An Eco-Effective Structure

A qualitative approach into eco-effective structural design perspectives, criteria, and strategies both in theory as in practice

Tim Vonck

“You can design the most optimal shoes in the world but when you want to play basketball with them, they will not make you happy.”

Wouter Schik (Sustainability Advisor, Arcadis)

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By
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in partial fulfilment of the requirements for the degree of

Master of Science
in Construction Management Engineering

at the Delft University of Technology.
to be defended publicly on Friday September 27th, 2019 at 13:00 PM.

An electronic version of this thesis is available at http://repository.tudelft.nl/.

Colophon

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Preface

This graduation thesis is the final deliverable of my graduation research for the Master of Science Construction Management & Engineering at Delft University of Technology. I conducted my graduation research in collaboration with Arcadis. The process of conducting the research and writing this thesis have resulted into answering the question on how to maximize the eco-effectiveness of a structure through design decisions. Moreover, the certification methods – BREEAM-NL, LEED, and GPR-Gebouw – are evaluated on their adherence to assessing the eco-effectiveness of a structure. During this period, I've not only learned a great deal about the structure of a building and its potential, I also developed myself on both a personal level as a professional level.

I had the opportunity to learn a lot about the subject of inquiry of my graduation research. Although the Construction part in Construction Management & Engineering should say otherwise, this field of research was completely new to me. I conducted the research and wrote the thesis with great pleasure, due to the interesting subject and the great help from many people at both Arcadis and outside of it. Although I am glad about the final result, the process has not been without hurdles. As many subjects of inquiries and approaches are present to reduce the environmental impact a structure incurs, it took a rather lengthy while before the research was demarcated as it now is. Also, the broadness of the conducted research did not add to shortening that process. Furthermore, I would like to thank everyone who contributed to the content of this research.

First and foremost, I had the opportunity to interview a great deal of people that either worked for Arcadis or were experts in the field of research. From whom I have all learned a lot during the interesting and fun conversations we had. Furthermore, I am very grateful to Arcadis for the warm welcome and the excellent support I received throughout my research. All the colleagues I met at Arcadis were always very helpful and interested in my research

Secondly, I would like to say thank you to my graduation committee members from Delft University of Technology. The chair of my graduation committee, Marcel Hertogh, although seen a few times, was always sharp and apt during the meetings and drove me to see what the underlying value is of the research. In a year, if I would meet Marcel Hertogh again, I hope we both can remember the added value this research produced. Furthermore, my first supervisor, Henk Jonkers, helped me a great deal in brainstorming on demarcating the research into what it is today. It was always a joy stepping into his office as you were, without exception, greeted with a big smile and a cup of coffee. And for my second supervisor, Sander Pasterkamp, I want to thank him for his enthusiasm, honesty, and wit.

Finally, I want to thank my supervisor at Arcadis, who also took part in my graduation committee. Dieneke Grimmelius with whom I spent a great deal, was always there when I had questions and was always devoted and passionate when contemplating the direction and results of the research.

Tim Vonck

Delft, September 2019

Executive Summary

Introduction

Globally the construction sector accounts for 39% of the total CO_2 emissions and an estimated 40-50% of worldwide material flows. The built environmental thus plays a significant role in the overall environmental impact in the world. As the built environment adds to the growth of national economies, this sector is inevitability indispensable. Therefore, it is imperative that its environmental impact should be reduced for the continuation of the planet as we know it today. Within the built environment, there are numerous fields to focus on, of which one is the environmental impact of buildings. Not only is their environmental impact significant, it also withholds value, i.e. materials, that are salvageable on the long-term.

The environmental impact of a building can be dissected into two segments; the operational impact and the embodied impact. As the operational impact is reduced due to, for instance, deployment of renewable energy, the embodied impact of a building increases relative to the building's overall environmental impact. The embodied impact is attributed to the material environmental impact that is ingrained into the building. The structure of a building is the most material intensive attribute in a building.

As a structure is intended for a relatively long lifespan, the whole life cycle should be contemplated whence designing a structure. Whereas the eco-efficient model solely inquires reducing its initial environmental impact, the paradigm of eco-effectiveness aims at increasing value in the structure, resulting in generating a positive footprint in the future instead of only minimizing the negative footprint.

This thesis sets out to encapsulate the full scope of approaching the structure insofar the design contributes to maximizing the structure's eco-effectiveness. Through answering the following research question, this thesis aims to provide a structural design approach to grasp its full potential.

How can the eco-effectiveness of the structure be maximized and is the eco-effective structure represented in sustainability assessment methods?

The research question is twofold; one the one hand, it aims to discover the full scope of structural design capabilities to maximize its eco-effectiveness; and on the other hand, it aims to analyse what role the structure plays in practical applicabilities, i.e. certification methods BREEAM-NL, LEED and GPR-Gebouw, and if the full scope of an eco-effective structure is adequately embedded in these practical procedures.

Research Approach

This research is approached from a qualitative point of view. First, the literature is scrutinized to acquire the full scope of structural design perspectives that contributes to maximizing its eco-effectiveness. The acquired structural design perspectives are merged into structural design criteria that enclose the whole life cycle's environmental impact from which three eco-effective structural design strategies are established. The established theoretical framework is used to analyse sustainability assessment methods and to compare them on their integration of eco-effective structural features. Furthermore, empirical research is performed in which surveys and case studies are conducted. The surveys are used to perceive the knowledgeability of structural engineers on how to approach the determined structural design perspectives as it was used to validate the clustering of the design perspectives into the structural design criteria, i.e. the theoretical framework. The case studies are deployed to see how the structural design perspectives are implemented in practice and if the theoretical framework has been applied accordingly from which factors could be identified that assist in utilizing the theoretical framework. Furthermore, the case studies are utilized to analyse the applicability of sustainability assessment methods insofar their added value to the structural design.

Results & Conclusions

To fully account for the whole life cycle of the structure's environmental impact, ten structural design perspectives are identified which are depicted and explained accordingly below.

1. **Material selection:** the traditional materials used for structures are steel, reinforced concrete or timber. For the selection of materials, direct comparison is essential to know what type of material is required. The selection of materials from an environmental point of view is based on a variety of factors; environmental costs and technical properties.

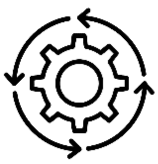
2. **Material use:** Intelligent use of structural materials can reduce emissions, resource use, and waste on the whole life cycle. Dematerialisation through generating more goods, services, or products with the same amount of materials or by producing the same end product with less material input

3. **Durability:** designing for durability encompass the extension of the service life of a building by maintaining its technical and functional requirements. Durability is an indicator which informs to the extent to which a structure conserves its original requirements over time, either technical, functional or economic wise.

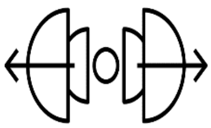
4. **Waste effectiveness:** Waste is an undesirable product, and should, therefore, be minimized, and/or treated as a valuable resource. Designing the structure as such that waste is minimized during construction and demolition phase.

5. **Maintenance:** the structure has to be designed so that maintenance of the structure is either minimized, insofar the input of material/energy during its service life is reduced; simplified, insofar the effort of maintenance is lowered; or targeted, insofar only worthwhile components are maintained for extension of the service life.

6. **Reusability:** designing the structure as such that structural component/elements/systems in the structure are of a reused nature, or can be reused one on one after the end of the building's life cycle for future structures/next cycle.

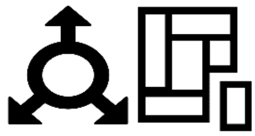


7. **Disassembly:** the structure is designed as such that the structure (or parts of it) could be effortlessly dismantled, insofar that the structural elements remain intact for future usage.



8. **Recyclability:** designing the structure as such that recycled material is embedded in the structure or incorporating the potential of recycling at the end of the structure's service life.

9. **Adaptability:** a building has the capacity to alter the structure itself. Scalability of the structure, insofar the structure could be expanded horizontally or vertically; or movable, insofar the structure is designed modular. The icons representing the two adaptable aspects respectively.



10. **Flexibility:** the structure facilitates the possibility to modify the internal spatial layout of the building without changing the structure itself. Also, a flexible design enables potential user function change.

The determined structural design perspectives can be merged into three criteria: *material environmental costs*, *service life*, and *residual value*. The clustering of the structural design perspectives into the structural design criteria are depicted in Figure 1 below.

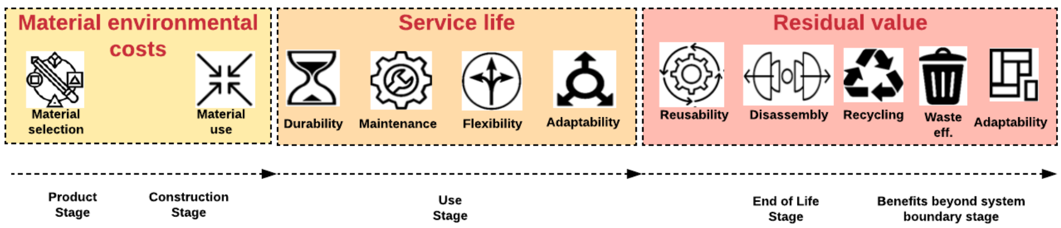


Figure 1: Clustering of structural design perspectives into the eco-effective structural design criteria: material environmental costs, service life, and residual value (own illustration)

Together the structural design criteria encompass the whole life cycle of the structure. However, it is difficult to reconcile all three design criteria. Focusing solely on minimizing the material environmental costs will have an adverse effect on both the service life and the residual value. Maximizing the service life is accompanied by higher material usage and the lower residual value. And, focusing on the residual value affects the maximization of the service life. From this can be concluded, that there is no such thing as *the* eco-effective structural design.

A structure has a technical and a functional service life wherein the former in practice regularly exceeds the latter. To maximize the structure's eco-effectiveness, it is imperative that the gap between the technical and functional service life is closed either on a building level or on system and component level. Three eco-effective design strategies are established which are depicted below and on the next page.

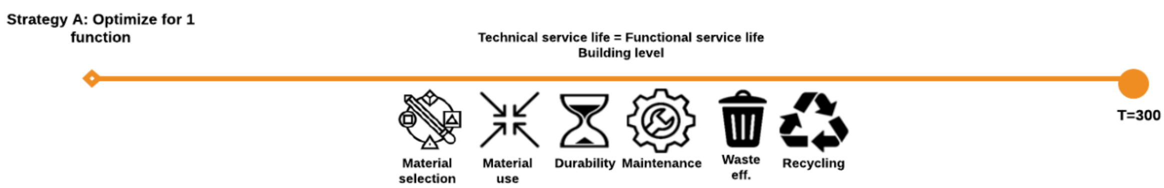


Figure 2: Strategy A: the technical and functional service life on a building level are maximized and equalized. (own illustration)

Figure 3: Strategy B: the technical service life is maximized and equalized through n functional service lives on a building level. (own illustration)

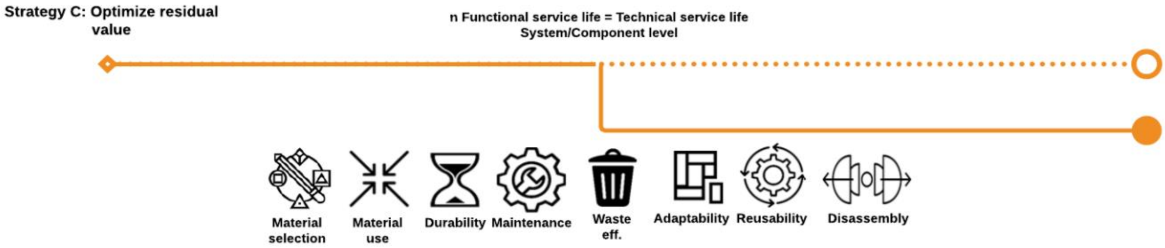


Figure 4: Strategy C: the technical service life is maximized and equalized through n functional service lives on a system/component level. (own illustration)

In Strategy A, the technical service life is maximized and equalized with the functional service life on a building level. For this strategy, it is imperative that solely one function will inhabit the structure. Examples are temples, churches, and museums. In Strategy B, the function of the building is known not to stand the test of time, but the technical service life is maximized on a building level, resulting creating conditions to convert the function of a building to reduce the technical and functional service life gap. An example could be an office or commercial buildings. Strategy C differs from the first two as the technical durability is maximized on a system and component level rather than on a building level. For adhering to this strategy, it should be known that the structure will become obsolete in the near future so that the salvageability should be optimized.

Through conducting the case study certain factors are identified that guides the selection of an eco-effective design strategy. The function of a building plays a huge role in adhering to a certain eco-effective design strategy. The intended function is derived from the goal of the client. Furthermore, the goal of the client sets the starting points on what is intended with the specific function. Moreover, socio-economic tendencies should be considered when selecting a design strategy. Additionally, factors have been identified that affects the design process: safeguarding measures, financial implications, dependency on other functional layers, and dependency on the assessors, contractors, and suppliers.

The structural design perspectives focus on the eco-effectiveness of the structure. Maximizing the eco-effectiveness of a structure is synonymous to the preservation of materials. However, the structure is not only a static material entity, it also facilitates, improves, and even obstructs other functional layers within a building. Therefore, an extra structural design perspective should be kept in mind: integrability. By coordination of the different disciplines with the design of the structure, the structure can also add value during the use stage of the building.

The second part of the main research question is the representability of the eco-effective structure in sustainability assessment methods BREEAM-NL, LEED, and GPR-Gebouw. All three assessment methods evaluate the design of a building on the integration of sustainability features. However, the scope differs as could be seen in Table 1. Deploying the methods could make a project eligible for substantial grants from the Dutch government. Therefore, making it valuable to analyse and compare the methods on their integration of eco-effective structural design features.

Table 1: Categories of sustainable assessment methods (BREEAM-NL, LEED, & GPR) with the accompanied weightings and bold where the structure is represented. (notably: the structure only encompasses a segment of the percentage bolded)

BREEAM-NL	**LEED**	**GPR Gebouw**
Management (12%)	**Integrated Process (1%)**	Energy (20%)
Health and Wellbeing (15%)	Location and Transport (16%)	**Environment (20%)**
Energy (19%)	Sustainable sites (10%)	Health (20%)
Transport (8%)	Water efficiency (11%)	**User quality/friendliness (20%)**
Water (6%)	Energy and Atmosphere (33%)	**Future value (20%)**
Materials (12,5%)	**Materials and Resources (13%)**	
Waste (7,5%)	Indoor environmental quality (16%)	
Land use and Ecology (10%)	**Innovation (Extra: 6%)**	
Pollution (10%)	Regional priority (Extra: 4%)	
Innovation (Extra: 10%)		

As is visualized in Figure 5, BREEAM-NL and LEED do not integrate the service life and the residual value criteria in their assessment. Both BREEAM-NL and LEED assess the structure from an eco-efficient point of view by only stimulating lowering the initial material impact. GPR-Gebouw, on the contrary, does incentivize prolonging the service life and optimization of residual value. However, prolonging the service life of a structure has implications on the optimization of the residual value, and vice-versa. The broadness and the generalizability of the sustainability assessment methods inhibit the actual value for which the methods are intended.

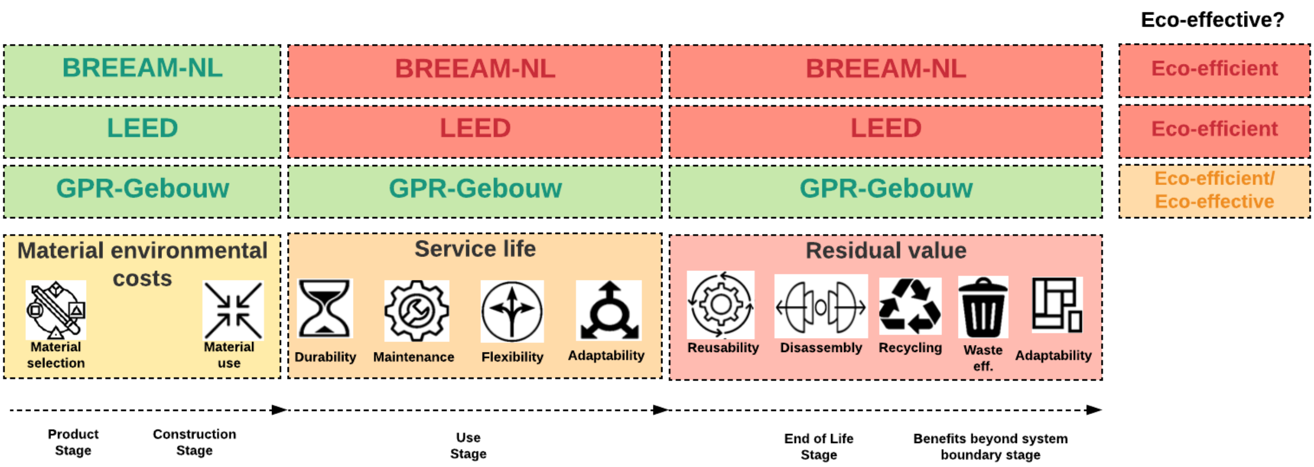


Figure 5: Adherence of the sustainability assessment methods - BREEAM-NL, LEED, and GPR-Gebouw – to the eco-effective structural design criteria. (own illustration)

Recommendations

For Arcadis, a framework is constructed in which it is shown how to select the most eco-effective structural design strategy on the basis of contemplation guiding factors. The strategies are accompanied by their structural design perspectives which should be executed to maximize the structure's eco-effectiveness. Additional to Strategy B and Strategy C, a list is presented on operationalized structural design features.

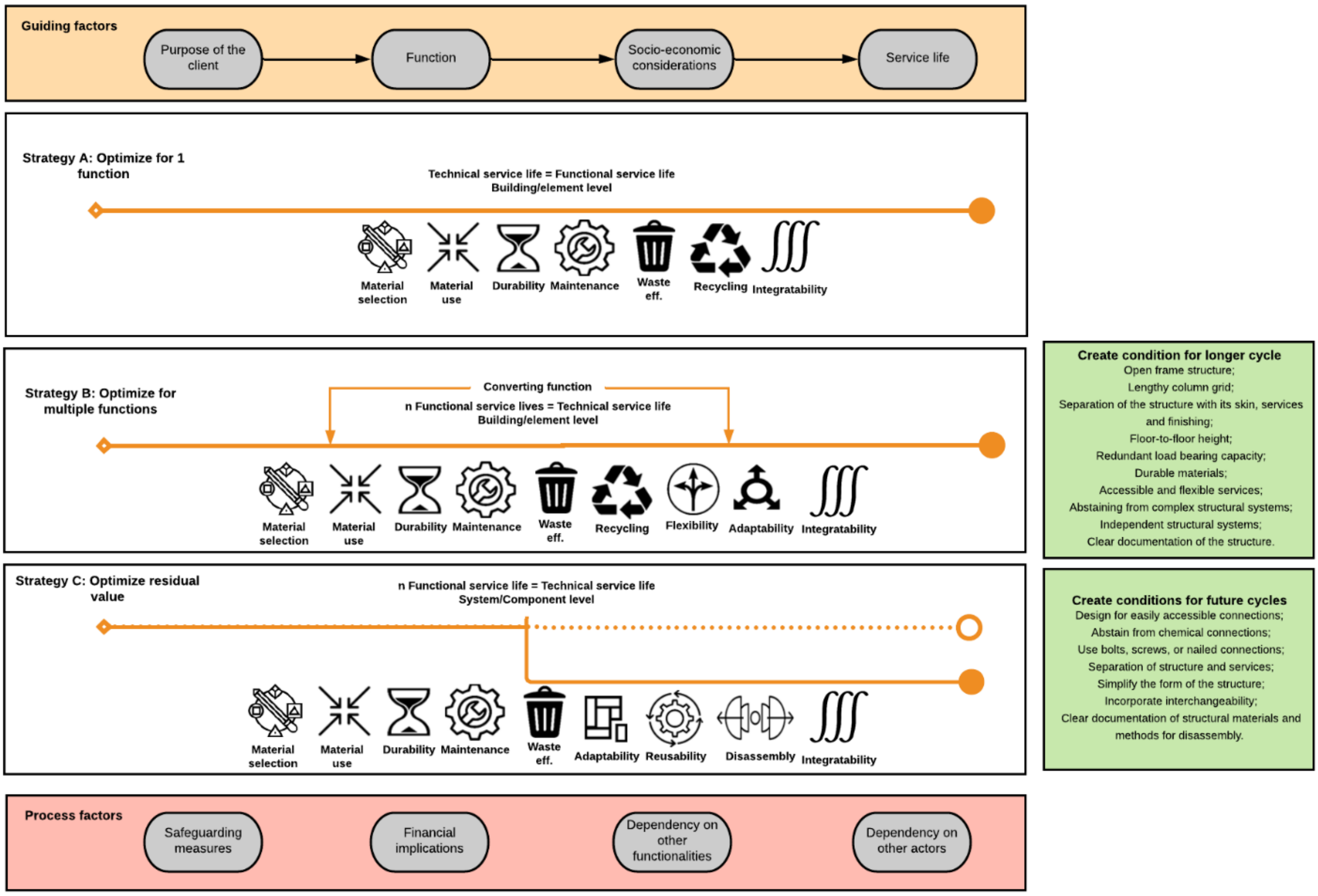


Figure 6: Eco-effective structural design framework (own illustration)

Further, general recommendations could be made on the basis of the interviews conducted during the case study. For one, it is vital to do the right thing instead of doing things, the right way. Structural engineers need a tool to grasp onto for making design decisions. Sustainability assessment methods have proven to be not the most fruitful method for designing the structure. Hence, a quantifiable tool would be beneficial for structural engineers. Secondly, the willingness of the structural engineer to contemplate the environmental impact of the structure is more than present. In a large company, the knowledge is diffused. The knowledge should be seized both nationally and internationally, and between departments as well.

Also, recommendations are established for sustainability assessment methods. Within all three assessment methods, all the embedded materials are merged into one category. By making a distinction between the structure and other embedded materials, the structure gets a more prominent spot in the assessment method. Moreover, BREEAM-NL and LEED should be more future-focused by integrating incentives for prolonging the service life and optimizing residual value. And lastly, within GPR-Gebouw optionalities should be incorporated that make it possible to focus on specific eco-effective structural design strategies.

And, finally, recommendations are established for future research. It is beneficial to conduct research for the structural design framework quantitatively. By implementing the framework into parametric design, it could help the structural engineer to have real-time feedback on design decisions. Furthermore, the deployment of the type of structural materials is not examined in detail in this thesis, research into what structural design materials are most applicable in certain strategies could give the framework more substance. In addition, only three cases were examined (two industrial functions and one casino), therefore, it was difficult to truly make the distinction between the service life and residual value. Research into the structure of more building functions could be beneficial for identifying guiding factors in more detail. Moreover, inquiries on maximization of the service life are not mature enough as building regulations have fixed service lives per function. Examination of possible alteration of building regulations is needed for the established framework to be fully applicable. Also, sustainability assessment methods should be evaluated and compared on other categories. And finally, the dichotomy of the service life and the residual value should be researched. This thesis assumed that maximization of the service life and optimization of residual value are irreconcilable. However, the questions arise, what is the timeframe of structural components to be reused in their primary state?

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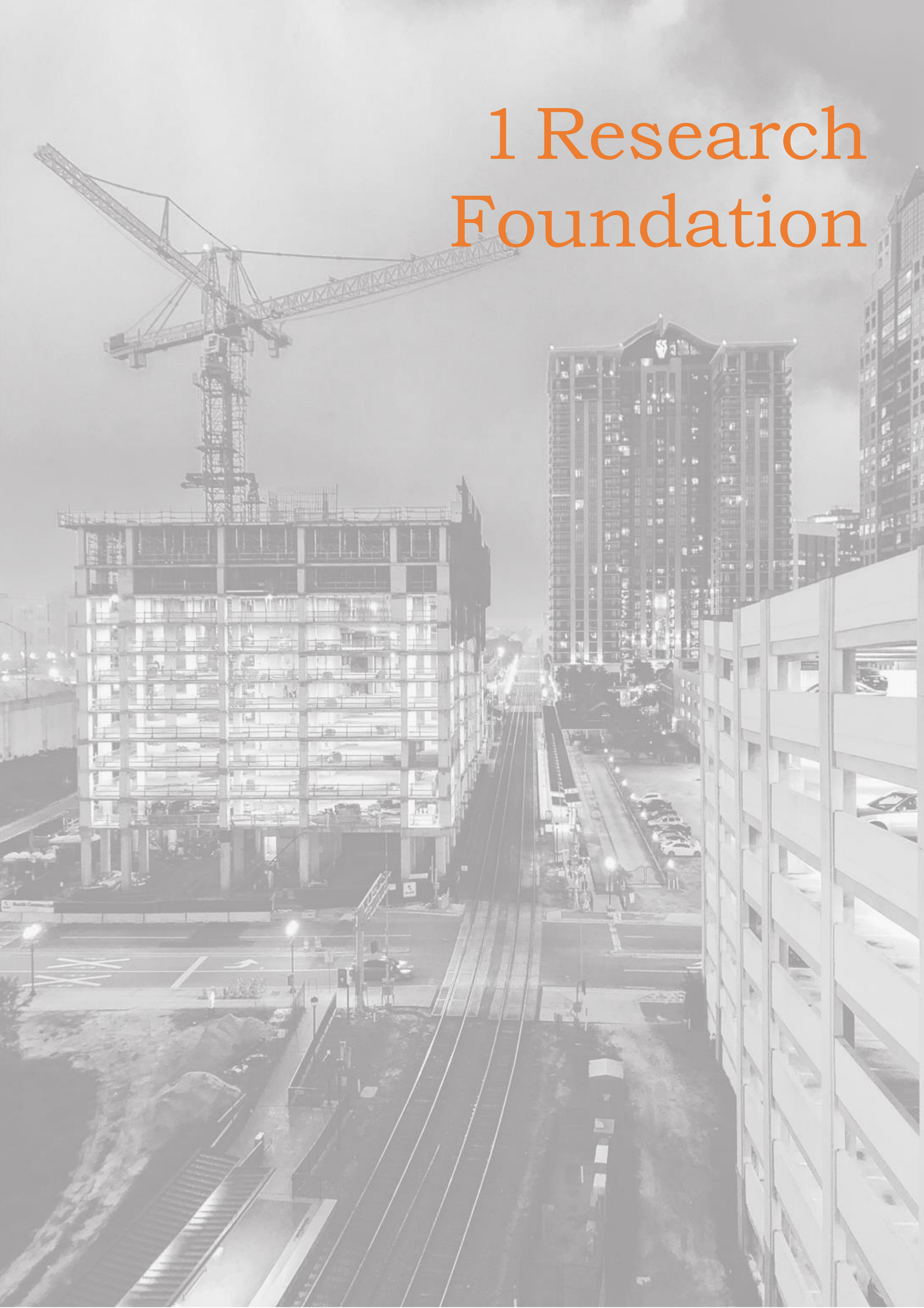
1 Research Foundation



1.1 Global warming in general

"Scientific evidence for warming of the climate is unequivocal", says the Intergovernmental Panel of Climate Change (IPCC, 2018). In the past decades, it has become evident that human activity is the driving force behind it. Although awareness is rising and global actions are implemented, the temperature of the earth's atmosphere is still rising with detrimental consequences as a result. Massive draughts which have caused food shortages in the Middle-east and Africa, increasingly more massive storms and fires which have caused, for example, the annihilation of houses in the United States, and of course the rising of the sea-level which already caused multiple cities worldwide to flood (Schiermeier, 2018). Not something to think lightly of. The IPCC says with 95% certainty that anthropogenic activities are the primary cause of global warming (IPCC, 2014). The more humanity disrupts the environment, the higher the risks are of irreversible and severe impacts on ecosystems and societies - and on the longer term - on the whole, climate system. Some climate scientists argue that the irreversible threshold is already surpassed; however, measures for reducing environmental are still indispensable to stagnate the climate change.

1.2 The role of the built environment

One of the main contributors to impacting the environment is the construction industry in the built environment. Globally the construction industry and the built environment account for 39% of the total CO_2 emissions (Huang et al., 2018). Besides being amongst the top emitters, the sector is also one of the largest consumers of natural resources. Worldwide it is estimated that the construction industry uses 40-50% of global material flows for manufacturing and building purposes (Dossche, Boel & Corte, 2017). It is safe to say that this anthropogenic sector influences the environment severely. However, on the other hand, the built environment encompasses the entire human-made landscape that facilitates people to live, work and recreate on a daily basis. Thus, the built environment plays a substantial beneficial role in social and economic development (Ilhan & Yobas, 2019).

The construction of hospitals, schools, and offices amongst countless other examples add to the growth of prosperous civilizations. Being of indispensable worth, the built environment will always be an essential segment of modern society. This sector has been of high value in the past and will inevitably be so in the future. As the built environment is one of the drivers behind a thriving economy newly developed buildings will be inescapable, consequently, reducing the environmental impact of buildings will be favourable, to say the least, to achieve international climate goals and safeguarding subsequent generations.

In the culture of civil engineering and architecture, the last couple of decades the environmental impact reducing desires have become increasingly more critical in their activities, and this trend appears to only increase (Dodge Data & Analytics, 2018).

1.3 Focus areas within buildings to reduce environmental impact

Since the '70s, the approach of achieving environmentally friendly buildings has predominantly come from reducing the operational energy in the building's energy mix (Peters & Westenbrugge-Bilardie, 2014). The building's total energy input comprises of operational energy and embodied energy. Operational energy is attributed to buildings installations such as ventilation, air conditioning, sanitation, and lighting, i.e. energy that is needed for a building to be in service, highlighted in blue in Figure 1. The embodied energy is cumulative of all energy that is required in the activities to construct a building from excavation activities to the transportation of materials and components to the installation of the building, i.e. the sum of all incorporated energy in a material or component, highlighted green in Figure 7 (Shoubi, Bagchi, & Barough, 2015).

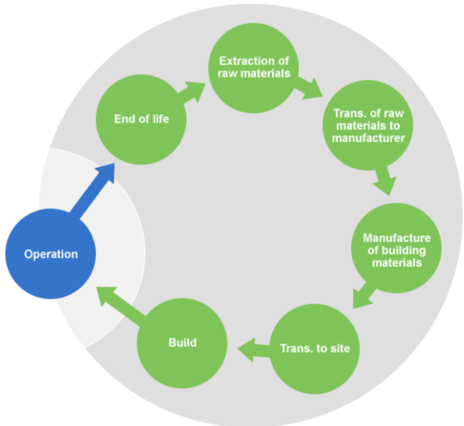


Figure 7: Life cycle of a building in which the green activities adds to the embodied impact and the blue to the operational (Zimin, 2018)

Operational energy comprises the largest share of the total energy consumption in the life cycle of a building, roughly 80-90% to 20-10% for the embodied share (Ramesh, Prakash & Shukla, 2010). In the past decades, the quantity and impact of operational energy of buildings have been drastically reduced. The introduction and expansion of renewable energy, better insulation of buildings, and more efficiency in installations amongst other things have attributed to this reduction. With declining operational energy in the building's energy mix, the share of embodied energy increases, consequently, encompassing a more significant portion in the energy mix resulting in becoming an increasingly more important subject of inquiry (Itard, 2009). It could even lead to an embodied share of 100% if net-zero buildings became a reality (Sartori, 2007). As could be subtracted from Figure 1, the embodied impact does not dissipate as materials and components still could hold a residual value as they could be utilized for subsequent projects, closing the material loop.

1.4 Eco-efficiency vs. eco-effectiveness

The current challenges that are faced by construction of buildings are diverse and range from ecological problems such as depletion of materials to economic problems such as excessive life cycle costs to sociocultural problems such as indoor air quality and user comfort. The abovementioned challenges related to buildings are currently approached from an eco-efficient viewpoint. Eco-efficiency is described by the World Business Council of Sustainable Development as "challenges being reached by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing environmental impacts and resource intensity throughout the life cycle, to a level at least in line with the earth's carrying capacity" (DeSimone & Popoff, 1997). Contextualize it for material and resources one gets the following statement; "more product or service value with less waste, less resource use or less toxicity" (Braungart, McDonough & Bollinger, 2006). In essence, this entails that approaching a building from an eco-efficient viewpoint, one focuses on linear cradle to grave flows of materials in which the sole purpose is to reduce the material input. Hence, a short-term approach which is neglective of the value that is embedded in a building on the long-term.

In opposition to an eco-efficient design point of view, the model of eco-effectiveness aims at generating a positive footprint instead of minimizing the negative footprint. Thus, alternatively than reducing the cradle-to-grave flows of materials, the eco-effectiveness model proposes cradle-to-cradle "metabolisms" that promotes maintaining or increasing the quality and productivity of materials through numerous cycles of use as a substitute for aiming to reduce waste and the use of resources. Eco-effectiveness, thus, puts more emphasis on the long-term. Which is vital for buildings as they tend to have a long service life with embedded value that could be harvested (Braungart, McDonough, & Bollinger, 2006).

