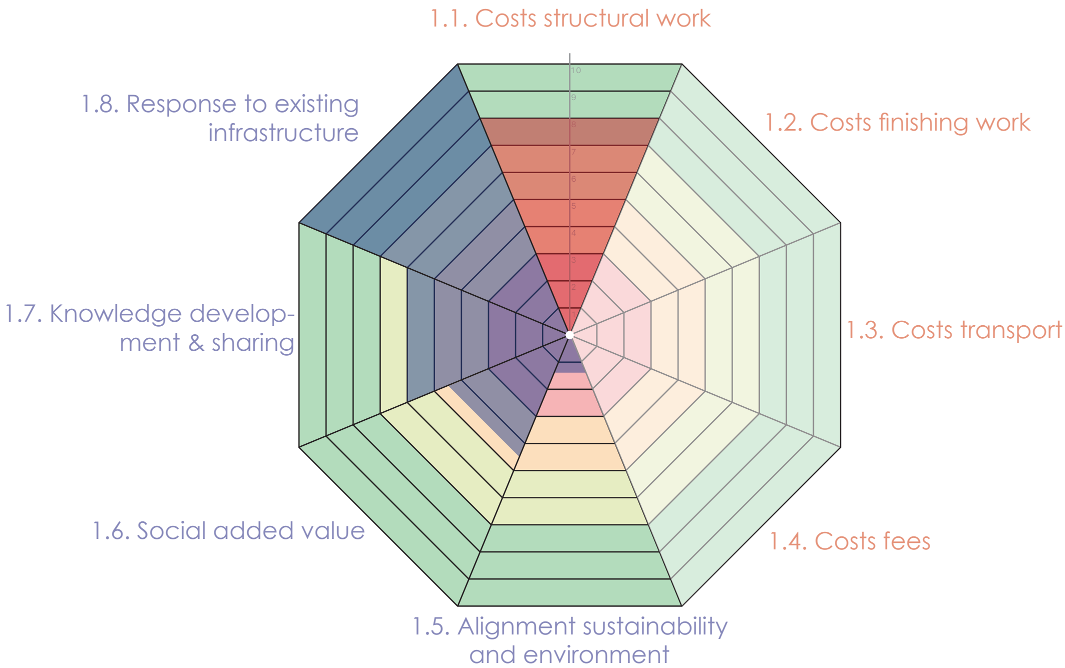

Figure 4. Rating graph affordability 'Brock Commons'.

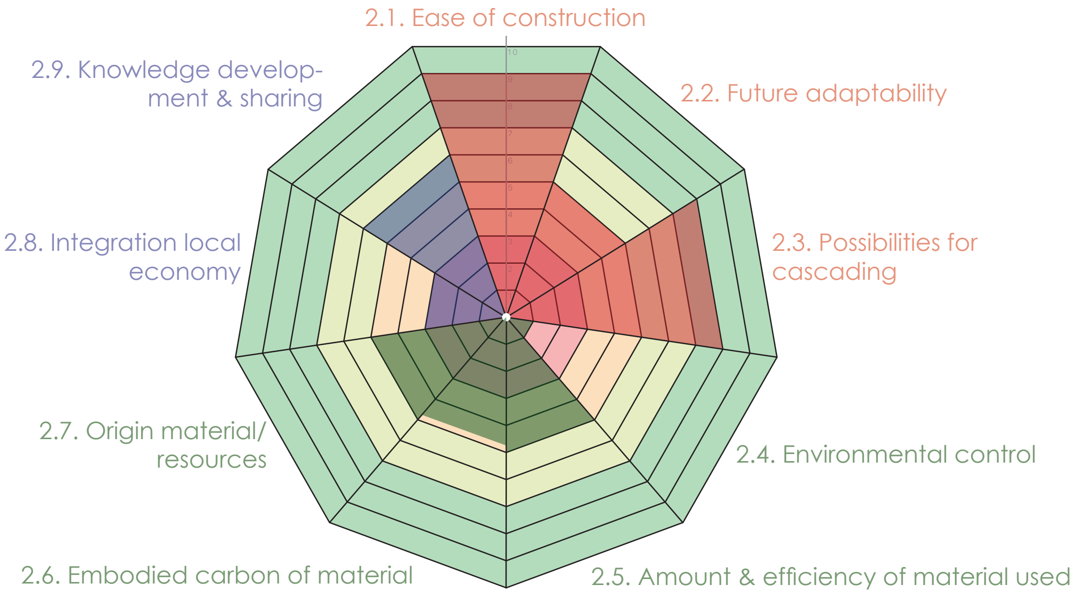

Figure 5. Rating graph low-tech 'Brock Commons'.

2.4.2. AIZ campus Kottenforst _ Waechter + Waechter Architekten.

The second analysed project is the timber module training centre/campus of the AIZ in Bonn by the architects Waechter + Waechter. The rating graphs of this project are as follows (figures 6&7):

Several conclusions can be drawn from this analysis. The lack of information about the cost items makes it difficult to draw well-founded conclusions. The presence of afforestation and a low degree of paving ensure more nature inclusivity, a natural water buffer and reduce the urban heat island effect. The open and adaptable structure of the building gives the user freedom of choice and influence on the way he/she uses the building and the surrounding space. In addition, this provides many opportunities for future adjustments to the function and the building, especially its layout. The fact that the building is a place for education does not immediately ensure that the project scores well in terms of knowledge development and sharing. It is not a publicly accessible place where city dwellers can participate in the learning landscape. Because very universal prefabricated building elements are used, the building is easy to assemble, even if a crane is still required. At the same time, this ensures that the universal elements can be reused after the life of the building has come to an end. The construction time here was really significantly longer than with the 'Brock Commons' project, which is surprising, since that building has a much larger scale. The vertical wooden slats, the roller blinds and the trees provide passive sun protection. Also in this project, the use of steel and concrete ensures that the score is moderate in terms of material use. Because the building has a public function in the education sector, employment and services are offered to the local population.

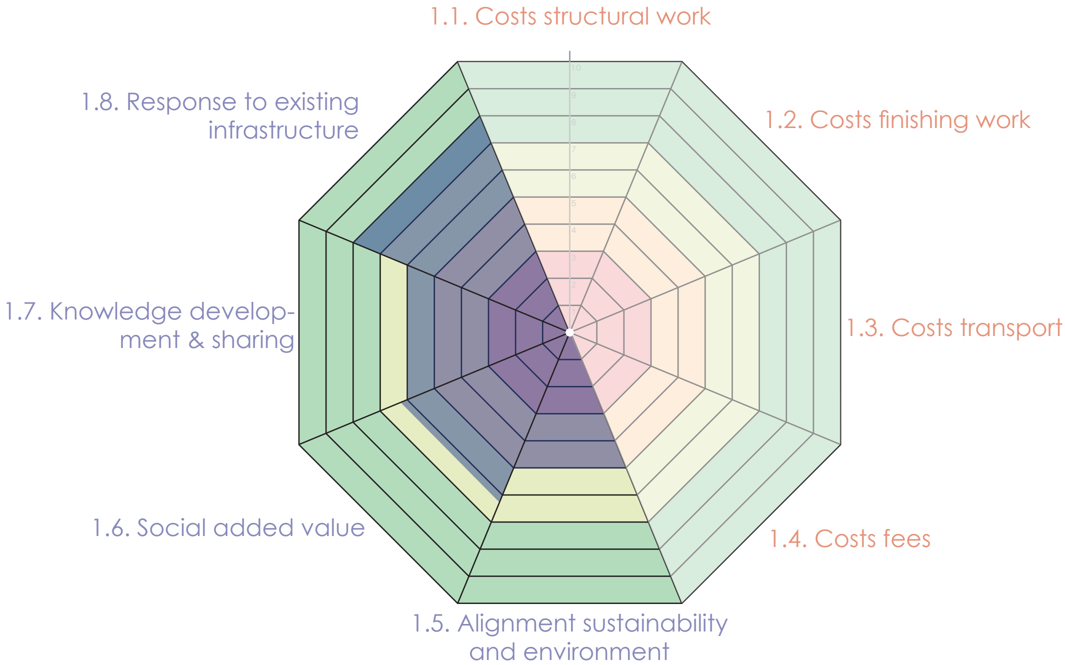

Figure 6. Rating graph affordability ‘AIZ campus Kottenforst’.

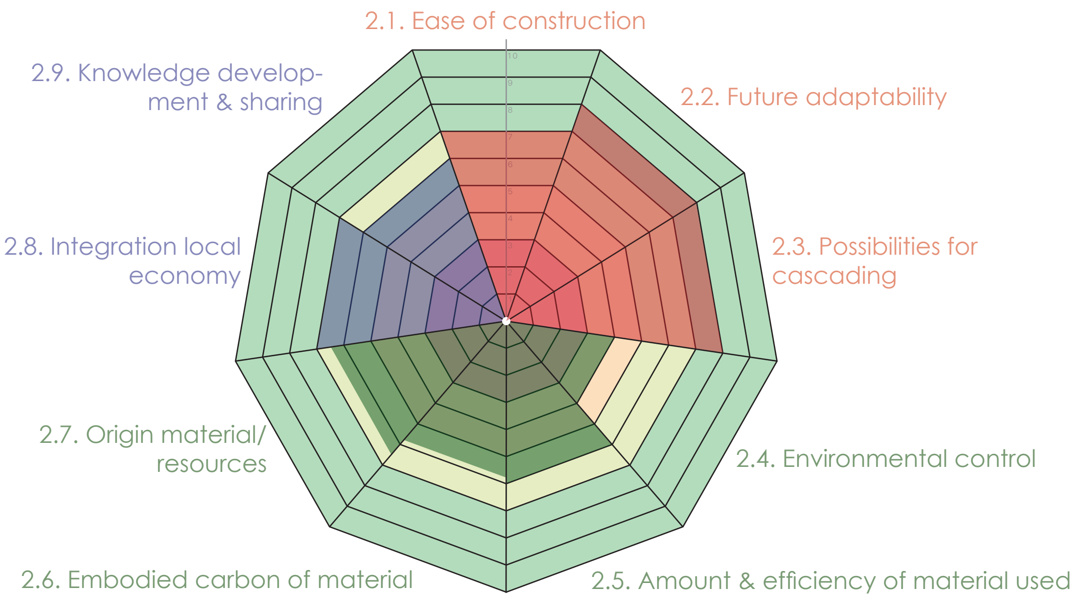

Figure 7. Rating graph low-tech ‘AIZ Kottenforst’.

