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Mapping structural engineering strategies for sustainable development

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Abstract

Considering current trends in the Netherlands with regards to sustainability, there is a strong desire at Delft University of Technology to incorporate sustainable structural design strategies in the civil and structural engineering curriculum. Based on literature study and own experiences in practice, a coherent approach was developed, that can help students and practitioners to increase sustainability in their projects. The approach consists of a roadmap with 4 key strategies: increase lifespan of existing structures by reusing them, increase lifespan of existing structural elements by reusing them, design future proof and with a long-life span, and optimise the design for environmental impact. The strategies are explained and illustrated with examples.

Keywords: sustainable structural design, environmental impact, carbon footprint

1 Introduction

Over the past century, humanity has been responsible for releasing large amounts of CO_2 (in this paper we will use CO_2, for all greenhouse gasses, although CO_2equivalent (CO_2e) might be more appropriate). As CO_2 levels in our atmosphere have risen, so has the global temperature. Our planet is now approximately 1 degree Celsius warmer, compared to pre-industrialization levels. Since 1975 the temperature increased with approximately 0,15-0,2 degrees per decade [1]. This temperature rise has manifested itself through floodings, droughts, hurricanes and fires, leading to large damages on multiple facets.

In 2015 many countries signed the Paris agreement. These countries agreed that global warming should be limited to 2 degrees, preferably 1,5 degrees Celsius, to avoid inevitable, catastrophic, and hard to control consequences. It is evident that a change of behaviour is needed across the whole of society to limit CO_2 emissions and get us anywhere near the set target of 1,5 degrees Celsius. To cite the Intergovernmental Panel on Climate Change (IPCC): "… unless there are immediate, rapid and large-scale reductions in greenhouse gas emissions, limiting warming to close to 1,5°C or even 2°C will be beyond reach" [2].

To appreciate the importance of sustainable structural engineering, it is important to realize buildings and construction together account for approximately 36% of global final energy use and 39% of energy-related carbon dioxide (CO_2) emissions [3, 4]. On the other hand, the sector continues to grow at unprecedented rates. Over the next 40 years, the world is expected to build 230 billion square meters in new construction, adding the equivalent of Paris to the planet every single week.

The last decades, emissions during use of buildings have been reduced significantly, further accelerated by the energy crisis of 2022. In a current best-practice building, the construction phase is accountable for approximately 50% of construction and use related emissions [5]. The relative share of the structure in this often called ‘embodied carbon’ emission is approximately 40-70% [6], and is expected to increase further, in part due to decarbonization of our energy supply and passive building concepts.

Therefore, it is of utmost importance that designers, and especially structural designers, are aware of their role in decreasing global CO_2 emissions and eventually contribute, to avoid a climate crisis.

TU Delft is aware of this responsibility, and the need was felt to provide students of structural and building engineering with more guidance on ways to reduce CO_2 emissions in structural designs.

2 Sustainable structural design strategies in literature

Strategies for sustainable design in the Netherlands have been developing over the past decades.

In 1979 the Dutch politician Ad Lansink developed a waste hierarchy, called Lansink’s ladder [7]. This hierarchy consists of the following levels: Prevention, Reuse, Recycling, Energy recovery, Burning and Disposal. These levels are of importance for sustainable structural design.

The Cradle to Cradle philosophy [8] even goes further. It makes a distinction between biological and technical nutrients, and it aims to transfer “waste” in one system to “food” in another system, thus, closing the loop. Moreover, it promotes using the clean and renewable resource, the sun, as much as possible.

In 1994 Kibert listed some relevant principles for sustainable construction (cited in: [9]):

- Minimize resource consumption
- Maximize resource reuse
- Use renewable or recyclable resources
- Protect the natural environment
- Create a healthy, nontoxic environment
- Pursue quality in creating the built environment

In the Netherlands the 10R model was developed, based on Lansink’s ladder consisting of the steps: Refuse, reduce, rethink, re-use, repair, refurbish, remanufacture, repurpose, recycle and recover [10]. Strategies higher on this ladder are more sustainable than strategies lower in the hierarchy.