Nonetheless, designing from an eco-efficiency point of view can still be regarded as useful when approaching the design for short-term goals. The eco-efficient paradigm, however, does not satisfy material flows in buildings as materials are deployed for longstanding use. The eco-effective approach, on the other hand, provides the momentum to benefit the ecological system in the long-term and convert weakness into positive potential (Lindner, Braungart, & Essig, 2019). In Figure 8, the graph depicts the difference in ecological harm/benefits over time from the two models.

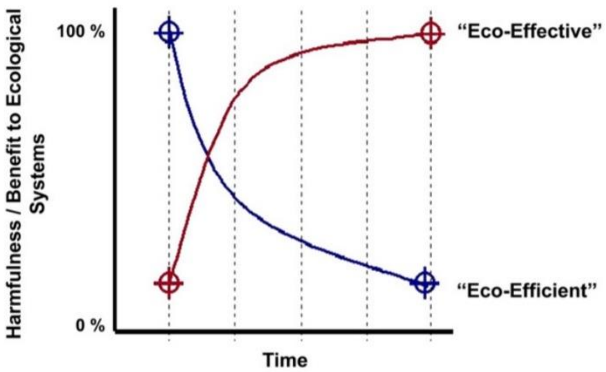


Figure 8: Eco-efficiency's and eco-effectiveness' harmfulness and benefits over time (Braungart, McDonough, & Bollinger, 2006)

1.5 Functional layers within buildings

The design of buildings is often approached from a holistic point of view. Although it is true that the functions in a building are interconnected and integrability in buildings is indispensable, they also have their own individual purpose, tasks, and usage. Moreover, in a relatively long lifespan of a building, a building is prone to constant pressure due to changing demands and changing environmental conditions. Hence, a building should be perceived as a fragmented entity prior to merging the functionalities in the overall design insofar the strengths of the individual functionalities could be maximized. Brand (1994) has proposed a model of a building in which the functional layers, also known as the Shearing Layers, are separated based on their service life, as is depicted in Figure 9:

- **Stuff:** Chairs, desks, phones, pictures, kitchen appliances.
- **Space plan:** The interior layout – walls, ceilings, floors, and doors.
- **Service:** Communication wiring, electrical wiring, plumbing, HVAC, and sprinkling.
- **Skin:** Exterior surfaces, cladding, envelope.
- **Structure:** Load-bearing elements and the foundation
- **Site:** Geographical setting, the urban location, and the legally defined lot.

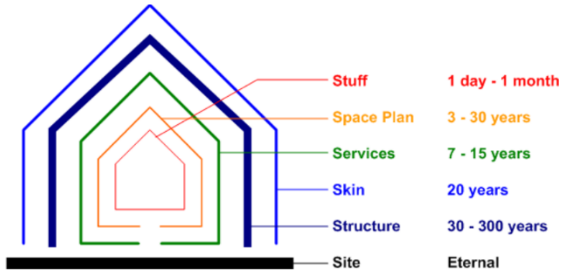


Figure 9: Shearing Layers that depict functional layers of a building based on their service life (Brand, 1994)

The different functional layers each have their own service life. Therefore, for an optimal design, the potential of a layer to be maintained, replaced, or refurbished should have no obstruction from functional layers with a lengthier service life. The life span of the separate functional layers can be attributed to the below-stated service life's which differ in length and cycle (Voordt & Heijer, 2004):

- **Technical lifetime:** The lifespan in which the technical and physical features can deliver sufficient performance to be occupied by its users while ensuring the safety and health of its users.
- **Economic lifetime:** The lifespan in which the current and future benefits outweigh the current and future costs from the owners' perspective.
- **Functional lifetime:** the lifespan in which the building gratifies all the functional demands and wishes of the user, which could be altered if the structure allows.
- **Cultural lifetime:** the lifespan in which the building represents the historical and aesthetic value of society.

1.6 The significant structure

In the prior paragraph, the significance of non-interference of lengthy functional layers with less extensive functional layers was put forward. The structure is the most lengthy human-induced functional layer. From which can be concluded that the structure, apart from being an entity on its own, affects the lower levels, and should, therefore, be designed accordingly. The structure of the building could be defined as a hierarchical arrangement of materials in which higher levels of technical composition subjugate lower levels. This is conceptualized by Durmevic (2006) in the 'hierarchy of materials'. In which every level within the building integrates the technical and functional life cycle of building materials. In Figure 10 seen below, the hierarchy of materials are divided into three levels (Durmisevic E. , 2006):

- **Building level:** represents the arrangement of systems, which are carriers of main building functions (*load-bearing construction*, enclosure, partitioning, services)
- **System level:** represents the arrangement of components, which are carriers of the system functions (*bearing*, finishing, insulation, reflection etc) - the subfunctions of the building.
- **Component level:** represents the arrangement of elements and materials, which are carriers of component functions, being sub-functions of the system.

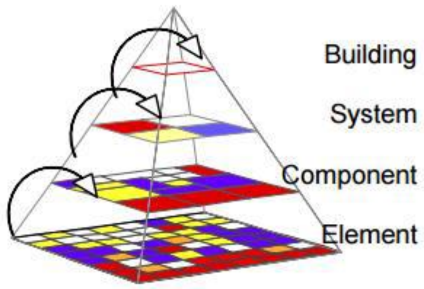


Figure 10: Hierarchy of material levels in buildings (Durmisevic E. , 2006)

The structure of a building is represented in every level in the material hierarchy. Moreover, as described earlier, the operational energy in buildings is declining, resulting in a relatively larger share of embodied energy in the overall energy mix of a building. All materials embedded in a building contribute to the embodied energy of a building. Webster et al. (2012) identified that the structure of a building is responsible for approximately half of the total embodied carbon emissions. As could be seen in Figure 11, when breaking down the embodied carbon in a building, the structure comprises of more than 50% of the embodied carbon emission. Although embodied energy and embodied carbon differ in definition and unit of measurement, for buildings, the percentages often do not (Hammond & Jones, 2008). With the building's declining operational footprint and the structure's large share in the embodied footprint, it can be deduced that the embodied energy of the building's structure is rising in significance concerning the overall building's footprint.

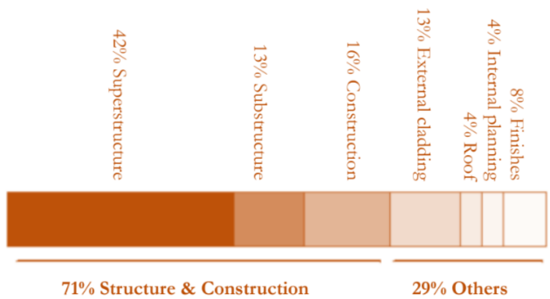


Figure 11: Average breakdown in building elements of embodied carbon in offices, hospitals and schools (Wolf, 2014; Kaethner & Burridge, 2012)

1.7 Sustainability assessment methods

Sustainability assessment methods have been established to measure the environmental performance of newly designed buildings and their surroundings. The rating and certifications systems are purposed to stimulate sustainable building design, construction, operation, maintenance, and deconstruction through incorporating additional design criteria to better integrate environmental societal, functional, and costs with the traditional design criteria (Bragança, Mateus, & Koukkari, 2010). Throughout the project's life cycle, sustainability assessment methods assist decision-making. In the Netherlands, the building industry can choose between three all-encompassing sustainability assessment methods: BREEAM-NL, LEED, and GPR-Gebouw. Although additional assessment methods exist, these three are most used in practice and could be deployed to appeal for grants from the Dutch government (RVO, 2017). The sustainability assessment methods, however, are not exempted from criticism. Although the assessment methods have specific categories in common, such as energy, materials, and indoor environment, they differ in perspective and scope. As is set out in the preceding paragraphs, a shift is forthcoming in which the embodied impact of a building is gaining momentum wherein the structure plays a significant part.

This thesis aims to put forth how the structure can be optimally designed, insofar that its eco-effectiveness is maximized. Additionally, the structure's role in the three determined sustainability assessment methods (BREEAM-NL, LEED, and GPR-Gebouw) is scrutinized and evaluated based on the determined structural design perspectives. Insofar shortcomings in or of the assessment methods can be established and what sustainability assessment method is paramount from a structural design point of view.

1.8 Problem description

As stated in paragraph 1.3, the emphasis of environmental impact reduction in buildings is mostly attributed to the operational phase of a building's lifecycle. Given that the operational environmental impact share is declining, the importance of the embodied impact of a building is increasing (Chaudhary & Piracha, 2013). Additionally, the most significant part of the embodied impact can be ascribed to the structure of a building in which the design plays a crucial role. Therefore, making the design of a structure of a building to reduce its environmental impact an important and exciting field of research.

To alleviate the environmental burden of a structure and to fulfil the structure's full potential one could opt for specific structural design choices. The choices made in designing a structure are not isolated in their outcome, meaning that structural design decisions could, on the one hand, be advantageous in reducing the environmental impact in the long-term, but on the other hand, be counterproductive in conceiving the goal of lowering its environmental impact on the short-term. Therefore, conceiving optimal structural design strategies could be of value to increase the eco-effectiveness for newly designed structures. Moreover, as sustainability assessment methods are widely used in practice, the role of the structure in BREEAM-NL, LEED, and GPR-Gebouw will be scrutinised and analysed if the sustainability assessment methods sufficient encompass structural design tendencies.

1.9 Research objective

Derived from the problem description that is described in paragraph 1.8, the following research objective is determined.

To gain insights into the design potentiality of a building's structure to enlarge its eco-effectiveness, and to examine if the structure is represented adequately in BREEAM-NL, LEED, and GPR-Gebouw.

With this primary objective, this thesis aims to provide knowledge that could be of added value in reducing the environmental impact of a building through design decisions in the structure. By establishing awareness of the implications of structural design approaches, the structural engineers could substantiate what consequences are linked to specific choices in structural design. Moreover, this thesis will examine which sustainability assessment method is paramount from a structural design point of view and what caveats are present when assessing the structure. The final result will be a framework in which sustainable structural design implications are manifested so that the structural engineer is more aware of the effects of their design decisions and also could communicate them clearly towards the clients or other disciplines.

1.10 Research questions

Derived from the problem description and the research objective, the main research question is put as follows:

How can the eco-effectiveness of the structure be maximized and is the eco-effective structure represented in sustainability assessment methods?

The research question of the thesis is two-folded; for one it aims at providing an answer on how to maximize the structure's eco-effectiveness; and secondly it attempts to examine sustainability assessment methods that are used in practice on their degree of adherence to the scope of an eco-effective structure. From this premise, the following sub-questions are stated which will together answer the main research question.

What does a building structure consist of?

This sub-question is focused on demarcating the structure of a building. It is essential first to understand what exactly is meant by the structure of a building, as it is the focal point of this thesis. Furthermore, it is essential for answering subsequent sub-questions. This sub-question is answered by reviewing the literature and conducting exploratory interviews.

What environmental areas are affected by a building's structure?

In this sub-question, the environmental impact areas of the building's structure are set forth. Through literature review, the full spectrum of the structural environmental impact is determined. Resulting in areas of focus that is supportive of further sub-questions. The first two sub-questions are used to demarcate the exploration of the structural design perspectives in the literature and to inventorize what structural features the sustainability assessment methods enclose; these two sub-questions are answered in Appendix 0.

1. *From what perspectives can the structural design be approached to maximize its eco-effectiveness?*

Which perspectives are present to improve the design of a structure, insofar that it adds to the contribution of lowering the environmental impact in the short- and long-term, are answered in the third sub-question. This sub-question is answered by reviewing the literature.

2. *What structural design criteria should be adhered to for an eco-effective design and what eco-effective structural design strategies encompass these criteria?*

A theoretical framework is established in which several structural design criteria are established by clustering the determined structural design perspectives to reduce the environmental impact a structure incurs.

3. *Do BREEAM-NL, LEED, and GPR-Gebouw represent the eco-effective structural design criteria and strategies?*

The structural design perspectives are operationalized by analysing BREEAM-NL, LEED, and GPR-Gebouw. By comparing the sustainability assessment methods with the constructed theoretical framework, it could be deduced which method is paramount when focusing on structural design, and what the shortcomings are present within the assessment method. By conducting surveys with structural engineers, the knowledge on the design criteria in practice is evaluated.

4. *What factors steer the extent of incorporation of structural design features that contribute to maximizing the structure's eco-effectiveness?*

Through conducting a case-study on three different projects, it can be assessed if the structural design indicators are implemented, how they are incorporated, and why they are or are not included. From which the factors that drive the structural design decision-making.

1.11 Research scope

The established research context, problem description, and research objective set out in the preceding paragraph provide information for research demarcation, insofar that the scope of the research can be established. The following paragraphs set the scope of the research.

1.11.1 The building structure

A building consists of a large variety of facets in which specific areas of expertise are appointed to, such as installations for mechanical/electrical engineers, aesthetics for architects *and* the building structure for structural engineers. The scope of this thesis is limited to the structure of a building, which is further dissected in Appendix A. Although the structure could coincide with the areas described above, as it also has a strong facilitative nature, the focal point will be the structure and its potential in increasing eco-effectiveness.

1.11.2 Structural design perspectives

When a structure of a building is constructed, and eventually the whole building is utilized by its occupants the performance of the building is more or less set in stone. Prior to construction and utilization is the design phase in which decisions are made that will be irreversible when the project is completed. Thus, the design of the structure is of utmost importance. Considering environmental issues as early as possible in the conceptual design, the more effective they will be (Ding, 2007). The list of structural design perspectives are determined, presented, and clarified in Chapter 2.1.

1.11.3 Material eco-effectiveness

Kemp and Martens (2017) argue that sustainable development is inherently subjective and needs to be defined and dissected in detail before research is possible (Kemp & Martens, 2017). In contemporary research, sustainability focuses on three pillars: economic, society and environment, also known as the triple bottom line which is based on the eco-efficient model. To overcome ambiguous and broadly defined sustainable development that puts emphasis on the short-term, the definition which will be used in this thesis should be differentiated. As stated earlier, the construction sector is the largest contributor of material usage and materials incorporated in a building do not necessarily lose their embedded value. Consequently, the emphasis of this thesis is set on the material eco-effectiveness of the structure.

1.11.4 Structure's life cycle

The structure of a building has environmental implications in every stage of the whole life cycle: from the extraction of natural resources to the structure's end-of-life and beyond. By assessing the whole life cycle of a structure, it is not possible to reduce environmental impact by reallocating environmental burden, also known as "problem shifting" (Buyle, Braet, & Audenaert, 2012). Therefore, it is essential to focus on the entire life cycle when examining the environmental impact and the eco-effectiveness of the structure.

1.11.5 Greenfield projects

Greenfield projects are new projects that are not constrained with any prior work as is the case with brownfield projects. Therefore, this thesis excludes refurbishment, renovation, expansion and other activities in which an existing structure is present. This thesis focuses solely on newly constructed buildings.

1.11.6 Sustainability assessment methods

The sustainability assessment methods which are scrutinized in this thesis are BREEAM-NL, LEED and, GPR Gebouw. The reason behind the selection of the three rating systems is threefold. Firstly, these methods assess whether a building is "sustainable" and all three incorporate structural design features in their assessment (although, non-identical in scope). Secondly, these three methods are used by Arcadis (for which this research was conducted), the one more extensively than the other. Thirdly, these three methods have the possibility, if they accomplish a certain rating within the method, to appeal for governmental grants (RVO, 2018).

1.11.7 Geographical scope

Lastly, the geographical scope of the thesis is the Netherlands; this is because the climate – weather temperature, soil characteristics, relative humidity and other aspects – play a huge role in structural design and construction practices (Zareaian & Zadeh, 2013). Although the local environmental variables are not identical for the entire country, BREEAM-NL and GPR are retrofitted for the Dutch climate, as well for Dutch legislation. LEED, on the other hand, is American based and not retrofitted.

1.12 Research method

Based on the problem description, research objective and the research questions, this paragraph sets forth, argues and describes the used research methods. The research design is divided into four sub-paragraphs. In the first paragraph, the research approach is put forward wherein

1.12.1 Research paradigm

A research methodology, as defined by Buckley and Chiang, is "a strategy or architectural design by which the researcher maps out an approach to problem-finding or problem-solving" (Buckley & Chiang, 1976). The choice of research methods is based on the type and features of the research problem which are related to the expected outcome (Crotty, 1998). There are two types of research approaches: qualitative and quantitative research. Also, a mixed approach can be taken in which both qualitative and quantitative research techniques are applied to single research (Johnson, Onwuegbuzie, & Turner, 2007).

This thesis is conducted on the basis of a qualitative approach. With qualitative research, data can be simplified and managed without destroying complexity and context. By using qualitative methods, new ways can be construed of seeing existing data. The primary purpose of this research is to determine eco-effective structural design strategies based on clustering determined structural design perspectives and putting them into practice to see whether sustainability assessment methods are useful from a structural design point of view. As the thesis does not begin with a hypothesis and is not testing the prior theory, but seeks to develop a framework, a qualitative approach is paramount (Atieno, 2009).

1.12.2 Research methods

This paragraph puts forward which research methods are deployed during this thesis. Additionally, the accompanying reasons for choosing the research methods are established.

1.12.2.1 Exploratory interviews

In qualitative research, the use of exploratory interviews is often preferred above testing procedures as is more the case in quantitative research. This does not diminish the value of mixing the techniques (Verschuren & Doorewaard, 2013). The start of the research is of a generic and abstract nature for which an explorative approach is fitting (Verschuren & Doorewaard, 2013).

1.12.2.2 Literature review

A literature review is conducted to obtain information surrounding several topics within the boundaries of an eco-effective structural design from which a theoretical framework is established. Firstly, the literature is explored in which the structure of a building is demarcated. Secondly, to understand in what areas the structure impacts the environment. Thirdly, to identify what sustainable structural design perspectives are present that are of value for an optimal structural design.

1.12.2.3 Survey

As the team of structural engineers at Arcadis B.V. is large, and expertise in structural engineering in utility projects is in abundance, a survey is conducted to obtain data from a large sample group. Utility buildings could have multiple functions; therefore, it is of value to attaining data that is of breadth and can be generalized so that the results of the research could be of added value to all buildings with utility purposes. Surveys are fitting for large sample sizes in which breadth and generalization are sought-after (Verschuren & Doorewaard, 2013). From the responses in the survey, it can be determined if the structural engineers are knowledgeable in the field of implementation of structural design approaches. Furthermore, by performing the survey, the clustering of structural design perspectives into structural design indicators which are the foundation of the theoretical framework will be validated.

1.12.2.1 Case study

One of the methods used in qualitative research is case studies. As mentioned in the previous paragraph, the use of case studies in research and utilizing elements of the grounded theory approach is widely accepted (Eisenhardt, 1989). Furthermore, it is possible to build a theory on a limited number of cases (Gummesson, 2000). A case study research, however, has an adverse effect on the external validity of the research. Eisenhardt (1989) puts forward the strengths of using case studies to build a framework: a strength of building theory from cases is the likelihood of creating a novel theory and that the resulting theory is likely to be empirically valid as it mostly draws its conclusions from empirical observation. For the case study, a mixed-method approach is used: document analysis and interviews. Using multiple cases and sources of evidence enhances the validity of the research (Yin, 2003; Gummesson, 2000).

1.12.2.2 Triangulation/synthesis

Yin (2003) emphasizes the significance of validation for designing and performing research that is of good quality. In this research, a variety of research methods are used, which can be used to triangulate data to validate the research results. A condition for utilizing triangulation is to use three different sources that contributed to the outcome (Guion, Diehl, & McDonald, 2002; Verschuren & Doorewaard, 2013). The reason for utilizing triangulation is to reduce bias which enlarges the internal validity of the research and improves the accuracy of the qualitative found data.

1.13 Research significance

The focal point of this thesis is determined in the previous paragraph: identifying optimal environmental reductive structural design strategies. This paragraph describes the research significance. This paragraph is divided into three sub-paragraphs. The first sub-paragraph presents the scientific relevance of the research, the second sub-paragraphs presents the practical relevance of the research, and the third sub-paragraphs present the societal relevance of the research.

1.13.1 Scientific relevance

In this research, the focal point is the structure (of utility buildings) and its burden on the environment. A single structural design perspective is not able to focus on every facet of environmental impact a structure incurs, thus, this results in the application of multiple designs perspectives to reduce its overall environmental impact (Hussain, 2012; Danatzko & Sezen, 2011). Scientific articles address the variety of perspectives to approach the structural design. However, the distinction in the literature lacks on how they are interwoven with one another and under what circumstances they should be deployed.

This research aims to contribute to the knowledge field of improving the structural design by gaining insights into structural design perspectives and how they relate with each other. Although a great deal of literature is written about reducing environmental impact through structural design, this body of work could be beneficial for decision-making in early stages of structural design.

1.13.2 Practical relevance

This research is conducted in collaboration with Arcadis B.V. and Delft University of Technology. Arcadis B.V. is a consulting, designing and engineering firm that focuses on the built environment, infrastructure, water, energy and environment in which they provide a wide range of activities. One of which is providing advice in designing building structures for new utility constructions. Arcadis B.V. assists a great variety of clients in designing building structures and, therefore, has much experience in this field. Arcadis B.V. has noticed the trend of the increasing demand in lowering the environmental impact of buildings and wants to contribute to solving this problem from a structural point of view. With this research, a framework will be established that aims to contribute to the structural design process of Arcadis B.V.

Additionally, the value of sustainability assessment methods for structural design is analysed and it is aimed to provide recommendations for improving the assessment methods from a structural design point of view.

1.13.3 Societal relevance

As is widely known, the climate is changing for the worse and it has been proven that humanity plays the protagonist. The role of humanity in environmentally impacting the planet is enormous and ranges through many different fields and sectors of which one is the construction sector. This thesis aims to provide a step in the direction in which the planet is affected less through handling materials in a more effective manner. Even if it is a small step towards a more material efficient future. Every little bit helps as charities often convey.

1.14 Outline of the thesis

The outline of the thesis will function as a short guide for reading the thesis. The structure of the thesis is as follows. Subsequent to the introduction, firstly Chapter 2.1 clarifies the multiple perspectives to design the structure eco-effectively. After which the structural design perspectives are merged into design criteria and eco-effective strategies which are depicted in Chapter 2.2. On the basis of the constructed framework, the sustainability assessment methods are analysed and compared in Chapter 3. In Chapter 0, empirical research is conducted in the form of surveys and case studies. Subsequently, in Chapter 5, a synthesis is made by analysing and comparing the literature, theoretical framework, sustainability assessment methods, and the empirical research together. Finally, in Chapter 6, the discussion, conclusion and recommendations are presented.

2 Theoretical Framework

2.1 Structural design perspectives

This paragraph puts forth a variety of structural design perspectives that help to alleviate the environmental impact a structure incurs. In Appendix I.A and I.B, the structure is demarcated, and the field of environmental impact of the structure has been identified respectively. The structural design perspectives are based on minimizing the life cycle input and output, extending the service life of a building and utilizing structural components for further purposes. This paragraph aims to answer the first sub-question: *From what perspectives can the structural design be approached to maximize its eco-effectiveness?*

2.1.1 Design for material selection

Design for materials is based upon the material's environmental profiles in addition to their technical properties. The focus of material selection can be brought back to two aspects: direct material comparison and material modifications (Anderson & Silman, 2009).

The direct impact of materials on the environment could be assigned to the analysis of the whole life cycle of a specific material. Only through consideration of the whole life cycle materials can be aptly compared. For structural materials, such as steel, reinforced concrete, and timber the level of primary (embodied) energy needed, to extract, manufacture, transport, construct and deconstruct differ (Webster, 2004). The energy input variation also surfaces within the same materials as the primary energy input is reliant on for example the location from which the raw materials are excavated: locally harvested timber has a lower life cycle impact than timber from Canada (Danatzko & Sezen, 2011).

Besides the selection of the type of materials, one can choose to modify the material. For example, concrete is a burden on the environment: vast quantities of virgin materials are needed, the go-to binder is Portland cement which has a high level of global warming potential, and many concrete structures are lacking in durability when exposed for extensive periods (Mehta, 2002). Despite the high initial environmental impact, concrete is still an often-used structural material. Modifying concrete, for instance, by inserting 50% fly ash results in less water needed, enhancement of durability and other features which are beneficial for the environment and resource consumption.

Replacement of natural resources with recycled materials as a strategy to lower the environmental impact is gaining importance as policies on the materialisation of buildings are becoming more widespread. It is already common to incorporate recycled scrap in steel material, and also usage of recycled aggregates in concrete is not rare (Malmqvist et al., 2018).

To directly compare materials, the structural engineer depends on the respective industries (excavators, transport, or manufactures) to quantify the energy used and the greenhouse gases emitted and only they could seize the opportunities to improve their energy usages and production methods. Therefore, structural engineers are designated to databases, such as Nationale Milieu Database (NMD) in which structural materials, products and components could be selected which are based on the life cycle's environmental costs. The explanation of what environmental costs is, is provided in Appendix I.B. Besides the Dutch database for environmental costs, other international databases exist, such as the ICE database which is widely applied in scientific articles. A drawback of the ICE database, opposed to the NMD, is that the focus solely is set on the embodied energy and carbon of materials. Thus, excluding other areas of environmental impact incurred by materials, such as acidification, ozone layer depletion, and eutrophication.

2.1.2 Design for material use

The enormous volumes of materials used in a structure and the ability of the structural engineer to specify material usage create a potential opportunity for a more environmental effective design. Total material minimisation could be one objective of sustainable structural design (Moon, 2008). Intelligent use of structural materials can reduce emissions, resource use, and waste.

Designing for material use is interlinked with the issue of dematerialisation. Dematerialisation or resource efficiency can be achieved in two ways; either by generating more goods, services, or products with the same amount or more of resources or by producing the same end product with less material input. Shi and Han (2010) suggested this could be achieved in two ways: by a combination of *various material types* to form more efficient structural systems, or by optimising the structural model in which the structure is designed with a *single material type*. As the structure also includes the substructure i.e. the foundation, lightweight material for the superstructure results in fewer materials needed for the foundation (Malmqvist et al., 2018). Furthermore, efficient use of materials could be attained by the duality of use in the superstructure and innovative structural solutions (Anderson & Silman, 2009).

Design for materials usage is also concerned with waste, particularly waste produced during the construction process. For instance, prefabricated structural systems will generate less waste during construction. However, the burden is shifted towards the manufacturing stage. For instance, for in-situ concrete, the percentage of cement in the concrete mix could be lower than if it was prefabricated.

The minimisation of materials will consequently result in less impact on the natural environment, as the need for raw materials is lowered. However, it could also lead to more complexity in the structural design, which entails more extended design and analyses time (Danatzko & Sezen, 2011).

2.1.3 Design for durability and (reduced) maintenance

Durability is an indicator which informs of the extent to which a structure maintains its original requirements over time, either technical, functional or economic wise. The higher the material durability, the lower the time and resources required to maintain it (Mora, 2007). When designing for technical durability, two approaches have to be kept in mind individually: the durability of the engineering works and the durability of the selected materials. When selecting non-permanent materials, one could establish endurance by allowing for maintenance and repair to conserve the original structure (Mora, 2007). However, durable materials that require less frequent replacement or maintenance will require fewer raw materials and will produce less landfill waste annualised over the building's lifetime as the technical lifetime is extensive.

Generally, the structural systems of a building are the most challenging part to repair or replace; therefore, it should be designed to fulfil the entire lifetime of a building for which it was intended. Natural or human-caused events could cause degradation of the structural system. Failure of the structural system results in a shortened technical lifespan, consequently leading to wasting of environmental resources, subverting well-intentioned design and dissipating the owner's money (Webster, 2004).

In 2004, O'Connor discovered that only 5% of the buildings are demolished due to structural deficiencies after their intended lifetime of 50 years. This entails that buildings 95% of the buildings still hold their structural integrity but are demolished due to other factors of which one recurring element is the change in demand, thus, the functional lifetime of a building often does not correspond with the technical lifetime. By incorporating functional modification in the structure, the functional service life will approach that of the structural technical service life.

Designing for durability or extending a building's lifetime could lead to an increase in the use of raw materials as the design should incorporate different environmental loads. However, the longevity of a building is a desired sustainable attribute as the overall embodied impact of the life cycle decreases per year. Moreover, building elements, such as cladding or services have a shorter lifespan and, thus, a shorter cycle in which they ought to be replaced. Therefore, an increase in the service life of a building results in more maintenance on "faster" functional layers.

2.1.4 Design for waste effectiveness

The construction sector is one of the most significant contributors to waste generated globally. The life cycle stages where the largest share of structural waste is generated is during construction and at the end-of-life of a building. The most substantial impact on construction and demolition waste volume could be made at the early design stage. Although a waste management plan is of great importance for redirecting waste, the design of the structure of the building sets the standard for how waste could be minimised and salvaged. Critical design decisions determine to what extent existing structural materials and components of buildings are to be demolished, recycled and/or reused. To reduce waste, five design principles could be adopted according to WRAP (WRAP, 2010): *design for reuse and recovery, design for offsite construction, design for material optimisation* (which is already mentioned in paragraph 2.1.2), *design for waste efficient procurement* and *design for deconstruction and flexibility*. *Waste efficient procurement* is more a question of contracts than of design decisions. In Figure 12, the waste hierarchy is depicted, from avoiding and reducing waste to be most preferred to the disposal of waste being preferred the least. The following design strategies in paragraph 2.1.5, 2.1.6, 2.1.7 are an extension of designing for waste effectiveness.

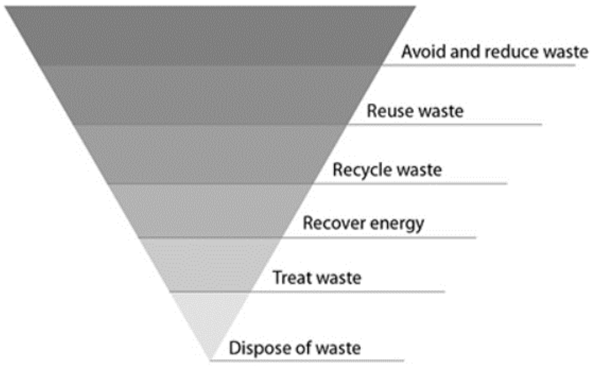


Figure 12: Waste Hierarchy

2.1.5 Design for reusability and disassembly

Designing for structural disassembly gives rise to the opportunity for structural systems to be reused directly after the EoL for subsequent projects. Consequently, resulting in even a more significant decrease in waste as structural components could be used one-on-one in a new structure. Maximizing structural reusability produces less solid waste and enables whole or partial systems to be reused (Danatzko & Sezen, 2011). Consequently, resulting in a lower impact in the disposal stage of the life cycle than landfilling or incineration. Moreover, the highest influence of reusability of structural components could be attributed to the product stage impact of future buildings as they fence of virgin materials (Birgisdóttir et al., 2016). Furthermore, another objective of designing for structural disassembly is to design the structure in such a way that the possibility is present for prolonging the structural lifespan as the structure itself could be dismantled and therefore also adjusted. Such designs are beneficial for adaptation and addition to the size of a building. To maximise reusability of structures it is essential to design the structure with disassembly features insofar that the structure could easily be dismantled during refurbishment and at the end of the building life (Webster, 2004). To simplify disassembly a structure ought to be transparent; building systems are visible and easy to identify. Or thoroughly map materials, components and systems prior to construction; repeating patterns and simplicity, such as consistent beam size and readily demountable joints and connection types; limited number of components, a limited amount of large components are more favourable than a large number of small components, and easily separable (Webster, Gumpertz & Costello, 2005). Additionally, other characteristics that benefit deconstructable structures are accessory joint types, application of parallel disassembly, use of mechanical instead of chemical connections and an open hierarchy. The open hierarchy entails that structural components could be dismantled as such that no other system or component is affected. As seen in Figure 13 on the left side a closed hierarchy is portrayed in which every structural system is supported by another, and on the right side, the majority of structural systems could be dismantled without repercussions for the other systems.

