THE FEASIBILITY OF LIGHT STRUCTURES

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1. PURSUING LIGHTNESS

1.1 Natural resource efficiency

Natural organisms give us a fine example of resource efficient use of material whilst achieving high functional capacity. Trees, for instance, need to penetrate deep into the soil for water and nutrients, reach up towards the sky for harvesting precious solar radiation and stand firmly against the physical and chemical loads of the environment. They achieve all this with an optimised amount of solid mass.

Exactly how the growth of a tree adopts to these conditions in an optimised manner is not known. However, maintaining a sound balance between height, mass, form and metabolism is essential. Trees can bend and absorb wind energy gradually through a complex swaying motion. Fine twigs bend and take the wind load first, then branches and finally the trunk and roots with the help of soil´s weight. With every cell optimised for survival, trees may grow on harsh outer islands and stand wind loads as high as 600 kN-m [1].

Yet, wood can be logged and crafted manually with simple tools. No wonder why the most ancient known man-made buildings - found in Nice, France, and dating back some 400,000 years - were made of slender wooden poles that were bent to form a strong, tensioned dome structure [2]. Similar structures are still used in vernacular and nomadic shelters in rural Africa, for example.

1.2 Drivers for resource efficiency

Today, we are facing several drivers towards more material-efficient construction. We consume too much of our planetary resources, cause too much waste and still cannot provide our growing population with equally healthy and sustainable lives.

To decouple financial growth from resource use, more added value has to be created with less material-related negative impacts. In the EU, a flagship initiative "Roadmap to a Resource Efficient Europe" was launched in 2011 [3]. One of its key focus areas is construction, which consumes around half of the extracted materials in Europe [3, p. 18].

1.3 How do we use construction materials today?

Today, great energy and emission implications from the processing of construction materials result from the use of metals, especially steel, copper and aluminium [4]. Aggregates and concrete are the most-used resources in terms of mass. We need to find alternatives for materials that make our cities heavy polluters and slow to change direction towards a more sustainable future. The natural qualities of wood, resource efficiency, lightness and great strength are much-needed features for building our societies.

Construction materials are not always used efficiently at the building site. According to the UK´s Waste & Resources Action Programme, approximately 15 – 45% remains unused or turns into waste [5]. A saving of up to 35% in this figure could be achieved by implementing more efficient practices in logistics and material handling. These include construction consolidation centres, just-in-time delivery, demand smoothing, on-site market places and offsite fabrication [5].

An important aspect of resource efficiency is the reduction of waste. Construction and demolition waste (CDW) is the largest waste fraction in Europe, totalling 33% of all waste in 2012 [6]. The Waste Framework Directive [7] aims at reuse or recycling of at least 70% of the weight of non-hazardous CDW by the year 2020. This calls for changes in how buildings are planned, constructed, repaired and demolished. Prefabrication, again, has been identified as an option for reducing CDW [8] [9].

2. THE LIGHTNESS OF WOOD

2.1 Organic strength optimised

Trees are built of cells that consist of cellulose, hemicellulose and lignin molecules. Cells can have a number of functions: transporting water, nutrients, maintaining growth and supporting the stem of the plant. They have a tubular structure with multi-layered walls. The lignin in the cell walls can take compression forces and the micro-fibrils consisting of reinforcing cellulose and hemi-cellulose molecules withstand tension forces. This composite structure gives wood its lightness and strength. In spruce tree, the raw-material for laminated veneer lumber, the compression strength parallel to the grain is up to 11 N/mm^2 and tensile strength up to 9 N/mm^2 [10].

The properties that make trees strong with an optimal amount of mass are present in wooden construction products as well. For example, engineered wooden beams compare well to steel and concrete beam alternatives. The span to depth ratio of laminated veneer lumber (LVL) beams is in the range of 20:1. Alternative steel beams reach figures from 15:1 to 25:1 and different concrete beams range from 7:1 to 26:1 [11].

However, it is the lightness of wooden structural members in comparison to concrete and steel alternatives that deserves special attention. The "specific strength" of construction materials is the ratio of their strength and density. This figure is 5.22 kN-m/kg for typical concrete, 63.1 kN-m/kg for average stainless steel and in the range of 115 to 521 kN-m/kg for different wood species [12]. In other words, much less wood is needed for achieving the same strength as with steel and concrete beams.

