Resource-efficient Structural Design

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Abstract

The building and construction industry is by far the most resource intensive sector in the European Union [1] and the numbers worldwide are comparable. This sector, which is based on a very strong responsibility of architects as well structural engineers takes approximately 50% of all primary raw materials and therefore exhausting natural resources substantially. In the past decades the focus in the construction industry was mainly on the reduction of energy consumption of buildings as well as use of renewable energy, but the impact of material use will be in the spotlight in the future as well.

Keywords: Resource efficiency, Life-cycle assessment, Lightweight, Re-use, Bio-based materials

1. Introduction

Recently the Dutch governments formulated the program “Nederland Circulair in 2050”, which states the ambition to use 50% less primary materials in 2030 and to have a full circular economy in 2050. As one of the consequences as of 1st of January 2018 the Dutch municipalities will check compliance with a so-called MPG calculation (in Dutch: MilieuPrestatie Gebouwen; in English: Environmental Performance Buildings) for all new buildings. This material impact calculation is mandatory and evaluates the total effect of the weighted environmental impacts of the total building’s materials.

To meet these ambitions, resulting from the Paris Climate agreement, it is essential to re-think the use of materials in structural systems and various approached can be followed. In this paper following approaches will be elaborated:

1. Minimal use of materials: The optimisation of structural systems in terms of minimal weight as well as more recent developments in the field of adaptive structures will create new opportunities to even further minimise the use of natural resources.

2. Re-use of materials, elements and structures: In all industrial countries there is a huge amount of existing building stock. Even if there will be further need for new buildings, a good understanding of the potential to re-use existing buildings can also contribute to save natural resources.

3. Renewable materials: Another possibility is to replace traditional (mainly cement-based) materials with renewable bio-based materials or even use completely ephemeral materials, such as ice for temporary buildings.

The authors carried out case studies with all the three above mentioned strategies and within this paper will review and compare the various approaches in terms of further research needs and possibilities of combining then, as well as possible practical applications and societal impact and benefits.
2. Environmental performance of buildings

From the 1st of January 2018 for all new buildings in the Netherlands the MPG [2] calculation is mandatory in the application for a building permit. Contrary to its name, the MPG calculates the environmental impact of (only) the materials in the building construction. It does this for new housing as well as for new office buildings (a calculation for other buildings or the civil engineering sector, (roads, bridges etc.), is not yet mandatory). The MPG-result is expressed in a single figure called environmental (shadow) cost. This resulting figure is the aggregated total of each environmental effect multiplied by its monetarisation number (cost). They are called shadow or prevention costs and are expressing a reflection of the cost that a society is willing to pay in order to achieve or prevent a certain environmental target-effect. It also considers the distance to achieving these results. This aggregation towards total cost obviously needs weighing of the impacts. This is however in most cases a subjective step and thus a matter of stakeholders’ views, or, in other words, politics. For obvious reasons the aggregation of weighted values is therefore usually not a scientifically supported step in the LCA approach. The obvious concept behind the MPG is that a lower MPG indicates a more sustainable material use. The current maximum value for new buildings is set at a reference value of 1,0 EU per m² gross floor area/per year. Studies [3] have indicated that this value of 1,0 is currently an easy to reach target, but it is expected that this maximum value will gradually be lowered over the coming years, thus aiming at a significant reduction of the environmental value for new buildings.

The MPG calculation is based on approved Life Cycle Assessments (LCA calculations) of materials and products that are collected, maintained and updated in a national Dutch database. Based on these LCA’s, (that use 11 damage indicators such as Global Warming Impact (CO₂eq) Potential Abiotic (Primary material) depletion, Ozone layer depletion, Human toxicity, Acidification) one assembled indicator figure, the so-called environmental “shadow cost” is the final result. The total sum of all the material shadow costs for the building is divided by the years of use (using forfeit values, taken into account life cycles, expected repairs and replacements during this life cycle) and the gross floor area. The MPG calculation is now also part of the Dutch BREEAM certification, giving credits for values below the reference value. [2].