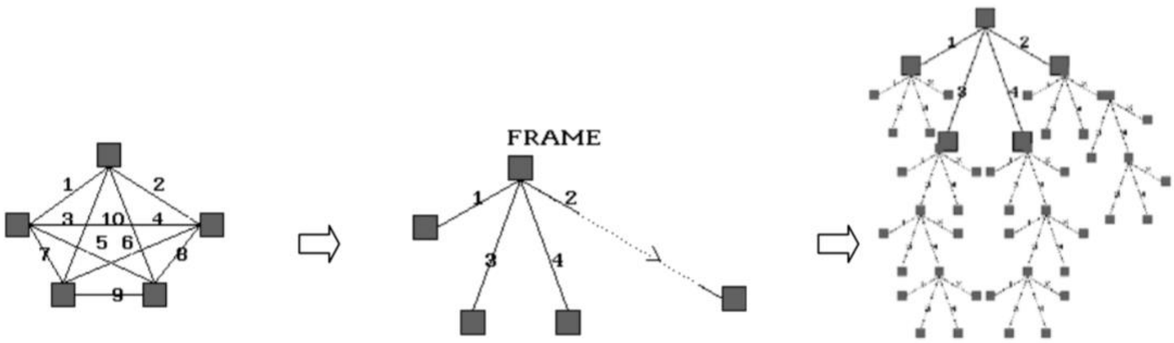


Figure 13: From closed hierarchy, left, to open hierarchical structure (Durmisevic & Noort, 2003)

2.1.6 Design for recycling

Reusability is environmentally preferred above recycling (Thormark, 2000). However, not all systems in buildings are salvageable in their primary state. Recycling could be defined as “the useful application in which waste materials are reprocessed into products, materials or substances, for the original purpose or another. Energy recovery and processing waste materials into secondary fuel are excluded” (Rijkswaterstaat, 2013). For the construction sector, this boils down to the end-of-life recovery and reprocessing of construction products to form new products (Durmisevic & Noort, 2003).

Design for recycling is concentrated on the end-of-life use of materials and components of a structure. Consequently, waste minimisation occurs as waste is treated as a feedstock for new products when recycled. Design *for* recycling differs from design *with* recycled content as the recycled content is embedded in the structure - as mentioned in the paragraph design with materials. Material or component choices made in the design phase have consequences after the structure's service life (Anderson & Silman, 2009).

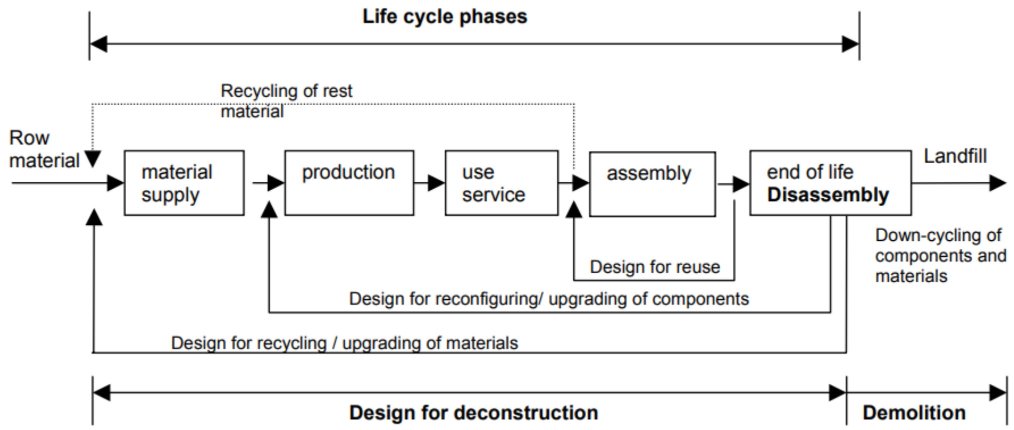


Figure 14: Circular life cycle model of materials and products achieved by design for deconstruction (Durmisevic & Noort, 2003)

2.1.7 Design for adaptability and flexibility

At the top of the waste hierarchy in Figure 12 avoidance and reduction of waste are represented. Avoiding and reducing waste could be achieved through designing for adaptable or flexible structures as probability of the longevity of a building is enlarged. Designing for adaptability does not only comprise of structural systems to be adapted. It also facilitates adaptation in buildings as well. There is a broad body of literature on adaptability and flexibility and the meaning of both. Below a list is given on different types of adaptability that could be ascribed to the structure for different time frames – in which *versatile* and *convertible* could be seen as flexible types (Schmidt et al., 2010):

- **Versatile** - changing the dimension of space, for example, movable partitions such as interior walls (every 1-5 years)
- **Convertible –** changing the use/function of a building, for example, a floor to soffit heights that allow the office to residential conversion (once or twice in a buildings lifetime)
- **Scalable –** changing the size of a building, for example, oversized foundations to accommodate extension (once or twice in a buildings lifetime)
- **Moveable –** changing the location of a building, for example, modular pods that enable disassembly/deconstruction (rarely)

Even in the literature the term adaptability and flexibility are entangled with each other. Therefore confusion seems to arise. The multiple interpretations may ultimately lead to misunderstanding about project objectives during briefings and design (Pinder et al., 2016). The two terms are based on the context in which they are set in, from that premise the following definitions in structural context will be used (Blok & Herwijnen, 2005):

Structural flexibility: "The capacity of the building structure to provide changes in other building storeys, without the necessity to modify the bearing structure itself."

Structural adaptability: "The capacity of the building structure to be able to undergo changes to the structure itself, with or without only small consequences for the remaining building storeys."

Looking back at the shearing layers that were introduced in paragraph I.A.a; both strategies could be applied on a different level. Flexibility in the structure entails that the structure can facilitate alterations in the spatial plan and services without meddling with the structure itself. Hence, increasing flexibility results in more functional versatility and convertibility. When looking at adaptability, the alteration of the structure itself is the focal point. Hence, design for adaptability increases the potential for scalable or movable building.

By designing structures flexible the possibility of prolonging the service life is incorporated, consequently, demolition is postponed, and the materials embedded in the structure are preserved. By designing buildings to be adaptable, i.e. movable, design for disassembly of structural components should be incorporated. Therefore, materials embedded in the structure are preserved as modular systems are of a reusable nature.

2.1.8 Life cycle assessment

As introduced and explained in paragraph I.B.b, approaching the structure from a life cycle perspective is an important element in determining the overall environmental impact of a structure. The method of life cycle assessment is underlying to the predetermined structural design perspectives (Danatzko & Sezen, 2011; Birgisdóttir, Houlihan-Wiberg, Malmqvist, Moncaster, & Rasmussen, 2016; Webster M. , 2004).

2.1.9 Conclusion structural design perspectives

This paragraph identified the scope of existing structural design perspectives that have a favourable effect in increasing its eco-effectiveness. The structural design perspectives are identified by reviewing the literature. This paragraph provided the answer to the first sub-question.

From what perspectives can the structural design be approached to maximize its eco-effectiveness?

From reviewing the literature ten different design perspectives are obtained (excluding life cycle assessment as a perspective). These structural design perspectives either reduce the material or energy input, reduce the waste and pollution output, extend the technical or functional service life, or utilize waste output. Consequently, encompassing the full life cycle of a structure. On the next page, the list is put forward with each having a short description of what the perspective entails.

1. **Material selection:** the traditional materials used for structures are steel, reinforced concrete or timber. For the selection of materials, direct comparison is essential to know what type of material is required. The selection of materials from an environmental point of view is based on a variety of factors; environmental costs and technical properties.

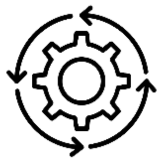
2. **Material use:** Intelligent use of structural materials can reduce emissions, resource use, and waste on the whole life cycle. Dematerialisation through generating more goods, services, or products with the same amount of materials or by producing the same end product with less material input

3. **Durability:** designing for durability encompass the extension of the service life of a building by maintaining its technical and functional requirements. Durability is an indicator which informs to the extent to which a structure conserves its original requirements over time, either technical, functional or economic wise.

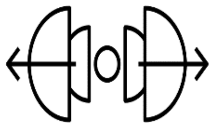
4. **Waste effectiveness:** Waste is an undesirable product, and should, therefore, be minimized, and/or treated as a valuable resource. Designing the structure as such that disposal of waste is minimized during construction and demolition phase.

5. **Maintenance:** the structure has to be designed so that maintenance of the structure is either minimized, insofar the input of material/energy during its service life is reduced; simplified, insofar the effort of maintenance is lowered; or targeted, insofar only worthwhile components are maintained for extension of the service life.

6. **Reusability:** designing the structure as such that structural component/elements/systems in the structure are of a reused nature, or can be reused one on one after the end of the building's life cycle for future structures/next cycle.



7. **Disassembly:** the structure is designed as such that the structure (or parts of it) could be effortlessly dismantled, insofar that the structural components remain intact for future purposes.



8. **Recyclability:** designing the structure as such that recycled material is embedded in the structure or incorporating the potential of recycling at the end of the structure's service life.

9. **Adaptability:** a building has the capacity to alter the structure itself. Scalability of the structure, insofar the structure could be expanded horizontally or vertically; or movable, insofar the structure is designed modular. The icons representing the two adaptable aspects respectively.

10. **Flexibility:** the structure facilitates the possibility to modify the internal spatial layout of the building without changing the structure itself. Also, a flexible design enables potential user function change.

11. **Life cycle assessment:** Although life cycle assessment is mentioned as a strategy, in this thesis it is assumed that assessing the life cycle is a prerequisite for structural design optimisation. This strategy is the basis of all the prior design strategies. Together they comprise of the whole life cycle. In the following chapter, this will be explained in more depth.

Table 2: Structural design perspectives derived from various scientific articles.

Strategy	Datatzko & Sezen (2011)	Birgisdóttir et al. (2016)	Malmqvist et al. (2018)	Anderson & Silman (2009)	Yilmiz & Bakis (2015)	Kertner et al. (2010)	Webster (2004)	Chaudhary and Piracha (2013)	Honkanen (2013)	Akbarnezhad and Xiao (2017)
Material selection		X	X	X	X	X	X		X	
Material use	X	X	X	X				X		X
Durability		X	X			X	X	X	X	
Waste effectiveness		X	X						X	
Maintenance		X				X			X	
Reusability	X	X	X		X	X		X	X	X
Recyclability		X		X	X		X			X
Flexibility		X	X	X	X				X	
Adaptability		X	X	X			X	X		
Life cycle assessment	X	X				X	X			

2.2 Theoretical Framework

A theoretical framework is constructed in this paragraph. The constructed theoretical framework is based on the reviewed literature in which structural design perspectives are determined. Merging the perspectives of structural design; three structural design criteria are established. The theoretical framework criteria lay the foundation of the optimal structural design strategies which are aimed to maximize the eco-effectiveness of the structure.

2.2.1 Clustering of structural design perspectives

When assessing the environmental impact the structure incurs, one ought to examine the whole life cycle of the structure. Through the assessment of the whole life cycle, every possible environmental burden can be identified. In Appendix I.B the environmental impact of the structure is identified, the environmental impact is based on the input and output of the life cycle, for clarity they will be enumerated anew:

- Material input
- Waste output
- Service life

To reduce the structural environmental impact the goal is to increase effectiveness for both the input and the output of the structural life cycle. Increasing effectiveness does not solely entail that the material or energy input should be lowered, but that materials that are chosen incur little pollution and waste over a long period of time. An indicator that tries to grasp the pollution and the primary energy source of a certain material type in its life cycle is the environmental costs which can be dissected into two variables: *material environmental costs* and *the service life*. The total environmental costs of a building are the sum of the environmental costs of all materials embedded in the building divided the years the building is estimated to be serviceable. Derived from the literature, structural design perspectives that reduce the material environmental costs and increase the probability of a prolonged service life are identified. The merging of the structural design perspectives into *material environmental costs* and *service life* are depicted in Figure 15.

The environmental costs and its structural design perspectives cover the product stage, construction process stage and the use stage of the life cycle, however, the environmental costs per year neglect the subsequent two stages: end-of-life stage and the benefits and loads beyond the system boundary. Moreover, the two established criteria do not account for the fact that structural waste could be seen as a valuable resource. The environmental costs are embodied in the structure and do not dissipate after the structural service life. Which entails that the structure holds residual value and that structural materials and components embody a potential to be utilized for successive projects. Additionally, as traditional structural materials are finite resources and excavation of raw materials has a high degree of pollution, an increase in utilization of residual value would contribute to lowering the structural environmental impact. Thus, to cover the full life cycle a third criterium surfaces: *residual value.* The structural design perspectives are identified that promotes more efficient resource use and maximization of the residual value.

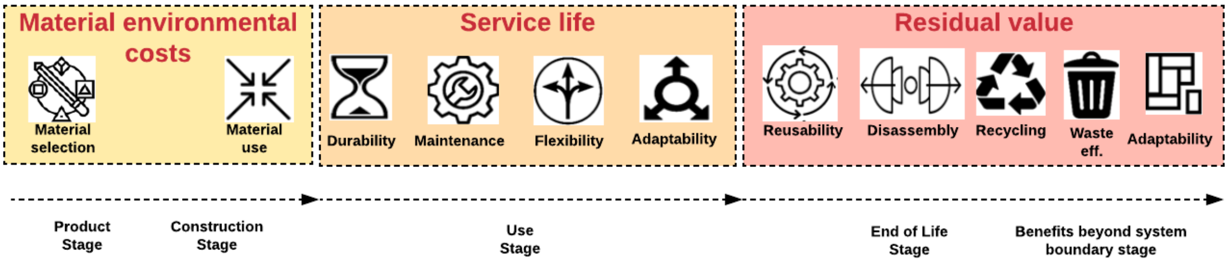


Figure 15: Clustering of structural design perspectives into three structural design criteria: *material environmental costs, service life, and residual value.* **(own illustration)**

2.2.2 Optimal structural design strategies

As portrayed in Figure 15, the structural design perspectives can be merged into three criteria. Although the criteria can be individually approached, they are not isolated in their outcome as focus on one could have an adverse effect on the other. Hence, one could conclude that there is no such thing as an optimal structural design strategy to maximize the structure's eco-effectiveness. Nevertheless, optimal design strategies can be established by putting emphasis on either minimisation of material environmental costs, maximizing the service life, or optimizing the residual value.

Focusing solely on the material environmental costs is unsatisfactory when designing an eco-effective structure. This is due to the fact that a structure tends to have a relatively long lifespan and value is embedded within it. By excluding the service life and residual value in the design equation, the full potential of the structure could not be attained. This evidently does not entail that minimization of material environmental costs should be neglected as every structural design should strive towards minimizing its initial environmental impact. Though, the service life and residual value should be addressed first and foremost.

As discussed, a structure has multiple service life's, wherein the technical and functional service lives are the most crucial in the structural design. The technical life span of internal structural parts is generally endless, on the condition it is revised periodically. Nonetheless, due to shifts in demand, the function within the structure often does not reach the full technical longevity (Hermans, 1999). When the functional service life of a building comes to an end, often the structure is still in outstanding condition. Consequently, when focusing on the structural design on prolonging the structure's service life, the building's service life should either *fulfil* its technical service life or, at least, *surpass* the functional service life of the building.

When a structure is intended for relatively short service life, the emphasis in the design should be directed towards optimizing the residual value of the structure. As the service life is relatively short, the structural materials or components are still high in residual value as they were not exposed to a lot of stresses over extended period of time. To preserve the structural materials and harvest them when the structure reaches its end of life, the structural design should create design conditions that maximizes the potential of the structure to be dismantled and, thus, be reused in their primary shape. Prolonging the service life and optimization of residual value cannot be deployed simultaneously. The residual value of the structure decreases over time and incorporation of disassembly features in the structure is not favourable for a lengthy structure.

In the waste hierarchy, put forward in paragraph 2.1.4, it states that the optimal strategy for material preservation is to do nothing, or better said avoid activities whatsoever. From which can be assumed that extension of the service life prevails over optimization of residual value. Elefante (2007) signalled correctly that the most environmentally friendly strategy, regarding material preservation, is to occupy a building that already has been built, thus, preserving the initial embodied impact. Extrapolating this premise to the future of new construction, it is more eco-effective to safeguard a structure from being dismantled or demolished even when the initial material input needs to be increased.

On the basis of the preceding explanations on the three criteria, the following optimal conceptual structural design strategies are established:

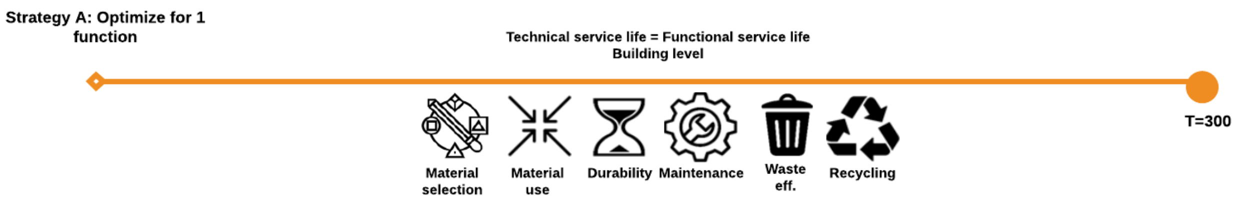


Figure 16: Strategy A: the technical and functional service life on a building level are maximized and equalized. (own illustration)

The structural design Strategy A, as is depicted in Figure 16, for an eco-effective structural design perspective is to maximize the service life. It is imperative that solely one function will occupy the building in this strategy; equalizing the lengthy technical service life with the functional service life on a system level, with the result that the material input of the structure could be optimized and squeezed for that specific function. Although the assumption of one function occupying the structure could be far-fetched as demands have been proven to change during a long service life, for some structural functions the probability is low to zero. For example; temples, churches, or museums have a specific function which is not prone to functional alteration over an extended period of time. These demand for these functions, however, occurs seldom.

Despite the fact that the focal point of this strategy is the maximization of service life – technically and functionally – and material environmental costs being an accessory to that focal point; the structural design should still aim to reduce its initial material environmental costs by either choosing a certain material type or optimizing the material use. Evidently, on the condition that the technical properties of the structural materials, components, and systems are reliable to fulfil the long technical lifetime, i.e. the structure should be durable in its system and its components.

As the service life is to be maximized, connections between structural components will be firmly or chemically secured meaning that the structural components will not be demountable. Next to that, structural components will deteriorate and deform during a lengthy service life, thus, thwarting its salvageability to be reused in its primary state for subsequent projects. However, recycling is always an option after the structure's end of life, into what degree is dependent on the type of material chosen.

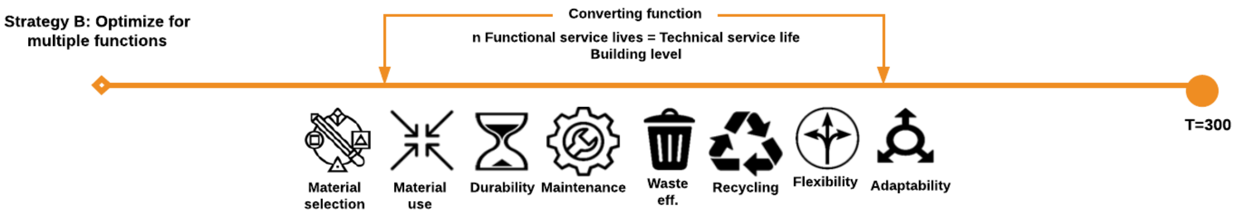


Figure 17: Strategy B: the technical service life is maximized and equalized through n functional service lives on a building level. (own illustration)

As is put forward in the above-clarified Strategy A, the assumption of a building retaining its primary function over a lengthy period of time is highly doubtful. In Strategy B, the uncertainty of the functional service life not fulfilling the technical service life is addressed and integrated accordingly.

The design of the structure should be both fitted for the intended primary function as well as for the subsequent functions. Either with the knowledge of what the subsequent function of the building will be or by incorporating universal function-fitted structural design features. This entails that the structure could not be optimized for one specific function. Consequently, the initial use of materials will most likely increase as the structure should incorporate uncertainty avoiding structural design features, or if the subsequent function is known, embed materials for that function respectively. By implementing the potential of functional convertibility, the probability increases of equalization of the functional service life with the technical service life as the structure could also inhabit subsequent functions. This results in postponement of demolition, thus, preserving the initial embodied materials.

The selection of structural materials with low environmental costs with high technical durability of the materials, components, and systems are also in Strategy B a to strive for aim. Furthermore, as is also depicted in Strategy A, the lengthy service life has an adverse effect on optimizing of residual value on a component level. Hence, recyclability is the most effective waste treatment option after the end of life of the structure.

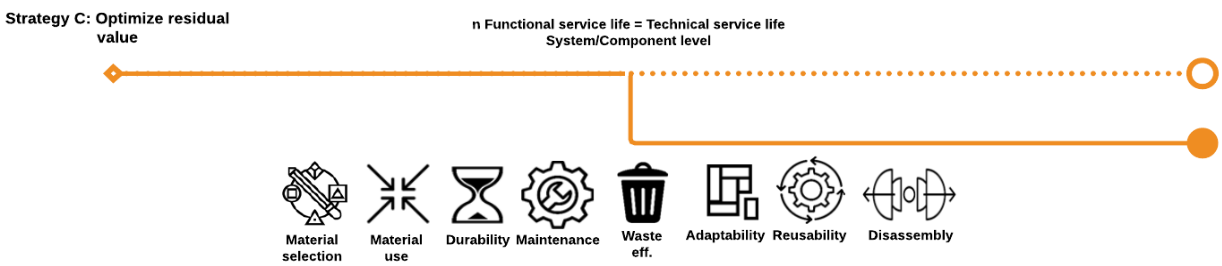
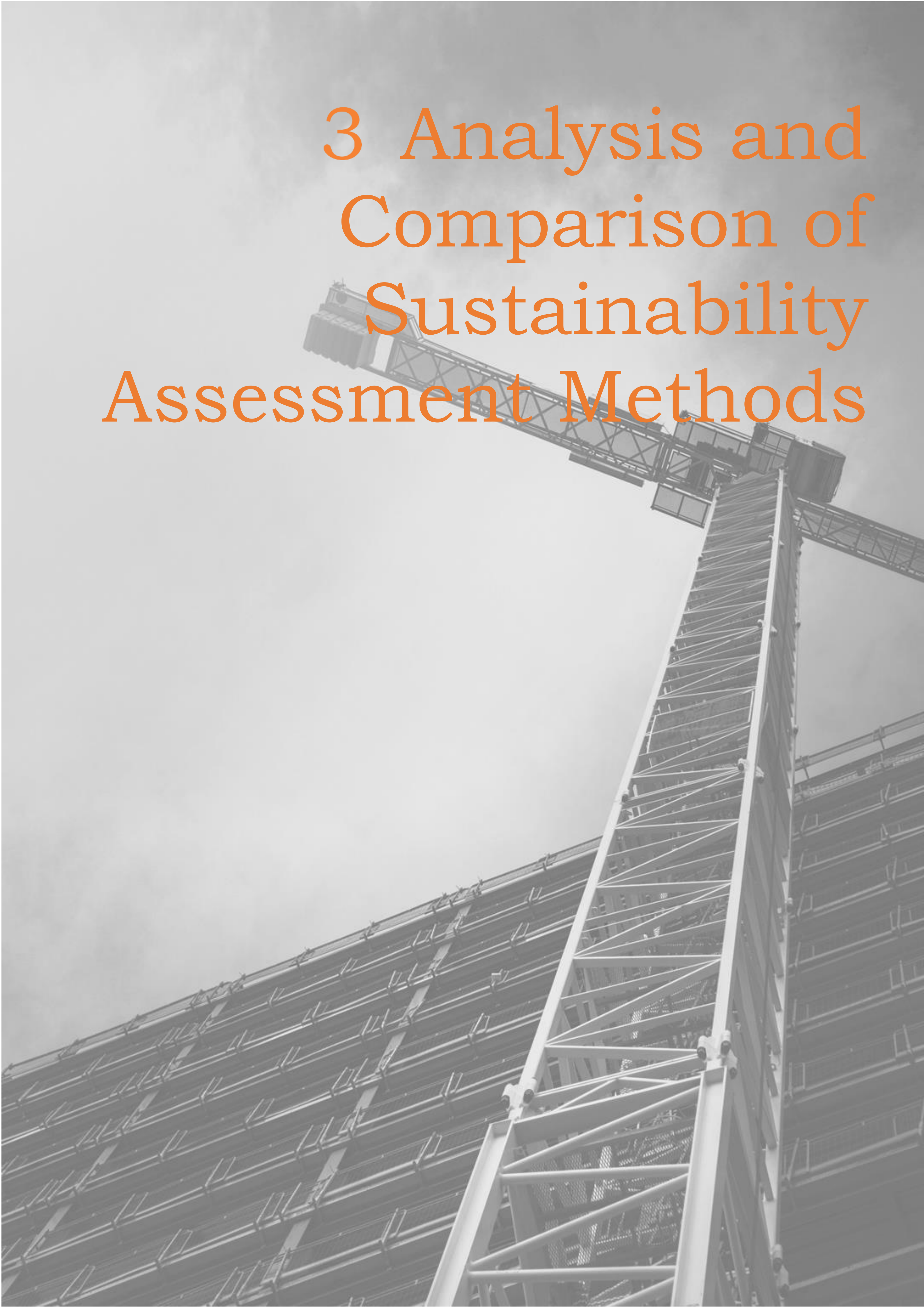


Figure 18: Strategy C: the technical service life is maximized and equalized through n functional service lives on a system/component level. (own illustration)

For Strategy C, it should be known that the functional service life of a structure on a building level is relatively short. Although the functional service life is limited on a building level, the technical durability of the structure on a system and component level remains unflawed. Thus, one must direct their focus on optimizing the residual value of the structure on a system and componential level. It follows from a building with a relatively short service life that the material environmental costs per year are relatively high, simultaneously the value of the structure after its end of life of a specific cycle is also high. In the waste hierarchy; avoiding and reducing material usage are the most efficient to lower the material impact. After that, reusing materials is the most optimal approach. To be able to reuse structural systems or components, it is imperative that the structure is able to be demountable. Through incorporation of disassembly features, structural systems and components could be used in their primary state for subsequent cycles.

3 Analysis and Comparison of Sustainability Assessment Methods



3.1 Sustainability assessment methods in The Netherlands

To evaluate the level of sustainability in the design of buildings, sustainability assessment methods (SAMs) are constructed to converge, operationalise and normalise sustainability features in the design of buildings into a comparable scale. The internationally most popular nowadays are BREEAM and LEED. In 2000, they were the sole contributors, but as time progresses more sustainability assessment methods enter the sector. In 2009 over 40 SAMs are operational globally. One of which is the Dutch assessment method: GPR-Gebouw. These three methods – BREEAM-NL, LEED, and GPR-Gebouw indicate what aspects to focus on to increase sustainable features in the design of a building. The sustainable assessments methods differ in scope, focus and purpose amongst other things (Markelj et al., 2014). For instance, a high rating on the internationally known methods BREEAM and LEED improves the marketability of offices spaces or apartment buildings. In comparison to the Dutch GPR-Gebouw which is mostly used by governmental parties and only deployed in the Netherlands. Additionally, by attaining a sufficient rating on the assessment methods BREEAM-NL, LEED, or GPR Gebouw, a project could be eligible for grants up to 1.8 million euro in the Netherlands (RVO, 2018). Furthermore, these tools serve as a means for communication purposes between project stakeholders as the assessment methods are relatively accessible and clarifying.

The rating systems are generic, meaning that they do not always fit with project-specific cases and the rating systems can also be interpreted as narrow by experts (Schweber & Haroglu, 2014). Moreover, they are often time-consuming, plus assessors and experts are needed to evaluate the buildings.

In Table 3, the categories on which the buildings are appraised for new construction are depicted. The three methods are extensively used in practice and the categories are operationalised in detail in the sustainability assessment methods. Hence, it is beneficial to extract the structural aspects and its operationalized parameters. Furthermore, the sustainability assessment methods will be evaluated on the representation of an eco-effective structure.

Table 3: Categories of sustainable assessment methods (BREEAM-NL, LEED, & GPR) with the accompanied weightings

BREEAM-NL	LEED	GPR Gebouw
Management (12%)	Integrated Process (1%)	Energy (20%)
Health and Wellbeing (15%)	Location and Transport (16%)	Environment (20%)
Energy (19%)	Sustainable sites (10%)	Health (20%)
Transport (8%)	Water efficiency (11%)	User quality/friendliness (20%)
Water (6%)	Energy and Atmosphere (33%)	Future value (20%)
Materials (12,5%)	Materials and Resources (13%)	
Waste (7,5%)	Indoor environmental quality (16%)	
Land use and Ecology (10%)	Innovation (Extra: 6%)	
Pollution (10%)	Regional priority (Extra: 4%)	
Innovation (Extra: 10%)		

3.1.1 BREEAM-NL (New Construction)

BREEAM is developed by the Building Research Establishment (BRE) in the United Kingdom in 1990, making it the oldest building sustainability assessment method (Kajikawa, Toshihiro, & Goh, 2011). Nowadays, BREEAM forms the basis of a variety of buildings assessment methods across the globe. Due to the fact that countries differ in legislation, climate, economic status, and other attributes it is not possible to copy and paste the exact format of BREEAM from one country to another (Cole, 2010). For that reason, the Dutch Green Building Council retrofitted the building assessment method insofar it could be used in the Netherlands, resulting in BREEAM-NL. BREEAM-NL has 9 categories of focus with each their own weightings and credits, as depicted in Table 3.

Every category is subdivided in multiple criteria. The design of the building is assessed in two stages. Temporary design certification is given after the design phase in which sufficient evidence has to be transferred to an independent assessor. After completion of the construction, the building receives a permanent certificate dependent on what rating the overall building achieves. As BREEAM is internationally recognized it serves as a commercial trademark, which is also one of the reasons a temporary certificate is given early in the design phase, as investors/partners/inhabitants could be sought-after early in the process (Lee & Burnett, 2008).

In Appendix II.A, an analysis is performed to see what credits are linked to the structural aspects of a building.

3.1.2 LEED (New Construction – v4.0)

LEED, Leadership in Energy and Environmental Design, is a building assessment method that originated in the United States. Developed by the U.S. Green Building Council (USGBC) in 1998, it is created as a practical rating tool to deliver verifiable sustainability status for building practices. The categories for LEED are depicted in Table 3.

Although this method is developed in America, it is implemented in the Netherlands without alteration. Other than with BREEAM-NL, it is not mandatory to involve an independent assessor. One could take an exam and receive an expert status to assess a project (Kajikawa, Toshihiro, & Goh, 2011). Therefore, it could be said it is less trustworthy than with an independent assessor as is the case with both BREEAM-NL and GPR Gebouw. However, it is still recognized as an international hallmark, thus, for commercial purposes a good tool (Lee & Burnett, 2008). There are three timeframes in which the project is assessed, that is after the planning phase, after the design phase and after the construction of the building.

3.1.3 GPR-Gebouw

In 1995, the GPR-Gebouw method was developed by a private company W/E adviseurs which is located in Tilburg (W/E Adviseurs, 2018). Firstly, it was solely implemented in the municipal area of Tilburg, however since 2004, GPR-Gebouw expanded in several other areas in the Netherlands. This method assesses new construction on the basis of 5 categories, see Table 3. These categories are subdivided in multiple indicators. Every category receives a grade between 1-10, with a final score ranging from 1-10 as well. GPR-Gebouw serves as a means to convey the ambition of a building; it could also be captured in the zoning plan in the masterplan phase or in the urban development planning phase. After the identification of the ambition level the calculations have to be made and checked, finally, the degree of sustainability will be evaluated with GPR-Gebouw (RVO, 2010). Dependent on which grade is obtained an appeal can be made for subsidizing the project (RVO, 2018).

3.2 Structural design perspectives in sustainability assessment methods

To assess to what degree a building is sustainable, rating systems are constructed. These rating systems are all three focused on the triple bottom line; economic, environmental and social. The scope is far broader than only the structure of a building. For instance, energy and health inquiries are also part of all three assessment methods. As in practice, these methods often used to strive for sustainability in buildings it is important to see what it entails. This paragraph extracts the structural features that are based on the impact on the environment. In Appendix 0I, the three methods are scrutinized and analyzed in detail.

3.2.1 Inventory criteria

In this paragraph, the structure of a building has been demarcated, the environmental impact of the structure has been stated, and the determined structural design perspectives are put forward. From these outputs, the influence of the structure on sustainable assessment methods can be analysed and the operationalized criteria can be extracted and turned into concrete indicators which are will help to operationalize the ten structural design perspectives.

To extract the structural elements embedded in the three rating systems, criteria need to be established. These criteria are based on the literature review in Appendix I.A, I.B, Chapter 2.1 and 2.2.. Through reviewing the literature, it is known what is meant with the structure, in what areas the structure puts its mark on the environment and what structural design perspectives exist. Only the elements of the rating systems are extracted on which the structure has a direct influence.

Structure. For a structure to be occupiable, it should withstand any internal and external forces, meaning it should be safe and serviceable over a specified amount of time. The function of a building is deeply associated with the structure’s typology. Design criteria such as floor-to-floor height, number of storeys, structural grid, stability measures and amount of square meters are inherent to the structure. The structure consists of the foundation and its superstructure in which materials, components, and systems are incorporated.

Reduction of structural environmental impact. Minimize input of material, maximize renewable primary energy, minimize the output of pollution and waste, prolong the service life of a building, and utilize waste.

Structural design perspectives. Design for materials, design for material use, design for waste effectiveness, design for durability, design for maintenance, design for reusability, design for recyclability, design for flexibility, and design for adaptability.