In 2009 Wiltjer and Peters, directors of a Dutch engineering company with a focus on sustainable structural design of buildings, published five principles of sustainable structural engineering, which were updated in 2020 [11].

These principles are:

1. Increase the lifetime of a building/structure
2. Reduce the use of materials
3. Use sustainable materials
4. Include the environmental impact of construction logistics and transport
5. Design for circular use in the future

Since 2014 The Institution of Structural Engineers published various relevant resources to guide engineers in sustainable design choices [12, 13].They advocate to set an ambitious target for the maximum acceptable level of CO_2 emission, if building is unavoidable [14].

While the strategies mentioned above provide guidance to structural engineers looking to design sustainable structures, a clear hierarchy is lacking. The result is that many engineers have a different approach to sustainable structural engineering, or might look into one aspect of sustainable structural design whilst not explore other areas.

For example, for many years, when faced with a brief for an existing plot, demolishing existing buildings has been the norm. This resulted in a newly built structure where sustainability is often interpreted as e.g. flexibility of use in the future, use cement replacement, and optimizing certain elements to minimize their material use. In this example, donor materials, reuse of the existing building, or the use of bio-based alternatives are not explored.

Therefore, authors deemed it necessary to provide an overview of strategies, giving engineers a roadmap for sustainable structural design.

3 Road map

The road map consists of four core strategies:

1. Increase the lifespan of existing structures by reusing them
2. Increase the lifespan of existing structural elements by reusing them
3. Design future proof and with a long-life span and loose fit
4. Optimise the design to be lean and low carbon

This road map has been integrated with a basic outline of the design process in mind.

Starting off with a brief, the structural engineer, and in fact the whole project team, are stimulated to first consider the use of an existing structure, or consider the use of existing donor elements. If a new build is required however, the engineer and the team are challenged to first make the right choices in the overall design with future-proofing the structure, and subsequently make more specific choices in the engineering and specification to further drive down the environmental impact.

The main structure of this road map is depicted in figure 1.