2.5. Degree of low-tech existing timber products

To determine the degree of low-tech of existing timber products, case studies have been investigated on an element scale. For this, the different timber construction elements given by Kaufmann et al. (2018) are used to determine which existing timber products are analyzed and compared. This has resulted in the following timber products:

- Light frame timber construction.
- Glue laminated timber construction (glulam).
- Cross laminated timber construction (CLT).
- Laminated veneer lumber (LVL).

Two case studies have been analyzed to investigate the degree of low-tech in the production process of the above mentioned timber products. One case study uses a combination of glulam and light frame timber construction. The other uses a combination of CLT, LVL and light frame timber construction. These analyses are also an elaboration on the parameters 'ease of construction', 'cascading possibilities', 'material efficiency', and 'embodied carbon'. So the focus is on the manufacturability of the timber products used. Relevant aspects here are the amount of steps, the amount of heavy machinery, and the amount of additives needed in the process, as well as the cascading possibilities at the end of the products' life cycle. The full analyses of the projects can be found in appendix 3.

2.5.1. S'lowtecture - Tomasz Broma

"The project is an experimental housing structure arising from the slow-life philosophy and low-tech architecture. It is based on the DIY idea and allows inhabitants to build their own houses according to the rules of simple spatial game using building technologies from local, natural or recycled and easily accessible materials." - Broma (2016)

A fixed structure of glulam columns and beams forms the playing field within which the residents can form their own home. A multifunctional hall on the ground floor lets the users work with simple techniques and local, natural and easily accessible materials.

The project is very experimental, so few statements are made about aspects such as fire safety, construction and ownership. But it is very bold in terms of material use, user participation and creating a self-sufficient supply chain. The project clearly shows how residents can learn hands-on about and contribute to the use of low-tech techniques and materials. In addition, the grid provides possibilities for universal modules and freedom to adapt the building over time.

The manufacturability of the glulam construction elements and of the wood and paper façades are schematized in figure 8. The glulam construction needs eight steps to go from resource to product, using at least three types of machinery and using adhesives in two of the required steps. The light timber frame façades and walls are made of a timber frame, OSB boards, wood fibre insulation and wooden shingles. In this process the required sawmill can simultaneously produce the necessary boards for the frame or shingles and the chips/strands for the wood fibre insulation or the OSB boards. Both the OSB boards and the wood fibre insulation need an additional machine to either heatpress or cure the product and need an adhesive. For the paper walls a lot of machines and additional materials are needed to make the desired products. Furthermore, paper is a product using wood as a resource. Therefor, manufacturing paper walls always requires more steps than manufacturing wooden walls. For al the building elements the preferred use at the end of the buildings life cycle is direct reuse of the element. Otherwise they can be downcycled into strands/chips/shavings/shreds for new products. The last possibility is to use the products for energy recovery.

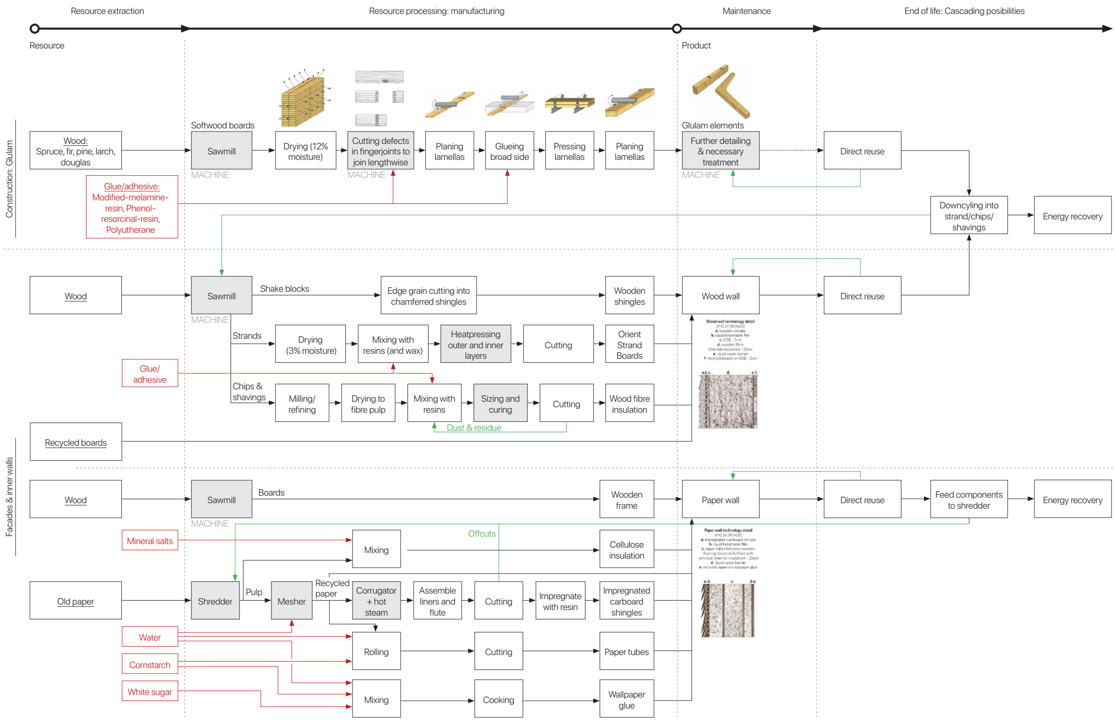

Figure 8. Manufacturability timber products S'lowtecture - Tomasz Broma

2.5.2. Malmöhus - Tigchelaar Architects

The Malmohus in Almere is the first four-storey timber construction project in the Netherlands. The U-shaped building block consists of five layers, housing 52 starter homes and workshops for start-up companies. The building has a stone plinth with lime sandstone walls and concrete floors to counter fire hazard. The construction of the wooden layers on top consists of load-bearing Lenotec walls (CLT) and prefab Kerto rib floors (LVL - laminated veneer lumber). The facade consists of a timber frame construction.

Several aspects of low-tech and affordability are addressed in this project. First of all, the construction of CLT walls and LVL floors, together with the timberframe façades, ensure that the top four floors are made entirely of wood and therefore of low-embodied carbon materials. An exception to this are the plasterboards that have been installed for fire safety. The architect could also have used 20 mm thicker Lenotec panels for this, but from a cost point of view this option was dropped. A panel construction was chosen for the floors, because solid wood floors would be 30-40% more expensive. In addition, a panel construction makes it easier to process installations in the floor. For sound insulation (impact sound), the floors are placed on the walls by means of a rubber support.

The manufacturability of the CLT and LVL construction elements and of the light timber frame façades is schematized in figure 9. The manufacturing proces of the CLT walls is very similar to that of the glulam construction as shown before. For the production of LVL products a rotary cutter is needed to make the veneer layers from the logs. An additional heatpress is needed to press the glued veneer layers together. Therefor, an additive is also needed in this process. The light frame timber facades and the LVL floors use mineral wool insulation which uses non-biobased slag or basalt as a resource as well as multiple machines. For al the building elements the preferred use at the end of the buildings life cycle is direct reuse of the element. If that is not possible, the screws can be extruded to be reused in new products. Otherwise the timber products be downcycled into

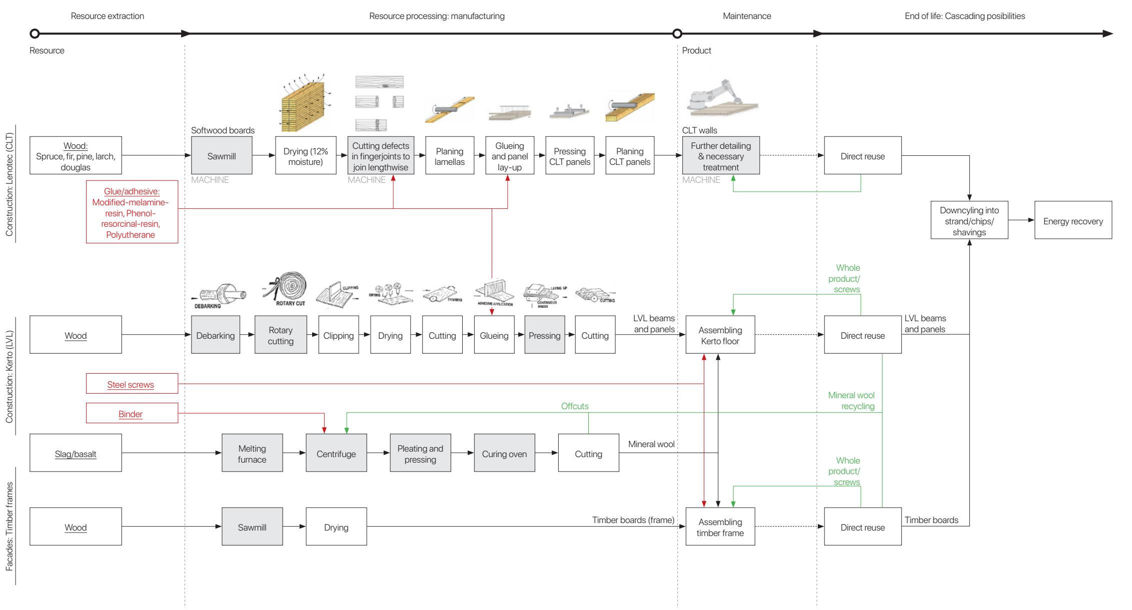

Figure 9. Manufacturability timber products Malmöhus - Tigchelaar Architects

strands/chips/shavings/shreds for new products and the mineral wool can be recycled for new insulation. The last possibility for the timber products is to use them for energy recovery.

From these case studies it can be concluded that the use of light frame timber construction in combination with wood fibre insulation is the most low-tech of timber products. This way, the main construction requires the least amount of steps, machines and adhesives. Besides, the entire construction can be made from low-carbon materials. Furthermore, the resources are used efficiently, since the offcuts and chips resulting from cutting the boards for the frames can be used to produce the wood fibre insulation and/or the boards for stabilizing the frames. Any necessary steel screws or nails can be reused at the end of the products' lifecycle.