The following paragraphs sets forth the operationalization of the identified structural design focus areas through analysis of BREEAM-NL, LEED, and GPR-Gebouw.

3.2.1.1 Material selection

The structure of a building is one giant body of materials and in all three rating systems, this is an important recurring feature. Both BREEAM-NL and GPR use the life cycle material database Nationale MilieuDatabase in which the environmental costs of materials are secured. By inserting the quantity of materials in the database, the initial material environmental cost is set. The final environmental cost is based on the environmental costs of the materials, the square feet of the building, and the estimated service life (m^2 GFA/year). All three assessment methods incentivize choosing materials with low environmental costs. In BREEAM-NL, an innovation credit can be obtained by directly comparing different structural design materials on the basis of environmental costs.

Furthermore, in BREEAM-NL the use of secondary material is stimulated, however, this is only focused on recycled material and not on direct reusable structural components. In LEED and GPR, reusing of structural components is encouraged. By incorporating recycled or reused materials in the structure, the weight of the materials could be deducted from the environmental costs.

Important to note, is that all the materials embedded in the building are incorporated in the overall environmental costs. This entails that next to the materials of the structure also insulation, internal walls, envelope claddings, and solar panels amongst other materials are part of the overall environmental costs.

3.2.1.2 Material use

In BREEAM-NL, quantity of material use is stimulated through incentivizing lowering the environmental costs. The fewer materials embedded in the structure, the lower the environmental costs will be.

In LEED, the full score can be obtained by not building new constructions, which entails using old buildings, thus, avoiding any type of structural material input. Although it could be argued that this is a paramount approach, this thesis focusses on newly designed constructions. Through stimulation of building and material reusability or lowering the environmental costs, material minimisation is promoted.

In GPR-Gebouw also the environmental costs are a stimulant in lowering the material input as is encouraging of incorporating reused components. Additionally, credits can be obtained to design a thin construction by focussing on special design solutions insofar the structural elements can be reduced with 25%.

3.2.1.3 Durability

In BREEAM-NL, credits can be earned by the protection of structural components where the risk of damage is high resulting in preservation of the structure’s technical service life. Furthermore, in BREEAM-NL, apart from encouraging a flexible design, no direct stimulation is given to prolong the lifetime of the building. In LEED no mentioning is given about either preserving the structure or by extending the service life.

In both BREEAM-NL and LEED, the estimated service life is fixed on either 50 years or 75 years depending on the function of the building. With GPR-Gebouw, however, it is possible to extend the estimated service life by increasing the internal (functional/comfort), external (landmark) amenity value, and the accommodating value. The role of the structure can be reduced to solely the third aspect: accommodating value. Which is divided into four aspects: functional future-oriented; the structural spatial layout flexibility; spaces are subdivisible; and the possibility of adaptability (enlarging the building volume). The environmental costs are an important facet of the structure which could either be reduced by the choice of the type of material, the amount of material and by extension of the estimated service life. Thus, through the possibility of prolonging the service life of a building, the environmental costs could be reduced tremendously.

Moreover, GPR-Gebouw also focusses on a robust design or detailed design for sensitive building elements in which the repairability is an important feature. Also, the building and structural components should be designed for multiple cycles, insofar increasing the durability of the building or structural components through prefabrication of systems, separation of structure and finishing design, and demountable structural components. Moreover, structural elements with short lifespan should not interfere with elements that have a long lifespan.

3.2.1.4 Waste effectiveness

BREEAM-NL promotes efficient use of raw materials on the construction site and stimulates responsible management by using environmentally friendly materials. These are, however, mostly managerial issues. BREEAM-NL stimulates the use of recycled materials or secondary aggregates; 30% share in the superstructure of a building and 35% in the foundation. In LEED one can choose between two options; divert 75% of the waste material streams of at least 4 materials or reduce the total waste (< 12.2 kg/m^2 GFA). In GPR-Gebouw no mention is given on minimization of waste.

3.2.1.5 Maintenance

No direct mentioning is given on maintaining the structure in BREEAM-NL, although, it stimulates to make a maintenance plan. However, in the maintenance most emphasis is put on building parts with short lifespans. Consequently, the structure is not mentioned directly. Furthermore, in BREEAM-NL sensitive structural areas are stimulated to be protected resulting in the prevention of maintenance. Also, in LEED no direct mentioning is given about maintenance. GPR-Gebouw promotes robust design and stimulates that building components with a lifespan of 25 years or less won't interfere with other components with longer lifespans.

3.2.1.6 Reusability

In BREEAM-NL reusability inquiries do not occur in the assessment. In LEED building and material reuse is promoted by re-usage or salvaging building materials as a percentage of the surface area. This includes; structural elements such as; floors, roof decking, but also enclosure materials and permanently installed interior elements. Also, the sourcing of materials is stimulated is promoted in LEED, insofar certificates are present to see if the materials are indeed already used. In GPR, prior used elements in the structure is stimulated so that >= 50% of three chosen elements are reused.

3.2.1.7 Disassembly

Whereas the prior design focus area of reusability focusses on reused content, this strategy focuses on whether the structure could be dismantled i.e. reused after the End of Life. Also, no mentioning in BREEAM-NL of disassembly of structural systems. The same goes for LEED. In GPR, however, the potential of structural dismantlement is stimulated in which the most important part of the structure could be disassembled without damaging other parts of the building. Moreover, the joints of the structural elements should be accessible and easily dismantlable.

3.2.1.8 Recyclability

In BREEAM-NL the amount of secondary materials in the superstructure (30%) and in the substructure (35%) is mandatory with the accompanying certificates. In LEED, recycled content is stimulated through sourcing of materials in which a certain recycled content could be demonstrated as well as the diversion of materials during construction (75% of at least four materials). In GPR-Gebouw secondary material is stimulated and the compulsory amount is dependent upon the type of structural material (metals >75%, timber >50%, and concrete <50%).

3.2.1.9 Adaptability

In BREEAM-NL, adaptability or expandability could be brought back to one indicator and that is sufficient load capacity. Within LEED the flexibility credit only focusses on adaptability measures; through identifying the capacity of horizontal expansion and by designing the roof insofar that 75% of the roof is capable to add another level. In GRP-Gebouw, expandability of +50% of the surface area (GFA) is incentivized and incorporation of possibility for a 'green roof' is stimulated.

3.2.1.10 Flexibility

In BREEAM-NL flexibility is an important facet. In BREEAM-NL a separate tool is embedded to calculate to what degree a building could be seen as flexible as could be seen in Appendix D. Although, the flexibility of a building is covered by more disciplines than the structure alone, the structure is significant as it comprises of more than 50% of the calculation tool. Although, this category is not attributed to buildings with an industrial function. The following indicators could be attributed to the structure:

Column placement (structural grid) – no inner columns and free span
Movable internal walls – movable, demountable, and modular wall
Non-bearing function separating walls – movable, demountable, and modular wall
Building accessibility – building divides into>2 wings with a combined core and entrance
Non-bearing facades – non-load bearing facades and open surface and no obstacles
Sufficient bearing capacity – >4,0 kN/m²
Floor-to-floor height - >3000-3500mm

LEED only has a flexible design category specific for hospitals and aspects of the flexibility credit that are of a universal nature are either adaptable or expandable facets.

For GPR-Gebouw the future value is an important facet for the overall score. The *structural type* should be a column-/beam structure, or a frame structure so that internal flexibility is possible. Furthermore, the structure should encompass *modifiable elements.* Which entails that the structure and services should not interfere with each other, the façade and the structure should be separated, and openings in the ceilings, floors and walls should be incorporated. Moreover, the *possibility for altering the internal spatial layout* should be incorporated through easily modifying the size of a space, the spaces should be subdivisible, and harbouring other building functions without changing the structure is incentivized.

3.3 Theoretical framework compatibility

In this paragraph, the theoretical framework that is established in Chapter 2.1 and 2.2 will function as a means to evaluate BREEAM-NL, LEED, and GPR-Gebouw on their adherence to the eco-effective structural design. Moreover, the sustainability assessment methods will be compared to learn what sustainability assessment methods is supreme relative to the other assessment methods from a structural design point of view.

3.3.1 BREEAM-NL (New Construction)

In Appendix II.A, an analysis is performed to see what credits are linked to the structural aspects of a building. The structural design focus areas are depicted in Figure 19 accompanied by the focus points that BREEAM-NL puts emphasis on.

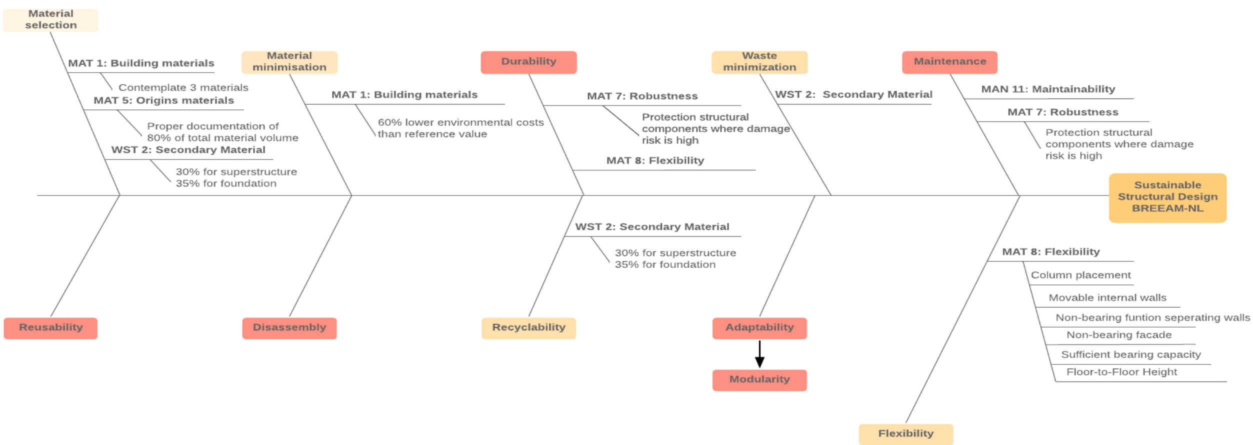


Figure 19: Ikashawa diagram of the operationaliztion of structural design persepectives in BREEAM-NL

3.3.1.1 Material environmental costs

BREEAM-NL stimulates that three different structural materials are contemplated in the design; however, it does not secure what type of structural material that should be or that the structural material with the lowest environmental costs is chosen. However, BREEAM-NL does stimulate to lower its environmental costs relative to its reference case, attaining the full score if the environmental costs are 60% lower than the reference case. Furthermore, the incorporation of secondary materials in the structural materials is incentivized.

3.3.1.2 Service life

The service life is fixed and is not subjected to change. The service life differs on the basis of the function. For utility buildings, an estimated service life is chosen of 50 years, for residential purposes the estimated service life is 75 years, as it is for mixed-use functions.

In BREEAM-NL, credits can be attained by incorporating measures in the structure that increases the flexibility of a building. The flexibility, however, is mostly focused on internal flexibility, meaning that the spatial layout could be adjusted whilst preserving the same function. Flexibility is not stimulated in all functions; it excludes industrial and residential functions. The main reason for flexibility in BREEAM-NL is to sublet office spaces for multiple tenants. BREEAM-NL does not specifically stimulate structural design measures for subsequent function use: multifunctionality, or functional convertibility.

3.3.1.3 Residual value

As can be seen in Figure 19, BREEAM-NL has not incorporated credits for reusability and disassembly. BREEAM-NL - New Constructions - solely focuses on the product phase, construction phase, and use phase of the life cycle omitting the subsequent phases in which reusability of the structure and, thus, disassembly of structural components is vital for optimizing the structural's residual value.

Table 4: The compatibility of the theoretical framework criteria with BREEAM-NL

Structural design criteria	BREEAM-NL
Structural share	21%
Environmental costs	Material environmental costs based on NIBE and contemplation of three materials
Service Life	Fixed for specific functions: • Utility - 50 years • Residential - 75 years • Mixed-use - 75 years (for example stores with apartment on top) Structural flexibility (excluding industrial and residential functions): • Column grid • Non-bearing function separating walls • Load-bearing capacity • Floor-to-floor height • More focused on internal flexibility than for multi-functionality
Residual value	No mention of reusability, recyclability, or disassembly after EoL

3.3.2 LEED (New Construction – v4.0)

In Appendix II.B, an analysis is performed to examine which credits are related to structural aspects of a building. In this paragraph, the structural elements within LEED are put forward and the compatibility of the optimal structural design is evaluated.

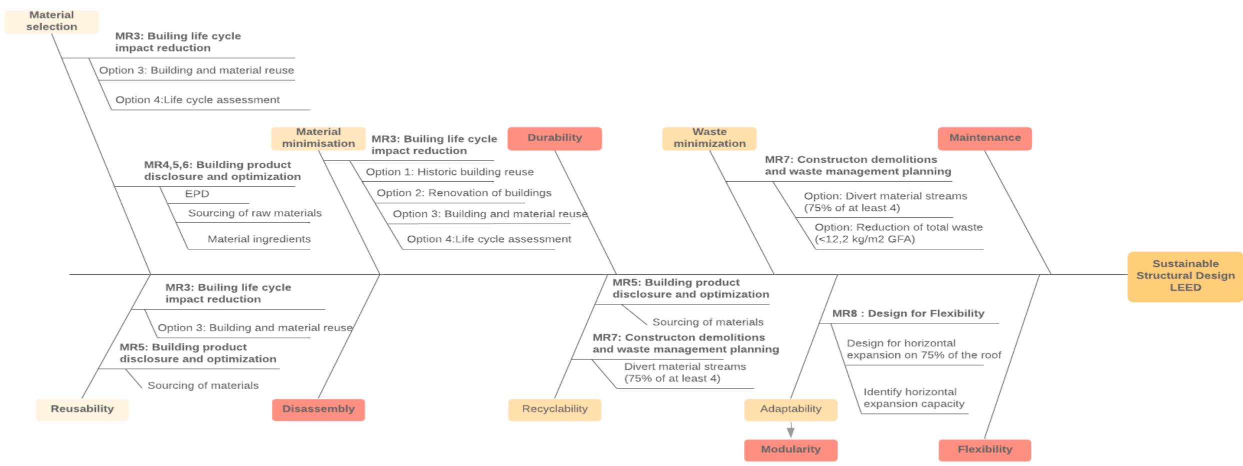


Figure 20: Ikashawa diagram of the operationaliztion of structural design perspectives in LEED (own illustration)

3.3.2.1 Material environmental costs

LEED stimulates avoiding the environmental costs firstly by circumventing new construction by encouraging the use of existing building. However, as this thesis only looks at newly designed constructions these options are not applied. After these options, LEED stimulates utilization of structural materials that already surpassed a life cycle, thus, embed reused structural materials. If this is not done, LEED promotes the use of life cycle assessment on selecting three of the following environmental impact categories:

- GWP
- Ozone layer depletion
- Eutrophication
- Formation of tropospheric ozone
- Depletion of non-renewables
- Acidification on water or land

As LEED is an American-based certification assessment method, and not retrofitted for Dutch use specifically, it does not explicitly stimulate the use of the NIBE database. However, this will be the case as it is mandatory to calculate the environmental costs incurred by the building on the basis of NIBE by legislation in The Netherlands.

3.3.2.2 Service life

LEED does not explicitly mention the service life of the building. Although, the reference case in which the life cycle assessment will be compared should at least be 60 years to fully account for the maintenance and replacement.

LEED does not stimulate the implementation of structural design measures that increase the possibility to alter the initial function of the building. Although credits can be attained for a flexible design, this is solely focused on healthcare buildings. In which one aspect could be generalized to other functions; however, these aspects are not attributed to flexibility of the structure, but to the adaptability, or expandability for the structure. The following aspect is of a generalizable nature:

- Design horizontal expansion, insofar 75% of the roof of the building could sustain an extra floor.

3.3.2.3 Residual value

No mention is given to optimize residual value on a system or component level. Only reusability is stimulated by embedding used structural materials in the building. However, no credits could be attained by incorporating design possibilities for disassembling the structure after its service life.

Table 5: The compatibility of the theoretical framework criteria with LEED

Structural features	LEED
Structural share	15 %
Material environmental costs	*Selection of three impact measures from*: • GWP • Ozone layer depletion • Acidification on water or land • Eutrophication • Formation of tropospheric ozone • Depletion of non-renewables Minimally 10% lower than the reference case.
Service Life	No explicit mention, although the service life should be the same or at least 60 years of the lifespan of the reference case for the life cycle assessment
Residual value	No mention of reusability, recyclability, or disassembly after EoL

3.3.3 GPR-Gebouw

In Appendix II.E, an analysis is performed to examine what credits are related to structural features of a building. In this paragraph, the structural elements within GPR-Gebouw are put forward and the compatibility of the optimal structural design is evaluated.

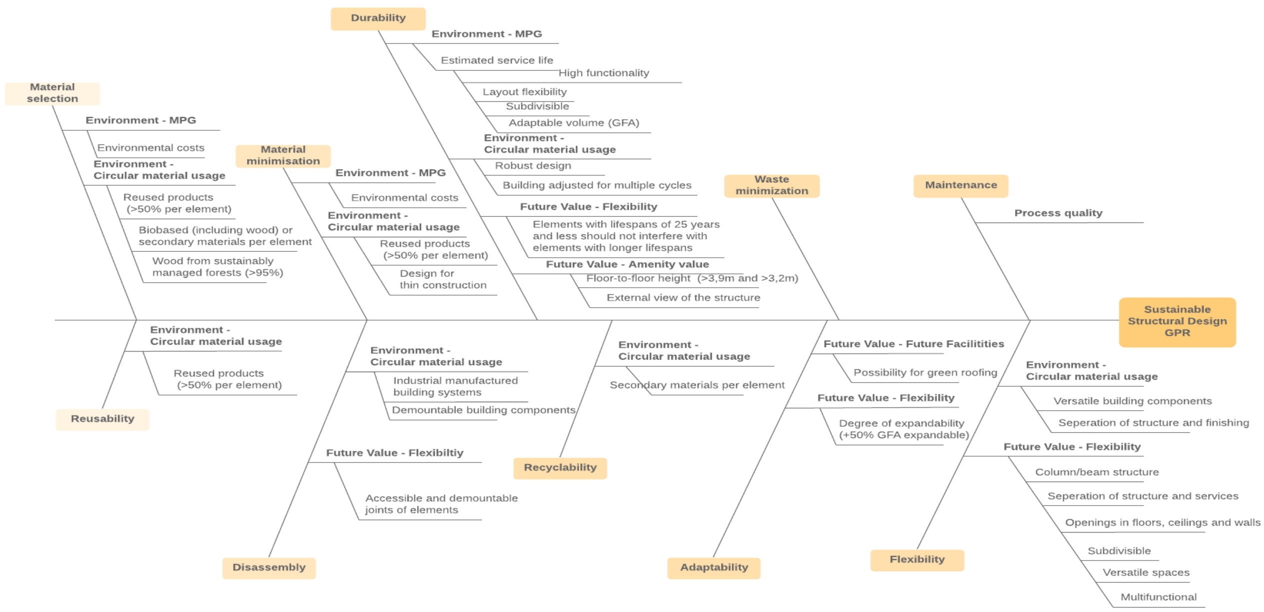


Figure 21: Ikashawa diagram of the operationalization of structural design perspectives in GPR-Gebouw (own illustration)

3.3.3.1 Material environmental costs

The environmental costs in GPR-Gebouw are calculated through the use of the NIBE database in which the environmental costs are depicted per structural material type or component. The threshold of the environmental costs to receive the maximum score in GPR-Gebouw is € 0.45 per m^2 GFA year or lower. This can be done by choosing structural materials that have a low environmental impact, thus, low environmental costs, or by prolonging the estimated service life which is depicted in the following paragraph.

Furthermore, it stimulates the use of reused structural materials for two reasons: the environmental costs of the structural material can be subtracted from the overall environmental costs, and credits can be earned for the incorporation of reused materials aside from the environmental costs credit. Also, credits can be earned by incorporation of bio-based (wood) and secondary materials, or recycled content. Also, GPR-Gebouw incentivize special design solution that reduces the material input with 25%.

3.3.3.2 Service life

In GPR-Gebouw, the estimated service life is not fixed and prolonging of the service life can be acquired by the following features (although it is dependent on more than the structure, the prolonging of the service life greatly influences the reduction of environmental impact, the structural factors are **bolded**):

- *High internal amenity value* **– high functionality**, special daylight and/or view, high comfort
- *High external amenity value* – a landmark and powerful identity
- ***High accommodating value*** – **future-oriented**, **layout flexibility**, **flexible subdivisible** and **adaptable building volume**

It is stimulated to implement measures that are aimed for extension of the functional service life, insofar that the building could possess different functions, this is secured in the method by incentivizing general dimensions of the structure (structural grid) and the type of the structure (frame structure). Stimulation of a load-bearing capacity that is sufficient for multiple functions (>5.0 kN/m^2) is integrated in the rating system. Moreover, credits can be attained by designing the structure, insofar it will not be a hindrance for re-allotment of the building so that the structure could harbour different functions and could alter spaces. Furthermore, it is incentivized to implement the potential of expansion of surface usage.

3.3.3.3 Residual value

The sustainability assessment methods GPR-Gebouw incentives to increase the potential of disassembly in the structure. This is done by granting credits for accessible and demountable joints of structural elements. Furthermore, GPR-Gebouw stimulates industrial manufactured building systems (shell, façade, storage, roof) with the aim that they will be assembled with demountable connections. Lastly, GPR-Gebouw directly stimulates the use of demountable building components (shell, roof, façade, etc.), insofar the components are secured that they could be disassembled, or removed, without compromising the quality and usefulness of the building component.

Table 6: The compatibility of the theoretical framework criteria with GPR-Gebouw

Structural features	GPR-Gebouw
Structural share	23 %
Material environmental costs	Environmental costs based on NIBE Database with a maximum overall score below €0.45 per m² GFA year. Circular material usage • Reused materials • Bio-based (wood) – from sustainable grown forests • Recycled content Stimulation of special design decisions that contribute to 25% material input reduction in that component.
Service Life	The estimated service life is subjected to change, not excluded to but on the basis of the following structural features: • High functionality – multiple functions in building • Future-oriented – • Versatile – • Adaptable building volume - +50% GFA potential Functional convertibility: • Frame structure with a universal column grid • Load-bearing capacity aimed for multiple functions • No re-allotment hindrance from the structure • Incorporate the potential for green roof
Residual value	Value is attributed on optimization of residual value as it incentivized to design for multiple cycles: • Accessible and demountable joints and connections • Industrial manufactured building components (shell, façade, roof, etc.) • Demountable building components

3.4 Conclusion analysis and comparison sustainability assessment methods

The goal of analyses of the sustainability assessment methods is to discover if the eco-effectiveness of the structure is appropriately represented in BREEAM-NL, LEED, and GPR-Gebouw. Furthermore, from the extensiveness of the structural share within the methods, it could be determined which method is paramount to design a building from a structural viewpoint. Also, determining how the structural design perspectives and the theoretical framework are operationalised and *if* they are integrated according to the established optimal strategies. To which the following sub-question could be answered: *Do BREEAM-NL, LEED, and GPR-Gebouw represent the eco-effective structural design criteria and its optimal structural design strategies?*

The categories and weightings differ between the three sustainable assessment methods which are depicted in Table 7 in which the categories where structural features are present are bolded. *Notably*, not the full percentages can be attributed to the structure as the scope of the categories are broader than the structure alone.

Table 7: Categories of sustainable assessment methods (BREEAM-NL, LEED, & GPR) with the accompanied weightings and bold where the structure is influential.

BREEAM-NL	LEED	GPR Gebouw
Management (12%)	**Integrated Process (1%)**	Energy (20%)
Health and Wellbeing (15%)	Location and Transport (16%)	**Environment (20%)**
Energy (19%)	Sustainable sites (10%)	Health (20%)
Transport (8%)	Water efficiency (11%)	**User quality/friendliness (20%)**
Water (6%)	Energy and Atmosphere (33%)	**Future value (20%)**
Materials (12,5%)	**Materials and Resources (13%)**	
Waste (7,5%)	Indoor environmental quality (16%)	
Land use and Ecology (10%)	**Innovation (Extra: 6%)**	
Pollution (10%)	Regional priority (Extra: 4%)	
Innovation (Extra: 10%)		

To eco-effectively design a structure, it is imperative that the three established structural design criteria – *material environmental costs, service life*, and *residual value* – could at least be contemplated in the sustainability assessment methods. Moreover, as there is no such thing as an optimal eco-effective structure, it should be possible to redirect the focus on specific criteria exempting criteria that are not applicable in that specific case.

In both BREEAM-NL and LEED, the service life is estimated on the basis of the function and fixed accordingly on either 50 or 75 years. Moreover, no mention is given on the specific inquiries of residual value after the end of life of a building in BREEAM-NL and LEED. Only value is attributed to material environmental costs. Which leads to the conclusion that both BREEAM-NL and LEED base their assessment on the short-term advantageous eco-efficient paradigm.

On the contrary in GPR-Gebouw; the service life could be prolonged, and credits are integrated that stimulate optimizing the residual value on the structural system and component level. Moreover, GPR-Gebouw stimulates material environmental costs reduction more detailed than the two other assessment methods. Nonetheless, as determined with the three optimal structural design strategies in Chapter 2.2.2; to truly design the structure eco-effective, it is vital to approach the inquiries of the service life and residual value criteria individually. In GPR-Gebouw both the extension of the service life and optimization of residual value are put together and normalized in the same rating even though they contradict each other's effectiveness. This is in essence highly in-effective.

To summarize, GRP-Gebouw is paramount in designing the structure from an eco-effective point of view than BREEAM-NL and LEED as it encompasses all three structural design criteria that are necessary to adhere to for an eco-effective structural design. However, the following conclusion should also be drawn, all three assessment methods do not integrate the full extensiveness of the capabilities of maximizing the eco-effectiveness of the structure. This entails that none of the assessment methods is truly effective when designing the structure.

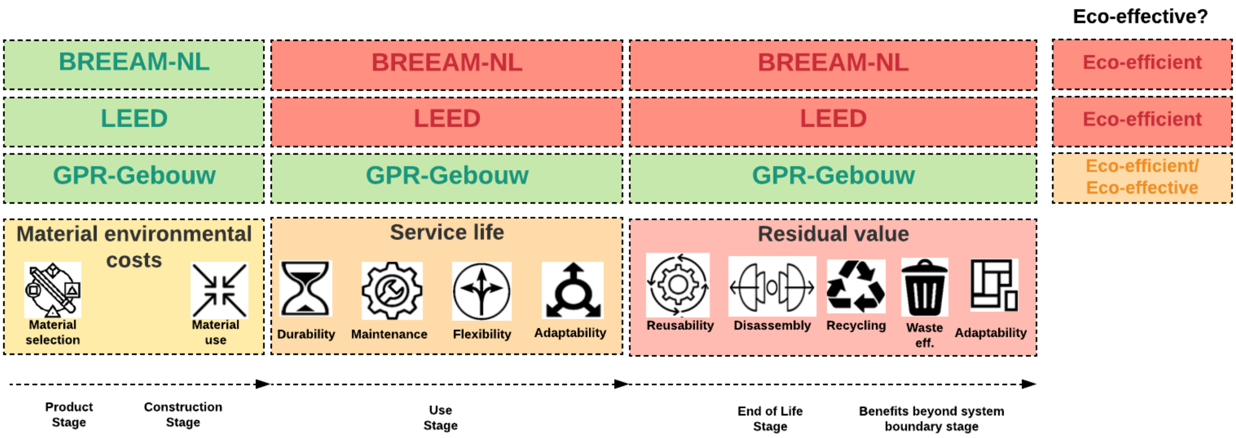


Figure 22: Adherence of the sustainability assessment methods - BREEAM-NL, LEED, and GPR-Gebouw – to the eco-effective structural design criteria. (own illustration)

4 Empirical Research

Qualitative empirical research is performed by conducting surveys and case studies. This chapter puts forward the empirical research methods; why they are used, how they are used, and finally, what the results are. The empirical research is focused on the structural design perspectives determined through reviewing the literature which is set forth in Chapter 2.1. This chapter merely presents the methods and results. In Chapter 0, the synthesis is put forward in which the results of the survey and the case studies will be compared with the theoretical framework.

4.1 Survey method

4.1.1 Purpose of the survey

The structural design perspectives are the basis of the theoretical framework established in Chapter 2.2. Valuable knowledge can be obtained on the theoretical framework by gaining information on the structural design perspectives. The purpose of the survey is twofold; to obtain information on how structural engineers approach the ten determined structural design perspectives, i.e. the practical design criteria; and, to identify the relations between the sustainable structural design perspectives from which the clustering of the structural design perspectives could be validated. By posing open-ended questions concerning the design criteria of the structural design perspectives, and posing open- and closed-ended questions on the influence of the design perspectives on each other, data is obtained that gives more insight on what aspects are focused on in practice and what relations are present between the structural design perspectives. The survey, therefore, acts as both an evaluation of the knowledge of the structural engineer and as means to identify dynamics within the theoretical framework, i.e. validate the three merged structural design criteria and the constructed eco-effective structural design strategies.

The research method of conducting a survey is chosen as it can yield valuable information from a large group of participants. By obtaining relevant empirical data via a survey, the data is of more breadth and generalizable nature (Verschuren & Doorewaard, 2013). As the structural engineering inquiries differ per project, the survey encapsulates a broad view.

4.1.2 Selection of Survey Participants

At Arcadis B.V., the department of structural engineering consists of around 40 structural engineers. The criteria for selecting the survey sample is that their daily work revolves around the engineering of the structure for buildings. They are experts in designing the structure of a building and have therefore valuable knowledge on the effects of specific structural approaches. The goal is to get at least 10 respondents. The participants range from senior advisors in structural engineering to project leaders for construction. The department of structural engineering is based in Rotterdam, Den Bosch and Maastricht. The survey is presented and explained in detail in a meeting prior to conducting the survey so that the participants are informed what the survey questions entail. Eventually, 11 respondents were willing to contribute to the survey with all a background in structural engineering with different levels of experience.

4.1.3 Survey Design

In this paragraph, the design of the conducted surveys is established. The steps taken, the methods used and utilized tools will be explained. As stated in the first paragraph, the purpose of the survey is to obtain data on what design criteria are considered when implementing a specific structural design perspectives, and how the perspectives relate to each other.

Derived from the literature review, structural design perspectives were identified. The structural design perspectives are presented to structural engineers. Every perspective is treated separately in the survey. The design perspectives are stated and explained at the beginning of the survey so that no misconception is present on what they entail. Questions are posed on how the design perspectives are contemplated in the design and what their influence is on other perspectives. For example, what are design criteria when reusability is essential, and what is the effect of reusability on other design perspectives such as flexibility or durability? The survey consists of closed and open-ended questions; an example of the survey is presented in Appendix IV.

In the survey, an introduction is given and the goal is explained of the research. Each of the participants has been sent a survey via email. The structural design perspective that are treated in the survey will be clarified afresh below:

1. **Material selection:** the traditional materials used for structures are steel, reinforced concrete or timber. For the selection of materials, direct comparison is essential to know what type of material is required. The selection of materials from an environmental point of view is based on a variety of factors; environmental costs and technical properties.

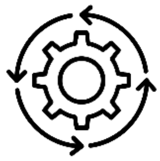
2. **Material use:** Intelligent use of structural materials can reduce emissions, resource use, and waste on the whole life cycle. Dematerialisation through generating more goods, services, or products with the same amount of materials or by producing the same end product with less material input

3. **Durability:** designing for durability encompass the extension of the service life of a building by maintaining its technical and functional requirements. Durability is an indicator which informs to the extent to which a structure conserves its original requirements over time, either technical, functional or economic wise.

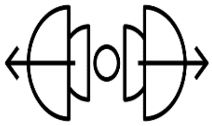
4. **Waste effectiveness:** Waste is an undesirable product, and should, therefore, be minimized, and/or treated as a valuable resource. Designing the structure as such that disposal of waste is minimized during construction and demolition phase.

5. **Maintenance:** the structure has to be designed so that maintenance of the structure is either minimized, insofar the input of material/energy during its service life is reduced; simplified, insofar the effort of maintenance is lowered; or targeted, insofar only worthwhile components are maintained for extension of the service life.

6. **Reusability:** designing the structure as such that structural component/elements/systems in the structure are of a reused nature, or can be reused one on one after the end of the building's life cycle for future structures/next cycle.

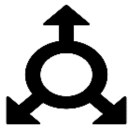
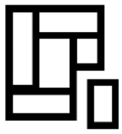


7. **Disassembly:** the structure is designed as such that the structure (or parts of it) could be effortlessly dismantled, insofar that the structural components remain intact for future purposes.



8. **Recyclability:** designing the structure as such that recycled material is embedded in the structure or incorporating the potential of recycling at the end of the structure's service life.