The high specific strength of wood and engineered wood products is an important feature in resource efficient construction. The lighter the building parts are, the less there is a need to spend energy on their transportation and erection. This leads into savings in the building process.

2.2 Comparing the weight of alternative structures

For comparison, a calculation was made with several alternative structure types for roofs, intermediate floors and ground floors. Kerto LVL structure types, provided by Metsä Wood, were compared to typical concrete and steel structure types from a Finnish standard structure catalogue [13]. The weight comparison is shown in Figure 1.

As can be seen, typical Kerto LVL structures are lightest in comparison to alternative structures in roofs, intermediate floors and ground floors. This is caused by the lightness of LVL in comparison to its strength (specific strength) [11] and the optimised amount of LVL used in the elements.

The consequences of the light weight of building elements are multiple and mostly positive. They include a smaller own weight of structure, easier handling at the building site, less energy required for handling and logistics and quicker response to indoor thermal adjustments in highly energy- efficient buildings.

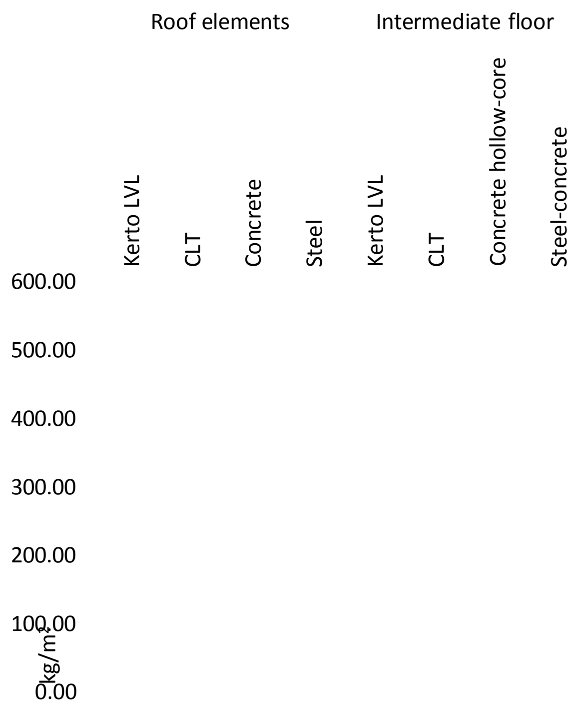

***Figure 1.** Weight of typical building elements.*

3. THE BENEFITS OF LIGHTNESS IN CONSTRUCTION

3.1 Lighter logistics, lighter budget

Favouring light and prefabricated building elements can thus be justified from the viewpoints of improving material efficiency, reducing waste, improving the efficiency at building sites and enhancing the productivity of building product manufacturers.

The benefits of lightness start during from the transportation. If the product is light, it is generally cheaper and more energy efficient to transport. The same applies to the internal logistics at the building site. Material handling at the building site may take 14% of the working time [14] and may control up to 80% of the schedule of the entire construction project. Material handling should be minimised, as it only adds costs, not value to the product. Ideally, individual sub-components should be combined into single "unit load", which is more effective to be handled at the building site. Therefore, prefabricated building products, such as Kerto LVL roof and floor elements, may improve the efficiency of material handling. Furthermore, construction logistics may range from 12% [15] to 30% [16] of all production costs.

In growing urban areas, the importance of enhancing the efficiency of logistics and material handling is highlighted. In Croydon, London, for instance, the large-scale development of the area added a considerable amount of construction-related traffic while urban infrastructure and utilities construction work narrowed the roads. This increased noise and pollution, decreased traffic safety and had a negative influence on the local economy [17]. As the world's urban infrastructure will go through a major transformation during the next 15 years [18], solutions for increasing the efficiency of logistics are valuable because of economic, environmental and social sustainability. If prefabricated and light-weight construction products could be favoured instead of heavier components, less time and energy would be required for the transportation and handling of construction materials.