III. Conclusion

In conclusion, it is first of all important to adopt a different approach to the creation of affordable housing, when social and environmental aspects are given a leading role. By creating a housing cooperative, in which social and environmental goals are an integral part of the business model, the dwellings remain accessible to people with low and middle incomes. At the same time, the residents have a direct influence on the way they live together. In the long term, housing cooperatives can even function without government funding. The amount to be financed for planning, construction and maintenance costs and the incentives for the municipality to finance a project can be influenced by the degree of low-tech of a project. The construction method (technical), the use of materials (environmental) and the integration of the local community (social) determine the parameters for the degree of low-tech of a project. Overarching aspects within these parameters are 'simplicity', 'rationality', 'locality' and 'human scale'. These aspects either reduce costs or increase the incentives for government agencies to provide financing.

When looking at the degree of low-tech and affordability of an entire project, certain conclusions can also be drawn from the case study analyses. The assessments of the student housing Brock Commons and the AIZ campus on the proposed parameters have shown that it is difficult to determine the score of the cost parameters when little information is available. However, they have shown that the construction methods used have decreased construction time, failure costs, and the required materials and logistics on site. In addition, it can be concluded that the use of prefabricated universal elements and modules greatly improves the ease of construction, as the elements can be quickly assembled on the construction site. The use of additional concrete and/or steel resulted in the projects scoring more moderately on the parameters for material use, despite their heavy focus on the use of timber. Furthermore, an open structure in the building promotes the future adaptability of the building in function, especially when the building has a public function. Besides, it can be concluded that integrating a public function in the project is almost necessary to create social added value, to focus on knowledge development and sharing, and to integrate the local community. Few passive techniques for controlling the indoor climate have emerged from these analyses. However, giving space to nature such as trees and unpaved ground in the project is beneficial for passive sun protection, nature inclusivity and climate adaptivity.

When looking at the degree of low-tech of existing timber products on an element scale, it can be concluded that the use of light frame timber construction in combination with wood fibre insulation has the highest degree of low-tech of existing timber products. This way, the main construction requires the least amount of steps, machines and adhesives. Besides, the entire construction can be made from low-carbon materials. Furthermore, the resources are used efficiently, since the offcuts and chips resulting from cutting the boards for the frames, can be used to produce the wood fibre insulation and/or the boards for stabilizing the frames. Any necessary steel screws or nails can be reused at the end of the products' lifecycle.

Discussion

For this research it is necessary to critically evaluate certain aspects. First of all, during the research it became clear that the parameters for the costs of the project were set up in the wrong way, making it difficult to extract clear and useful information from them. Although, it has become clear that the construction method, which plays the main role in determining the technical aspects of the degree of low-tech, has a major influence on the cost parameters. Furthermore, it would be beneficial for the research if a project is investigated that focuses more on passive climate control and/or that has a strong focus on integrating the local community into the activities and knowledge that the project possesses. This research has attempted to establish parameters that should determine the degree of low-tech and affordability of projects, but these parameters currently remain on the surface and lack a certain degree of depth. This is partly because the parameters were regarded as equivalent, which made it hard to determine what the essence of low-tech actually was. A parameter such as 'ease of construction' should be a much more decisive aspect in terms of manufacturability and required processes than a parameter such as 'cascading possibilities', which should be regarded more as a good side effect. By comparing different timber products in terms of manufacturability and required processes, it quickly became clear that a purely light timber frame system is the most low-tech, since engineered timber products require a lot of high-energy consuming machines and additives. As a result, the analyses of the projects that do use processed wood are undermined in terms of the construction method. The environmental and social parameters are still relevant in these analyses as well as the prefabrication aspect within these projects.

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Appendix 1: Explanation scoring criteria parameters

Parameters Affordability	Poor (1-3)	Insufficient (4-5)	Sufficient (6-7)	Outstanding (8-10)
Parameters costs project	Cost item ratio to total construction costs. Building level			
1.1. Costs structural work	100% - 70%	60% - 50%	40% - 30%	20% - 0%
1.2. Costs finishing work	100% - 70%	60% - 50%	40% - 30%	20% - 0%
1.3. Costs transport	100% - 70%	60% - 50%	40% - 30%	20% - 0%
1.4. Costs fees	100% - 70%	60% - 50%	40% - 30%	20% - 0%
Parameters potential funding	Value creation for the surroundings and alignment of government agenda items. Project level			
1.5. Alignment sustainability and environment.	0-1 points	2-3 points	4-5 points	6 points
1.6. Social added value	The project responds to 1-3 of the 13 points that ensure social quality.	The project responds to 4-6 of the 13 points that ensure social quality.	The project responds to 7-9 of the 13 points that ensure social quality.	The project responds to 10-13 of the 13 points that ensure social quality.
1.7. Knowledge development & sharing	The project allows the users to learn informally with passive contributions	The project allows the users and townspeople to learn informally with passive contributions.	The project allows the users and townspeople to learn informally with active contributions.	The project allows the users and townspeople to learn informally with active contributions. In addition, non-formal learning activities have been organised.
1.8. Response to existing infrastructure	Replace existing for new infrastructure.	Partially replacing existing.	Using existing plus new additions.	No additions needed.

Table 1. Parameters affordability.

Parameters Low-tech	Poor (1-3)	Insufficient (4-5)	Sufficient (6-7)	Outstanding (8-10)
Technical Parameters	Building level			
2.1. Ease of construction	The building can be constructed slowly with complicated construction techniques.	The building can be constructed fast with complicated construction techniques.	The building can be constructed slowly with simple construction techniques.	The building can be constructed quickly with simple construction techniques.
2.2. Future adaptability	The building is incapable of changing building elements and of function.	The building is capable of changing building elements and/or of function with major interventions.	The building is capable of changing building elements with minor interventions and of function with major interventions.	The building is capable of changing building elements and function with minor or no interventions.
2.3. Possibilities for cascading	Materials are dumped or incinerated (with energy recovery).	Building rubble is downcycled or recycled.	Seperated building materials are downcycled or recycled.	Building elements are reused, the construction is reused or the entire building is reused.
Environmental Parameters	Building level			
2.4. Environmental control	Active environmental control without energy production	Active environmental control with energy production.	Passive environmental control without energy production.	Passive environmental control with energy production.
2.5. Amount and efficiency of material used	Unnecessary components. Raw materials need energy intensive processing.	Additional components for material joints. Raw materials need energy intensive processing.	Additional components for material joints. Raw materials need low energy processing.	Few to no additional components for joints. Few to no processing needed.
2.6. Embodied carbon of material	High embodied carbon materials. (> 100 kg CO_2/m^3)	Medium embodied carbon materials. (10<x<100 kg CO_2/m^3)	Low/neutral embodied carbon materials. (0<x<10 kg CO_2/m^3)	Positive embodied carbon materials. (< 0 kg CO_2/m^3)
2.7. Origin material/resources	Resources come from unsustainable source. Location source > 200 km.	Resources come from unsustainable source. Location source < 200 km.	Resources come from sustainable source. Location source < 200 km.	Resources come from sustainable source. Location source < 100 km.
Social Parameters	Project level			
2.8. Integration local economy	Project does not support local economy.	Project provides employment.	Project provides employment. It provides products and/or services to the local community.	Project provides employment. It provides products or services to the local community. It collaborates with local businesses.
2.9. Knowledge development & sharing	The project allows the users to learn informally with passive contributions	The project allows the users and townspeople to learn informally with passive contributions.	The project allows the users and townspeople to learn informally with active contributions.	The project allows the users and townspeople to learn informally with active contributions. In addition, non-formal learning activities have been organised.

Table 2. Parameters low-tech.

Parameters affordability, costs (PA 1.1 - 1.4).

For the scoring criteria of the cost parameters, the ratio of the cost item to the total construction costs of the project will be used. This makes it possible to compare projects with different construction costs/scales. For the cost items with a low share of the total costs, it can then be determined which aspects and interventions have led to this. The scope for these parameters will mainly focus on the building level.

A downside to this method is that the ratio of a certain cost items will always be in a certain range, resulting in a misleading score for that cost item.

Parameters affordability, potential funding (PA 1.5 - 1.8).

For the parameters for the potential financing of the project, the main focus is on the value creation for the area and the alignment with the agenda items of the relevant governments. Logically, the scope for these parameters will mainly focus on the project level.

1.5. Alignment sustainability and environment.

This parameter looks at the connection with other agenda items in the field of sustainability and the environment. A points-based system to determine the score is used here.

Points can be earned in the following areas:

- Energy transition: The project offers options for sustainable energy generation for itself and/or its surroundings.
- Circularity: The project offers possibilities for circular use in the field of materials, food and/or waste management.
- Climate adaptivity: The project offers opportunities for water management and counteracting the urban heat island effect.
- Material use: The materials used in the project are CO2-neutral or CO2-positive.
- Green living environment: The project offers possibilities for implementing nature-inclusive building.
- Biodiversity: The project contributes to the management/improvement of the biodiversity of flora and fauna.

1.6. Social added value.

Another aspect that can increase the potential for funding is the social added value of the project. A points-based system to determine the score is used here.

'Social quality' is defined by Notten (2008) as 'the extent to which people are able to participate in social and economic life, under conditions that stimulate their well-being and individual potential'. Within the concept there are two playing fields in which quality can be created (figure 1):

- Individual (micro) - society (macro): within this the playing field ranges from 'the individual environment of people' to 'life on the street/in the city'.
- Institutions - communities: within this the playing field ranges from 'the spatial planning of the built city' to 'the functioning of society/communities'.

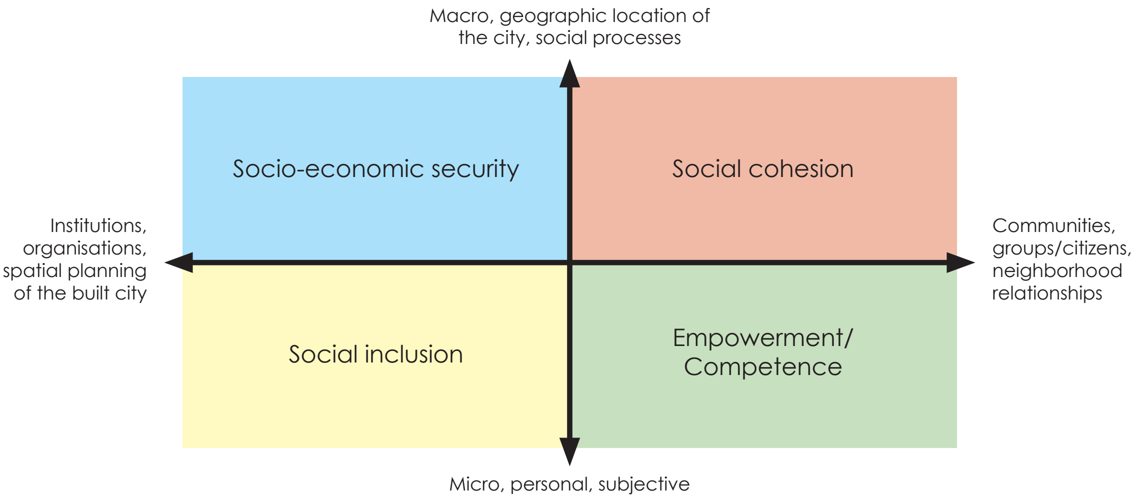


Figure 1. Quadrant social quality (Meeuwisse, 2015)

These fields within social quality can be divided into four main topics: ‘socio-economic security’, ‘social cohesion’, ‘social inclusion’ and ‘empowerment’ (self-reliance). Interventions in the city can respond to these topics in order to create social quality.