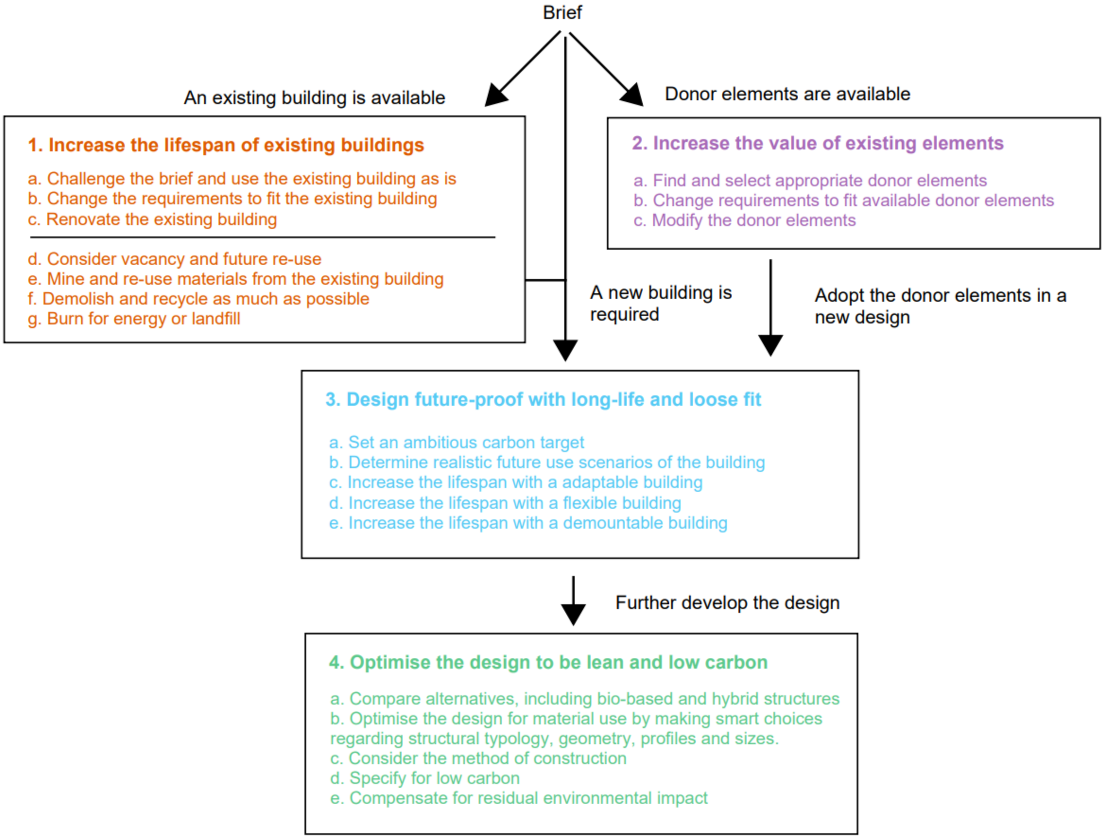

Figure 1: Road map with 4 main strategies to improve sustainable structural design

4 Strategy 1: Increase the lifespan of existing buildings (figure 3)

If a structure can be avoided, this usually is the most sustainable option. When a client presents a certain brief, one should argue first if a new building is necessary, or if this can be avoided by for instance a clever use of the existing building. For the construction industry it seems irrational to reduce demand but considering the urgency of reducing the carbon footprint in a relatively short period, building less is inevitable. It should be the responsibility of the structural engineer and the design team to meet the underlying client's wishes, which is not always to build a new building, despite what the client might state in the brief. Structural engineers should be advisors who challenge the clients brief and look for the "question behind the question", or the "why" of the brief.

Ideally, the client's functional requirement can be met using an existing building, without any changes. Preferably, this is a building already owned and used by the client, or another existing building available.

However, if, after challenging the client's brief, it becomes evident that the functional requirements cannot be met without changing the current situation, the first option is to see if an existing building can be refurbished or renovated. Often an investigation is required to find out if the existing building meets the demands of applicable building codes (example provided in figure 2).

Figure 2: Reuse of existing factor for a modern office building (source: IMd/ Vincent Basler)

If the existing structure cannot meet the requirements of the new situation, the design team should also challenge the requirements; e.g. would it be possible to accept lower floor loads, if as a result heavy strengthening can be avoided?

Furthermore, careful structural analysis and creative thinking can reveal hidden strengths in the structure, thus providing more options for reuse. The industry doesn't have the luxury anymore to state so easily that an existing building doesn't fulfil the requirements, and therefore demolition and new build is required.

If requirements cannot be adjusted, the structure needs to be adjusted or strengthened. It will be necessary to check the financial feasibility of the necessary changes. Note that financial objections are increasingly harder to justify considering the developing climate emergency. Furthermore, we could see carbon tax and other measures shifting what is financially feasible. If however, after thorough analysis, there is no promising business case for the reuse of the existing building, one has to consider if temporary vacancy of the building is acceptable, to wait for future reuse. If other reuse is not realistic, demolition or demounting might be the only option. It should be aimed for that most elements can be 'mined' and reused, so these elements should be demounted instead of demolished. Elements that cannot be reused can be a source for new material through recycling, or in the worst case can be burnt to deliver some energy. A landfill is the last resort.