9. **Adaptability:** a building has the capacity to alter the structure itself. Scalability of the structure, insofar the structure could be expanded horizontally or vertically; or movable, insofar the structure is designed modular. The icons representing the two adaptable aspects respectively.

10. **Flexibility:** the structure facilitates the possibility to modify the internal spatial layout of the building without changing the structure itself. Also, a flexible design enables potential user function change.

4.2 Survey results

In this paragraph, the results of the survey are presented. The survey questions are posed to 11 respondents who have a structural engineering background and are involved in the structural design and engineering projects of utility buildings.

4.2.1 Design criteria structural design perspectives

To obtain information about what detailed design criteria should be contemplated per structural design perspectives an open-ended question is posed. The open-ended question is concentrated on what variables the structural engineer focuses when designing the structure from the point of view of a certain design focus area. The findings of this question aim to provide a broad view of how structural design perspectives should be tackled in the design of the structure. Every structural design strategy is regarded separately in this paragraph. In Appendix III.A, the design criteria are more elaborated based on the responses of the participants.

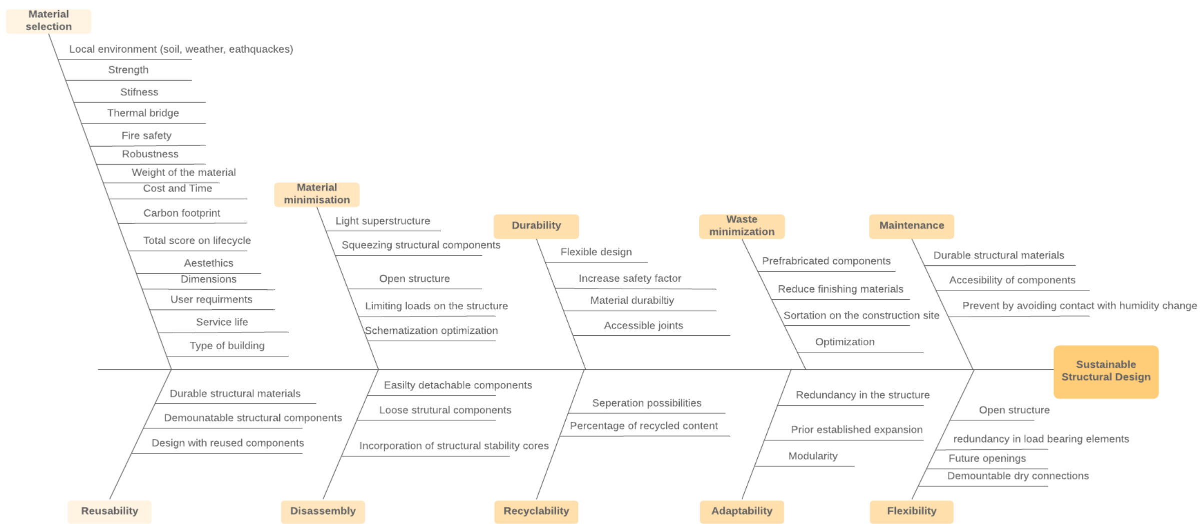


Figure 23: Design criteria on structural design perspectives derived from structural engineer's responds in the survey. (own illustration)

4.2.2 Interlinkages of structural design perspectives

In the survey, every structural design perspective is considered separately. Within the structural design perspectives and thus the theoretical framework and the structural design, strategies seem to emerge. By posing a closed question about which design strategies are affected by implementing a certain strategy, the existence of relations between the sustainable structural design strategies can be directly determined. Furthermore, elaborations are given by the respondents on what the effects entail through an additional open-ended question. Table 8, depicted below, portrays the amount the respondents have identified relations between two sustainable structural design strategies. Every design perspective is handled individually, thus, relations had to be identified twice. Table 8

Table 8: Through closed questions, the respondents of the survey could identify relations between the design strategies; the relations could be identified twice in the survey as every strategy was handled separately. In this table, the amount of relation was merged resulting in a maximum amount of 22.

Strategy	Flexibility	Adaptability	Disassembly	Material selection	Material use	Reusability	Recyclability	Maintenance	Durability	Waste effectiveness
Flexibility	X	X	X	X	X	X	X	X	X	X
Adaptability	**19**	X	X	X	X	X	X	X	X	X
Disassembly	6	**12**	X	X	X	X	X	X	X	X
Material selection	7	**9**	**12**	X	X	X	X	X	X	X
Material use	**12**	**9**	2	8	X	X	X	X	X	X
Reusability	6	6	**15**	**12**	-	X	X	X	X	X
Recyclability	4	4	**9**	**14**	3	7	X	X	X	X
Maintenance	4	4	4	**12**	1	2	1	X	X	X
Durability	**12**	**11**	3	**10**	2	4	6	**9**	X	X
Waste effectiveness	3	2	7	**10**	**7**	**11**	**10**	3	2	X

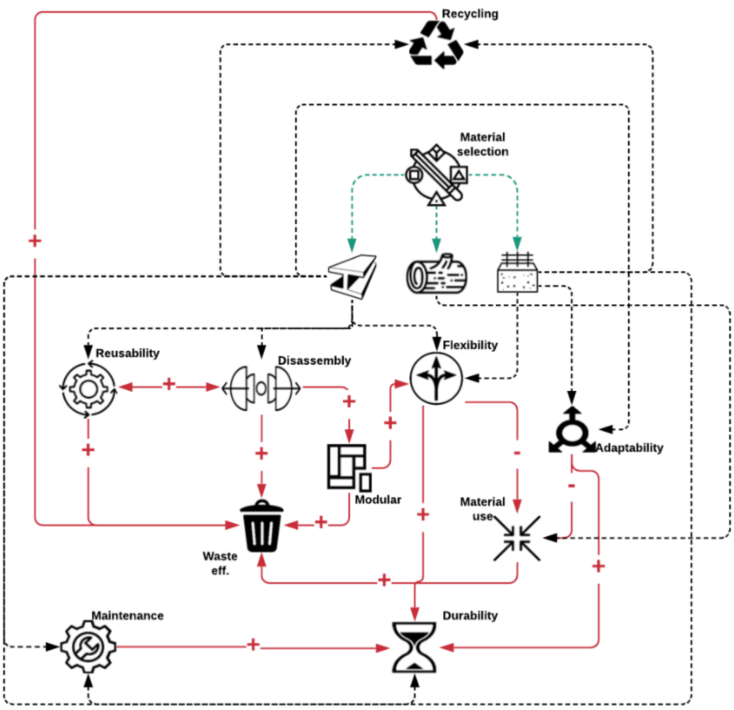


Figure 24: Visualization of the relations between the sustainable structural design approaches in which the red line depicts the relations, the black dotted line the preferred structural material of the strategy, and the green dotted line the three traditional structural material (own illustration).

4.2.3 Limitations survey

Although the survey produced valuable information there are some limitations on the method itself and the way how it is used. This will be explained in this paragraph.

The use of open questions in a survey could possibly result in misinterpretation by the respondent. Ambiguity has been attempted to be minimized by giving a presentation on what the structural design perspectives entail and how to interpret the questions in the survey. Furthermore, a line of communication was given so that if questions arose, they could be answered immediately. Lastly, a clarification per structural design perspective was attached, so that the respondents could use it during the survey.

The time duration of filling in the survey was close to an hour. The focus could flatten during as the survey progresses. The respondents, all of Arcadis B.V., were compensated for putting in their effort/time by the given the possibility of writing down the hour. This could give an incentive to remain focused. However, as the survey progresses the quantity and quality of the answers became increasingly less elaborate.

All the respondents are employees of Arcadis. This could potentially produce biased answers as certain technical competencies, or the cultural background could be of influence in the approach of the structural engineer. 75% of the respondents were based in Rotterdam which also increases the potential of bias. Furthermore, the approached structural engineers have different roles in a project on the basis of their experience (junior, senior, project manager, modeller). This means that they are involved in different stages of a project and state their design criteria accordingly.

Although the possibility is present to ask follow-up questions after the survey, the survey itself doesn't allow for follow-up questions.

By performing a survey, the answers collected are of a breadth nature. This entails that the no in-depth conclusions could be drawn from the answers.

4.2.4 Conclusion survey results

This chapter looked at the results of the conducted survey. Information is presented on what elements the structural engineers focus when contemplating structural design perspectives. Moreover, how the structural design perspectives are of influence on other structural design perspectives. Although structural inquiries are often case-specific, by conducting a survey, data is obtained of a more breadth and generalizable nature, resulting in valuable information on a higher aggregate level.

With the design perspectives for materials, three structural materials were recurring in the answers; steel, reinforced concrete and timber. The recurrence of the three materials unanimously brought forward the preference of the structural materials for specific design perspectives. In which, despite of the higher environmental costs than timber, concrete and steel are the favourable materials when designing the structure.

Through the survey, it became apparent that the structural design perspectives are overlapping, thus, influencing the effectiveness – either positive or negative - or even possibility of implementation of other design perspectives. The important findings will be mentioned below:

- Structural components are only reusable (reusability) when they could be dismantled accordingly by implementing loose structural components with accessible joints and connections (disassembly). Both perspectives add to the waste effectiveness design perspective as does the recyclability perspective.

- Designing for reusability or disassembly, the structural material steel is the most favourable as it is prefabricated and could be assembled with demountable joints and connections. The least favourable is concrete.
- The design perspectives of maintenance, flexibility, and adaptability add to the durability of the structure; both technical and functional.
- Flexibility drives up the amount of material embedded in the structure as the load capacity is unknown in the future, this, however, results in a higher probability of a longer functional service life, i.e. functional durability.
- For a highly flexible structural design, an open structure (frame structure) is a prerequisite which also adds to lengthening the functional service life of a building. Additionally, a frame structure is more efficient with material input.
- The amount of maintenance is dependent on the type of materials. However, little attention is given to the maintenance of the structure as it should only be protected from open-air and revisited once every 50 years for coating or furnishing.

A structural design perspective could illustrate different roles; it could be a goal, or it could be a means to a goal. This is prone to the ambition and objective of what kind of building/structure is aimed for. For instance, a flexible design could be a goal on its own to achieve high functional versatility to change the spatial layout. However, a flexible design could also be a means to an end; the end, in this case, being designed for durability, i.e., the extension of the service life.

It can be stated that certain structural design perspectives subjected to perspectives or prerequisite of. Consequently, some design perspectives are starting points depending on the aim of the structure, whereas other design perspectives could and should be implemented despite the objective.

4.3 Case study method

4.3.1 Purpose of the case study

A multiple case study is conducted to examine the implementation of structural design perspectives; if the theoretical framework criteria and its optimal eco-effective design strategies are applied (or not); what the role is of the sustainability assessment methods; and *most important* what factors for choosing the optimal structural design are decisive. This chapter merely illustrates the results of the case-study and its interviews. The following Chapter 0 provides a more in-depth analysis of the results by comparing it to the theoretical framework criteria, optimal design strategies, and analysis of the sustainability assessment methods. By questioning the established theory in multiple cases, it evaluates the explanatory power of theories and their boundaries, thus, contributes to the external validity of the constructed theory (Løkke & Sørensen, 2014). Yin (2014) also argues that theory testing is a form of external validity and cases can contribute with the purpose of identifying if conceived results also extend to new cases.

A case study is a research method that could be both qualitative and quantitative. The findings from the surveys collected data that is of a breadth and generalizable nature. On the contrary, case studies are predominantly used to gain in-depth insights into the phenomenon (Verschuren & Doorewaard, 2013). By examining the data in multiple cases, the theoretical framework and its optimal structural design strategies can be appraised more in-depth and supplemented if needed be.

4.3.2 Case selection

The cases that are selected are based on the below stated criteria. These criteria are associated with the scope of the research put forward in paragraph **Error! Reference source not found.**. The following criteria will be explained more in-depth in this paragraph:

- Greenfield projects
- Using sustainability assessment tools for new construction with the aim to achieve the highest possible rating (BREEAM-NL, LEED & GPR). One case per tool. (*Unfortunately, there were no viable projects where LEED was the go-to assessment methods. Therefore, two cases are examined that are designed with BREEAM-NL and one with GPR-Gebouw*)
- A variety of structural design perspectives are implemented
- The detailed/definitive design is established
- Involvement of Arcadis' *structural engineers/project managers/sustainability advisors*
- The geographical location of the structure is in the Netherlands

4.3.3 Interviewee selection

Additionally, criteria are established for the selection of interviewees in the case study. The aim was to conduct three interviews per case with participants that play a role in the project; project manager, head of structural engineering, and the sustainability advisor. Through email correspondence, the aim and content of the interviews are communicated in which the potential interviewee could be acquainted with the topic and confirm their willingness and added value to the field of research. The case study interviewee selection is executed on the basis of the criteria stated below.

- Understanding of the structural influence of the project
- Knowledge of the research subject
- Involvement in structural inquiries
- Project manager of the case study
- The head of structural engineers of the case study projects
- Sustainability advisor of the case study
- The actors' willingness

Fortunately, the willingness to help of Arcadis' employees was very high, therefore, making the pursuit of finding interview participants effortless.

4.3.4 Case study design

This paragraph puts forward the design of the case studies. In which the execution of the cases studies is described. Prior to interviewing the interviewees, documentation of the project is explored. By examining the documents, data is collected on the cases in which a first comprehension of the structure is obtained. Subsequently, the interviews are conducted to pose questions more in-depth on how the structural design perspectives are approached. The goal of the interviews is to identify the driving forces behind making certain decisions in structural design perspectives. Both the project documentation, interviews set-up, and the coding steps are explained below.

4.3.4.1 Project documentation

Data is collected on individual cases by examining the following documents:

- Program of demands (Programma van eisen)
- Design drawings
- Document analysis (Tender, purchases, planning, financial)
- Sustainable assessments method documents
- Pre-design and detailed design documents

4.3.4.2 Case study interview set-up

In Appendix V, the interview guide of the three case studies is presented. The interviews are of a semi-structured nature in which the existing structural design perspectives are individually handled. Insofar in-depth knowledge can be obtained about the driving forces behind decisions so that factors can be established that are decisive in choosing the most suitable optimal structural design strategy.

4.4 Case study results

4.4.1 Project A: Holland Casino Venlo

Project A, Holland Casino Venlo, is a new casino that will be located on the industry grounds of Trade Port Oost next to the junction of Zaarderheiken where the A67 and A73 highways meet in the proximity of the city of Venlo. The building has a GFA of around 14.000 m^2. The building is designed as such that a parking lot is present on ground level with additional installation rooms and storage rooms, on top of the parking garage the gaming floor is built which encompass the first floor, on the second floor a multifunctional room is present accompanied with offices and installation rooms.

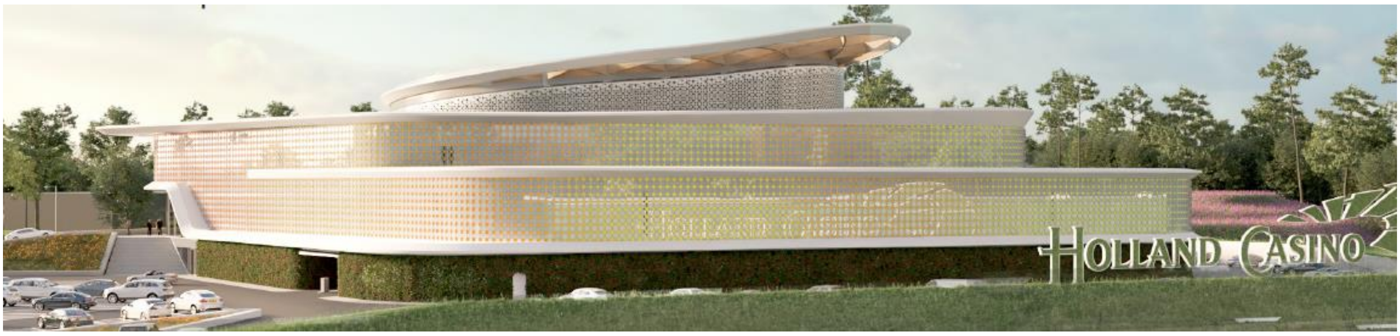


Figure 25: A Rendered version of the definitive design of Holland Casino Venlo (Arcadis, 2018)

The first stated overall project goal by Holland Casino is to realise an adaptable building with an iconic appearance, and visible and profitable sustainability that facilitates en strengthens the primary function of the casino which corresponds with the cradle-to-cradle principles of the municipality of Venlo. The design of the building is based on a holistic approach, insofar the building resembles a breathing organism; with a skin, skeleton, metabolism and brain. In Figure 26, a sustainability cross-section of the casino is portrayed.

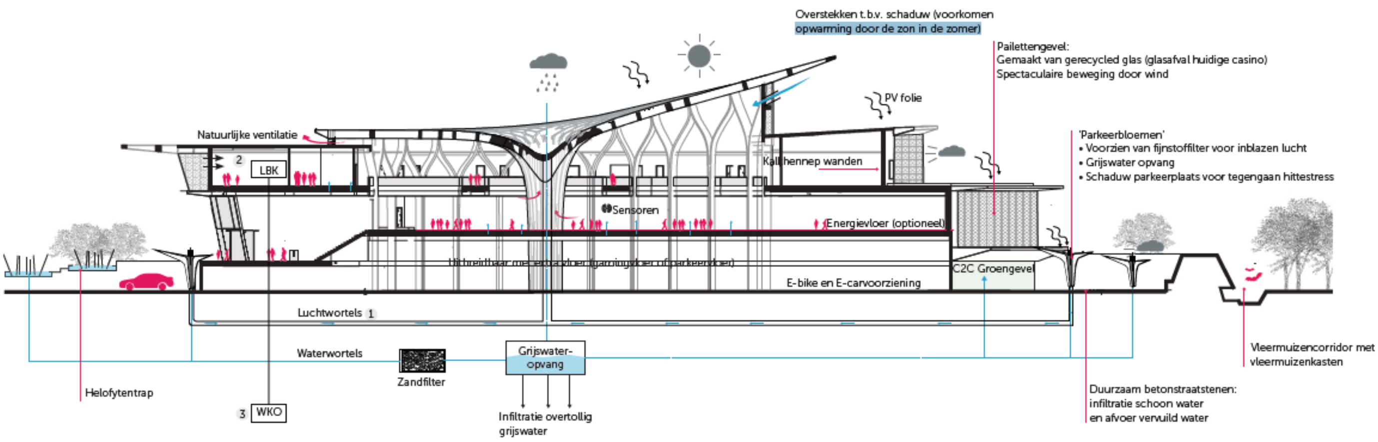


Figure 26: A sustainable cross-section of Holland Casino Venlo – Dutch language (Arcadis, 2018)

4.4.1.1 Sustainability – GPR Gebouw

As already touched on in the previous paragraph, one of the main objectives of the building is to design the building with the intention of implementation of sustainbiltiy features. Firstly, the emphasis was put on visible and profitable sustainability measures with a sufficient rating on GPR Gebouw. During the process, the focus was shifted from visible and profitable sustainability to solely attaining a high GPR-Gebouw score. Thus, GPR-Gebouw is the sustainable framework upon which design decisions are made. In Figure 27, the scoring of the five categories and its sub-categories is depicted. As identified in Chapter 3, the role of the structure in GPR-Gebouw can be appointed to specific (sub-)categories. This project has attained the following score after the detailed design done by an independent GPR assessor: environmental performance (7,5), circular material usage (10) – green in Figure 27, accessibility (10), functionality (7,4) - blue in Figure 27, future value (9), flexibility (9,1), and amenity value (8,6) - Yellow in Figure 27. The overall scores per category are depicted in Figure 27.

4.4.1.2 Structure of Holland Casino Venlo

Figure 27: GPR-Gebouw attained scores per category (red= energy, green=materials, purple=health, blue=use quality, yellow=future value) (Arcadis, 2019)

As it can be seen in both Figure 25 and Figure 26, the structure shapes the building, although that is often the case in traditional buildings, the special shape of the structure here contributes to the iconic value of the building. The wooden roof structure passes through to the outside on the top of the building so that it could be seen from the highway. Thus, the wooden structure adds to the external visual experience. The wooden roof structure serves as a stability column in the centre of the main playroom which also adds to the internal visual experience. Moreover, as could be seen in Figure 26, the wooden stability column in the centre of main playroom is open for the reason that rainwater can pass through and could be captured and reused. Consequently, the wooden structure accommodates three purposes: stability, aesthetic, and capturing of rainwater. Furthermore, the frame structure is designed with steel columns and beams with a built-in slim-line floors. Slim-line floors are hollow floors with a concrete subshell and surface layer supported by I-profile steel beams. Although the usage of slim-line floors reduces material input, the primary motive of using slim-line floors is the deployment of services in those hollow spaces, insofar the applied service can easily be displaced on the basis of the demanded spatial plan. Hence, accommodating modification to the internal spatial layout. The slim-line floors are specially customized and prefabricated and welded to one another on-site. The floor of the entrance zone is a hollow core slab with concrete topping, the same goes for the ramp towards the entrance zone with an additional steel-sheet concrete flooring system. On the ground floor, in the installations room a concrete floor is deployed of 300mm thick. The superstructure mentioned above is supported by a foundation made of concrete beams and bases.

4.4.1.3 Case interview results – Project A

For Holland Casino Venlo, three persons were interviewed who played a role in the design of the structure; project manager, the head of structural engineering and the sustainability advisor. From these three interviews, information was gathered on the presence and deployment of structural design perspectives.

4.4.1.3.1 Sustainable structural design strategies implementation

In this paragraph, the structural design perspectives are introduced accompanied by the motive of the decisions and process in which they are implemented. The below description per structural focus area are derived from the three conducted interviews for the Holland Casino Venlo case.

1. **Material selection**

At first the whole superstructure, excluding the floors and stability cores, was designed in timber, however, as the frame of the structure did not add to the visible sustainability and timber is high in costs, a less costly option was chosen for the frame of the structure: steel. The alteration resulted in the fact that the buffer was reduced for the environmental category in GPR-Gebouw (MPG). Timber, however, still remains an important part of the structure as it is the central column on which the wooden roof structure supports. The timber adds to the internal experience value as it is the centre of the main playing hall which could be seen on multiple storeys. Moreover, the upper side of the timber structure has ornaments which could be seen from the highway adding to the external experience value. As this was a specific design which needs expertise, suppliers were contacted in an early stage of the design, whereas traditionally suppliers enter the project after the detailed design. The floors are slimline which entails that they are hollow with an I-profile steel beam and concrete upper and lower layer in which ventilation and service wiring is distributed. The slimline floors are customized and easily demountable.

On the ground level storage and installation room floors are of concrete as well as the floor of the parking garage.

The design of the foundation was based on cradle-2-cradle principles as was stated in the program of demands. The foundation was grounded in hollow steel poles which are easily retractable, however, this option was too costly and the influence on the environmental costs not decisive Consequently, the hollow steel poles was swapped with traditional concrete pillars. Resulting in the dissipation of the GPR material buffer, meaning no further economizing in the environmental category of the GPR-Gebouw.

2. **Material minimisation**

Minimizing material use is one of the starting points of the structural design.

One of the design inquiries is that the envelope should be permeated so that the outer walls could breathe due to the high internal humidity caused by a large number of people inside. Consequently, a structural frame design, opposite to a structure with load-bearing walls, is paramount. This resulted in more efficient handling of columns and beams, so that a relatively low amount of material is embedded which was beneficial for the overall environmental cost, or MPG. Slimline floors are relatively low in material input in comparison with concrete hollow core slabs of 30 cm thick.

3. **Durability**

Traditionally this type of building is designed on the basis of the estimated service life of 50 years, however, within GPR-Gebouw a function is incorporated that gives the possibility to “extend” the estimated service life. Through design decisions in architectural value, visible experience, functionality, and flexibility, the estimated service life is set, critically investigated by the GPR assessor, on approximately 90 years. The safety factor remained unaltered when increasing the estimated service life. The material durability and engineering durability were assumed to withstand the longevity of at least 90 years.

4. Waste effectiveness

Structural elements of the superstructure, steel and timber, are prefabricated resulting in no structural waste accumulation on the construction site.

5. Maintenance

The structure of a building doesn't need a lot of maintenance. The accessible steel structure columns are coated with fire-resistant paint and should be revised periodically. The steel columns or parts of the steel columns that are not easily accessible are enclosed with special plasterboard or promolex plates. The roof segment of the wooden structure is in contact with the open air and the steel beams in the parking garage should be inspected more often than the internal structural elements.

6. Reusability

An attempt is made for the incorporation of reused long steel beams by searching for steel beams that have the same dimensions as stated in the design. However, the market has been found not to be sufficiently mature to supply the specifically needed steel beams.

The slimline floors are customized and differ in size in the building's design. Resulting in large amount of different steel I-profiles for which it is uncertain if there is demand after the demolition of the building.

The steel structural frame elements (beams and columns) are assumed to be reusable at the end of the building's service life. However, all three interviewees did not know if the steel will be reused in the same state after the building's service life is surpassed as the longevity of the building is fairly high.

7. Disassembly

The possibility of disassembly of structural elements was one of the starting points in the structural design.

The slimline floor could be disassembled as the floor consist of specific customized pie-shaped parts that are fitted together. As they are customized the probability of reusing for subsequent cycles is decreased tremendously. The frame structure could be disassembled as the frame comprises of steel columns and beams.

The type of connections and joints of the steel frame structure are bolts. The eventual execution one is reliant upon the construction plan of the contractor as they will choose their preferred way to construct (or assemble) the steel frame. Arcadis will verify the contractor's design decisions, but it's the contractor's decision to make.

8. Recyclability

In structural steel, no recycled content is attained. In the building specifications of steel there is no chapter dedicated to recycled content. In the concrete parts granulate is added, but that is common practice nowadays. No specific attention is given on the structural design perspective.

9. Adaptability

No structural adaptation options are incorporated into the design of the structure. Horizontal or vertical expansion potential is not integrated. In the first schematic design, however, the parking garage on the ground level had a floor-to-floor height of 7 meters so another layer could be added in the future. Also, the double-height of the parking garage elevated the building, so it was visible from a distance. Moreover, the foundation should take into account a potential extra layer. The double floor-to-floor height was cutback from the eventual design.

10. Flexibility

Maximizing flexibility in the building is one of the starting points of the structural and overall design.

The slimline floor is very important for the internal flexibility of the building. The floor encloses services such as wiring and ventilation shafts which are not obstructed by inner walls. Thus, incorporating the possibility to change the spatial layout as the hollow thin slimline floor simplifies redirecting electricity and HVAC in comparison with a monolithic thick concrete floor. Moreover, if needed, as the slimline floor is thin and supported with steel beams, openings could be easily created for stairs to connect the storeys in specific areas.

The structure is constructed with a steel frame with large spans without the use of load-bearing walls in crowded areas. Resulting in a maximization of open floor surface which is beneficial for the degree of flexibility.

The degree of flexibility is mostly attributed to the fact that the internal spatial layout can be altered whilst preserving the primary function. No real effort is made to look into the possibilities of functional convertibility.

4.4.1.3.2 Additional findings – Holland Casino Venlo

- Standardized tools, such as GPR-Gebouw, are not sufficient for specific (structural) inquiries which result in deviation of the tool itself (customization accompanied with the burden of proof). The independent GPR assessor has the final verdict.
- The early emphasis on visible sustainability, profitable sustainability, flexibility, cradle-to-cradle principles, and low environmental costs in the program of demands is crucial for the degree to which measures are incorporated in the final design.
- Financial implications rise in significance as the execution of the design is approaching. Approaching the execution, a shift is identified from the total cost of ownership (TCO) to initial investment (CAPEX). Too many structural features were too costly and did not have a feasible return on investment.
- The sustainability assessment method functions as a means to secure sustainability measures. Grants will be omitted if a certain rating is not achieved. Thus, retaining sustainability measures has a financial motive. The sustainability assessment method functions as a baseline.
- The motive to eliminate sustainability measures is the costs of the measure relative to its implication on GPR-Gebouw.

- The steel structural elements are assumed to be dismantlable and reusable. They are connected with bolts. However, with 90-year service life, the question arises if the structural elements are indeed reusable, or even dismantle, in their primary state.
- The sensitivity of the MPG was found to be difficult to predict.
- The structure has a high facilitative value in this building. It interfaces with all other disciplines; The slimline floor increases the flexibility of installations, the wooden structure adds to the internal and external architectural value, the wooden centre acts as a funnel for rainwater to be reused, and the frame structure amplifies the role of the breathing envelope.
- Flexibility should be approached from a multi-disciplinary point of view.
- Structural design is ultimately dependent on the contractor. The contractor eventually decides how the structure is going to be constructed. Furthermore, the contractor also is the one who procures the materials, thus, for the origin of materials and the degree of certificates, one is dependent on the contractor.

4.4.2 Project B: Distribution Centre Hoogvliet (DCH)

Other like than with Project A, there were no distinct defined sustainability goals prior to the design. Through extensive communication with Arcadis' design team and Hoogvliet, it was established that BREEAM-NL could be of added value. The added value being a financial incentive at the start as grants outweigh the financial burden of the extra engineering costs BREEAM-NL encompasses. The structure of the distribution centre has a subordinate role in the operation of the distribution centre. Nevertheless, the structure evidently plays a crucial part in the overall design.

Project B, the Distribution Centre of Hoogvliet, is a distribution centre of the supermarket chain Hoogvliet and is located in Bleiswijk in the Netherlands next to the A12 highway. The building comprises of around 80.000 square meters GFA. The design was completed in September of 2017 and is intended to be completed in 2021. Currently, the distribution centre is under construction.

Figure 28: A rendered visualisation of the intended distribution centre of Hoogvliet (Arcadis, 2018)

The distribution centre is designed with the newest technologies of automatization to set the supermarket chain for at least the next 20 years. It comprises of distribution equipment and provisions for dry, fresh, cooled and deep-frozen products that make use of cross-docking practices. Next to the distribution facilities, the building also accommodates packaging, service centre with offices, a bakery, and a butchery. This building will act as a crucial hub in the supply chain of the supermarket chain Hoogvliet. The design of the building and logistic processes is aimed to secure a competitive advantage by reducing distribution and logistics cost.

4.4.2.1.1 Sustainability – BREEAM-NL

With the design of the distribution centre an 'Outstanding' rating in BREEAM-NL is sought-after which is the highest possible ranking in BREEAM-NL. This entails that the design and the eventual building must attain 85% of the possible credits plus some mandatory side issues, such as performing a case study. As seen in Table 9, the threshold of 85% is well passed. In the pre-assessment, a score of almost 96% is obtained.

Categorieën		Categoriescore		Weging		Resultaat
MAN	Management	100,00%	x	12,00%	=	12,00%
HEA	Gezondheid en Comfort	99,42%	x	15,00%	=	14,91%
ENE	Energie	92,59%	x	19,00%	=	17,59%
TRA	Transport	83,04%	x	8,00%	=	6,64%
WAT	Water	100,00%	x	6,00%	=	6,00%
MAT	Materialen	69,34%	x	12,50%	=	8,67%
WST	Afval	100,00%	x	7,50%	=	7,50%
LE	Landgebruik en Ecologie	63,64%	x	10,00%	=	6,36%
POL	Vervuiling	99,32%	x	10,00%	=	9,93%
IC	Innovatiecredits	n.v.t.	x	0,00%	=	0,00%
Innovatiepunten + Exemplary Performance						6,00%
Pre-assessmentkwalificatie		★★★★★				95,61%

Table 9: BREEAM-NL categories depicted with their scores, weightings and results.

As identified in Chapter 3, the role of the structure in BREEAM-NL can only be attributed to certain categories and sub-categories. In BREEAM-NL that is partly materials (MAT) with a score of 70%, partly management (MAN) with a score of 100%, and partly waste (WST) with a score of 100%.

The primary focus of the distribution centre is the operational activities, due to the high operational workload, the emphasis is put on lowering the exploitation costs. This results in the focus on reducing its overall operational energy and maximizing its renewable operational energy potential. Hence, the deployment of solar panels on the roof of the distribution centre, which could be seen as one of the reasons for the relatively low MAT1 scoring.

The potential contractors have been given the option on how they perceive the building method the most efficient in economic terms and, as it is put in the documentation, therefore, "the environmental friendliest". The options comprised of constructing the roof and afterwards covered laying the concrete floor, or first the concrete floor in open-air and then the steel construction and finishing the roof. All four potential contractors recommended the former building method. The method is efficient and reduces the environmental impact, i.e. material usage, as no subsequent measures are needed to be taken to correct the concrete floor.

4.4.2.1.2 The structure of Distribution Centre Hoogvliet

The building has multiple functions. The main function is industrial accompanied by office space. The industry comprises of almost 70.000 GFA with the ground floor of around 50.000 GFA, first floor of around 10.000 GFA and the second floor of around 8.000 GFA. Also, an office is integrated into the building that comprises of around 5.000 GFA divided into three floors. The office is located at the front of the building, above the docking areas, overlooking the A12, as could be seen in Figure 28.