A project can respond to these main topics of social quality in the following ways:

Socio-economic security:

- Provide housing.
- Provide employment.
- Provide a safe living environment.

Social cohesion:

- Ensure solidarity between different generations.
- Stimulate interaction between people.
- Attractive to people with different incomes/financial assets.

Social inclusion:

- Provide housing for disadvantaged population groups.
- Provide employment for disadvantaged population groups.
- Ensure that disadvantaged population groups can experience public space on an equal footing.

Empowerment

- The individual has freedom of choice in the way he/she lives.
- The individual can influence the way he/she lives.
- The individual has freedom of choice in the way he/she uses the public space.
- The individual can influence public space.

These are a total of 13 points on which a project can provide social quality. The score for the parameter ‘social added value’ is determined on the basis of the number of points integrated in the project.

1.7. Knowledge development & sharing.

A focus on knowledge development and sharing can increase the potential for funding. Therefore, it is necessary to explore the notion of the city as a learning environment.

The daily new perceptions and impressions in the city influence how people interpret, explain and understand the world around them (Meeuwisse, 2015). This means that the built environment allows people to become acquainted with and learn about the latest developments in modern society. At the same time, city dwellers contribute to these developments: world cities reflect world changes. The city is therefore a learning environment in which people contribute to the ever-changing circumstances in which people find themselves. Human contributions can be active (by participating) or passive (by observing others).

According to Meeuwisse (2015), the city as a learning environment responds to two core concepts within psychology: ‘informal learning’ and ‘non-formal learning’.

- Informal learning refers to all forms of learning that take place in everyday life. Every experience or encounter influences this.
- Non-formal learning refers to organized activities that do not take place in the formal educational systems (e.g. schools).

Therefore, in order to have an environment of knowledge development and sharing, the project must function as a learning environment for the city, where people come into contact with the used technologies and methods. The parameter determines to what extent the project functions as a learning environment. A level-based system to determine the score is used here:

1. The project allows the users to learn informally with passive contributions.
2. The project allows the users and townspeople to learn informally with passive contributions.
3. The project allows the users and townspeople to learn informally with active contributions from the users and passive contributions from the townspeople.
4. The project allows the users and townspeople to learn informally with active contributions.
5. The project allows the users and townspeople to learn informally with active contributions. In addition, non-formal learning activities have been organised.

		Users			Townspeople		
Level	Score	Informal passive [1]	Informal active [2]	Non-formal [3]	Informal passive [1]	Informal active [2]	Non-formal [3]
1	2	x					
2	4	x			x		
3	6	x	x		x		
4	8	x	x		x	x	
5	10	x	x	x	x	x	x

Table 3. Content different levels parameter knowledge development and sharing

[1]: Informal passive: The activities concerning the techniques and methods used can be observed by the users/townspeople.

[2]: Informal active: There is participation by the users/townspeople in the activities concerning the techniques and methods. If the townspeople participate, the project needs to be (partially) public.

[3]: Non-formal: People can learn about the techniques and methods non-formally because there are organized activities (courses/tours/information centres) in the project that serve this purpose.

1.8. Response to existing infrastructure.

The chance for potential funding for a project increases when there is a good connection to the existing infrastructure, because it means that less investments have to be made in resources for new infrastructure. The parameter determines to what extent the project functions as a learning environment. A level-based system to determine the score is used here:

1. Replace existing for new infrastructure. Resources are needed to remove all of the existing and to introduce new infrastructure.
2. Partially replacing existing. Resources are needed to remove part of the existing and to introduce new infrastructure.
3. Using existing plus new additions. Resources are needed to add onto the existing infrastructure.
4. No additions needed. (Almost) no resources are needed to connect the project to the existing infrastructure.

Parameters low-tech, technical parameters (2.1 - 2.3).

The technical parameters for low-tech are determined at the building level, because they mainly respond to the functionality and construction method of the building.

2.1. Ease of construction.

This parameter determines how easy and fast the construction method used is. Two aspects are important here: the construction speed and the construction techniques. A level-based system to determine the score is used here:

1. The construction speed is slow and the construction techniques are complicated.
2. The construction speed is fast and the construction techniques are complicated.
3. The construction speed is slow and the construction techniques are simple.
4. The construction speed is fast and the construction techniques are simple.

The construction speed is slow when most of the construction takes place on site and fast when prefabricated. Construction techniques are complicated when large machines are required to build the building, there are many different building elements, and the joints are difficult to assemble and disassemble. The techniques are simple when they are on a human scale, universal elements are used, and the joints are easy to assemble and disassemble. In this parameter the construction technique is more important than the construction speed.

2.2. Future adaptability.

This parameter determines to what extent the building is able to make adjustments to building elements and to the function of the building. A level-based system to determine the score is used here:

1. The building is incapable of changing building elements and of function.
2. The building is capable of changing building elements and/or of function with major interventions.
3. The building is capable of changing building elements with minor interventions and of function with major interventions.
4. The building is capable of changing building elements and function with minor or no interventions.

The use of modules and easy to dismantle joints improve the ability to change building elements. The use of open building principles improve the ability to change the function of the building. In this parameter the ability to change building elements is more important than the ability to change the function of the building.

2.3. Possibilities for cascading.

This parameter determines what the possibilities are for cascading the building in the future. This is done on the basis of the 'Delftse Ladder' by Hendriks (2000). A level-based system to determine the score is used here:

1. Landfill: dump the material in a closed and secured waste storage area.
2. Incineration of the material.
3. Incineration of the material with energy recovery (thermal recycling).
4. Rubble downcycling: process building rubble into lower-grade functions.
5. Rubble recycling or composting: process building rubble into new, equivalent functions.
6. Material downcycling: process separated building materials into lower-grade functions.
7. Material recycling: reuse separated building materials into new, equivalent functions.
8. Element reuse: reuse - demountable or removable - building elements.
9. Construction reuse or object renovation: maintain and reuse the construction of a building; redo the installation and finishing.
10. Prevention: maintain and reuse, possibly with adjustments, a building.

Parameters low-tech, environmental parameters (2.4 - 2.7).

The environmental parameters for low-tech are determined at the building level, because they mainly focus on energy and material use and control of the indoor climate in the building.

2.4. Environmental control.

This parameter determines the degree of low-tech in the field of indoor climate management and energy use. A level-based system to determine the score is used here:

1. Active environmental control without energy production
2. Active environmental control with energy production.
3. Passive environmental control without energy production.
4. Passive environmental control with energy production.

Active climate management means that energy-consuming methods are needed to control the indoor climate. This is not the case with passive climate control. The building only scores in the field of energy production when it generates at least the amount of energy needed for its own use. In order to score well on this parameter, it is first of all important to manage the indoor climate with passive techniques.

2.5. Amount and efficiency of material used.

This parameter determines the efficiency of material use. The amount of components in the building elements and connections is important here, as is the amount of energy needed to process the materials used. A level-based system to determine the score is used here:

1. Unnecessary components. Raw materials need energy intensive processing.
2. Additional components for material joints. Raw materials need energy intensive processing.
3. Additional components for material joints. Raw materials need low energy processing.
4. Few to no additional components for joints. Few to no processing needed.

Unnecessary components consist of oversized elements and elements that only have an aesthetic function. In order to score well on this parameter, it is important that no unnecessary components are present and that the amount of energy needed to process the materials used is low.

2.6. Embodied carbon of material.

This parameter determines the environmental impact of the materials used based on the embodied carbon of the material. The material pyramid of CINARK, The Royal Danish Academy (2019) is used for this (figure 2). This gives a good overview of the embodied carbon of many common materials in the construction industry. To determine the score, the average amount of embodied carbon per cubic meter of the materials used (x kg CO_2/m^3) is considered. A level-based system to determine the score is used here:

1. The average embodied carbon is higher than 10.000 kg CO_2/m^3.
2. The average embodied carbon is higher than 1000 kg CO_2/m^3.
3. The average embodied carbon is higher than 100 kg CO_2/m^3.
4. The average embodied carbon is higher than 50 kg CO_2/m^3.
5. The average embodied carbon is higher than 10 kg CO_2/m^3.

Figure 2. The material pyramid (CINARK, The Royal Danish Academy, 2019)

6. The average embodied carbon is higher than 5 kg CO_2/m^3.
7. The average embodied carbon is higher than 0 kg CO_2/m^3.
8. The average embodied carbon is higher than -100 kg CO_2/m^3.
9. The average embodied carbon is higher than -500 kg CO_2/m^3.
10. The average embodied carbon is higher than -1.000 kg CO_2/m^3.

2.7. Origin of material/resources.

This parameter determines the sustainability of the materials used in terms of its origin. The elements that influence this are the renewability of the raw materials used and the distance from the source to the project location. A level-based system to determine the score is used here:

1. Resources come from unsustainable source. Location source > 200 km.
2. Resources come from unsustainable source. Location source < 200 km.
3. Resources come from sustainable source. Location source < 200 km.
4. Resources come from sustainable source. Location source < 100 km.

The renewability of the raw materials is the most important aspect in this parameter. A sustainable source here does not only mean that the materials are renewable, but the method of acquirement has to be sustainable as well. This means that at least as many raw materials are produced as are extracted. An example for this is sustainable forestry.

Parameters low-tech, social parameters (2.8 - 2.9).

The social parameters for low-tech mainly focus on the integration and connection with the local population and community. Therefore, these parameters are at the project level.

2.8. Integration local economy.

This parameter determines to what extent the project supports the local economy. Elements that play a role here are the provision of employment, products, and services, as well as the collaboration with other local businesses. A level-based system to determine the score is used here:

1. Project does not support local economy.
2. Project provides employment.
3. Project provides employment. It provides products and/or services to the local community.
4. Project provides employment. It provides products or services to the local community. It collaborates with local businesses.