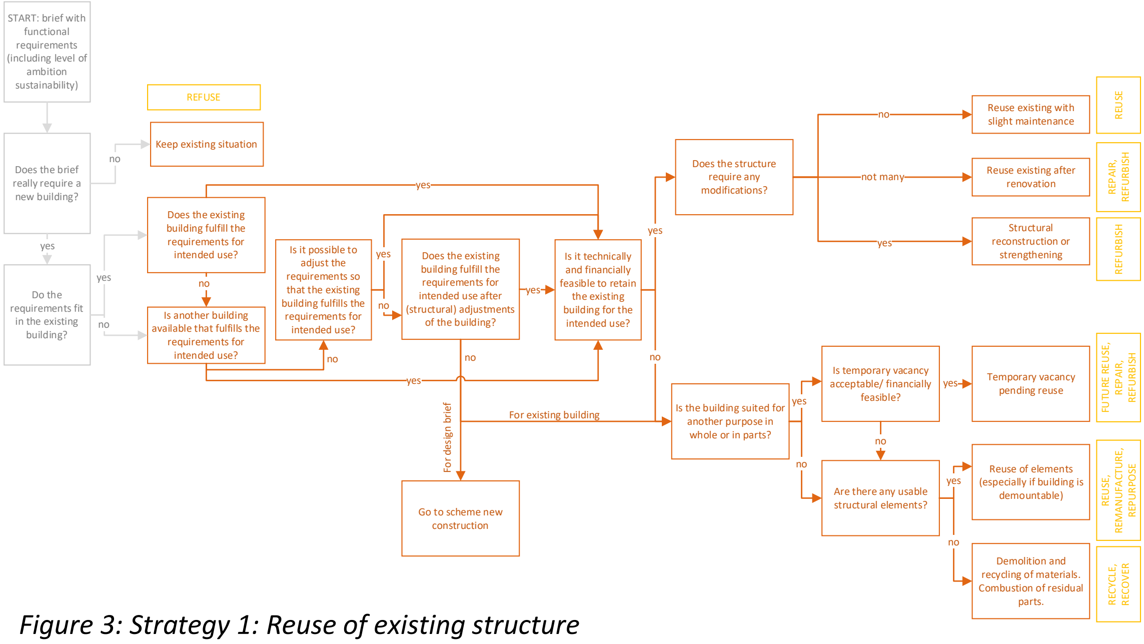

Figure 3: Strategy 1: Reuse of existing structure

5 Strategy 2: Increase the lifespan of existing structural elements (figure 5)

If it turns out the use of an existing building is not feasible, it is recommended to search for existing elements from other structures, so called donor elements, suitable for the new structure. An example is provided in figure 4. These elements should be available within the time frame that fits the project planning. Furthermore, the elements need to fulfill the structural requirements, so more elaborate structural checking and material testing will be needed. If elements do not fulfill the requirements, one needs to reconsider if lowering requirements would be acceptable. For instance, by accepting a lower allowable live load on the floors. Finally, the cost of donor elements should be acceptable.

Often, various adjustments to the structure are needed, so it is advisable to adjust the design where possible to meet the possibilities of the donor elements (related to dimensions and capacities), otherwise the necessary adjustments might become too expensive. In practice, sometimes a donor building becomes available in a later stadium of the project. This requires flexibility of the project team, and additional time and budget of the client [11].

Figure 4: Use of donor skeleton on a large scale for Biopartner in Oegstgeest (The Netherlands) (source IMd/ Rene de Wit)