Offsite prefabrication offers benefits for the constructor and manufacturer at the same time. Constructors can benefit from more efficient logistics, material handling and less waste. Manufacturers may benefit from a possibility to improve their productivity as a result of higher prefabrication levels [8]. Prefabricated building elements may have less wastage and reduced transportation needs when compared to onsite construction [5, p. 19].

The weight of the construction material may play an important part in its pricing. Material costs may range from 30% [19] to as much as 70% [20] of the total construction cost estimates. Depending on material and transportation distances, logistics may form an important part of this cost. For instance, researchers in Finland found already in 2001 that the price of gypsum board was influenced up to 27% by its logistic costs [21]. Polish researchers concluded that if supplies are provided by one central supplier instead of many, 6% cost savings in logistics may follow [20].

The logistic costs can be broken down into several sub-cost-categories. One of these is the consumption of fuel. The fuel efficiency of road transportation, which is the most common mode of transportation in construction sector, increases as the total weight of vehicle decreases. In other words, if building elements that fulfil comparable functions in the building can be loaded into the truck in similar quantities, the lighter element load will improve fuel efficiency [22].

The weights of the alternative structures in Figure 1 can be used for exemplary calculation of the CO_2 emissions of their transportation. Assuming that the distances from factory to the construction site and the terrain profile of the route would be the same, the differences in transportation emissions can be compared from Table 1. As can be observed, the Kerto LVL element alternatives have the lowest emissions and thus best fuel efficiency.

Table 1. *CO_2 emissions from transportation of 1m^2 of element (kg CO_2e / km).*

Roof elements	Kerto LVL	3.82
	CLT	6.30
	Concrete	15.66
	Steel	9.37
Intermediate floor elements	Kerto LVL	7.25
	CLT	15.82
	Concrete hollow-core	24.62
	Steel-concrete	32.12

3.3 Lightness and energy efficiency

Buildings that have moderate energy efficiency usually benefit from massive structures that can store heat and buffer indoor temperature changes. In many conventional green design instructions the use of mass has been recommended e.g. in front of windows so that solar rays can warm the materials inside the house. Warm structures can then warm the apartment during nights. Similar methods can also be used for cooling the building. The benefits of thermal mass have widely been described in scientific literature as well.

However, in highly energy efficient buildings, such as passive houses, the role of thermal mass may be less important [23]. In Nordic countries, the energy efficiency benefit of thermal mass in structures may be as low as 0.7-2.0 % [24]. A study from the UK found no practical difference in the thermal performance of heavy and light buildings in a simulation that extended until 2050 and included the predicted warming of climate [25]. Researchers in Sweden compared the effect of thermal mass in concrete and wooden residential buildings and concluded that although the massive concrete building consumes slightly less energy for heating, these gains are over-run by the considerably higher level of embodied energy in heavier construction materials [26].

Thermal mass can become a drawback in hot climates. Researchers compared a zero energy house option made from massive concrete and another made from light timber in the climate of Las Vegas. They concluded that the solar heat gains add more heat into concrete during the day that can be cooled off during the night. Thus the concrete-framed zero energy house alternative required more energy for cooling than the light timber version [27]. Where thermal mass is required, it may also be optimised through the selection of fixed furniture and interior surface materials [28].

Light-weight buildings respond rapidly to adjusting of heating or cooling. The mass of heavy-weight structures, on the other hand, slows such adjustment. Whether this is finally beneficial or not is dependent on the use, location, orientation and full life cycle energy balance of the building.

Based on emerging scientific findings, it can be argued that light-weight zero energy buildings from wood may be optimal for the future. They allow for agile adjustment of thermal performance without the delay of thermal mass. This may help to balance the hourly heating and cooling demand and better respond to changes in daily temperature, solar radiation, internal heat gains and occupancy.

3.4 Heavy refurbishments with light materials

Our existing built environment is going through an era of refurbishment. The technical service lives of building service systems, such as sewage and ventilation are a driver of residential refurbishments. In addition, the dire need to cut down CO_2 emissions from the building sector leads to energy refurbishments. To finance such operations, new stories are in some cases being added on top of existing buildings.