2.9. Knowledge development and sharing.

This parameter is the same as the affordability parameter 1.7.

Appendix 2: Case study analyses (all parameters)

1. Brock Commons _ Acton Ostry architects.

Figure 3. Brock Commons (Canadian Wood Council, 2019)

Brock Commons is one of five apartment buildings that facilitates the student housing on the University of British Columbia campus. At the time of construction, it was the first and tallest mass hybrid timber residential high-rise building in North America. The 53 meter high building consists of eighteen floors, of which the top sixteen floors are made of a mass timber construction. These are fixed on a concrete podium at the plinth and on two stable concrete cores, where the stairwells are located. Although this project does not technically fall under a low-tech approach at first, it is interesting to analyse how the project scores on the other low-tech parameters, as it is a multi-storey timber housing project.

1.1. Costs project (PA 1.1 -1.4).

Although not all of the project's cost items could be identified exactly, the total construction cost came in at $40.5 million. 20% of this went to construction. This is because this project had a strong focus on being able to build the building in a tight time schedule. This required a multi-disciplinary approach up front. Ultimately, it was decided to use a construction of GLT and PSL columns, and a longitudinal two-way CLT flatplate system, which eliminated the need for beams in the mass timber super-structure (Canadian Wood Council, 2019). This decision was based on cost factors per material type, labour requirements for fabrication and installation, single span vs. multi-span orientations, and the integration of services (Canadian Wood Council, 2019). In addition, the failure costs during the construction process were significantly lower because 3D virtual modelling was used during the design process.

During the design, certain choices were made that ensured that costs were reduced:

- Simplicity was the essence from both architectural and structural standpoints. The flat slab CLT panels, the elimination of horizontal beams and optimization of the column grid significantly helped to reduce the volume of wood and amount of elements needed.
- Encapsulating mass timber with gypsum board reduced the amount of wood needed to meet fire and structural performance requirements.
- The choice for concentric HSS tube column connections resulted in lower column component weight and the opportunity for many columns on each level to be installed manually.
- Simplified floor plans, with stacked units created many cost-related efficiencies.
- Prefabrication produces higher quality and more precise components resulting in: reduced on-site installation time and overall schedule, reduced site deliveries, reduced on-site waste and related disposal costs, and reduced schedule time and on-site labour costs.

Score PA 1.1: 8

Score PA 1.2: n.a.

Score PA 1.3: n.a.

Score PA 1.4: n.a.

1.2. Alignment sustainability and environment. (PA 1.5)

The project has little connection with the other agenda items in the field of sustainability and the environment. In terms of material use, it is ambiguous; because the building is designed to meet Leadership in Energy and Environmental Design (LEED) Gold certification and they state to avoid 679 metric tons of CO_2 (Canadian Wood Council, 2019), but when looking at the types of materials used, materials with a high carbon impact are still present; such as structural steel, aluminium window frames and concrete. But either way, the project scores poorly on this parameter since the other sustainability and environment goals have not been met.

Score PA 1.5: 1.7

1.3. Social added value (PA 1.6).

In terms of social added value, the project offers housing and a safe living environment for students. The communal areas on the ground floor allow for interaction. Even if you only have to go up the stairwell, you have to go through the common areas first. The ramp and lifts ensure that the public areas can be used equally by handicapped people. The individual has the freedom to choose between a single studio or a quad unit. The communal areas are laid out in an open manner, giving the individual freedom in how he/she uses them. This ensures that this project scores 6 out of 13 points on this parameter.

Score PA 1.6: 4.6.

1.4. Knowledge development and sharing (PA 1.7 & PL 2.9).

The techniques and methods used can be observed by both the users and the townspeople from the inside and the outside, especially on the ground floor. Here the building has an open character and the timber construction can be seen. At the apartments the timber construction is covered with plasterboard. Monitoring systems were put in place to collect data and information on moisture content; vertical building movement and settlement; and horizontal vibration due to wind and seismic movement. UBC researchers, staff and students will work with industry and government partners to continue monitoring the building throughout its lifetime (Canadian Wood Council, 2019), making this active contributions by the users.

Score PA 1.7 & 2.9: 6

1.5. Response to existing infrastructure (PA 1.8).

This project is part of a campus. As a result, it fits perfectly into its master plan and with the existing infrastructure, additions are not necessary.

Score PA 1.8: 10

1.6. Ease of construction (PL 2.1).

Most of the building was produced off-site. All facade panels, CLT floor slabs and glulam columns are prefabricated with the help of virtual design models and physical mock-ups. The concrete foundation, podium and cores have been poured on site. Therefore, most of the construction time consists of completing the concrete structure (about four months). As soon as the concrete structure was in place, all prefabricated timber elements could be assembled. This took a total of only two weeks, because all steel fastening elements were already attached to the timber elements or to the concrete cores. The fixing of the facade elements of one floor could be started at the same time as the fixing of floor slabs and columns of the next floor. The elements can be joined together manually using simple techniques. However, the elements had to be lifted with cranes. All this makes that the building can be constructed quickly with simple construction techniques, but heavy machinery is still needed to lift the elements.

Score PL 2.1: 9

1.7. Future adaptability (PL 2.2).

Technically, all columns and floor slabs can be taken apart again, but the floor slabs are cast to the

Figure 4. Hybrid system of concrete and timber (Canadian Wood Council, 2019)

concrete cores and each floor has a top layer of concrete, so that all the concrete has to be removed first. The open column structure means that adjustments can be made to the layout, but the storey height of 2.81 meters makes it more difficult to change the building's function. So despite its easy and fast construction, the building is capable of changing building elements and/or of function with major interventions.

Score PL 2.2: 5

1.8. Possibilities or cascading (PL 2.3).

When this building comes to the end of its life cycle, and can no longer be reused in its entirety, it can be taken apart at the element level; the columns, floor slabs and facade elements can be separated in the same way as they are put together. Since it is processed wood, it is better to reuse the element than to try to reclaim the wood. When the elements are taken apart, however, construction rubble will be created due to the concrete top layers of the floor elements.

Score PL 2.3: 8

1.9. Environmental control (PL 2.4).

This building uses a complete mechanical system for ventilation, heating and cooling. In addition,

Figure 5. Prefabricated CLT floor, glulam columns, and facade elements (Canadian Wood Council, 2019)

no energy generation is involved here.

Score PL 2.4: 1

1.10. Amount and efficiency of material used (PL 2.5)

Most of the building consists of timber construction. This in itself requires little energy for processing. In addition, there is no unnecessary oversizing. However, in addition to timber, a large part is made of concrete and all connections (concrete-timber and timber-timber) are made of steel. The processing of these materials does require a lot of energy.

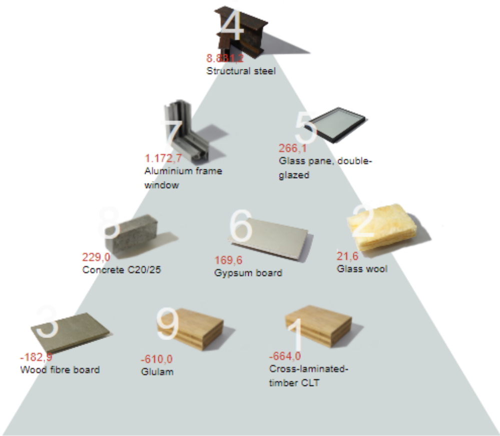
Score PL 2.5: 5

1.11. Embodied carbon of material (PL 2.6).

This is where the ambiguity of the use of materials comes into play again. The majority of the building is made of timber, but when considering the average embodied carbon of the types of materials used, the building scores insufficiently on this parameter. The average score of the materials used is an 4.8.

Score PL 2.6: 4.8

1.12. Origin material/resources (PL 2.7).



Scores:

Structural steel:	1.2
Aluminium frames:	2.0
Glass (double):	2.8
Concrete:	2.9
Gypsum board:	2.9
Glass wool:	4.7
Wood fibre board:	8.3
Glulam:	9.2
CLT:	9.3
Average:	4.8

Figure 6. Materials Brock Commons (CINARK, The Royal Danish Academy, 2019)

The three main materials are timber, concrete and steel.

Material	Supplier	Source	Distance	Score
Timber	Structurlam Products LP.	Sustainable (SCS Global Services, 2017)	267 km	6
Concrete	Lafarge Canada Inc.	Unsustainable	12 km	5
Steel	BarNone Metalworks Inc.	Unsustainable	90 km	4

Score PL 2.7: 5

1.13. Integration local economy (PL 2.8).

This project does not provide employment, services or products, but is in collaboration with the local university by being part of the campus and offering student housing.

Score PL 2.8: 3

2. AIZ campus Kottenforst _ Waechter + Waechter Architekten.

The building for the German Academy for International Cooperation (AIZ) is a low-rise educational building with an open spatial concept. It is constructed from a timber modular system in an open grid, creating an adaptable learning landscape. The modular system consists of fully prefabricated finished columns, beams, floor plates, facade elements and roof elements. These elements were then taken to the construction site, after which they could be fixed to the concrete structure. The concrete construction consists of the basement, the ground floor, the parapets and the stable cores.

2.1. Costs project (PA 1.1 -1.4).

Figure 7. AIZ campus Kottenforst (Waechter + Waechter Architekten, 2019)

The gross total construction costs of the project (according to DIN 276) are € 11.25 million (KG 200 - 700). € 9.96 million of this went to building structures and technical systems (KG 300 + 400) (Reich et al., 2019). This cost item probably includes both building construction and finishing. This equates to a percentage of 88.5%. This is a significantly large share, but at the same time it means that for the other cost items within the construction costs only a small part remains (11.5%). This includes preparatory work (KG 200), outdoor facilities and open spaces (KG 500), equipment (KG 600), and additional construction costs (KG 700). Unfortunately, costs for financing and fees (KG 800) are not indicated and it is also unclear where the cost item for transport falls under this subdivision. Reasons for the low share of preparatory work, equipment and additional construction costs can largely be attributed to the large-scale use of prefabrication in this project.

Due to this different way of cost allocation and the fact that the data for all cost items is not available, it is very difficult to give a representative figure for the cost parameters for this project. However, it can be concluded that here too the use of prefabrication saves a lot of costs on the construction site.

Score PA 1.1: n.a.

Score PA 1.2: n.a.

Score PA 1.3: n.a.

Score PA 1.4: n.a.