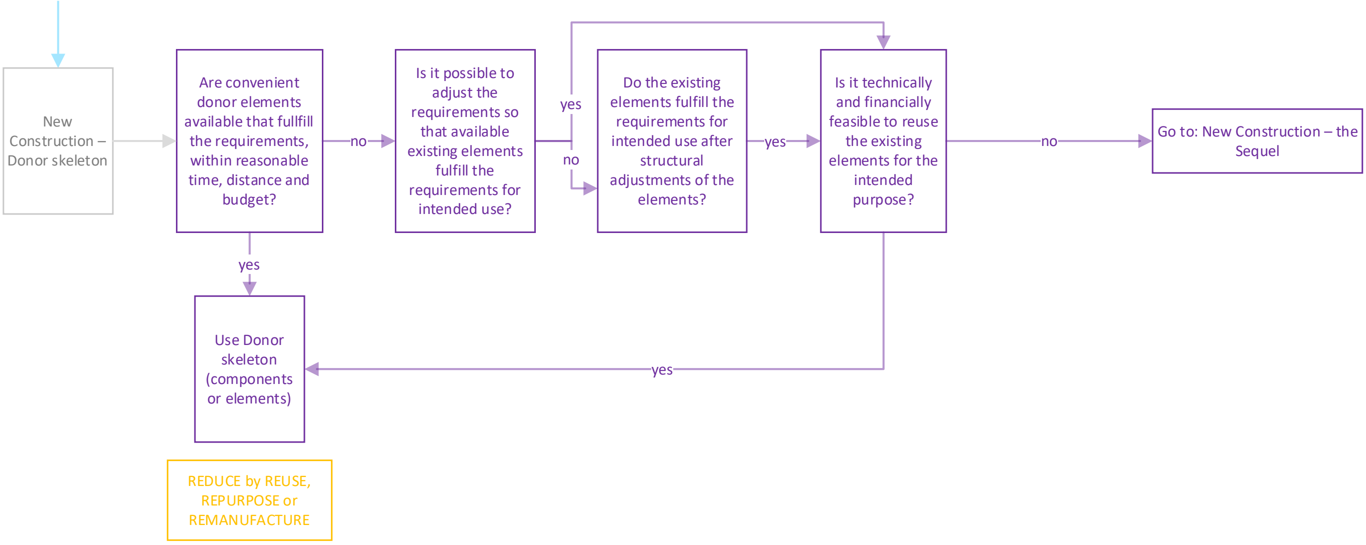

Figure 5: Strategy 2: Reuse of existing structural elements

6 Strategy 3: Design future proof with long life and loose fit (figure 7)

If the use of an existing building is not possible (irrespective of the use of donor elements), it is important to first set the limits for the allowable environmental impact of the new build. The engineer, design team and client are strongly encouraged to use more stringer demands than legally required. Currently, authors see a trend where investors and public clients are aiming for lower environmental impacts than what would be necessary according to law. Guidance is provided by various organisations, including the Dutch green building council, LETI, and the Institution of Structural Engineers.

Value can be added, when a future proof building is designed with a long lifespan. This strategy recognizes that after completion and delivery of a building, the building is not actually “finished”. It is the starting point of the life of a building, and many adjustments in use can be expected.

Adding flexibility and adaptability often requires an initial investment in additional material (with the accompanying higher initial environmental impact). Therefore, it is relevant to think in advance about future use, and to come up with several realistic scenarios of the expected use.

If the expected lifespan is more than 25 years, i.e. typically 50 years or more, it is relevant to predict if many changes in use and accompanying requirements are to be expected. If limited changes are to be expected it is important to design a robust structure, with a high level of quality, that is adequately protected against the elements and that can be easily maintained over the years. By using these starting points, a structure can be designed that can easily reach lifespans of 50 years or longer.

If within 5-10 years significant changes are to be expected, it is advisable to design an adaptable, flexible building that can easily accommodate these changes. First, one can consider making an adjustable structure, by making it easier to expand or shrink the structure. Second, to accommodate the changes during lifetime, it is helpful to disconnect the various layers of a building (façade, loadbearing structure, finishing, etc.). An integrated design, where for instance technical services are integrated in a concrete floor, have advantages, but is not flexible during its lifetime. Therefore, it is advised to be careful with integrating the various layers of Brand (site, structure, skin, services, space plan, stuff) [15]. Third, one can think of using modular sizes, which eases the change of technical services and finishing structures.

One can design for flexibility by incorporating higher floor loads, large column free spaces and higher ceilings, which enables future changes of use. The engineer and design team should judge what flexibility results in the most value considering the realistic change scenarios.

Figure 6: Temporary, demountable pavilion for the World Design Event during Dutch Design Week 2017 (source: Filip du Jardin)

If the expected lifespan of the structure is (much) smaller than 25 years, a demountable structure should be considered, where elements are suited for future reuse (See example in figure 6). Demountable connections can also be considered for structures with an expected life span of over 25 years, but it is debatable if after 25 years actually the elements will be demounted and reused. If this is doubtful, it is advisable not to focus on demountability with accompanying cost and sometimes reduced robustness. However, if demountability can be easily incorporated without much additional cost and consequences on robustness, one should consider this.