Although the intentions of the MPG are praiseworthy, it is still questionable whether its effects are fully positive. This is also recognized by various municipalities that thus far have taken different stands in maintaining the MPG. So far, the National Database has limited information especially where it concerns materials for installations and PV-panels. These however have a significant influence on the final MPG score. Obviously, criticism can be heard about the weighing and assembling all impact indicators into 1 final figure. Also, the given information seems insufficient for users. A much-heard criticism is on background data: data on data, meta data, reliability etc. are often missing or are insufficiently transparent. Scientific research and proof of the concept also seems insufficient. A particular important and influential aspect for the final score - the Service Life of the buildings (and their components) have been given insufficient attention. The MPG calculation uses various forfeit values of which the most influential: 50 years as the maximum Service Life of Housing and 75 years as the Service Life of Offices. Another example of the direct impact of service life is the recent update of the lifespan of EPDM Roofing material in the MPG from 30 to 50 years, thus reducing the material impact according to the MPG with 67%.

3. Minimal use of materials

3.1 Lightweight structures

To minimize the use of resources in the building industry, the first step is to reduce the amount needed in new structures to be build and this has a long history in the IASS community. In structural optimisation typically cross-sections, shape and topology optimisation are applied. The following approaches are developing rapidly.
3.2 Structural optimisation

Shape optimisation

The structural geometry (form) will strongly influence the structural behaviour (forces and deformations). Optimising the form increase the load-path via axial internal forces and decrease bending in the structure. This will increase the efficiency of the material use and therefore a reduction in the amount needed. This is the basis for all lightweight structures.

A shape can be optimum for a certain load pattern, but in reality, multiple load patterns will act on one structure at various times. The optimisation method should find the shape that can support all different loading situation with minimum amount of material.

Topology optimisation

When the global shape is known the efficiency can be improved by relocating the materials towards the most efficient location. Iterative structural calculations within a parametric environment are often used to find the highest structural capacity.

![Figure 1: Shape and topology optimisation [4]](image)

Case study: Shape and topology optimisation

A study is done with the goal to realize a parametric structural optimization model for a shell structures. The optimisation is for both shape and topology. Different form-finding tools are used to define the shape of a shell with constant thickness. To reduce material use, holes with varying diameter are created where material was used less efficient.

![Figure 2: Study model of a form and topology optimised shell structure: [4]](image)

3.3 Adaptive structures and optimisation

The concept of adaptive structures is based on the approach that the behaviour of a structure is not established only once during the initial design phase, but the structural response is controlled
continuously via the integration of active components. The activation of these components can be used to manipulate the internal stresses, displacements as well as control vibrations. This approach allows the structure to react to variable loads with the goal of optimizing the load-carrying behaviour in real-time. The design of structural elements can thus be carried out for reduced demands, ideally resulting in substantial material savings in comparison with passive structures. The use of smart materials is one promising approach to achieve this [5].

In a second study [6] topology optimisation and adaptive structures were combined. This combination was tested on the simply supported Messerschmidt-Bölkow-Blohm (MMB) beam loaded with multiple point loads that represent a moving load. When the different point loads are considered separately the model will results different designs. The model was extended in order that it results one optimal design for the different locations of the moving point load. Second, the model was extended by taking into account an active adaptive horizontal pre-stress tendon (red line in figure 3) between the two supports. This is done by updating its pre-stress in every iteration of the optimization process for every load condition. The result is an optimal topology for multiple load conditions and the corresponding state of the adaptive system that is different for every load case. This extension gives further minimization of the used material.

Figure 3: Results and test problems for different load scenarios and systems [6], (top) Passive MBB beam loaded with one point load., (middle) Passive MBB beam loaded with twenty different load cases (moving line load), (bottom) Adaptive MBB beam loaded with twenty different load cases (moving line load). An active adaptive pre-stress tendon (force a) was added between the two supports.

Case study: Adaptive structures example
At the Eindhoven University of Technology, numerical and experimental research is done on the structural behaviour of an actively controlled thin arch of Plexiglas.

The active control system consists of two actuators which can rotate the supports. Four strain gauges are placed on the arch to monitor the strains. In the starting situation no rotation and no moment are applied to the arch by the actuators. With the measured strains, the loading pattern and loading value must be determined to calculate the optimum location of the actuators to minimise the stresses in the arch.
Significant stress reduction is achieved using the active control system compared to the same passive structure. On average for all load cases, the maximum stress is reduced by 18%, with a maximum of 26%.