2.2. Alignment sustainability and environment. (PA 1.5)

This project mainly uses timber building materials, both in the construction and in the facade. In addition, the project is situated on a forest edge of the Kottenforst. It respects the site by adding little paved ground to the project and leaving a lot of space to be surrounded by trees. There is no natural inclusiveness in the building itself. Furthermore, no approach has been described for energy generation, circular use of flows or for promoting biodiversity.

Score PA 1.5: 5

2.3. Social added value (PA 1.6).

This project creates employment through jobs in the education sector. Due to the many open spaces and the large amount of windows on all sides of the building, there is a lot of social control, creating a safe living environment. The open character of the building offers many opportunities for interaction. Most interaction will take place in the communal areas, which are located in the center of both wings and the private areas on the façades. The lift and ramps allow disabled people to experience the building and the public space around the building in the same way. Due to the open and adaptable character of the building, users have the freedom of choice and the influence to furnish and use it as they wish.

Score PA 1.6: 6.2

2.4. Knowledge development and sharing (PA 1.7 & PL 2.9).

The modular wood construction techniques used can be viewed passively from both the inside and the outside. In addition, there are active contributions from the users of the school because they are continuously in the open learning landscape and can exert influence on it. Apart from being a school, the building has no other public functions and no non-formal activities have been organized to develop and share knowledge about the techniques used.

Score PA 1.7: 6

2.5. Response to existing infrastructure (PA 1.8).

No major infrastructure interventions were required for the realization of this project. The plot is located on an existing road (In d. Wehrhecke) and only a few additions had to be made to reach the building.

Score PA 1.8: 8

2.6. Ease of construction (PL 2.1).

In this project only two different sizes of prefab modules were used. This has ensured that the building elements are very universally applicable. In addition, the prefabrication of the elements ensured that the majority of the construction took place off-site, so that the elements only had to be assembled on the construction site. The assembly of the timber construction took a total of five months and the building could be delivered nine months later (Reich et al., 2019). The columns, beams and floor slabs were separate elements, but the roof elements had been brought to the construction site in their entirety. This method required the use of a crane. Once the elements were in place, they could be attached manually with the help of steel fasteners.

Score PL 2.1: 7

Figure 8. Assembling building on site (Waechter + Waechter Architekten, 2019)

Figure 9. Prefabricated timber columns (Waechter + Waechter Architekten, 2019)

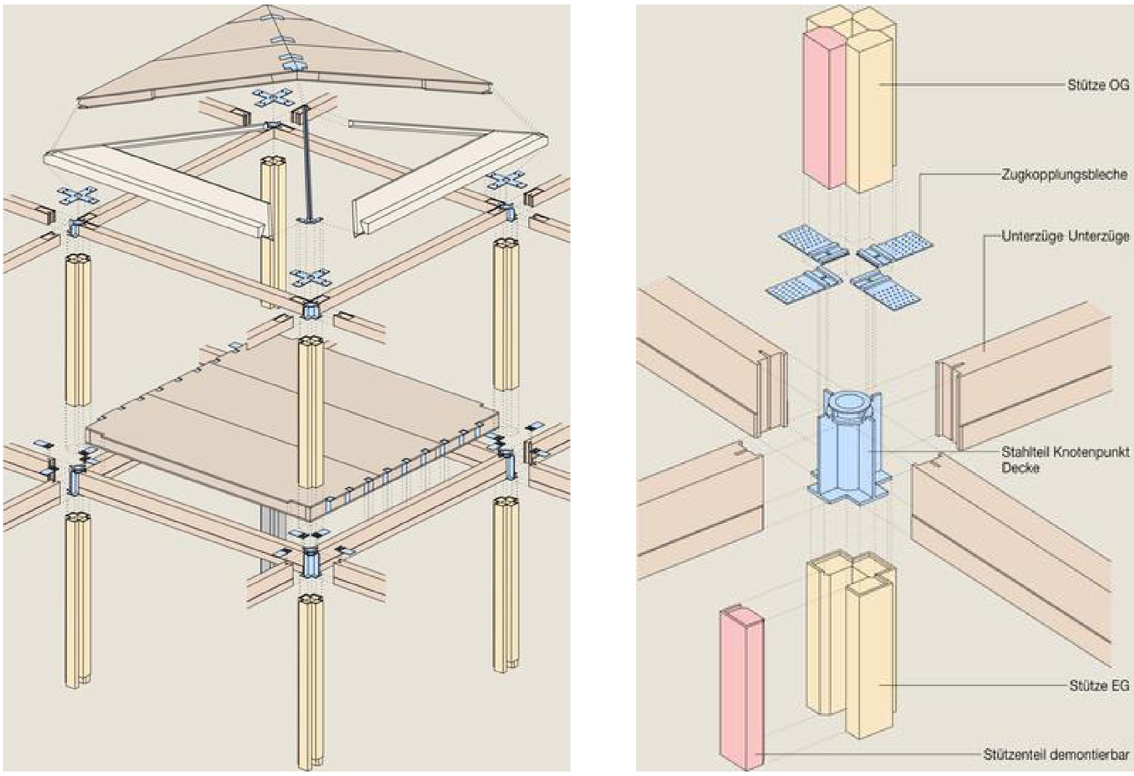


Figure 10. Construction principles modules and columns (Baukobox, 2019)

2.7. Future adaptability (PL 2.2).

The tight grid and the universal modules make it very easy to make changes in the layout of the building. It is most suitable for a public building, such as a school. Housing might be possible if access can be centrally arranged. Because each module has a skylight, it might even be possible to make homes that do not adjoin the facade. Adjusting elements in the facade is easy to do, but adjustments in the construction become more difficult, as every part is connected to each other.

Score PL 2.2: 8

2.8. Possibilities or cascading (PL 2.3).

When this building comes to the end of its life cycle, and can no longer be reused in its entirety, it can be taken apart at the element level; the columns, floor slabs, roof and facade elements can be separated in the same way as they are put together. Since it is processed wood, it is better to reuse the element than to try to reclaim the wood. When the elements are taken apart, however, construction rubble will be created due to the concrete screed of the floor elements. These elements were designed for this building, so their reuse would be optimal if a similar grid is used.

Score PL 2.3: 8

2.9. Environmental control (PL 2.4).

The indoor climate is controlled by a mix of passive and active techniques. The vertical wooden slats on the facade, the roller blinds on the outside of the facade and the surrounding trees provide passive sun protection. In addition, a heat pump with geothermal heat/cooling is used (Reich et al., 2019). No energy production is present in this building.

Score PL 2.4: 4

2.10. Amount and efficiency of material used (PL 2.5)

Most of the building consists of timber construction. This in itself requires little energy for processing. In addition, there is no unnecessary oversizing. As with the Brock Commons, a combination of timber construction and concrete construction has been used here. In this project, however, only a small part of the building is made of concrete. This is most likely due to the scale of the project. This project has only two floors, so little extra reinforcement is needed. In addition, steel connectors are also used here. Steel node joints and tension plates are used to connect the beams and the columns. The processing of steel and concrete does require a lot of energy.

Score PL 2.5: 6

2.11. Embodied carbon of material (PL 2.6).

In this project, too, the story in terms of material use is ambiguous. The majority of the material consists of carbon positive materials, but when looking at the types of materials, this building scores a meager 5.8 on average.

Score PL 2.7: 5.8

Figure 11. Materials AIZ campus Kottenforst (CINARK, The Royal Danish Academy, 2019)

2.12. Origin material/resources (PL 2.7).

The modules used are made by Grossmann Bau GmbH & Co. This company has three sponsors: Holzkompetenzzentrum Rheinland, Holzbau-Cluster Rheinland-Pfalz, and WFG Ostbelgien VoG - Wirtschafts- & Regionalförderung (Grossmann, 2018). These are local companies that focus on sustainable timber construction and stimulating the local economy. In addition, the suppliers of the concrete and steel cannot be traced, but for this parameter it does not matter much since they are unsustainable sources.

Material	Supplier	Source	Distance	Score
Timber	Grossmann Bau GmbH	Sustainable	160 km	6.5

Score PL 2.7: 6.5

2.13. Integration local economy (PL 2.8).

This project provides employment in the education sector. In addition, it offers a training center for the local community as a service. It is also part of the Deutsche Gesellschaft fur Internationale Zusammenarbeit, where they prepare people for collaboration over the entire world. However, this has little bearing on cooperation with other local companies in Bonn.

Score PL 2.8: 7

Appendix 3: Case study analyses (element scale)

S'LOWTECTURE - TOMASZ BROMA

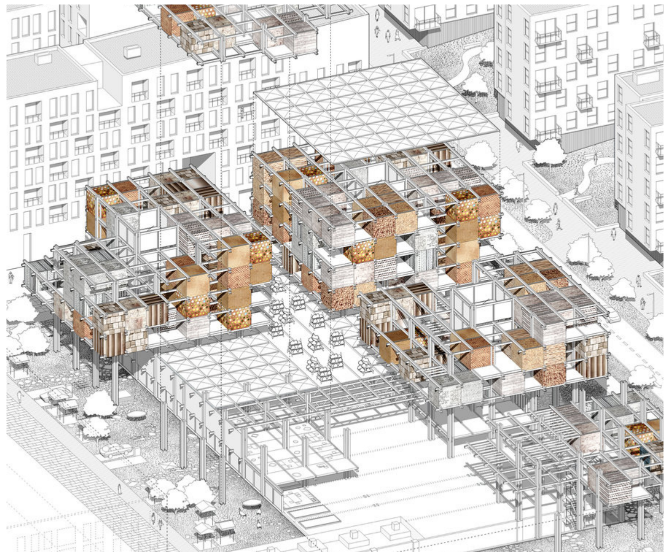


Figure 12. S'lowtecture (Broma, 2016a)

Architect: Tomasz Broma
Function: housing, vertical village, production
Scale: High-rise
Project state: experimental project.
Location: Wrocław, Poland

"The project is an experimental housing structure arising from the slow-life philosophy and low-tech architecture. It is based on the DIY idea and allows inhabitants to build their own houses according to the rules of simple spatial game using building technologies from local, natural or recycled and easily accessible materials." - Broma (2016)

A fixed structure of glulam columns and beams forms the playing field within which the residents can form their own home. The users actively participate in the process, because there is a multifunctional hall on the ground floor, in which they can work with simple techniques and local, natural and easily accessible materials.

The project is very experimental, so few statements are made about aspects such as fire safety, construction and ownership. But it is very bold in terms of material use, user participation and creating a self-sufficient supply chain. The project clearly shows how residents can learn hands-on about and contribute to the use of low-tech techniques and materials. In addition, the grid provides possibilities for the use of universal modules and freedom to adapt the building over time.