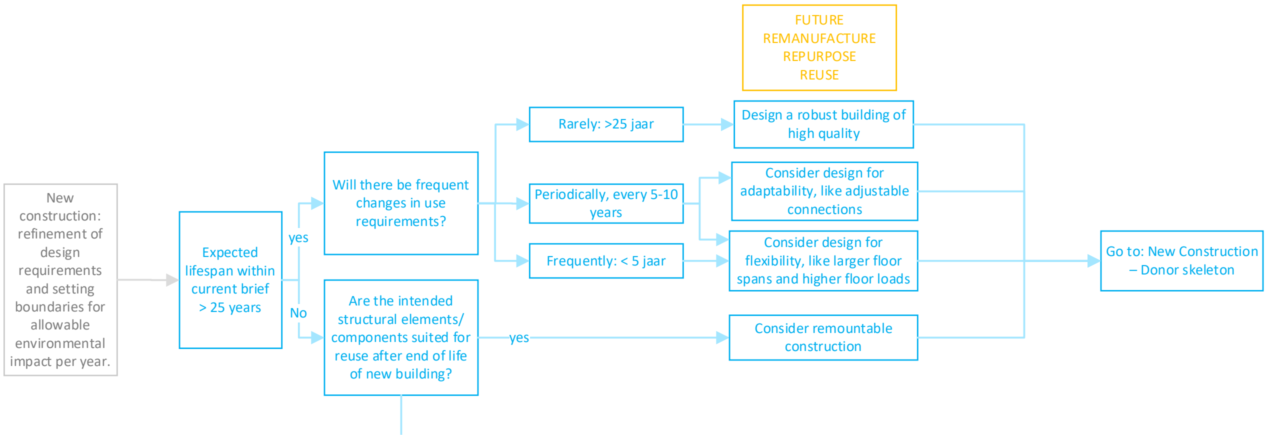

Figure 7: Strategy 3: Design future proof with long life and loose fit

7 Strategy 4: Optimise the design to be lean and low carbon (figure 9)

In the previous steps, one has to decide if an existing building can be reused, if useable existing elements are available for reuse and to what extent the structure can be designed with the long life, loose fit strategy. When that design is developed, the design needs to be optimized on environmental impact within the boundaries of strategies 1 to 3. One should strive for low carbon and a lean design.

Various structural design alternatives in various materials can be developed considering the design requirements and budget restrictions. These design alternatives can be compared on environmental impact, on the short term (for CO_2e) or on the longer term (where lifespan and future reuse is incorporated). Given the urgency of the climate emergency, biobased and low carbon solutions should be adopted when reasonably possible. An example of a timber high rise building is provided in figure 8.

Irrespective of the material, the engineer should consider if the structural system is efficient with regards to its typology, geometry and chosen profiles and sizes. For example, structures with elements loaded predominantly with axial forces are more efficient than elements loaded with bending moments, and reduced spans or increased structural height requires less material use.

The aim in this step is to create a lean structure within the constraints set by the previous steps. Of course, one must take into account that the structure is robust, and that optimizing elements can negatively influence loads on connections or the constructability of the connections.

Figure 8: Haut the highest hybrid timber residential building in the Netherlands (source: Jannes Linders)

As a final step one must consider if the material specification is optimal. For example: would it be possible to use a concrete mixture that uses less cement? Can basalt reinforcement be applied? Is the origin of timber traceable, and is it forested sustainable? Is the used material at the end of life useable for reuse or recycling? If for instances fibres are added to concrete mixtures, this might improve initial performance, but can hamper recycling. New and more sustainable structural materials are rapidly introduced and the engineer should explore these options.

Finally, after the structure is optimised on environmental impact, one can consider compensating the remaining environmental impact [16].