As derived from Table 9, the category MAT (Materials), in which the structure is most influential, only scores a mere 70%. One of the main causes of this can be attributed to the fact that the whole roof is covered with PV-panels for which a large quantity of material is required. As the primary function of the structure is of industrial nature and, therefore, incorporates heavy machinery, the structure of the building has a subordinate role to the operations.

The distribution facilities are constructed with a steel frame, both columns and beams, with monolithic concrete floors with vertical steel braces specifically placed in the walls to provide stability. The gigantic logistical handling equipment is mounted in the concrete floor and kept upright by its own steel structure as the stand comprises of an altitude of 30 meters. The roof and envelope, therefore, need their own steel construction and the concrete floors are prone to high flatness requirements to avert deflection. The steel structure of the roof and envelope are attached to the steel structure of the logistical handling equipment which in turn relieves the stringent requirements of the concrete floor.

The building temperature is complex as it encompasses several compartments with each their own temperatures; -24, 2, 4, 12, 16 and 20 degrees Celsius. Which is something that the steel construction should be able to withstand.

4.4.2.2 Results case interviews – DCH

For Distribution Centre Hoogvliet, three persons were interviewed who played a role in the design of the structure; project manager, the head of structural engineering and the sustainability advisor. From these three interviews, information was gathered on the (process of the) implementation of the design perspectives.

4.4.2.2.1 Implementation of the structural focus areas

In this paragraph, the sustainable structural design perspectives that are implemented in the design will be introduced accompanied by the motive of the decisions and process in which they are implemented. The below description per sustainable structural design perspectives is derived from the three conducted interviews for the Distribution Centre of Hoogvliet.

1. **Material selection**

The floors in the Distribution Centre are 50cm thick concrete over a surface of 18.000 m^2. This is due to the fact that 30-meter steel operational distribution stands are constructed on top of the floor that contains heavy products. Therefore, the risk of movement is reduced by implementing a stiff thick concrete floor. As the operational activities are paramount, no cutbacks in the stiffness of the floor can be afforded. For the offices, concrete hollow slabs are used with DEJO grates with a light steel frame structure. The frame structure of the Distribution Centre is also steel. A comparison study has been done between concrete and steel in which steel was the victor due to the fact that large spans are required, and that concrete is heavier material and the foundation requires more strength. Moreover, a life cycle cost analysis is performed in which steel proved to be the less costly option by 5 to 10%. The roof is designed with steel trusses.

The contractor engineered the structural frame anew. The positioning and dimensioning of the steel structure remained the same, however, they optimized it differently. It was verified by Arcadis.

2. Material use

The amount of materials necessary for the foundation is reduced by choosing a steel frame structure opposed to a concrete frame structure as it is more lightweight. Furthermore, the structural elements are optimized for economic purposes as is common practice.

3. Durability

An industry function set the service life on 50 years. However, the durability, or the technical service life, of the system, components, and materials outlast the 50 years easily. The functional service life will be less as the innovation within the logistics of the operational distributive activities disrupt the market every 20 years. The distribution centre is their main distribution centre in which the distribution practices that could not be replaced as it means that operations should be shut down. Which leads to the fact that in 20 years a new distribution centre should most likely be constructed. The structure is suited specifically for this type of operations with the potential to increase 20% capacity over the next 20 years.

4. Waste effectiveness

The delivered structural elements were prefabricated apart from the concrete floor on the ground level. Furthermore, no attention is given to lowering the waste produced on the construction site or at the end of life of the building.

5. Maintenance

A maintenance plan is developed; however, this is predominantly focused on installations, i.e. elements with a short life span. The structural components are considered to preserve their quality for the next 50 years. Fire-resistant coating is not necessary as it consists of major fire compartments.

6. Reusability

Reusability of structural elements was not contemplated. The steel frame structure is welded together.

7. Disassembly

No thought is given on the degree of disassembly of the structure in both the distribution centre and office.

8. Recyclability

The steel that is used is recycled. Most steel nowadays comes from furnishes that integrate a share of scrap. After the end of life, the steel could be recycled, the same goes for concrete.

9. Adaptability

No structural adaptation possibilities are incorporated in the Distribution Centre. The production capacity could be increased with 20%, however, when exceeding the 20% a new building is required.

The office is located above the shipping lane of the trucks. A two-storey office was considered which covered the whole area of the shipping lane, but a three-storey office is chosen that still leaves room for horizontal expandability. In the outer walls potential openings have been implemented, so that horizontal expansion could be realized without the obstruction of the existing office.

10. Flexibility

In the function of industry (Distribution Centre) the flexibility credit is omitted in BREEAM-NL; thus, no attention is given to flexibility in the design of the industrial function.

For the office, a degree of flexibility is implemented. The structural engineer incorporated flexible measures as the structural conceptual design was first to be completed before the architectural design was done. Meaning, that overcapacity is implemented throughout the office so that changing the spatial layout won't be obstructed by insufficient load-bearing capacity. However, the office will be used as the main office excluding the fact that other parties will accommodate in that office that means that no multifunctional inquiries are made.

4.4.2.2.2 Additional findings – DCH

- Business plan for BREEAM-NL is lucrative due to financial feasibility. Thus, seeking the most financially beneficial path to attain BREEAM-NL Outstanding.
- Incorporate a buffer, or reserves, in BREEAM-NL categories due to the risk of not attaining credits and losing the grant as the project progresses.
- BREEAM-NL functions as a push to create awareness in an early stage of the project as one has to contemplate what measures ought to be taken to increase the probability of attaining high BREEAM-NL status.
- Environmental costs issues are often focused on after the design. Incorporation in the conceptual phase will increase the potential of giving strategic advice to the client.
- The contractor is a risk in attaining the MAT5 credit – origins of materials - as they will choose the suppliers of structural materials who must have sustainable certificates which is often more expensive to procure. This should be specified in the tendering phase of the contractor.
- BREEAM-NL stimulates recycled content; however, the recycled content is not embedded in the structural materials. Cleansed toxic sand is used to raise the Distribution Centre which in BREEAM-NL counted as the incorporation of recycled content. Circumventing BREEAM-NL purpose.
- BREEAM-NL functions as an extra program of demands with fundamental issues to which the engineers should adhere to.
- Incorporating overall overcapacity in the office is less costly than designating specific areas with a higher load capacity due to easier design and less manpower needed.

- Disassembly for industry purposes is discouraged as the structure is at the service of the operational activities. The structural engineer discouraged disassembly practices altogether for building with a longer service life as often the most lucrative option during the end of life stage is to cut the steel beams and columns and recycled it.
- Interfaces with other disciplines are crucial for an effective overall design. In the office, the direction of the steel beams was designed not to interfere with ventilation. In the industry, the installations are attached to the structure resulting in more strength required in the structure. The structure has other functionalities than its primary.

4.4.3 Project C: Friesland Campina Abel

Project C is a new factory for Friesland Campina, in which their production capacity of nutrients for babies will be enlarged. The new factory will be located in Borculo in the province of Gelderland. The project commenced in April 2018 in which the factory is designed at 50% of its operational capacity, insofar the factory is built so that production could be expanded. This is done for two reasons; future growth and contingency for other factories. Although the design was close to being finished, Friesland Campina found the costs of the new factory being too excessive and the project was cancelled. Friesland Campina is still interested in a new factory, however, the whole factory will be fitted for the maximum production capacity as it was meant, so without the surplus in production capacity. This meant that Arcadis is brought back to the drawing board to design a factory that is 50% smaller than first was intended. The structural engineer said: 'I never have encountered a cancelling of a project in this late stage is my whole career'. It was said that the BREEAM-NL engineering costs were not to a factor for the cancellation. The decision of cancelling the project was made during the execution of the case study and interviews. As the design of the cancelled project was completed, the focus will be on the first intended structure of the factory.

Figure 29: Rendered visualisation of Friesland Campina Abel (Arcadis, 2018)

4.4.3.1.1 Sustainable objective – BREEAM-NL

The sustainability objective of Friesland Campine for the new baby nutrition factory was to achieve an 'Outstanding' rating on BREEAM-NL which is the highest rating in BREEAM-NL. Although during the design of the building BREEAM-NL was closely followed there is no documentation of an in-depth analysis of BREEAM-NL as the project was cancelled prematurely. BREEAM-NL was not part of the initial design and was introduced later due to a lucrative business model.

4.4.3.1.2 The structure of Friesland Campina Abel

The Friesland Campina Abel has two functions: industry and office. The office is on the top floor (4^{th}) of the building and the industry comprises the other levels with a total GFA of about 15.000 m^2. A demand of the client was that the column distance should be 10 meters, so a square structural grid of 10 by 10 meters is incorporated in the structure. For the sole reason that it is lucrative for changing or expanding the internal production capacity without the structure being an obstacle. Furthermore, as the operational machinery is heavy, and the internal logistics is active the structure should facilitate this. Hence, the structure is subordinate to the production facilities. The material of the frame structure is in-situ concrete for both floors and columns. As this is a factory for nutrition preservation of the air quality is essential as it could interfere with the quality of the nutrients, therefore coating is applied on both the concrete floors and columns.

4.4.3.2 Results case interviews – FCA

For Friesland Campina Abel, three experts were interviewed who played a role in the design of the structure; project manager, the head of structural engineering and the sustainability advisor. From these three interviews, information was gathered on the (process of the) structural design and the roles the sustainable structural design strategies played.

4.4.3.2.1 Implementation of the structural design focus areas

In this paragraph, the sustainable structural design perspectives that are implemented in the design will be introduced accompanied by the motive of the decisions and process in which they are implemented. The below description per structural design perspective is derived from the three conducted interviews for the Friesland Campina Abel.

1. **Material selection**

The type of structural material is chosen based on the project drivers (costs, time, and technical): in-situ concrete. After, the introduction of BREEAM-NL, also the environmental costs became a factor. The environmental costs also pointed towards in-situ concrete. The materials that were contemplated were the following: prefabricated concrete, in-situ concrete, steel-sheet concrete, and grid floor. Both the floors and the columns are in-situ concrete. In-situ concrete prevails above prefabricated concrete as the cement percentages could be lowered with in-situ concrete.

Prior to the design, an external advisor for BREEAM-NL was included who gave information about what type of foundation material is paramount from which three types of poles were contemplated more in-depth.

Subsequently, the effects on the superstructure were researched and were the financial and technical aspects the most crucial in the decision making.

2. Material use

Optimization studies are performed to see to what extent the material quantity can be reduced, this is common practice. The optimized structures were compared to the indicators described above.

The façade began with a 10-meter span, thus, the envelope partitions only had support in every 10 meters. This resulted in very thick envelope partitions. A half grid (5 meters) was chosen in the façade so that the envelope partitions could be reduced to the appropriate isolation thickness. Moreover, due to the extra columns in the façade the internal structural columns could be reduced in size (from 80cm to 60cm). Consequently, minimizing material input.

3. Waste effectiveness

No requirements are given from the structural engineers on how to reduce waste production on-site and during the end of life.

4. Durability

The service life is set on 50 years for which the appropriate safety factor is used. However, the technical service life can be set on 100 or 150 years.

5. Maintenance

The concrete structural elements deteriorate through contact with humid air. As this is a nutrition factory in which powders are the raw materials, the installations try to control the humidity in the building. Therefore, the air is dry, and the structural concrete elements are not harmed. The concrete columns and floors are coated as they could produce dust. If damaged the concrete elements should be maintained. Only through calamities maintenance on the structure should necessary.

6. Reusability

As the structure consists of solely monolithic concrete structural elements there is no reusability.

7. Disassembly

The structure is not demountable.

8. Recyclability

After the buildings service life, the concrete structure can be reduced to concrete granulate.

The recycled content in the structural elements is none. At first, the concrete structural elements had 35% concrete granulate. However, the strength and the smoothness of the concrete columns and floors are reduced as a consequence of inserting concrete granulate. The quality of the structure could not be guaranteed with concrete granulate. Therefore, no granulate was incorporated in the structural elements.

The 35% recycled content which is mandatory in BREEAM-NL is added to the foundation, as there was room for extra material. This was redundant.

9. Adaptability

No adaptability is incorporated in the structure's design. However, now the production capacity of the factory will be cutback 50%, this will be an area of focus for the new factory.

10. Flexibility

The industry does not account for flexibility in the structure as it is not part of BREEAM-NL.

The office is located on top of the building, on top of the industrial segment. The grid of the structure is 10 by 10 meters which are evidently also the grid of the office resulting in a flexible grid. Moreover, as industrial equipment is attached to the ceiling of the structure, the floor of the office has a high overall load capacity resulting in flexible worthy load capacity for the office.

4.4.3.2.2 Additional findings – FCA

- BREEAM-NL is implemented due to being financially lucrative as the governmental grant outweighs the engineering costs.
- The BREEAM-NL philosophy does not fit one on one with the industrial building function. Therefore, rules are bend and assumptions are made together with an independent BREEAM-NL assessor.
- The structural flexibility credits in BREEAM-NL for the offices are obtained coincidentally as the structure needs a high load capacity and a 10-by-10 structural grid.
- The additional structural engineering costs for BREEAM-NL was a little more than 1% of the total BREEAM-NL budget. Most of the structural engineering costs have been made prior to the introduction of BREEAM-NL.
- Prefabricated concrete scores worse on environmental costs than in-situ concrete as the share of cement is higher in the former and possible to customize in the latter.
- The structural engineer cannot control the origin of materials as that is the responsibility of the contractor overseen by the project management team.
- The initial investments (CAPEX) become increasingly important as the project progresses.

5 Synthesis

5.1 Validation of the theoretical framework criteria

In Chapter 2.1, ten structural design perspectives are determined that adds to the eco-effectiveness of the structure. In Chapter 2.2, these structural design perspectives are merged into multiple indicators, resulting in a theoretical framework which could be utilized by the structural engineer for guidance in the design process. The ten identified design perspectives are underlying in the theoretical framework. Through the survey, seen in Chapter 4.2.2, interrelations are identified within the structural design perspectives. Wherefrom, the accuracy of the clustering of the perspectives into the theoretical framework design criteria could be evaluated.

It has been found that the perspectives are interlinked and, thus, are influential to one another when implemented. Consequently, the criteria in the theoretical framework are not isolated when implemented. As the structural design strategies are the basis of the theoretical framework, interlinkages can be identified within the theoretical framework. The relation diagram, as seen below, supports the clustering and merging of the structural design perspectives into the three theoretical framework criteria – material environmental costs, service life, and residual value. These theoretical framework criteria form the basis of the optimal eco-effective structural design strategies.

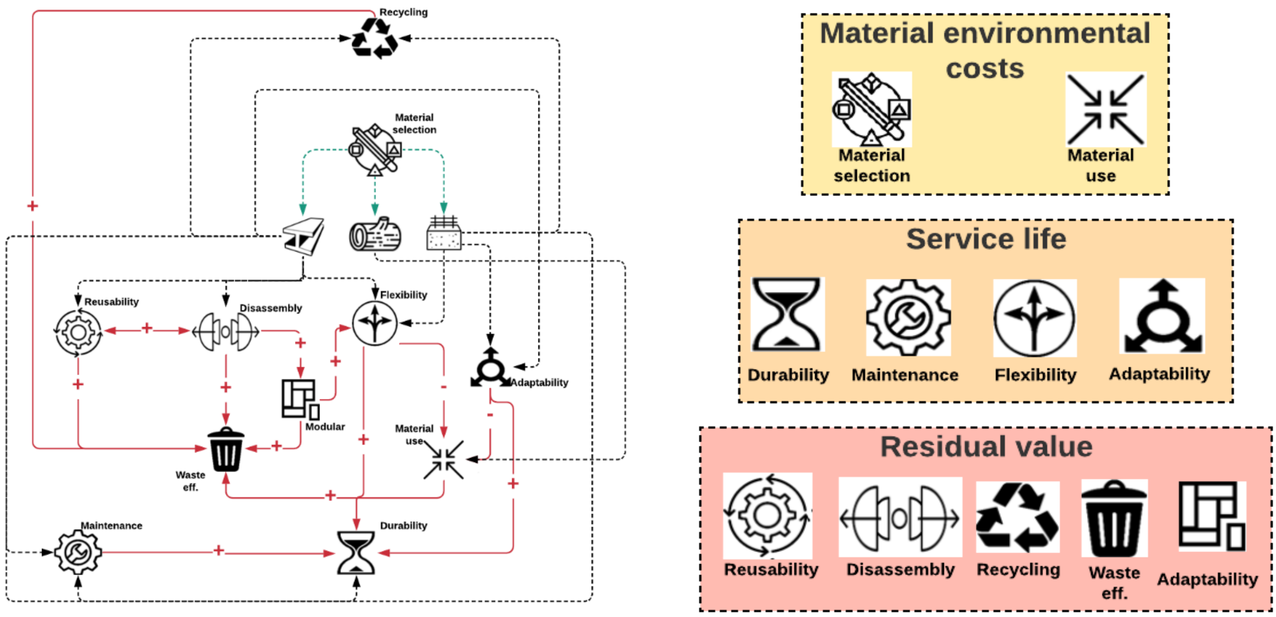


Figure 30: Clustering of structural design perspectives derived from surveys coincides with the merged structural design criteria in the theoretical framework

Durability can be dissected in both the material hierarchy (material, component, and system) and in the different service lives (technical, functional, and economic). The durability of a structure can be approached on a material level – is the structural material sufficiently strong enough to meet the intended technical service life – as it can be approached on a system level – is the structure as a whole able to satisfy the intended technical service life. The material hierarchy addresses the technical service life. In this research it is assumed that the technical durability should be equalized with the functional – either on building level or system and component level – as only a fraction of structures is demolished due to structural deficiencies. However, it is, of course, a possibility that structural deficiencies arise in which *maintenance* of the structure should mitigate these risks, i.e. maintenance positively affects the technical service life. On the other hand, durability of a building can be appointed to its functional service life. The functional service life is extended by designing for *flexibility* and *adaptability*. By designing for flexibility, one incorporates the potential to convert a building from its current function to another function. This is essential for retaining the structure, as over course of more than 50 years demands has been proven to change and, therefore, the original function could be outdated, resulting in demolition of the entire building. Consequently, by incorporating flexibility in the structure, the probability increases for a lengthier service life and, thus, preserving initial materials. Designing for adaptability also increases the durability of a building, as expansion of the building could be necessary. In the theoretical framework, the design perspectives *durability*, *maintenance*, *flexibility*, and *adaptability* all increase the probability of a lengthier service life. This is supported in the relation diagram in Figure 30, in which all four design focus areas are closely linked and have a positive effect on the design perspective: *durability*.

The clustering of waste minimisation, reusability, disassembly, and recyclability into the residual value can also be traced back in the relation diagram. Reusability, disassembly, and recyclability all three add to the waste effectiveness at the end of life of a structure. Depending on what material is used, recyclability can often always be attained to a certain degree after the end of life as this is on an element level. Reusability and disassembly of the structure, however, are, next to being somewhat interchangeable, essential to incorporate early in the structure's design as on a component and system level the structural design puts its mark on the overall design of the structure and other functionalities.

Flexibility could have a negative effect on material use. This is due to the fact that designing for flexibility is often interwoven with the uncertainty on how the spatial layout would be executed in the future, thus, how the live loads would be spread out. Therefore, redundancy in the structure is essential, so that the load capacity of the structure would not be a constraint in the capabilities to alter the spatial layout or convert functionality of a building. Thus, flexibility negatively affects the height of the material environmental costs. Notwithstanding, a flexible structure is synonymous with an open structure in which no load-bearing walls are incorporated. Hence, a flexible design also results in lowering the amount of materials.

To sum up, overall the relation diagram coincides with the clustering of ten design perspectives. For the extension of the service life, either technical or functional; durability, flexibility, adaptability, and maintenance provided the basis for this criterium. This is supported in the relation diagram subtracted through the survey. It can be stated that durability is a goal of incorporation of flexibility, adaptability, and/or maintenance. Furthermore, the relation diagram also supports the clustered design perspectives into the criteria: residual value. Therefore, it can be stated that the clustering of the structural design perspectives for an eco-effective structural design into *material environmental costs, service life,* and *residual value* is accurate and validated. Moreover, unfortunately, the material environmental costs criterium seems to cause friction as the extension of service life through flexibility and adaptability increases the deployment of materials. Thus, the indicators within the environmental costs are not mutually exclusive.

Moreover, as was both depicted in the relation diagram as was explicitly and pressingly mentioned by a structural engineer from the Hoogvliet case study is that designing for a lengthy service life, disassembly features in a structure is discouraged. This adds to the accuracy of the distinction made in the optimal eco-effective structural design strategies.

5.2 Design criteria - in practice vs. sustainability assessment methods

In Chapter 3.20, the structural design perspectives' detailed criteria are determined through analyses of the sustainability assessment methods BREEAM-NL, LEED, and GPR-Gebouw. In Figure 32, the design criteria of the three assessment methods are combined to visualize the full scope of operationalized structural design. In this paragraph, the three assessment methods' criteria are combined and subsequently compared with the design criteria subtracted from the structural engineers via a survey, as can be seen in Chapter 4.2.1, in which the respondents were asked on what aspects they focus when contemplating a specific structural design perspective. The goal of comparing the two-design criteria output is twofold; on the one hand it is to see if the structural engineers are knowledgeable in the field of the structural design perspectives, and on the other hand, to evaluate if the sustainability assessment methods suffice in their scope.

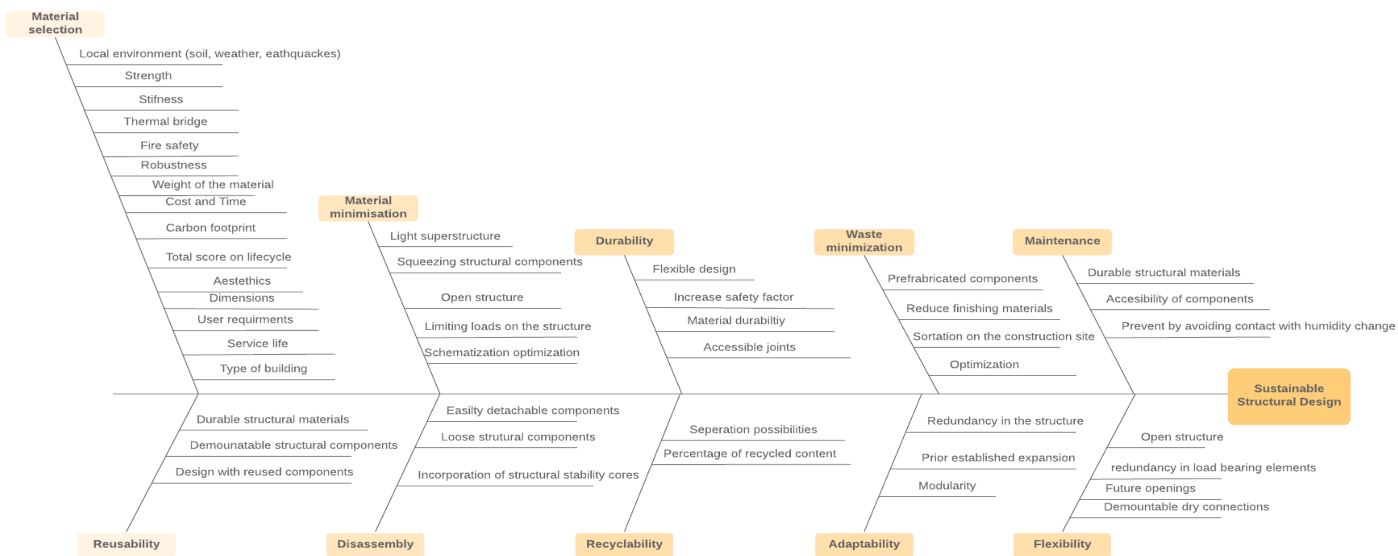


Figure 31: Design criteria on structural design perspectives derived from structural engineer's responds in the survey. (own illustration)

When comparing the design criteria derived from the survey with the combined design criteria of the sustainability assessment methods, many similarities appears to exist as do a few differences. The sustainability assessment methods go further in detail in comparison with the design criteria of the structural engineers, which is logical as the sustainability assessment methods are evidence-based. For instance, a floor-to-floor height of 3 meters instead of 3,5-meter could cost valuable credits. Moreover, the structural engineers tend to have responses that are more of a breadth nature as they approach the structure from a wider point of view than solely sustainable inquiries.

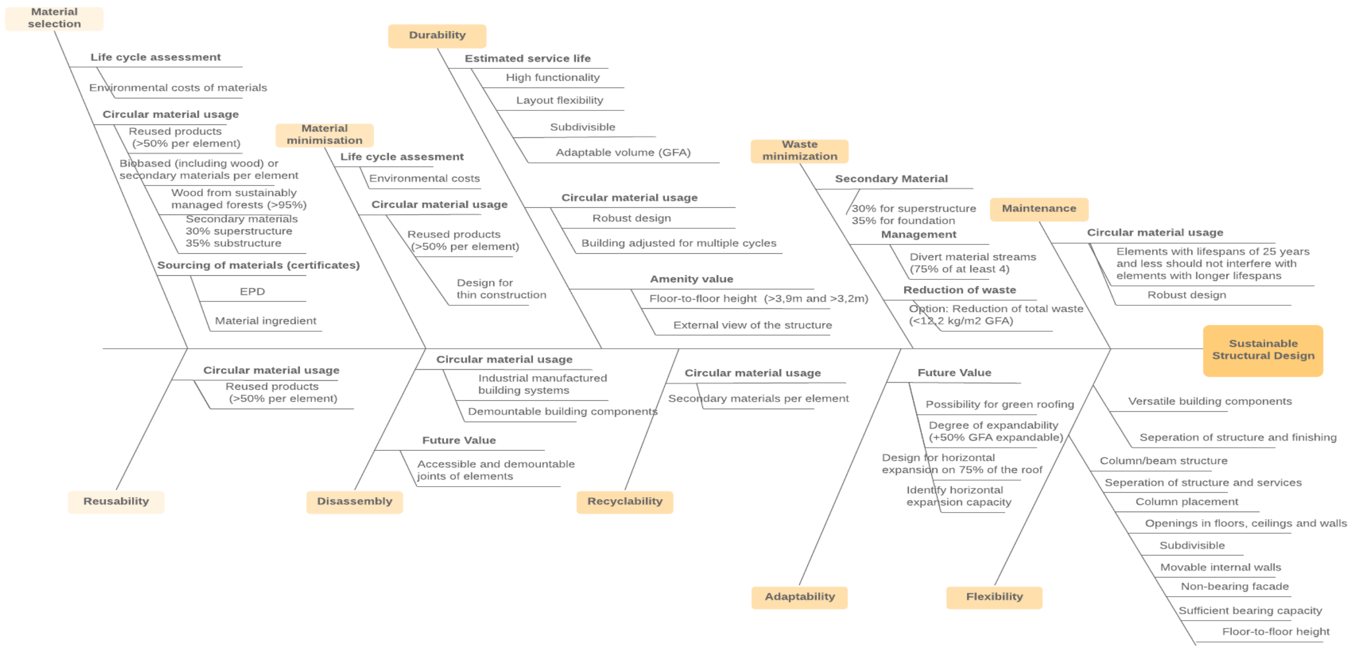


Figure 32: Design criteria of all three sustainability assessment methods merged. (own illustration)

A big difference in the both criteria trees is that some of the potential credits in the sustainability assessment methods are not appointed to the actual design, but attainable in later stages of the project or responsibility of other parties. As all three assessment methods are evidence-based methods, some of the credits are attainted after the design is made. The percentages of secondary material are not an inquiry during the first design stages. Plus, for the sourcing of materials, one is dependent on the contactors for certifications and the amount of reusable components per element. This is looked into in a later stage, also managing the waste streams on the construction site is not an aspect of the structure's design but more of a managerial issue which comes later as well in the process.

It can be deducted from the comparison that the structural engineers are overall aware of capabilities and possibilities of implementing structural design perspectives. Moreover, the design criteria subtracted from the survey did not shed any new valuable light on the structural design scope of the sustainability assessment methods.

5.3 Theoretical framework in practice

The theoretical framework established in Chapter 2.2 consist of two parts; one is the theoretical framework criteria and the other is the three optimal eco-effective structural design strategies. This paragraph will take a closer look into the cases and their adherence to both parts of the theoretical framework.

Table 10: The structural design indicators from the theoretical framework and the adherence to the framework from three cases.

Criteria	Holland Casino Venlo	Distribution Centre Hoogvliet	Friesland Campina Abel
Material environmental costs	Wooden roof structure and steel frame structure and concrete stability cores with concrete foundation	Steel frame structure with monolithic concrete floors and concrete foundation	In situ concrete frame structure with concrete foundation
Service life	The service life is estimated on 90 years • Landmark • Spatial layout flexibility The structure is designed for one specific function: casino; and is not convertible.	The service life is estimated on 50 years. However, practice learns that distribution processes are out-dated after 20 years. The structure is designed for one specific function and purpose: distribution centre with a specific process. (however, the halls are large with a redundant load bearing capacity, large spans, and high floor-to-floor height)	The service life is estimated on 50 years. The structural grid is 10-by-10 with high load bearing capacity The structure is designed for one specific function: nutrition factory.
Residual value	• Loose steel prefabricated structural elements in the frame. • Steel structural components are assumed to be demountable by the structural engineer after the service life (connected with bolts). • The slimline floors are demountable	The structure is not demountable.	The structure is not demountable

5.3.1 Holland Casino Venlo

The eco-effective structural design strategy of the structure of Holland Casino is a moderate merged strategy of A and C, in Figure 33 a visualization is portrayed and below a clarification is given.

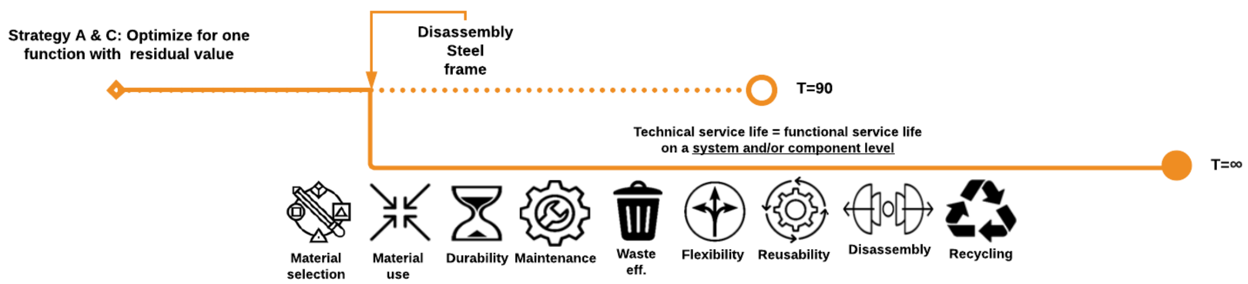


Figure 33: Holland Casino's structural design is partly in accordance with strategy A & Strategy C (own illustration)

The structure is designed for one specific function for a relatively long service life of 90 years (Strategy A). The structure is not designed for other functions to inhabit the building, however; internal flexibility is striven for through incorporation of a frame structure, lengthy spans, a slimline floor, and redundant load capacity in certain areas. Thus, although it is designed for one specific function, the structure is not optimized, i.e. the structural elements are not squeezed to its minimum. The incorporation of the internal flexibility's potential increases the probability of a lengthier functional service life as internal spatial demand shifts are accounted for by both the structure and services. Hence, reducing the gap between the functional and technical service life. However, as there is no possibility of functional convertibility, the gap still remains.

Furthermore, the frame structure is designed with the structural material steel with loose elements connected with bolts, which entails that the frame is demountable after the structure's service life (Strategy C). Although the internal flexibility increases the probability of prolonging the functional service life, uncertainties still play a major role in the future of a building. By designing the frame structure to be demountable, the uncertainty is lowered of losing the value of the structure on a system and component level if the building does not make its initial proposed service life. The steel components could be salvaged, thus, preserving steel components. When reaching the 90-year mark, the residual value would probably not be sufficient to be reused in its primary state due to stresses and deformation. Nonetheless, the structural residual value is hedged because if the initial function of a Casino is no longer required after a plausible relatively short period, the structural frame components could be harvested in its primary state. From this an important question arises; what is the time span of a structural component to be salvageable in its primary state and is it possible to maintain and prolonging its technical durability on a system and component level?

5.3.2 Distribution Centre Hoogvliet

The structural design strategy of the structure of the Distribution centre Hoogvliet coincides with Strategy A on the sole basis that is it designed for one specific function. However, the function will be outdated after an approximate period of 20 years. In Figure 34, the functional service life of the structure is visualized accompanied by its structural design perspectives.