Adding new layers into the facades or roofs of old buildings requires careful planning in order to avoid structural collapses. The old structures may have been calculated according to different standards than are applied today and the materials may have been damaged and lost part of their load-bearing capacity during their service life. Using lightweight refurbishment materials, such as wood, is one possibility to bypass this problem [29]. The use of wooden building elements in particular may become feasible when adding new stories on top of an existing building. Furthermore, refurbishment projects can cause risks to construction workers. In fact, the majority (41%) of construction worker fatalities in the UK were associated to refurbishment projects [30].

A typical energy refurbishment project was carried out on a residential building from the 1970s located in Riihimäki, Finland [31]. The project was a demonstration of new wood-framed façade panels that were developed by German, Norwegian and Finnish researchers [32]. The external layers of the existing concrete sandwich structure were removed and replaced with prefabricated wooden elements that had insulation, building service ducts and windows in place. In order to ensure a perfect fit to the existing building frame and to minimise moisture movements, Kerto LVL was used. With the help of these LVL-framed thermal insulation elements, the building is aiming to cut down 75% of its heating energy demand. If similar measures would be applied, the benefits would be drastic. According to BPIE, a Brussels-based policy research institute, energy renovation of the existing building stock can, in addition to cutting down energy consumption, reduce fuel poverty, create growth, innovation and employment and bring several co-benefits due to improved air-quality and living comfort [33]. However, these aims need to be pursued with material-efficient solutions that do not come with hidden, embodied burdens attached. Lightweight structures that are made from renewable materials and that have high degree of prefabrication seem to be an ideal solution for meeting the energy refurbishment requirements in a sustainable manner.

3.5 Slight concerns?

However, lightweight buildings have been associated with concerns regarding acoustic problems, vibration, wind loads and lack of thermal mass. These issues need to be considered when designing with light structures, framed with wood or steel.

The acoustic issues are mostly related to the absence of mass in the building and can be overcome by adding mass into floorings. Usually this is done with a gypsum or concrete cast. As a result, according to Swiss researchers, the acoustic satisfaction in wooden houses has been found to be very positive [34].

However, the conventional way of ensuring the acoustic comfort in wooden intermediate floors with gypsum or concrete cast conflicts with the benefits of lightweight materials and prefabrication. The floor area needs to be cleared for casting and the area needs to dry before any further work can continue. Therefore, Kerto LVL intermediate floor elements have layers of pre-assembled gypsum boards that give the structure the required acoustic properties. This way, the drying time of concrete or gypsum cast is avoided and the benefits of prefabrication enhanced.

To prevent light high-rise buildings from swaying in the wind, truss structures and additional mass can be added and, as explained earlier, the lack of thermal mass does not actually seem to be a major concern, as studies have shown that its assumed positive impact on energy consumption may be marginal and that lightweight structures may help to provide the buildings with quicker responses to adjusting indoor thermal comfort according to hourly needs.

4. THE CONCEPT OF LIGHTNESS IN ARCHITECTURE

Buildings are not only materials and structures. They are not built for the sake of using materials efficiently, for highlighting technological advances or for exemplifying novel materials and their outstanding structural properties.

Although structures are physical, they can have a haptic or immaterial quality to enrich architecture and make "spaces become places" [35]. This adds a layer of value to the physical properties described earlier. According to the great modernist architect Ludwig Mies van der Rohe, "where technology attains its true fulfilment, it transcends into architecture" [36].

In an architectural sense, structures can represent the objects of the natural world or they can symbolise abstract concepts, such as order, stability, simplicity or lightness.

In his book "Six Memos for the Next Millenium" [37], Italian writer Italo Calvino outlines values that he sees important for our millennium. The first one is "lightness". Calvino describes the "slow petrification" of our physical and metaphysical world and then states that in we have to change our approach, "look at the world from a different logic and with fresh methods of cognition and verification". This may help humanity, which he seems "condemned into heaviness". Calvino summarises that lightness is one of the virtues that we should try to bring to the new millennium.

Trees are built of air. Half of their dry weight is carbon sequestered from the CO_2 in our atmosphere through photosynthesis. Simultaneously, trees produce oxygen. In the end of their lives they decompose back into the air. These poetic facts give wooden structures a potential for achieving the sort of conceptual lightness that Calvino suggests for our millennium.

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