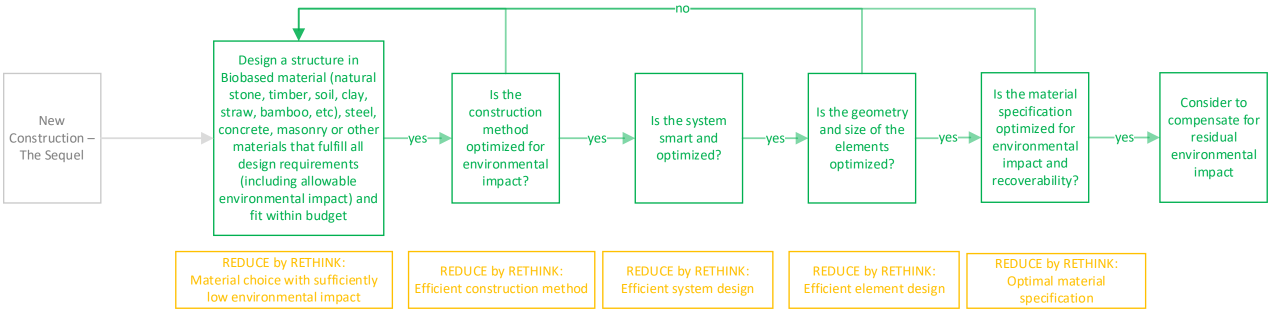

Figure 9: Strategy 4: low carbon and lean design

8 Dilemmas

When adopting the road map described in this paper, certain dilemmas remain, and sometimes strategies are contradictory. Some examples are given below:

- Reuse of existing buildings and elements results in design restrictions. Often this is solvable, but many designers see this as a limitation. Note however that within the constraints of the existing building or elements lies an interesting design space filled with opportunity.
- Furthermore, reuse of existing elements provides uncertainties regarding performance and reliability. Additional responsibilities are given to the structural engineer (together with contractor and client) to maintain an acceptable level of safety. This field is rapidly developing.
- Supply and demand of existing structures are not well organized in the current market. This needs to improve, to be able to use the strategy of reusing elements on a larger scale.
- Reuse of existing buildings prevents the use of new material. However, the energy performance of an existing building might be poor, so new material might be needed to improve this performance.
- If a donor skeleton is used, the available material is used as a starting point. This approach can result in a design with low unity checks, because only heavy sections are available (sometimes with considerable overlength). These low unity checks contradict with the aim to optimize profile dimensions. Note however that this is preferred over using new, unless a different project arises where the existing profile is used in a more economical way.
- If one designs for long life, loose fit (quality, flexibility and adaptability), sometimes overdesign is needed, with initially a higher environmental impact. For example, when floors are designed for possible future uses with higher loads, this demands initial overcapacity. When these higher loads never occur during the lifetime of the structure, it was designed with initial overcapacity with accompanying higher environmental impact. It might be wise to limit overcapacity, and to check after 25 or 50 years if the structure still fulfils the demands and if local strengthening is needed.
- On the other hand, when a structure is optimised for 1 use, this will lead to a lean design with efficient material use. But if future use results in higher structural requirements, the building can be made obsolete too early. By considering the relevant future scenarios, this can be avoided.

Because of these dilemmas, a careful consideration for every unique project has to be made regarding the strategies to be used.

9 Conclusion: the best sustainable strategy

The challenge for the structural engineer is to come up with a sustainable design that fits the (modified) brief. To achieve this, a clear hierarchy of strategies can be adopted. Most sustainable is not using new materials at all, by considering to what extent existing buildings, existing elements or renewable elements are available.

Irrespective of the use of existing or new materials, it is important to set the limits for the allowable environmental impact of the design, and to consider realistic use and change scenarios. This enables a future-proof building with the "long life, loose fit" strategy. Finally, within the constraints set by these previous steps, the aim is to create a lean structure with efficient material use and a sustainable specification, adopting biobased materials were reasonably possible.

This paper is based on an earlier article published in Dutch magazine Cement [17].

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