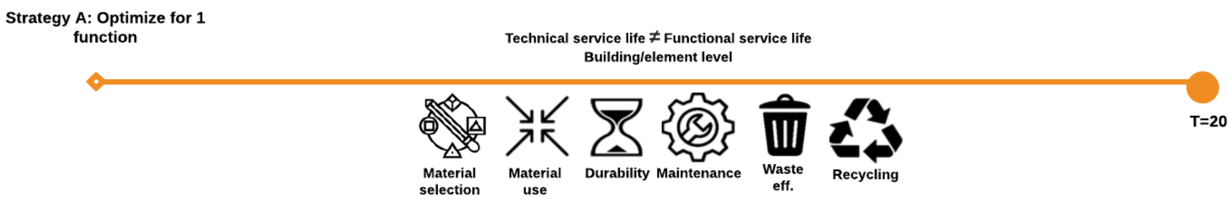


Figure 34: Hoogvliet's structural design is in accordance with Strategy A solely that it is optimized for one function. The estimated functional service life is 50 years, however in practice it would be 20 years (own illustration)

It is even more specifically designed, namely for the current most innovative distribution processes. In Strategy A, the functional service life of the structure should match the technical service life. This is where the structure of the distribution centre lacks. The structure is designed for a service life of 50 years; however, the technical service life on a building level will far exceed the 50 years. Moreover, the distribution processes have proven to be disrupted by innovation in approximately 20 years. As the structure is specifically designed and optimized for the current distribution process, the structure will also be outdated after 20 years. As in the interviews, it came forward that there was no possibility to refurbish the building to another distribution process without shutting down the operation. The distribution centre will be the main and sole distribution centre of Hoogvliet, which entails that when the distribution processes market is disrupted by more efficient processes, the building and its structure will not suffice for future distribution processes.

Resulting in relocating the activities and abandoning the structure. Therefore, the functional service life of the building is set for 20 years.

The distribution halls are large, the load capacity is sufficient for other functionalities, the structural grid has lengthy spans and floor-to-floor height is high. Resulting in the fact that it would be possible to convert functionalities. However, drastic refurbishments are needed in the building and the question will be who would be willing to embrace such a project. As the service life is approximately 20 years, it is possible to know what functions it could inhabit after the distribution cycle. Functional convertibility features could already be implemented to smooth over the functional change.

In the near future, a train station will be built in the proximity of the distribution centre, this entails that that area would become more accessible. As the area will be more accessible, the possibilities for functional convertibility would increase. Furthermore, it has a great visible location next to a busy highway which also adds value for possible subsequent functions.

The structure is not designed to be demountable, due to being subordinate to the heavy operational distribution activities. Thus, after 20 years, the best option to preserve the structural materials is either a drastic refurbishment or recycling of the structural materials.

It can be concluded, that the structure is not eco-effective. Although no thought is given on the future purpose of the building after 20 years, the industrial structure has a frame structure, with high load capacities, and lengthy span which could, in theory, be utilized for other functionalities but the building needs large refurbishments.

5.3.3 Friesland Campina Abel

The structural design strategy of the structure of Friesland Campina Abel corresponds with Strategy A on the sole basis that is designed for one specific function: baby nutrition factory.

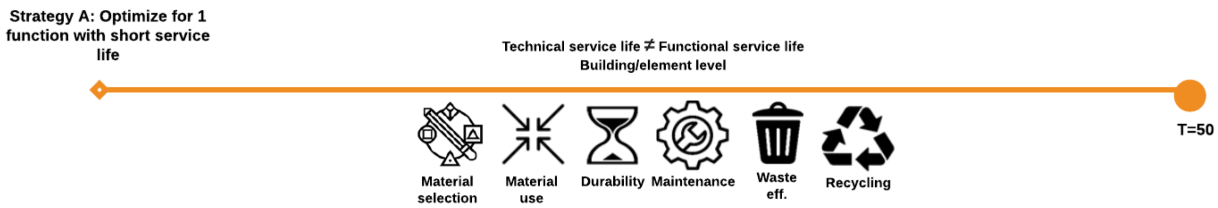


Figure 35: The Friesland Campina Abel's structural design is in accordance with Strategy A solely that it is optimized for one function. The estimated functional service life is 50 years (own illustration)

The estimated service life is set on 50 years whilst the technical service life easily be 150 years. Furthermore, the structural materials are in-situ concrete; for the frame, floors and the foundation. A variant study was performed in which in-situ monolithic concrete, prefab concrete, composite slab with profiled steel sheeting, and slatted floors. The environmental costs were the lowest for the in-situ concrete related to the other options. In-situ concrete, however, is far from a low environmental costs material. Furthermore, after the end of life, the concrete is at most recyclable, resulting in low residual value. Moreover, the structure is optimized for the estimated building service life of 50 years. In reality; however, the structure would far exceed its service life. This entails that the gap between the functional service life and the technical service life is substantial. Additionally, although the span of the beams is 10-by-10, the structure is still designed specifically for the factory. Summing up the prior stated elements, it can be concluded that the structure of Friesland Campina Abel does not coincide with an eco-effective structural design strategy.

The factory is located on an industrial terrain where the options of other building functions are limited. Hence, the options tend to point in the direction of industrial function. There are possibilities to retrofit the building for other industrial applicability. As the load-bearing capacity is high and the structural grid has lengthy spans, it gives room for other industrial purposes.

The building was purposed with a capacity of 50% higher than the new factory is intended for. This gives substance for applying structural features for potential expandability in the future.

5.4 Sustainability assessment methods' role

All three cases aimed for the highest certificate possible for the implementation of the credits in sustainability assessment methods. It has been concluded that two of the three cases did not coincide with the theoretical framework criteria and all three, not with any of the optimal structural design strategies. The two cases that didn't correspond with the theoretical framework were both BREEAM-NL-based designs. The case that did mostly correspond with the theoretical framework was GPR-Gebouw-based. This corresponds with the findings and conclusions made in Chapter 3.3 in which the sustainability assessment methods were compared in theory with one another on the basis of their compatibility with the theoretical framework. Thus, it can be stated that GPR-Gebouw both in theory as in practice is the best suited when contemplating structural design from a point-of-view that reduces the environmental impact incurred by the structure. However, all three cases did not fit any of the established optimal eco-effective structural design strategies. From which can be concluded both in theory as in practice, that none of the sustainability assessment methods is useful for an eco-effective structural design.

It is important to note, for the cases in which BREEAM-NL has been used, that the sustainability assessment method was introduced later in the process. BREEAM-NL was introduced due to the fact that the business case was *financially lucrative*. It can be said that no specific sustainable features were contemplated in the early stages of the structure's design of those two cases. Nonetheless, after the introduction of BREEAM-NL, in both cases, only minor alteration had to be made to the structural design to be BREEAM-NL approved. This also adds to the fact that *BREEAM-NL does not incorporate the optimal eco-effective structural design* put forward in the theoretical framework.

An interesting finding from the case study was that in all three cases the sustainability assessment methods *functions as an extra set of program of demands* to which should be adhered to during the course of the project. Alteration in the design had to constantly be reaffirmed with the sustainability assessment method at hand. If it did not coincide with the assessment methods or an alteration would reduce the amount of credits below the threshold of securing the certificate, it would not be incorporated in the design. Not acquiring the certificate would entail the loss of subsidy. From which can be deducted, that sustainability assessment methods *secure sustainable measures* during the process due to the risk of financial loss. In all three cases, *buffers* were incorporated. Buffers are extra credits within categories that are included insofar potential setbacks can be absorbed without the grants being at risk.

Sustainability assessment methods are *broad and generic* methods. A design of a building or a structure is very case-specific and, therefore, difficult to fit into a general method. Often *assumptions* have to be made insofar the measures could fit into the categories. The assumptions are made in dialogue with the assessor of the sustainability assessment method. In the interviews of Holland Casino (GPR-Gebouw) and distribution centre (BREEAM-NL), it was mentioned repeatedly that the method used was not suited for these types of buildings.

In all three cases, the structural engineer did not look into the sustainability assessment method during the conceptual design. For the two cases (Hoogvliet and FCA) the reason is evident as BREEAM-NL was introduced in a later stage. For Holland Casino, however, the highest rating of GPR-Gebouw was part of the original program of demands, thus, also in the conceptual design. During the interview with the structural engineer of Holland Casino, it was said that he did not actively use GPR-Gebouw. He designed the structure based on two sources; indicators that were stated in the program of demands and GPR-Gebouw criteria noted. Thus, based on three structural design perspectives he designed the structure – low environmental costs, flexibility, and disassembly - without utilizing GPR-Gebouw. This is an important finding as the structural engineers said to only need a certain range of perspectives when designing a structure on a conceptual level.

To conclude, the deployment of the sustainability assessment methods BREEAM-NL and GPR-Gebouw is not favourable for an eco-effective structure as was found in both theory and in practice. However, in practice, GPR-Gebouw has proven to incorporate more eco-effective features than BREEAM-NL. As the findings in theory and in practice are aligned, one can conclude that the sustainability assessment methods play a large role in the overall design. The adherence to the sustainability assessment method has a financial origin. When attaining the highest rating on the sustainability assessment methods, the potential grants are substantial, and, therefore, the threshold of attaining a certain rating should not be crossed. Resulting the most important feature of the sustainability assessment methods; securing measures. However, the structural engineers did not actively utilize the methods but subtracted perspectives from a specific assessment methods which served as the starting points of designing the structure of a conceptual level.

5.5 Factors at play

It has been concluded that GPR-Gebouw is paramount in relation to BREEAM-NL concerning an eco-effective structural design. However, also GPR-Gebouw does not truly embrace the full potential of designing the structure to be eco-effective as it does not incorporate the fact that the service life and residual value are inverses to one another. One of the three eco-effective structural design strategies, established in Chapter 2.2.2, should be adhered to, to truly embrace the eco-effective potential of the structure. However, the question arises which of the strategies should be selected under what circumstances. Deducted from the analysis of case study and through conducting the interviews, several factors that guide the decision-making into which eco-effective structural design strategy has to be deployed, have been established which will be set out below. Next to that, several factors have been identified that have an impact on the progress of structural design's eco-effectiveness.

5.5.1 Goal of the client

The purpose of the client has on two fronts proven to be a highly influential factor in the overall design of the building. On the one hand, it sets the stage for the scope of the building's design and on the other hand, a clear vision of the clients plays a role during the process of the design.

The purpose, or vision, of the client (in the case studies) was either set in the program of demands - which was won via a tender - or was based on exploratory meetings in which the client was interviewed on what they envisioned for the building. It is difficult to determine the origin of how a sustainable vision or goal of the client is established as there are multiple variables that underlie it. Nevertheless, a clear vision accompanied by concrete specifications on the degree of incorporation of environmental reductive measures contributes to safeguarding the measures until the final design. A striking example of this was that Holland Casino wanted to design the building on the basis visible and profitable sustainability features with cradle-to-cradle principles and a high degree of flexibility. Hence, the structure was an open steel frame structure in which the spatial layout is versatile (slimline floors) and the steel frame demountable and reusable plus the wooden roof structure adds to the visible sustainability. However, the material of the foundation was altered as the focus shifted towards exclusively GPR-Gebouw in which the effect on MPG did not outweigh the height of the costs. Nevertheless, due to the vision of the client and, thus, the early stated design principles, a large amount of the measures did make the final design. On the opposite, for Hoogvliet and Friesland Campina Abel, no particular or specific sustainability features were stated early on in the process. The only sustainability focus was BREEAM-NL which was introduced in a later stage in which the structure does not play a major role.

5.5.2 Function

The function of the building lays in the extension of the purpose of the client. The function of the building evidently plays a major role in which eco-effective strategy should be adhered to. The type of structure is the direct result from the type of function it will inhabit.

In an industrial function, as has been seen in the case study, the structure is subordinate to the operational activities. This entails that less attention is given to the structure than that of reducing the operational environmental impact. The function of a structure for industrial purposes is primarily that it should be reliable which results in the embodiment of reliable structural materials (steel and concrete) and reliable structural components and systems. Thus, incorporating biobased materials or features for disassembly of the structure are not applicable in industrial building functions. Due to the fact that the structure should be reliable adds to the technical longevity of the structure itself. However, the functional service life for an industrial function, in the Eurocodes, is set on 50 years which is far less than its technical durability. Therefore, to preserve the materials, one should contemplate future functions if it is known that the functional service life is limited. Other functions such as offices, schools or meeting buildings are buildings that are intended for humans rather than machineries.

This results a higher dynamic within the building as it is more focused on the diffusion of live loads, also less load capacity is needed. This allows for the possibility of the structure to be more dominant in the overall design.

5.5.3 Service life

The functional service life follows from the intended primary function as is clarified in the previous paragraph. A distinction should be made between the functional service life and the technical service life on the building and system/component level. Does one want a structure to be unaltered for a lengthy period of time on an exact location, or does one know that in the nearby future the building will become unwanted and indispensable, or it could be needed somewhere else. This is exactly, the distinction that is made for choosing either Strategy B or Strategy C.

5.5.4 Socio-economic considerations

Socio-economic tendencies that come with designing a new structure should be examined. A specific function that is currently demanded could be outdated and unwanted in the (near) future. The changing needs play a vital role in the scope of functional convertibility possibilities. For instance, an office can be built at a location that is easily accessible for cars, however, does it make it attractive for residential purposes in the future?

The location of a building and its surroundings is an important factor in what strategy should be adhered to. The scope of potential subsequent functions heavily depends on the location of the building. A building that is situated in an industrial area has fewer possibilities of inhabiting other function that if a building is located in or within accessible proximity of a city.

5.5.5 Financial implications

In all three cases, financial inquiries are a large factor is the decision-making on whether to implement measures that contribute to achieving more environmental reductive features. In two cases, the sustainability assessment method was introduced due to its profitable business case. Thus, for those two cases, the focus was put on specific (less costly) credits in the sustainability assessment method to realize the highest possible certificate with the least amount of costs.

Moreover, in all three cases, it is seen that during the process of the project the initial investments become increasingly important as the executive phase approaches. In the conceptual design of the structure and the building as a whole, there was less financial pressure in the conceptual design than in the end. It appeared to be that both the importance of environmental impact reductive measures and the total cost of ownership (TCO) are gradually replaced by the importance of the initial investments (CAPEX). With the condition that it does not interfere with the obtaining the certificate of sustainability assessment methods, as without the certificate the grants are lost which would result in more economizing. Thus, design features that are too high in costs and do not have a large impact on the sustainability assessment methods would not make the final design. All three cases explicitly mentioned that without the utilization of sustainability assessment methods more environmental beneficial design features would be cut.

A structure has value embedded within it in the form of materials, this entails that is also having financial value. Either on a building level or on a system/component level. In this a distinction is made between Strategy B in which the function could be converted and Strategy C in which the structural components could be utilized for subsequent projects. The financial implications at the start and in the future should be an area of consideration when designing the structure.

To sum up, the initial investments tend to increase in significance in the decision-making during the process to the execution phase. The opportunity of economizing will often be seized if the outcome of the design measure is either high in uncertainty, does not implicate a large effect on reducing the environmental impact, or when utilizing sustainability assessment methods, it does not endanger obtaining the certificate (read: grant). From this can be concluded that financial implications are a large factor in design decision-making.

5.5.6 Dependency on other disciplines

The structure's full potential can only be attained when other disciplines in the building are coordinated accordingly. Application and execution of services in a building could also be a hindrance for flexibility or disassembly of a structure. A close collaboration between disciplines is vital for the overall performance.

5.5.7 Dependent parties

A building design team that is part of the early design often consist of the following disciplines – structural, electrical/mechanical/sanitation, and (external and internal) architecture. The building can be optimally designed insofar the environmental impact is reduced drastically; however, the design team is eventually dependent upon other actors for a design to be executed.

Assessors – all sustainability assessment methods are evidence-based, which entails that evidence should be provided to attain certain credits to an assessor from the sustainability assessment method. Often, as was mentioned several times in the case interviews, buildings do not fit the sustainability assessment methods in its entirety. This entails that the design team should make assumptions which should be evaluated by the assessor. This can be either accepted or thwarted. In some instances, the assumptions are made in cooperation. Two examples illustrate this ordeal; the slimline floor in the Holland Casino structure is not to be found in the environmental costs database (MPG) for which the assessor had to make assumptions on what the exact environmental costs would entail; the other example is from the distribution centre building in which the whole rooftop is covered in PV-panels. The material input of the PV-panels was destructive for the material credits, even though all the energy credits were obtained the material credits plunged. For which the assessor Hence, although the design of a building could adhere to the sustainability assessment methods credits still the assessment methods can be inadequate in which the assessor should make assumptions to attain it.

Contractor – the contractor is the actor that executes the design. Often, the contractor enters the project in a later stage after the design is finished. The design team is dependent upon the knowledge of the contractor. Contractors each have their own skillset; the one is specialised in building with steel and the other with concrete. The higher the specialisation of the design, the harder it is to find contractors with a specific skillset. For Holland Casino, the wooden roof structure was highly specialized and was therefore tendered separately early on in the design stage. Additionally, in the design of the structure no contemplation if given on the origin and the ingredients of structural materials. The origin and ingredient of structural materials are set in certificates and the contractor is responsible for providing those certificates (EPD, ISO, BES). The contractors are in its turn dependent on the certificates that the suppliers have.

5.6 An extra structural design perspective

The identified structural design perspectives were all focused on the material aspect of the structure and its preservation on the long-term either on building level or on system/component level, i.e. its eco-effectiveness. The knowledge of the structure's environmental impact and its potential in the future is more or less set in stone after completion of the construction. However, the structure is more than just its own entity; the structure, as a static entity, could facilitate, improve, and also obstruct other disciplines within a building. During the structural design, it should be distinguished what the implications are of structural design decisions on other functionalities in the building. From this premise, the following structural design perspective should always be kept in mind:

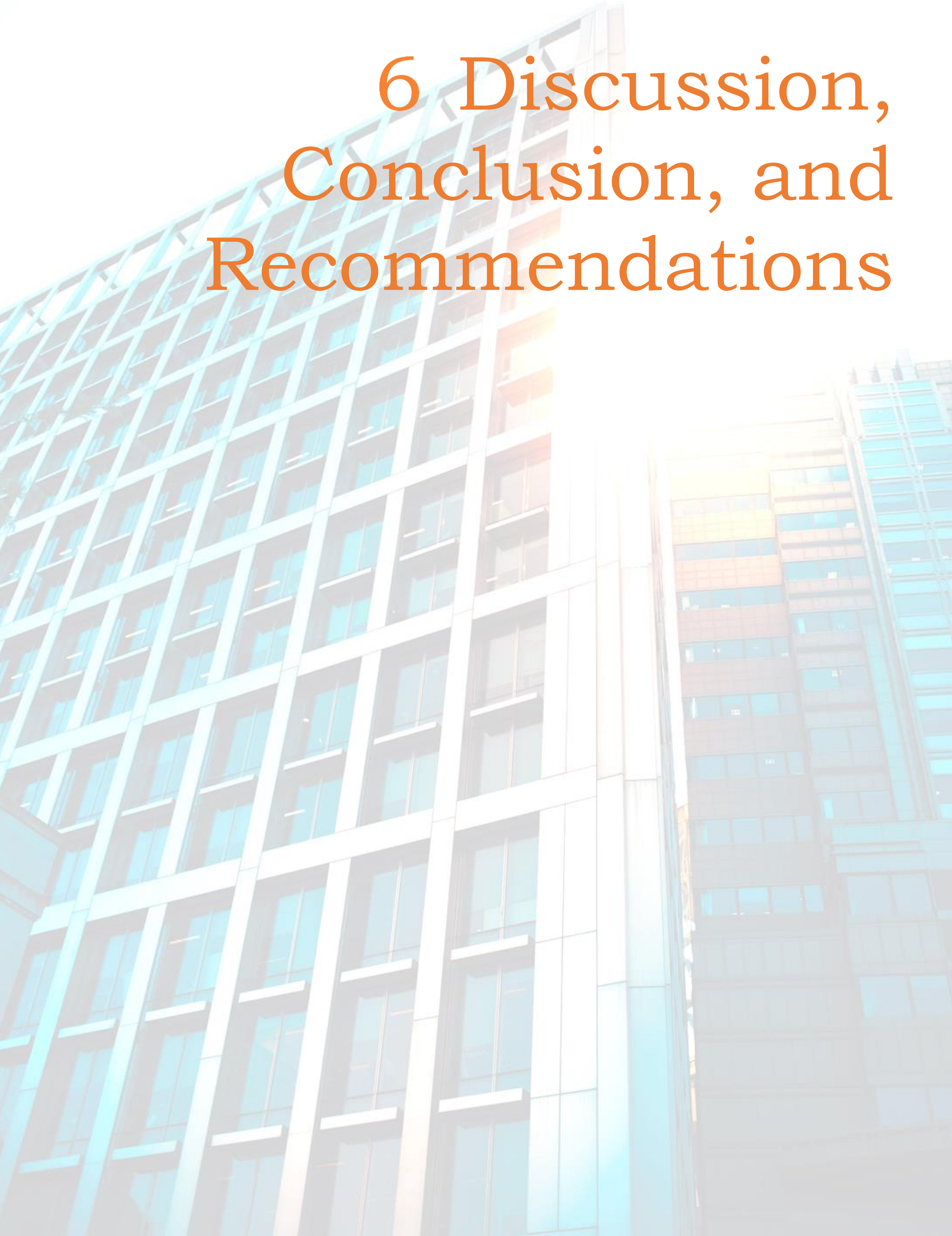
Integrability

The implications of the structure for improving other functionalities ranges from increasing energy efficiency through selection of materials, e.g. thermal bridging, to aesthetically adding value by integrating the loadbearing features in the architectural design, and from tilting the roof structure a few degrees insofar rainwater could be captured, to integrating services with the structural floor to increase flexibility of the services as well. The structural capabilities in other disciplines should be exploited in every new construction.

Facilitation and obstruction of the structure on other functionalities in a building go hand in hand. The structure should facilitate by not interfering, i.e. obstructing, other functionalities. In the Shearing Layers, depicted in Chapter 1.5, it is seen that the structure has the lengthiest service life of every functional layer in a building – lengthier than the skin, services, and spatial layout. As the service life of the other functionalities is shorter, the structure should be designed insofar that the functional layers with a shorter service life could be replaced, maintained, or altered without the structure being a barrier. If the structure would be a restriction, the service life of the entire building is reduced to the service life of that functional layer that is prone to alteration, replacement, or maintenance.

It is imperative that in every building design, the interrelationships of the structure with other functional layers within the building is examined and is exploited accordingly. The structure provides the basis for all other functionalities within a building, so from the

6 Discussion, Conclusion, and Recommendations



6.1 Discussion

The discussion chapter contains an interpretation and application of the findings made in the literature, analysis of sustainability assessment method, empirical research, and the synthesis.

6.1.1 Theoretical framework criteria

The theoretical framework criteria will be explained in detail below. Furthermore, the applicability of the criteria will be put word as well as the implications of adhering to them.

6.1.1.1 Material environmental costs

The material environmental costs are the societal costs that should be paid to compensate for the pollution made by certain materials or components. The material environmental cost is an accumulation of 11 categories that all have their own severity on the environment and, thus, the height of costs differs per indicator. It is problematic to monetize a certain environmental impact category, such as acidification or global warming potential, as it is difficult to know what the exact costs are. The material environmental costs are based on the environmental impact made within the system boundary of cradle-to-gate. This system boundary encompasses the excavation of the material, transport of the material, and manufacturing of the material.

The material environmental costs help to give an understanding of what the exact footprint is of a certain material or component. The higher the environmental costs, the higher the environmental impact. The government has set a threshold of 1-euro for new construction that may not be surpassed. Although it is a symbolic threshold, as it is easy to adhere to, the emphasis on material input is gaining attention. In the sustainability assessment methods lowering the environmental costs is incentivized.

The environmental costs are depicted in a large database. In this database, numerous materials and components are embedded. The material and components in the design can either be explicated in the database by weight – kg of steel or concrete – this usually is commonly used materials, or by selecting specific materials or components that are offered by suppliers.

The 11 categories are detailed impact indicator and are, therefore, difficult to measure one can say. The exact eutrophication of a kg of steel from an unknown place is hard to measure. Furthermore, suppliers analyse the life cycle individually and are not explicated for the public.

6.1.1.2 Service life

The estimated service life of a building is the second criteria for an eco-effective design. The estimated service life is embedded in the building codes and the specific estimated service life is set based on the function. The estimated service life of utility building is usually set on 50 years or in some cases 75 years. However, the structure of the building could far exceed the 50 or 75 years, on the condition that no structural deficiencies occur. This entails that a building is often demolished whilst the structure is still intact and could be so for an extended period of time. Although a structure could have a lengthy technical service life, the functional service life of the structure is often the cause that the structure is not applicable for other functionalities.

The building is optimized for its intended service life. As said frequently, the building and in particular the structure exceeds the intended lifespan. This means that a gap is present between the technical and the functional service life in which the technical far exceeds the functional. By that standard, the full potential of a structure is not grasped. This seems highly counter-productive in the quest for the preservation of materials.

Evidently, prolonging the service life of a building is valuable in obtaining environmental impact reductive goals as the material impact is reduced per year of being in service. However, this does not entail more durability in structural materials, components, and systems as that is not a root of demolition or replacement. It is more a functional issue than a technical or durability issue. This indicates that the structure should be able to facilitate multiple functions, or at least not obstruct functional convertibility.

Functional convertibility increases the probability of the preservation of structural materials. Functional convertibility entails that the structure facilitates alternation of the building's function, i.e. multifunctionality. Functional convertibility is a means of reducing the gap between the functional service life and the technical service life. By implementing universal functional dimensions in the design of the structure, the probability increases of prolonging the service life. As buildings are entities that are stretched over a long period of time, uncertainties of the demand for the intended increase. By incorporating universal functional dimensions, a shift in functional demands can be relatively effortlessly absorbed in the structure. Resulting in prolonging of the service life and, thus, postponing demolition, and, therefore, preserving structural materials.

The future functions are not necessarily known, there is no crystal ball. Moreover, implementation of universal dimensions increases the initial investments. For instance, the load-bearing capacity should be enlarged which is accompanied by incorporating more material, thus, an increase in costs. It is difficult to persuade a client to increase his costs if the outcome is uncertain and is troublesome to monetize.

Functional convertibility is not only ascribed to the structure. The deployment of services can also facilitate or hamper the possibility of converting to another function. Hence, functional convertibility demands an integral design.

If the structure would be able to be designed for a lengthier service life than 50 or 75 years, it should be accompanied by a change in the building design codes for environmental loads as particular safety factors and the such are based on a specific service life. A lengthier service life will also entail that other aspects of a building with a shorter lifespan, such as the envelope, have to be replaced more often which could entail a higher material input during the use-phase.

6.1.1.3 Optimization of the residual value

The material environmental costs and service life criteria fail to encompass the End of Life stage and the activities beyond in which the materials are recycled or reused. As mentioned earlier, structural deficiencies are often not the cause of demolition or replacement of the building, which entails that the structure still holds a great value when buildings/structures are demolished. By contemplating the residual value during the design of a new construction, the value could be harvested at the end of its life. Structural materials always have the possibility to be recycled, or at least to be downcycled; concrete can become granulate, steel is scrap and can become high valued steel again, and timber can become paper. However, to optimize the residual value, the structural components should be reusable one-on-one and not be downcycled. Residual value is reduced gradually during a long service life due to stresses and deformation on the structural material which lowers the probability of reusing a structural component for another structure. Also, disassembly of steel components is a problem after a long service life as the bolts are difficult to disconnect. In practice, this often leads to cutting steel components as it is more financially lucrative and time-efficient. Thus, optimization of residual value, concerning optimization of reusability and disassembly, should be accompanied by a relatively shorter life span of a structure.

Currently, the structural design is often made prior to the knowing if structural components are available in the secondary marketplace which leads to difficulty finding structural components that perfectly fit the intended design. By exploring the market beforehand, the design could be retrofitted to the secondary structural components found. Currently, the availability of secondary structural components is low, however, in the future, as governmental parties are more and more driven to increase circularity in the construction sector, the availability should increase. Next to the availability of secondary structural components other bottlenecks are present to deploy reusable structural materials in new constructions; the prices are higher than virgin materials and the quality is uncertain.

6.1.2 Service life and residual value trade-off

The ultimate issue of increasing the value of the structure is to maximize the preservation of embedded materials. The highest form of preservation of materials is to keep a building intact. By increasing the service life through the incorporation of functional convertibility, structural materials are preserved, or at least the demolition is postponed. Prolonging the service life leads to improving the efficiency of the embedded materials as its environmental impact is reduced per year utilized. However, a longer service life of a building results in depreciation of structural materials. This negatively affects the residual value of the structure. Thus, the residual value cannot be optimized when a structure is intended for a long service life. And vice-versa, when optimizing the residual value, the service life cannot be maximized.

Hence, when designing a structure for a long service life the emphasis should be put on increasing the functional performance of a building. With a long service life, the uncertainty grows for both retaining the primary function as the quality of structural components. Reusability is important in preserving; however, designing a structure insofar it could inhibit multiple functions is paramount over the implementation reusability and disassembly features. If on the short-term it is known that a building has become redundant or the location will be needed for completely other types of buildings, then the structural design should be aiming for incorporation of disassembly and reusability.

6.1.3 Doing things, the right way vs. doing the right thing

The sustainability assessment methods – BREEAM-NL, LEED, and GPR-Gebouw – are generic and broad. It fails to make distinctions for case-specific issues. This leads to compulsory adhering to categories or credits that are not necessarily productive in attaining a more sustainable building. By doing things, the right way, i.e. adhering to the assessment method, does not entail that one is doing the right thing. The assessor is the party that makes the final decision and circumventing credits, in accordance with the assessor, occurs frequently, they can be persuaded if a better option is presented to them.

6.1.4 Securing structural design features

At the beginning of the design process, during the conceptual design, design features are integrated that would not make the design prior to execution. This is often related to the costs invoked by those design features. Due to the sobering of the structural design, measures that have a positive impact on the environment tend to be cut due to their high costs with low or uncertain returns. In the case interviews, it came forward that the sustainability assessment methods are an outstanding means to secure design features. However, as of 2019, the grants are drastically cut back due to political decisions on the national government level. This could entail that the engineering costs, that are accompanied by carrying out measures from the sustainability assessment methods, are higher than the grants given. Hence, the private clients are discouraged to execute a design based on sustainability assessment methods as the business case is not cost-effective anymore – as is seen with the Friesland Campina Abel building. Thus, other means are necessary to secure sustainable measures. Measures could be secured by making the design features indispensable though incorporating it early in the conceptual design insofar it would be too costly to alter in later stages. Moreover, legislation can play an important role. Governmental legislation has proven to incentive companies, for instance, BENG and MPG should now be adhered to mandatory and the private sector follows accordingly.

6.1.5 Limitations of the research

The findings in this research are based on literature, analysis sustainability assessment methods and qualitative empirical research. The qualitative empirical research was based on surveys and interviews and, therefore, open to interpretation depending on the respondents in the survey and the interviewee.

For the survey, solely structural engineers were approached who gave a valuable manifestation on what aspects the emphasis lies during contemplation of structural design perspectives. However, a survey has its limitations; the respondents had varying roles and responsibilities within the design of the structure, this resulted in broad results but also generic and sometimes contradictory results. Also, a survey does not permit respondents to elaborate on their answers.

Additionally, for the case studies, three different cases were speculated. The cases were selected on the basis of their availability and their execution of sustainability assessment methods. Unfortunately, there were no cases available that incorporated LEED, therefore, no empirical data could be produced for LEED. The functions of the three cases comprise of a meeting building and two industrial buildings. For the two industrial buildings, the structure was subordinate to the operational activities which entail that relatively little attention was given to the real potential of the structure. Also, there were no early sustainability goals set. Although this thesis focuses on the structural design of utility buildings, it did not take with every possible building function. Analysing offices or residential buildings would also be valuable to assess. Per case three interviewees were selected – structural engineer, project manager, and the sustainability advisor. During the interviews, it became clear that the technical knowledge of what structural elements are incorporated in the design diverged per interviewee. Due to their different roles in the project team and their divergent responsibility on the conceptual structural design, not all interviews could be conducted in-depth. This, however, gave rise to the possibility of analysing external factors that drive certain decision-making from different actors in the project team.

This research tried to encompass the full scope of the potential of the structure to reduce its environmental impact over its entire life cycle. However, due to the all-encompassing nature of the research, it lacks depth in certain areas. Within this research, there are still a lot of ungrounded territories to be examined, however, due to the broad scope of this research it was not desirable go into detail on all possible subjects that add value to the overall eco-effective structural design strategy. For instance, the selection of what structural material is most applicable in the eco-effective structural design strategies would be fruitful research.