A second example considers a study of a slender high-rise office building existing of 27 levels. The main structure of the building consists of a steel frame, where the stability in the slender direction is governed by six stability frames. Over two third of the total steel weight is localised in these stability frames, where the stiffness was a decisive issue. These facts make the stability frame in this building a potential ideal application for an adaptive structure. Multiple beam elements are replaced by axial adaptive elements. With the optimal amount and location of these active elements, the clear profit of the adaptive frame is about 60% reduction of steel weight, which is mainly the outcome because of the regulation of the horizontal displacement.

4. Re-use of materials, elements and structures

4.1 Re-use of buildings

Re-use at the highest possible level is probably the best way forward to prevent and/ or further reduce building construction waste. Re-use of building structures and refurbishments, can effectively elongate
the service life of building structures, thus reducing the impact of the materials per year of use. Already in [9] while evaluating the influence of different Service Life Scenarios of a building’s environmental impact, one of the main conclusions was: “The impact results depend directly on the length of the assumed Service Life. Improvement on techniques to take into account possible differences in the lifespan of a structure are needed. For example, a method to evaluate differences in functional quality of a structure, and therefore a possibly longer expected Functional Working Life, is needed.” From then on further research indicates that for example larger floor to ceiling heights have a positive effect on the flexibility and adaptability of buildings thus increasing the probability of a longer Functional Service Life. However, in the MPG score this would not have a positive effect. Extra use of material in facades and internal walls show up as a negative result in the MPG calculation: Higher environmental shadow costs show up as a negative result in the MPG calculation: Higher environmental shadow costs, although this extra material may have a positive effect on the Service Life of buildings and thus lower the overall material impact.

If the future maximum Shadow costs in the MPG calculations will be lowered (as can be expected) to much harder to reach levels, the short time gain: reducing the Floor to ceiling height to the absolute minimum might well win over the long time goal: increasing the options and probability for re-use of the building and its building structure at the highest possible level, thus making the MPG calculation requirement counterproductive to its initial goal. In [10] the first results on the Flexibility score of Building structures and its positive correlation with the Service Life of 18 buildings is discussed. Current research on the probability of an elongated Service Life through re-use of a group of 60 buildings and their structures (depending on several different indicators) is ongoing. Preliminary results also show a higher probability of re-use (longer Service Life) for buildings with increased flexibility through for example higher Floor to Ceiling Heights. In short, the conclusion can be that not in all cases minimum material use means a maximum resource efficient structure.

4.2 Re-use of structural elements

Examples of re-use of structures at the highest possible level show that impacts per year of use can (obviously) significantly be lowered by extending the Service Lives of the elements and aiming more at re-use on component- and element-level rather than at material level. In Eindhoven (NL) is an old example close by: The re-use of so-called Bailey Bridge elements in the train-station roof-structure. The British Forces used standard truss segments (engineered by Donald Bailey) to cross rivers during the Second World War. A 10-foot truss panel could be carried by a six-man crew. From these elements Bridges of sometimes 300 feet length (90 m) were built [11]. This re-use of Bailey bridge elements form the Second World was not uncommon. Figure 6 shows two examples with these trusses.

4.3 Re-use of elements and materials

This research on the re-use of formwork is a good example of unused possibilities. The project was realised by a company producing concrete elements, Geelen Beton, in cooperation with the Eindhoven
University of Technology. The outcome of the research was used to realise a pilot project for the building of two houses in Amsterdam. Currently Geelen Beton annually produces 400 tons of wood waste from the formworks they produce. These formwork elements for stairs and balconies can only be used for one project. Various other flat products, such as floor and façade elements, can be re-used several times as formwork. After a while the formwork surfaces become unsuitable and therefore next to the factory Geelen Beton has a 'mold churchyard'. They are regularly squeezed to small pieces and burned in an oven. This method is becoming less and less attractive nowadays, since the expenses are rising. Also, for environmental reasons there is a growing need to look for a higher-quality way of re-use. The wasted wooden formworks may not be suitable for visual work because of their irregularity, but they have been used as a support structure for two houses in Amsterdam. The wood structure made from old formwork panels are rather thick and large. Although the elements are no longer suitable as formwork the structural properties are still sufficient.