No concrete information can be found about the construction method and connections, so the crucial detail is a representation of how it could be put together.

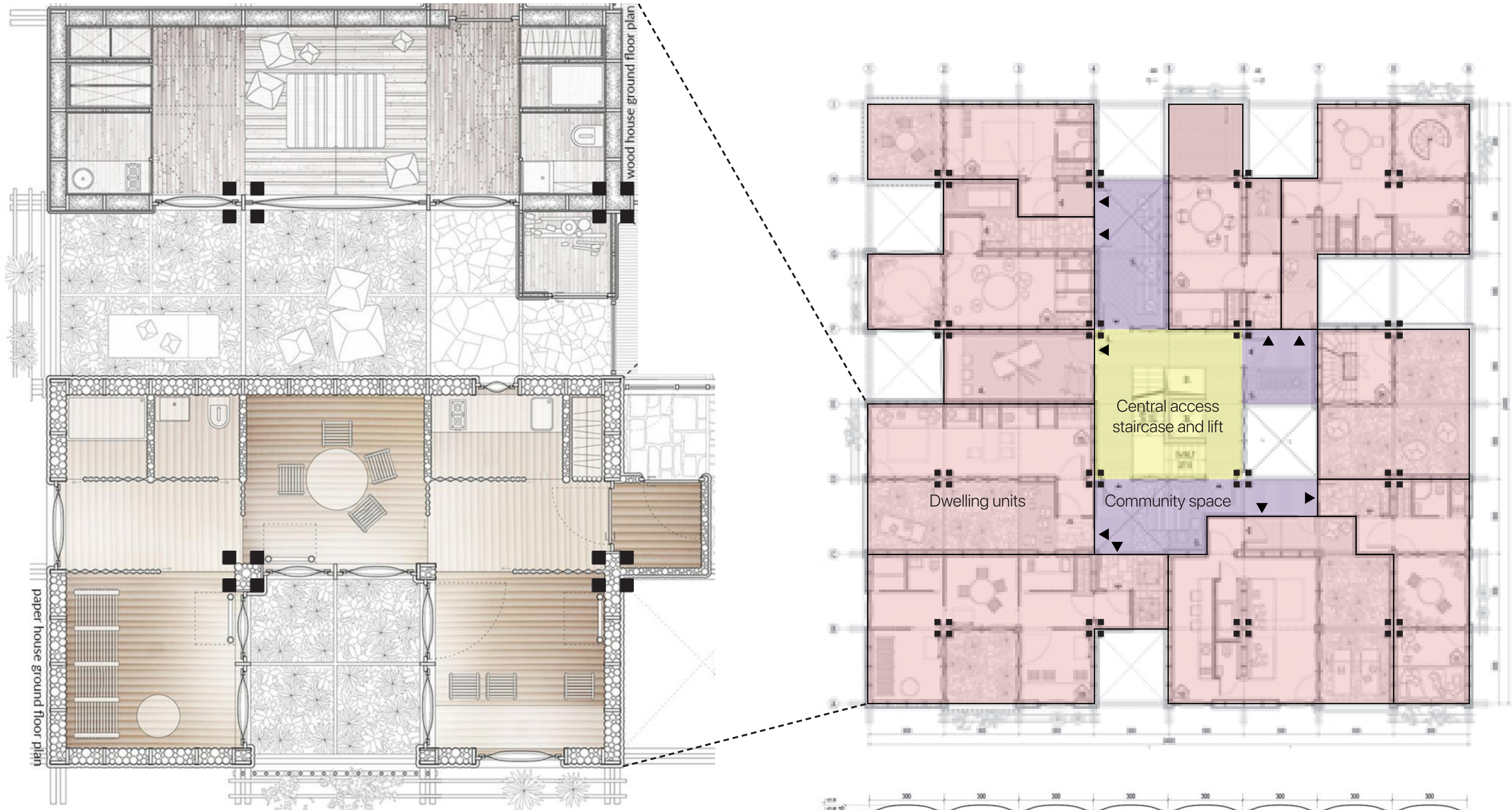
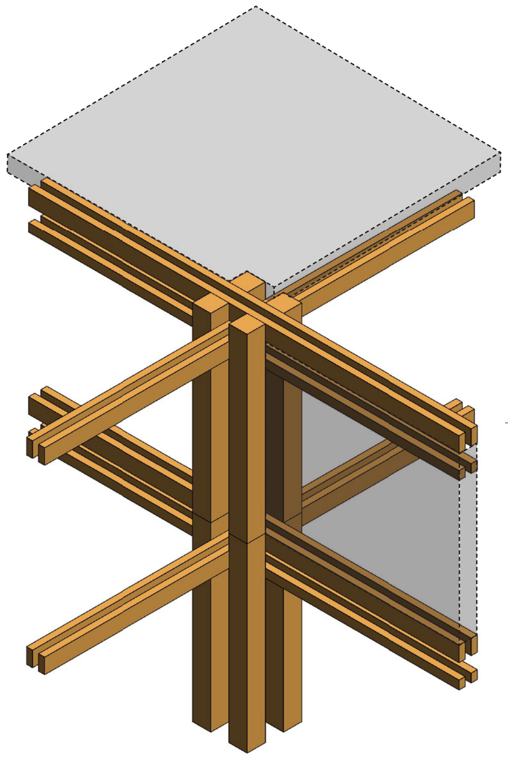
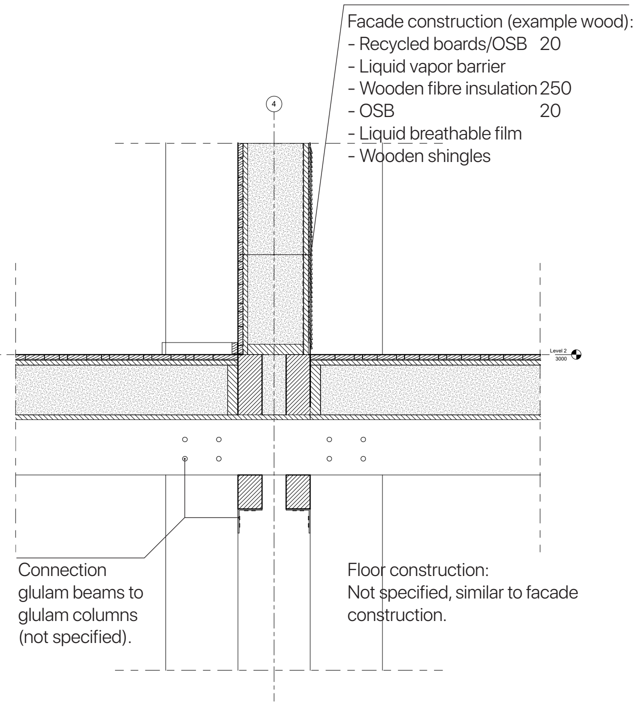


Figure 13. S'lowtecture floor plan (Broma, 2016b)





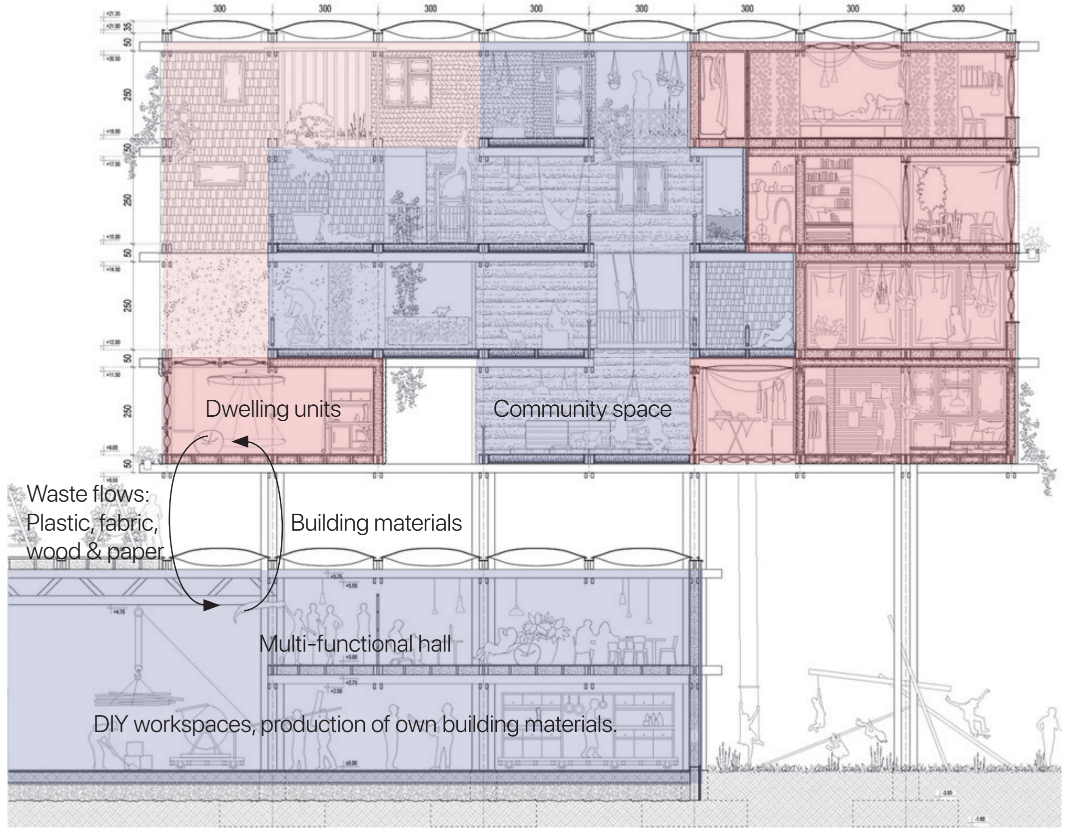
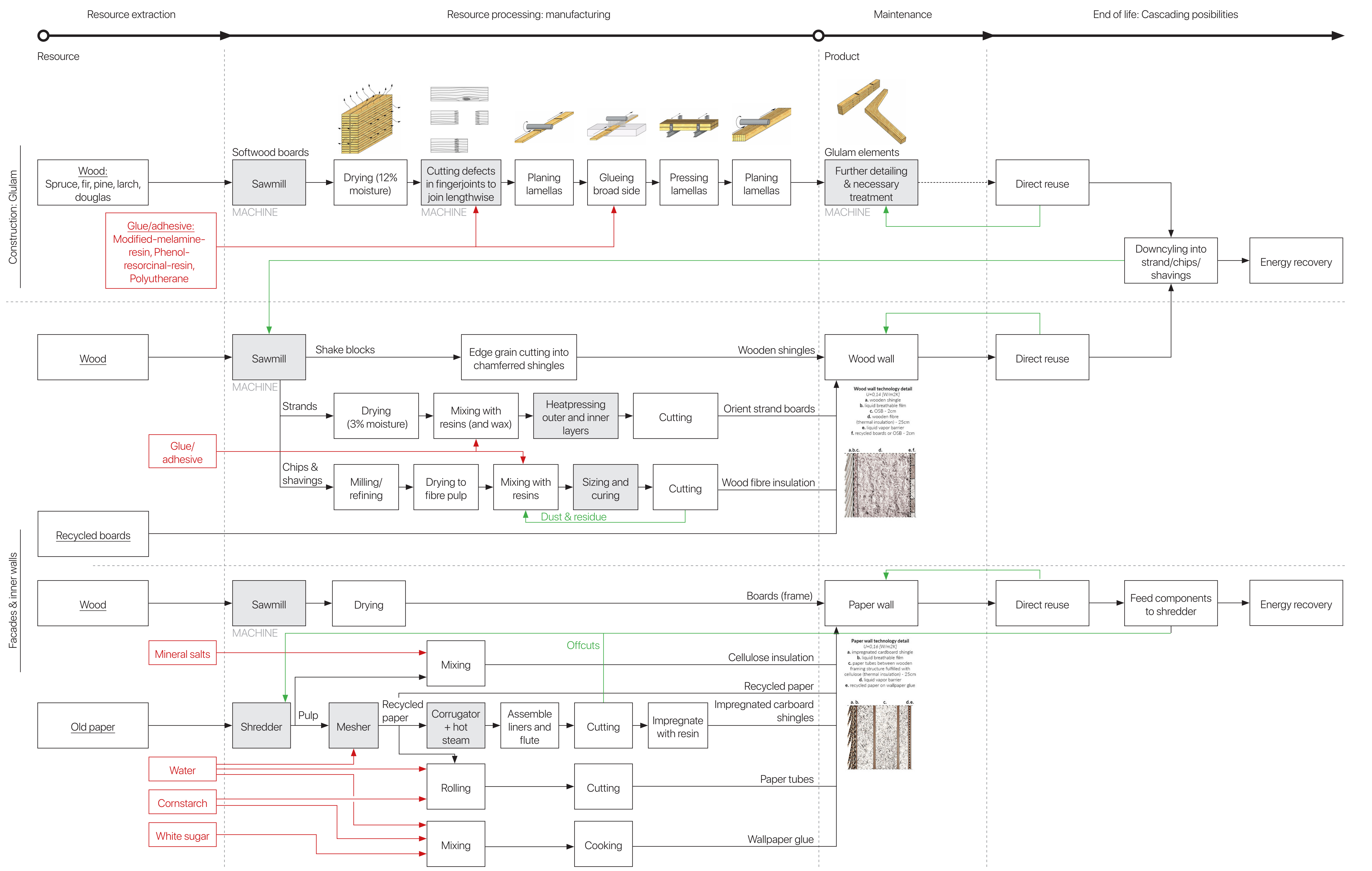