![House build with reused formwork](image.jpg)

**Figure 7: House build with reused formwork**

Although the wood for the construction was available for free, the house has not become substantially cheaper. The building process was very labour-intensive, as details have to be adjusted regularly due to the variation in the panels. This meant that carefully detailed drawings had to be redesigned for several times.

For future project it is planned to set up a BIM library to improve the design and construction process and save a lot of time in the overall project.

5. **Renewable materials**

5.1 **Recent material developments**

"The 21st century will face a radical paradigm shift in how we produce materials for the construction of our habitat. While the period of the first industrial revolution, in the 18th and 19th century has resulted in a conversion from regenerative (agrarian) to non-regenerative material sources (mines), our time might experience the reverse: a shift towards cultivating, breeding, raising, farming, or growing future resources going hand in hand with a reorientation of biological production methods and goals." [12]

Obviously natural, bio-based materials such as timber and bamboo have been used throughout these times, but nowadays other materials, which are not necessarily new themselves, but their application for building products are new, came up. Examples are hemp and flex fibres [13], Mycelium [14, 15] or lignin-based fibres for composite materials [16]. In addition to fibre a resin is required to create...
Composite materials and structures and various bio-based sources exist, such as linseed oil, furans or cashew nut shells, although the commercial development of these materials is not very far yet. Apart from the above mentioned natural grown materials the use of organic waste is another option for future applications [17].

Further on water, respectively ice, is presented as a possible construction material, which in some areas is practically endless available, although its application for buildings obviously is limited to regions with very specific climate conditions.

5.2 Bio-based composite materials

In 2016 the design and realisation of the first bio-based pedestrian bridge in the world has been achieved. The bridge consists of a core made from PLA (polylactide), which is a bio-degradable foam, and a shell consisting of a composite material made from hemp and flax fibres in combination with Greenpoxy. The bridge has a span of 14m and fulfils all loading requirements according the Eurocode. More information can be found here [13].

Figure 8: Bio-based bridge at Eindhoven University of Technology campus

Among other considerations further steps include the design and development of a canopy on the campus of Eindhoven University of Technology, where the use of bio-based composite materials will be combined with innovative and experimental manufacturing methods, such as knitting or braiding of these bio-based textiles.

5.3 Ice structures

Ice has been used for all kind of application for many years. The consumption of ice goes even back to even 2700 BC in Egypt. Ice blocks were traded since 1805 all over the world. The ice trade revolutionized the U.S. meat, vegetable and fruit industries, enabled significant growth in the fishing industry, and encouraged the introduction of a range of new drinks and foods. Since the introduction of the heat pump and refrigerator this industry has almost disappeared. Today, ice is occasionally harvested for ice carving and ice festivals. Ice and snow has been used for structures like igloos in artic areas. Also, in the north of Japan igloos named “Kamakuras” were made from blocks of wet snow. Ice has unique material properties but is relatively weak and brittle. The properties of ice can be influenced by adding fibres. In this way it is possible to make an ice composite that is 3 times stronger and much more ductile compared to regular ice. In 2014 the first large project with fibre reinforced ice - the 30-meter span pykrete dome - has been realised [18]. The success of this and other huge shell structures in fibre reinforced ice have been reported by many social media all over the world for its novelty and breakthroughs [18].
Nevertheless, shell constructions in ice composites are still in the experimental phase since the realizing conditions are limited by the solar radiation, atmospheric temperature, the material, air pressure etc. There is no technical standard for the ice shells neither for fibre reinforced ice. Nonetheless, the construction is very sustainable and fully recyclable. Fibre reinforced ice could be a solution for temporary constructions in cold areas and severe cold environments. To make these structures will cost some energy for devices to mix end spray the structures. The largest benefit is that they will not leave any waste after they melt down.

7. Conclusion

This paper describes three different approaches to achieve a resource efficient structural design, which can be applied for various, but also different contexts. The use of optimised lightweight structures as well as the application of adaptive systems is beneficial for high-rise and large span structures. At this stage probably, the re-use of buildings and elements has the biggest potential impact in daily life and for widely used office and residential buildings. This is due to the large number of potential projects, where this approach can be applied. The third approach – the use of renewable materials – offers also a lot of opportunities in the future. Obviously, the use of ice is limited to specific regions, but bio-based materials can be applied in many situations. Now this might be limited to small-scale application, but further research will extend this to large structures as well.

References