Figure 14. S'lowtecture section (Broma, 2016b)

S'LOWTECTURE - TOMASZ BROMA



MALMÖHUS - TIGCHELAAR ARCHITECTS

Architect: Tigchelaar Architects and advisors
Function: Housing, workplaces.
Scale: Medium-rise multi-storey timber.
Project state: Finished (2009)
Location: Almere, Netherlands

The Malmohus in Almere is the first four-storey timber construction project in the Netherlands. The U-shaped building block consists of five layers, housing 52 starter homes and workshops for start-up companies. The building has a stone plinth with lime sandstone walls and concrete floors in connection with fire hazard. The construction of the woorden layers on top consists of load-bearing Lenotec walls (CLT) and prefab Kerto rib floors (LVL - laminated veneer lumber). The facade consists of a timber frame construction.

Several aspects of low-tech and affordability are addressed in this project. First of all, the construction of CLT walls and LVL floors, together with the timber-frame façades, ensure that the top four floors are made entirely of wood and therefore of low-embodied carbon materials. An exception to this are the plasterboards that have been installed for fire safety. The architect could also have used 20 mm thicker Lenotec panels for this, but from a cost point of view this option was dropped. A panel construction was chosen for the floors, because such solid wood floors would be 30-40% more expensive. In addition, a panel construction makes it easier to process installations in the floor. For sound insulation (impact sound), the floors are placed on the walls by means of a rubber support.

"When constructing in wood, it is important to transfer the horizontal (wind) forces to the foundation as quickly as possible." - Emil Lüning (timber constructor)

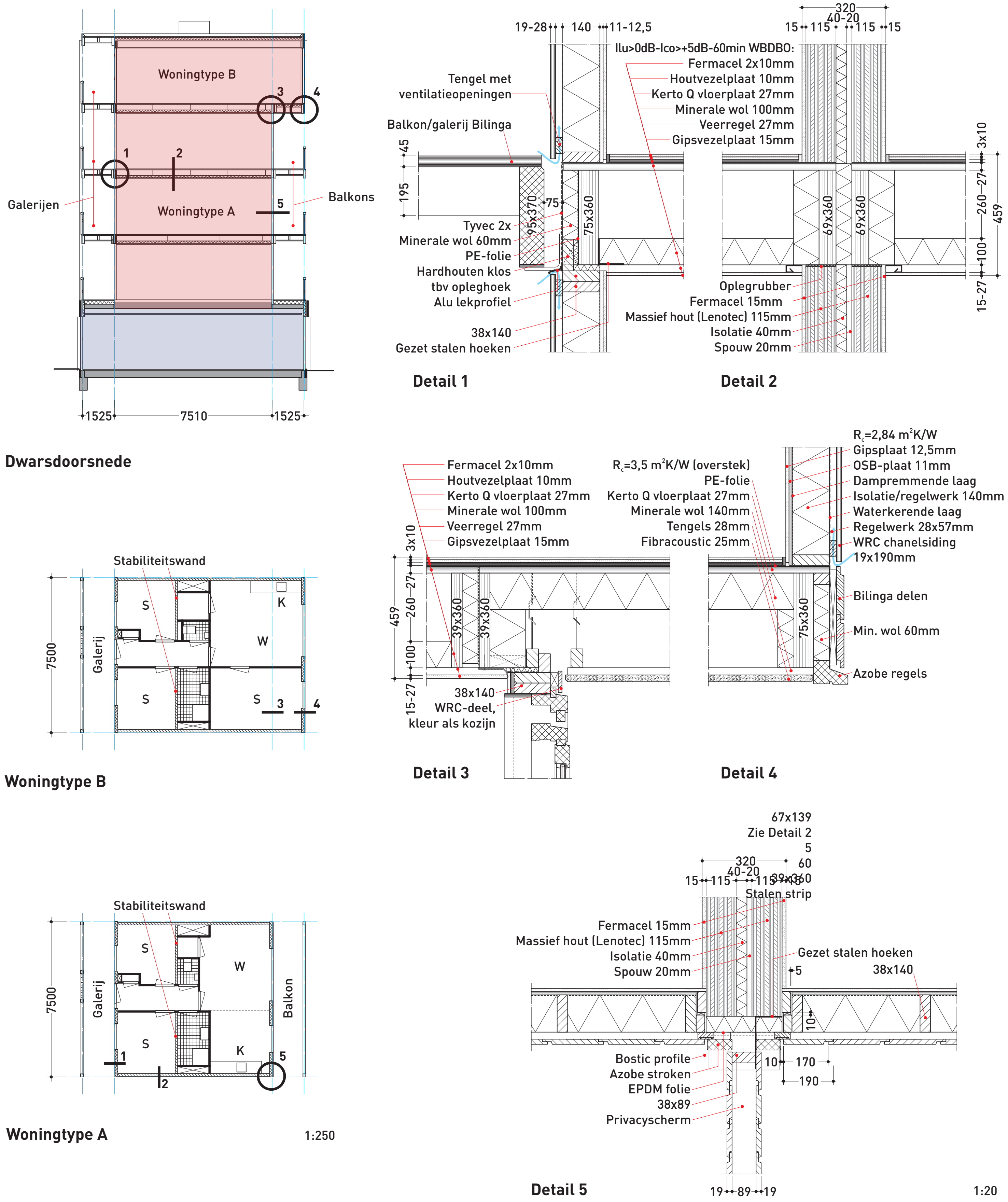
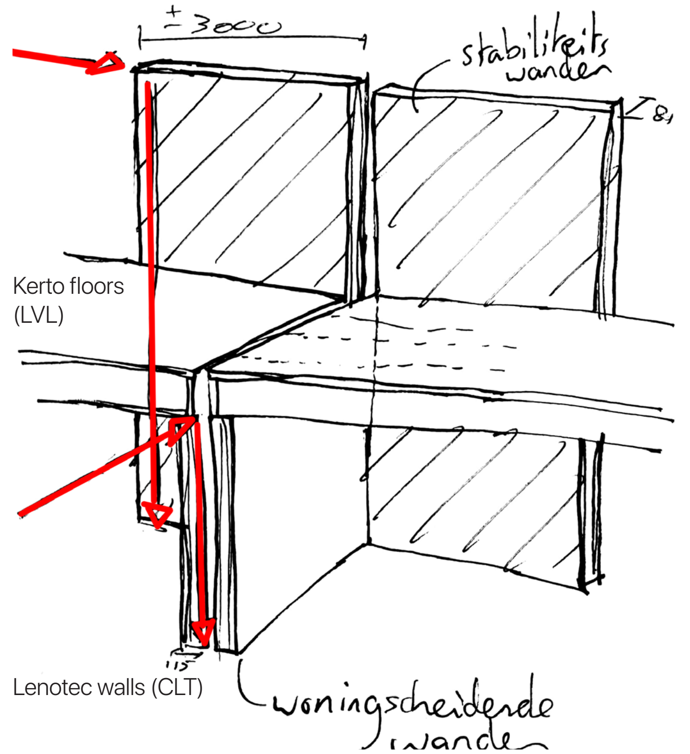


Figure 15. Drawings Malmohus (Lüning, 2009)



MALMÖHUS - TIGCHELAAR ARCHITECTS