This thesis is based on qualitative analysis of the structure and its potential in adding value to reducing the environmental impact of a structure over its life cycle. In hindsight, a more quantitative approach could also be beneficial. For instance, the environmental costs database is considered as a black box in this thesis; however; as the environmental costs are widely used in practice and are mandatory to utilize since 2018, knowledge and awareness are about the environmental costs of structural material is valuable. Quantifying the eco-effective structural design strategies, it is possible to insert them for parametric design which could result in giving the structural engineer real-time feedback on their design decisions.

6.2 Conclusion

This research addresses the notion of reducing the environmental impact of a structure of a building through making decisions in the design. Below the sub-questions will be answered separately before the main research question is answered.

6.2.1 Sub-questions

From what perspectives can the structural design be approached to maximize its eco-effectiveness?

Through reviewing the literature, ten structural design perspectives are identified that encapsulate all possible angles to maximize the structure's eco-effectiveness. The design perspectives encapsulate the entire life cycle of the structure; from cradle to cradle. *Material selection* and *material use* focuses on the initial environmental costs made in the product stage and both have a knock-on effect on the subsequent life cycle stages; *durability, maintenance, flexibility,* and, *adaptability* cover the use stage; whereas, *waste effectiveness, reusability, disassembly,* and, *recycling* reduces the environmental impact made during the end of life stage as it increases the potential for the structure to be used in a subsequent cycle. Together these design perspectives form the basis of potentially maximizing the eco-effectiveness of a structure. In Figure 20, the ten structural design perspectives are depicted.

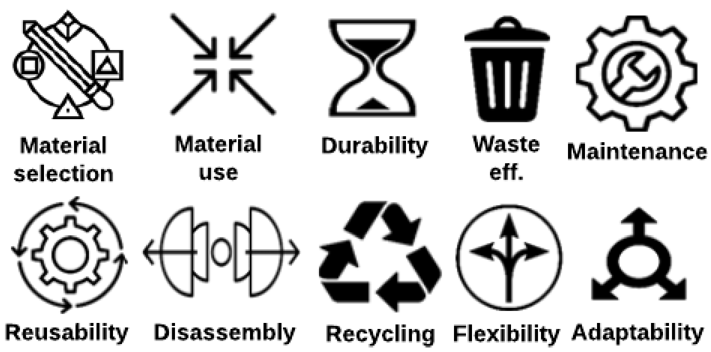


Figure 36: Ten design perspectives to approach the design of a structure to increase the structure's eco-effectiveness (own illustration)

What structural design criteria should be adhered to for an eco-effective design and what eco-effective structural design strategies encompass these criteria?

The above-depicted structural design perspectives are merged into three criteria – material environmental costs, service life, and residual value. Each has their own value and purpose in the design of an eco-effective structure. In Figure 37, the perspective of material selection and material use is merged into the *material environmental costs*; and the durability, maintenance, flexibility, and adaptability add to the extension of the *service life*. The material environmental costs combined with the service life are excellent gauge to measure the environmental impact caused by a material over a certain period of time. However, it fails to incorporate the embedded material value of the structure which could be harvested after the service life has ended. For that segment of the life cycle, the perspectives of reusability, disassembly, and recycling are merged into the criterium: *residual value.*

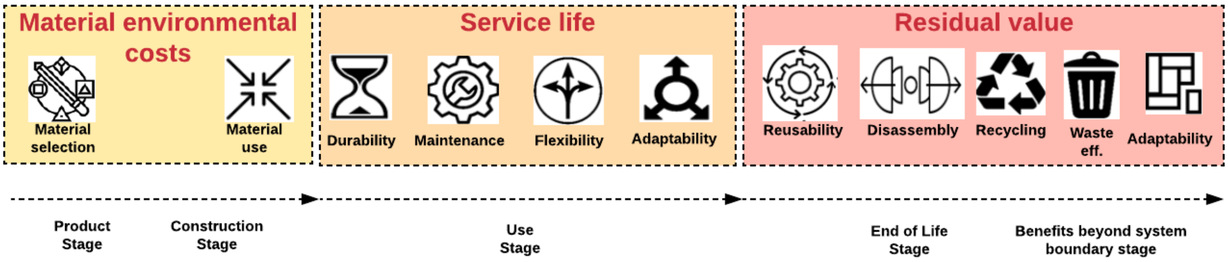
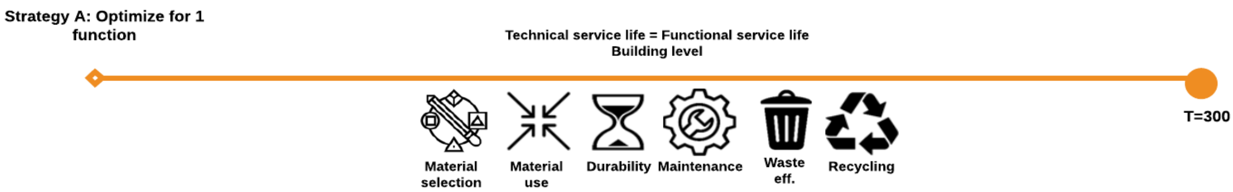


Figure 37: Clustering of structural design perspectives into material environmental costs, prolonging of the service life, and the optimization of residual value. (own illustration)

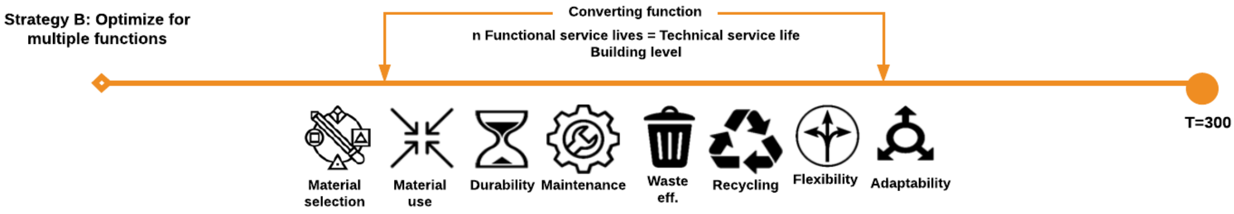
Examining the three criteria, one could not approach every criterion individually without affecting the other. If, for instance, the main focus would be put on minimizing the material environmental costs, it would have an adverse effect on the service life, and vice-versa. Additionally, putting emphasis on solely prolonging the service life of a structure, would decrease the value that can be obtained at the end of life of the structure, and vice-versa. From which can be concluded, that there is not one optimal eco-effective structure. Hence, three strategies are constructed. The strategies are focused on the two latter eco-effective design criteria as the material environmental costs are subordinate to the service life and residual value.

A structure has multiple service life's, wherein the technical and functional service lives are the most crucial when designing the structure. The technical lifespan of internal structural parts is generally endless, on the condition it is revised periodically. Nonetheless, due to change in building function needs, the function within the structure often does not reach the full technical longevity of the building structure. Consequently, when focusing on the structural design on prolonging the structure's service life, the building's service life should either fulfil its technical service life or, at least, surpass the functional service life either on a building level or on a system/components level.

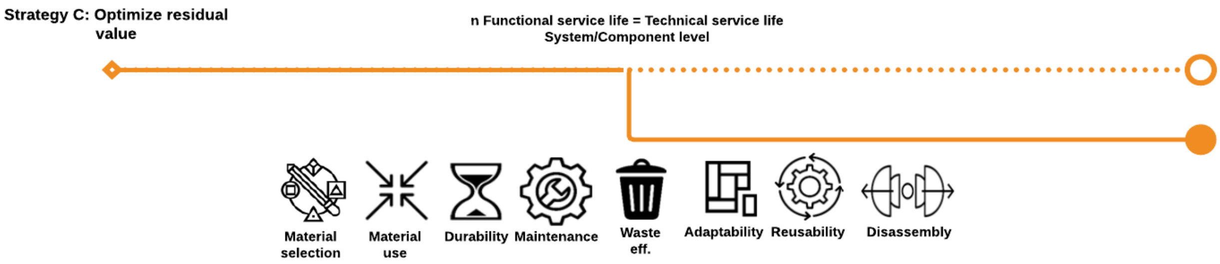
The three strategies are a focus on preservation of the initial embedded materials. In the waste hierarchy, the highest possible form of material preservation is avoiding activities and reducing material input followed by reusing materials. From this premise, three eco-effective structural design strategies can be established.



In Strategy A, the technical service life is maximized, and equalized with the functional service life on a building level. For this strategy, it is imperative that only function will inhabit the structure, as the initial material environmental costs can be optimized accordingly. Examples for this strategy are temples, churches, and museums. These functions are seldom prone to change in user needs as they have sentimental value. As the service life is maximized, the residual value can and should, therefore, not be optimized and recycling of those structural materials is highest possible option of subtracting value out of the structure.



In Strategy B, the initial function is uncertain to stand the test of time. As the technical service life on a building level is maximized, within the design of the structure conditions should be integrated for potential functional conversion. Resulting in closing the gap between the technical and the functional service life as multiple functions could inhabit the structure. Examples for this type of building are offices, commercial buildings, and dwellings.



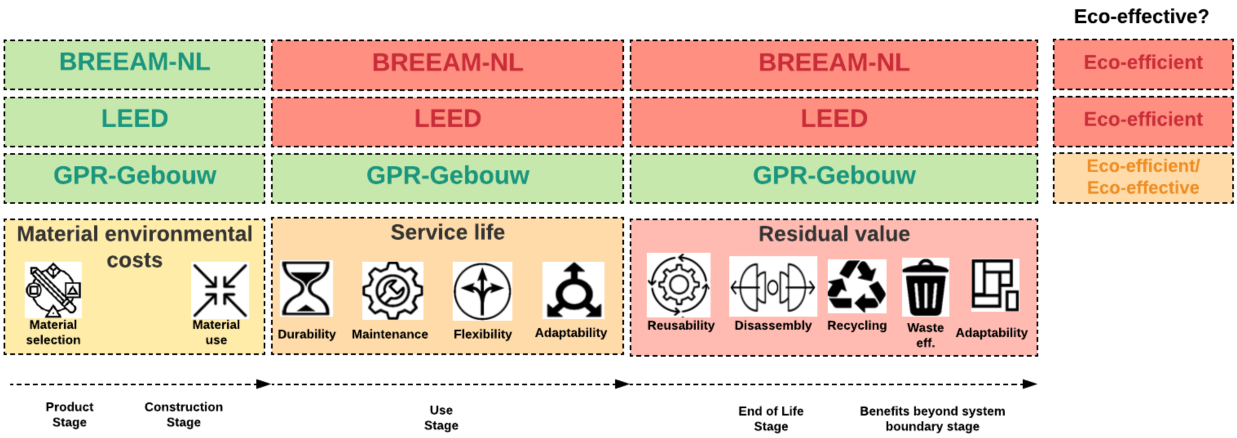
In Strategy C, the functional service life is known to be outdated in a relatively short time span. Although the technical service life on a building level is temporary, the technical service life of the structural systems and components is not. From the knowledge of designing a structure with a short life span, the design of the structure should direct its focus on optimizing its residual value. The value of the technical durability of structural systems and components should be able to be harvested during the end of life of the structure. By incorporating conditions for the structure to be dismantled, the structural systems and components could be utilized for subsequent projects in their primary shape. Examples for these buildings are agricultural buildings, warehouses, and parking garages.

Do BREEAM-NL, LEED, and GPR-Gebouw represent the eco-effective structural design criteria and strategies?

On the basis of the established eco-effective structural design criteria and strategies, the sustainability assessment methods – BREEAM-NL, LEED, and GPR-Gebouw – have been analysed and compared. All three assessment methods stimulate the reduction of initial material environmental costs. However, BREEAM-NL and LEED, do not incorporate the service life and residual value of the structure in their assessment. In both assessment methods, the service life of a building is fixed dependent on its function on either 50 or 75 years. Moreover, no mention is given on disassembly or reusability of the structure after the building has been in service. From which can be concluded, that BREEAM-NL and LEED, are more focused on the short-term environmental impact reduction possibilities of a structure, in opposition to the long-term which is inherently important for grasping the structure's full potential. Thus, BREEAM-NL and LEED both adhere to the eco-efficient paradigm.

On the contrary, GPR-Gebouw both incorporates the notion of prolonging the service life of a building as it does stimulate to increase the potential of harvesting the residual value. This service life can be prolonged in GPR-Gebouw by adhering to the following three variables; *high internal amenity value, high external amenity value*; and *high accommodating value*. By adhering to these variables, the probability of a lengthy service life is increased. This is more realistic as the technical service life of a building usually exceeds the 50- and 75-year threshold, as it is also beneficial for the overall environmental costs. Moreover, credits are integrated into GPR-Gebouw insofar the possibility should exist and is simplified to dismantle the structure to be used in its pristine form.

Although GPR-Gebouw incorporates all three criteria, the notion of them being irreconcilable is not explicitly assimilated in the assessment method. This entails that prolonging the service life is simultaneously stimulated with incorporating structural design features for the structure to be dismantled. Although GPR-Gebouw is the most comprehensive method when designing the structure to be eco-effective, GPR-Gebouw does not encapsulate the full potential of the eco-effective structural design strategies.



What factors steer the extent to which structural design features are incorporated that contribute to maximizing the structure's eco-effectiveness?

In the case studies, several factors have been identified that are of influence on the incorporation of eco-effective structural design features. Moreover, it is determined that there is no optimal eco-effective structural design and that within the structural design criteria dilemmas exist. In particular, the friction between the prolonging of the service life and the optimization of the residual value of a structure. The following factors determine what eco-effective strategy should be adhered to and what factors are influential during the course of the design phases.

The goal of the client: an important factor is the goal of the client and what they have envisioned for the structure in the building. Early stated goals and focal points on the structure tend to have a positive influence on the incorporation of structural features in the conceptual design and, thus, have a greater probability to reach the final design. However, the client could also be persuaded into setting specific goals. The following factors are implicit in the goal of the client.

Function: the function is embedded within the goal of the client. The primary function of a building is a crucial variable to what extent a structural design strategy is eco-effective. The structure for industrial purpose differs tremendously with the structure of an office. A distinction can be here between a *static* use of a building and *dynamic* use of a building. In a static building, the structure is subordinate to the operational activities for which the structure's main function is to be reliable, whereas, with a dynamic building, the structure is intended for humans, in which the structure should be more facilitating flexibility. Moreover, accompanied by the function is the perceived service life. This can be either aimed at a lengthy service life, in which functional convertibility is strongly suggested, or it is aimed at a structure with relative short service life, in which optimization of residual value is advised.

Socio-economic considerations: the location and the surroundings of a building are important for the future capabilities and applicabilities of a building. If a building is nearing its end of life as the function of that building becomes outdated, structural design features to convert functionalities could give a building the potential for a new life. However, the location within its environment is an essential determinant what type of function is suitable. As an example, a building on an industrial site has a low probability to be an office or have a residential purpose. Moreover, if a client knows that the site is in need of other purposes in the future, the design of the structure should adapt to that.

Financial implications: the costs of implementing structural features rise in importance as the design phases progress. The return of investment on incorporating structural design features are uncertain and difficult to predict, in contrast to operational costs such as increasing energy efficiency. The initial investments are relatively high. Therefore, structural design features tend to be cut back due to high initial investments and uncertain yield in the future.

Dependency on other functionalities: to realize the true potential of a structure, the design of a building should be approached from an integral viewpoint. The interaction with other disciplines is key to maximize the value of the structure on the long-term. The structure is the basis of the performance of a building; however, without corresponding coordination of installations (HVAC, electrical, sanitation) a building is not versatile or convertible. The overall performance of a building is grounded in the coupling of disciplines.

Dependent parties: as the design progresses towards the execution stage, external actors enter the project team. The implementation of structural design features into action is, thus, dependent on the knowledge and capabilities of the contractor. Furthermore, the origin of materials and ingredients of materials are the responsibility of the contractor. Therefore, for the eventual performance of the structural materials one is reliant upon the contractor and its suppliers.

6.2.2 Main research question

How can the eco-effectiveness of the structure be maximized and is the eco-effective structure represented in sustainability assessment methods?

Through answering the sub-questions, the main research question can be answered accordingly. The main research question consists of two elements. First, on how the structural design should be approached to maximize its eco-effectiveness. And secondly, if the optimal structural design is adequately expressed in the sustainability assessment methods BREEAM-NL, LEED, and GPR-Gebouw.

Firstly, individual structural design perspectives were identified which are portrayed in, Figure 36. Furthermore, these perspectives are merged into three criteria - material environmental costs, service life, and residual value. A structure is a material-intensive entity, and to minimize its environmental impact over its life cycle, one should seize the full potential of the embedded structural materials. Regularly, buildings are demolished while the structure is undamaged, and thus still holds great value, i.e. the technical service life is often not the cause of demolition. However, the structure is often a hindrance as it does not facilitate functionalities that the marketplace is in need for. This is highly ineffective use of structural materials. The gap between the functional service life and the technical service life should be diminished for the true potential of the structure to come to light. However, the true eco-effective potential of a structure is differently approachable as it is conditional to the requirements within and around a building.

By adhering to the established framework, the whole life cycle's environmental impact of the structure is enclosed. However, it has been identified that fundamental friction is present within the structural design criteria. The condition of the residual value of structural components is reliant upon the intended and actual service life of the building, or structure. By explicating design viewpoints, the emphasis on the framework is shifted from either incorporating functional convertibility to curtail the technical and functional service life by increasing the probability of inhibiting other functions, or to optimize the residual value by creating conditions for disassembly, and, therefore reusability of structural components.

The distinction between the strategies is grounded in vital factors that steer the decision to adhere to a specific eco-effective design strategy. The most important aspect is the function the structure will inhabit, the function is derived from the goal of the client. Subsequently, as the function is known, one should examine the socio-economic tendencies within the building and surrounding the building. From this, the intended service life can be deducted, and the aptest eco-effective structural designs strategy can be distinguished. Moreover, factors were identified that are important to consider during the design phases as they could be counterproductive for the final structural design. These factors are financial implications, dependency on other functionalities, and dependency on other actors.

This thesis has been focusing on the eco-effectiveness of a structure. However, the structure is not only a material entity, but it could also facilitate, improve, and even obstruct other disciplines within a building. Therefore, an extra structural design perspective should be adhered to whilst designing a building; *integrability.* Moreover, the structure is also dependent on other functional layers as they could also be a hindrance in grasping the full potential of an eco-effective structure. The structure lays the basis for all other disciplines within the building; thus, it is imperative that one should keep in mind the interrelationships of the structure with the skin, services, and spatial layout.

Secondly, the sustainability assessment method that is most representative for maximizing the eco-effectiveness of the structure is GPR-Gebouw. GPR-Gebouw encloses the full life cycle environmental impact of the structure in which the service life can be expanded whilst optimization of residual value stimulated. Both criteria are not integrated in assessments of BREEAM-NL and LEED, this entails that the whole life cycle and its possibilities to lower the environmental impact of the structure are not encapsulated within BREEAM-NL and LEED. Although, GPR-Gebouw is most suitable for an eco-effective design, it does not make a distinction between the eco-effective criteria service life and residual as they are all embedded within the same assessment. As no distinction is made, the focus within GPR-Gebouw can both be on prolonging the service life as optimizing the residual value, which is not contributory in eco-effectively designing the structure.

6.3 Recommendations

This chapter introduces the recommendations that are subtracted from the discussions and conclusions made in this research. Firstly, recommendations are provided for Arcadis B.V.; secondly, recommendations are given for sustainability assessment methods; and lastly, recommendations are given for future research.

6.3.1 Recommendations for Arcadis

In the future, the embodied impact of a building will increase in importance due to the increase in efficiency of the operational impact. This entails that the structure will enclose a larger portion of the overall environmental impact a building incurs. This research has put forward structural design criteria that encapsulate the entire life cycle of a structure and established structural design strategies that maximized the structure's eco-effectiveness. In Figure 38, the framework that could be utilized by Arcadis is presented.

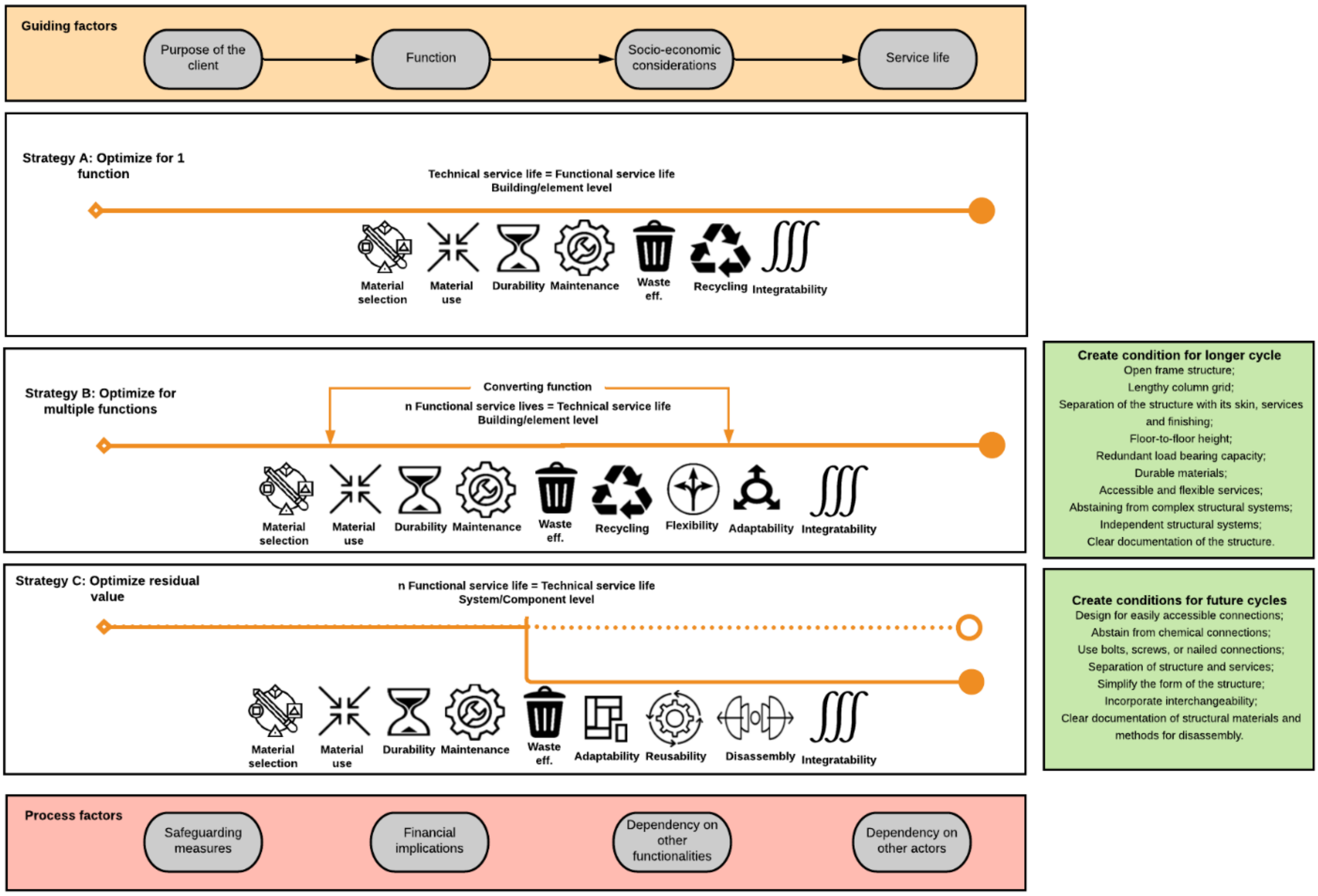


Figure 38: Eco-effective structural design framework (own illustration)

6.3.1.1 Utilizing the framework

This framework is a composition of the established theory in Chapter 2 and the synthesis of the theory with the empirical research in Chapter 0. The framework should be read from top to bottom. The framework will be clarified on the next page.

Guiding factors

Firstly, the guiding factors should be contemplated before adhering to a specific eco-effective strategy. The purpose of the client should firstly be demarcated in which the user needs are explicated accompanied by their internal consequences for the intended building. By stating the goal of the client, the function of the building is known. By identifying the function, a distinction can already be made between choosing either Strategy A if the function is known to stand the test of time, or either Strategy B and Strategy C. Furthermore, from the goal of the client the distinction can also be made between Strategy B or Strategy C. However, the client's goal could be ambiguous in its future application of the structure. If it is ambiguous, the socio-economic factors should be considered. This is location dependent. The socio-economic tendencies should be examined what the options are for the structure in the future. Either, the structure could stay for an extended period of time and possibly inhabit multiple functions, that one should adhere to Strategy B. If the structure will become obsolete in the near future, adherence to Strategy C is advised.

Strategy A, B, and C: Conservation of materials

The initial material usage of a structure is significant. By trying to either avoid material usage or incorporate materials that already have surpassed a cycle will reduce the environmental impact of a structure significantly.

Approach 1a: abstain from new construction

Evidently, this is the most environmentally friendly approach; however, this falls outside of the scope of this research as it is focused on designing new constructions. Nevertheless, it is recommended to first investigate possibilities to make use of other structures for the intended function which is aspired for.

Approach 1b: reuse structural materials

Structural materials that already have surpassed a cycle already impacted the environment, thus, by reusing structural materials initially, the environmental impact of a structure will decrease substantially. For implementing reused structural materials, one has to examine the market prior to beginning the conceptual phase as the design could follow according to the dimensions of the structural components.

Approach 1c: use secondary materials

By using secondary structural materials, or recycled materials, less virgin materials have to be excavated, resulting in a lower initial environmental impact.

In all strategies, the following structural design perspectives play a role: structural material selection, structural material use, technical structural durability, maintenance, and integrability. In every strategy, it is important to strive for lowering of the material environmental costs. Evidently, on the condition that the structure is technical durable either on building, system, or component level to maximize the technical service life on building level or on system/component level.

Strategy B: Create conditions for a longer cycle

Prolonging the service life is important for preserving already existing structural materials. Although it could entail that more material has to be applied, by extending the service life the yearly embodied impact will decrease. By incorporating functional convertibility features, the structure could be exploited for other functions resulting in an increase of the probability that the gap between the functional service life and the technical service life is thwarted. The following key principles should be adhered to when creating conditions for a lengthy cycle.

Open frame structure;
Lengthy column grid;
Separation of the structure with its skin, services and finishing;
Floor-to-floor height;
Redundant load-bearing capacity;
Durable materials;
Accessible and flexible services;
Abstaining from complex structural systems;
Independent structural systems;
Clear documentation of the structure.

Strategy C: Create conditions for future cycles

If the building is known to have a relatively short service life; one should incorporate structural design features that optimize the residual value, so that the structural components could be utilized for subsequent purposes. The following key principles should be adhered to when contemplating the optimization of residual value.

Design for easily accessible connections;
Abstain from chemical connections;
Use bolts, screws, or nailed connections;
Separation of structure and services;
Simplify the form of the structure;
Incorporate interchangeability;
Clear documentation of structural materials and methods for disassembly.

Integrability

The effect of structural design decisions should always be coordinated with other functional layers such and vice-versa. The eco-effectiveness of the structure can only be maximized if it's in accordance with other functional layers.

Process factors

During the process of the design, it has proven to be difficult to maintain early made design decisions on the basis of several factors. Actively safeguarding design measures and coordination of design alterations, the ultimate design should be aimed to resemble the early design. The focus of total costs of ownership shifts towards the initial investments during the design stages. Furthermore, as several disciplines are needed for a building to be serviceable, functionalities in a building should be constantly coordinated with each other. Generally, in later stages of the design, contractors are introduced to the design team.

6.3.1.2 General recommendations

The framework presented above takes a step in the direction of maximizing the structure's eco-effectiveness. Besides the framework, general recommendations for Arcadis are presented that are based on interesting findings made during the interviews which can to a certain extent be linked to the eco-effective structure's design.

Embark on "Doing the right thing"

The sustainability assessment methods have proven to be not applicable for designing a true eco-effective structure. However, they still have a valuable function in giving the design team a means to grasp onto and, therefore, making the direction of the design unambiguous for the whole project team. Moreover, the willingness of the structural engineers to contemplate sustainability inquiries have proven to be well embraced. Nonetheless, the structural engineers are in need of an instrument to adhere to and convey their design decisions. By constructing a specific tool for the design of a structure – next to the sustainability assessment methods - ambiguous aspects can be left out and the most value can be obtained from the structure. Resulting in a shift from doing things, the right way in sustainability assessment methods to doing the right thing. As the sustainability assessment methods are often circumvented in consultation with the assessor due to the broad and generic nature of the assessment, the assessors should be able to be persuaded when presented a more effective design.

Seizing knowledge

During the interviews and the time being at Arcadis, it became apparent that the willingness of the structural engineers is high. This means that awareness is present. However, it was also seen that the structural engineer lacks the knowledge and the means to know what possible and what aspects should be focused on. The sustainability assessment methods also have proven to be a learning experience for structural engineers. Moreover, the knowledge within Arcadis seems to be diffused. In a large company like Arcadis, there is a lot of knowledge present. Although it may seem as imperative, the knowledge could and should be seized.

6.3.2 Recommendations for sustainability assessment methods

In the thesis, the sustainability assessment methods BREEAM-NL, LEED, and GPR-Gebouw are scrutinized in detail on their incorporation of the capabilities a structure possesses. Below some recommendations are given that would increase the notion of the structure as well as increase the value that could be obtained from it.

Division in the material credit

All materials embedded in the building are part of the same credit. There should evidently still be a parameter that puts the material impact all together but when looking at the score, one cannot deduce what materials are underlying that score. For instance, with Hoogvliet, the material category had a score of 70%, however, that was mostly due to the deployment of solar panels. A division between the material impact of the structure and other embedded materials could give the structure a more prominent spot in reducing the overall material impact.

Encompass the entire life cycle

From eco-efficiency to eco-effectiveness. The sustainability assessment methods – especially BREEAM-NL and LEED – do not incorporate the notion that the structure has embedded value either preserved on a building level or a system/component level. As buildings tend to have a lengthy lifespan, the focus should also be on the future. However, the assessment methods mostly focus on short-term issues when assessing material input rather than its future value. Both for extension of the service life as for optimization of residual value credits should be integrated to improve the effectiveness of the assessment methods. Lessons can be derived from the assessment methods GPR-Gebouw.

Integrate optionalities for specific focus

Although lessons can be learned for BREEAM-NL and LEED from GPR-Gebouw, this assessment method still lacks the strength to truly embrace the eco-effectiveness of a structure. This is due to the fact that sustainability assessment methods are generic and broad and do encapsulate every notion into the same rating. By integrating options to redirect its focus on credits that are of essence for a specific project, more value can be derived from deploying an assessment method. This is also part of the focus shift from doing things, the right way towards doing the right thing.

6.3.3 Recommendation for future research

From the limitations set forward in the discussion chapter, several gaps were identified that through research could be beneficial towards increasing the potential of structural design in relation to reducing its environmental impact.

- **Approach the structural design framework quantitively –** this research provided a qualitative step towards a more environmental advantageous structural design. Criteria in the framework could be quantified and research into this quantification could give more substance to the framework.
- **Environmental parametric design –** structural engineers could be helped in their design decision-making by being provided immediate environmental impact data on their design decisions.

Parametric design with environmental impact feedback could minimize the initial material environmental impact.

- **Other building functions–** the applicability of the theoretical framework should also be tested on more building functions than is done in this research. More guiding and process factors will evidently exist.
- **An in-depth study of structural materials –** the structural materials that are most applied are steel, concrete, and timber. Analysing the applicability of the three structural materials with the structural design perspectives and the theoretical framework could produce valuable information on using structural elements under certain circumstances.
- **Examine and compare other categories within sustainability assessment methods –** in this research GPR-Gebouw has proven to be the victor. However, this was concentrated on the structure whereas all three sustainability assessment methods are much broader in scope. By knowing what assessment methods best applicable in what category, one can consider and learn from that.
- **Operational vs. Embodied –** all the materials embedded in a building are incorporated in the final environmental costs. This also pertains materials from PV-solar panels, which is detrimental for the overall environmental costs. Research into the exact relations between operational impact and embodied impact could be helpful for sustainability assessment methods.
- **The validity of environmental costs –** the database portrays the environmental costs of materials based on 11 indicators. The question arises how the environmental costs are precisely measured. The environmental costs black box.
- **Assessing the dichotomy of service life vs. residual value –** Strategy B and C are both strategies that optimize the residual value. Strategy B focusing on the residual value on building level and Strategy C focusing on residual value on component level. The question arises what the service life is of a structural component? When is it not useful for subsequent function? Further research is vital for making the distinction between Strategy B and Strategy C.
- **Examine the buildings codes:** the applicability of the eco-effective structural design strategies does not coincide with the building as in the building codes the service life is fixed. The length is dependent on the function. Therefore, the buildings are optimized for that specific fixed service life. Examining the possibility to alter the notion of fixed service could increase the applicability of the theoretical framework. Moreover, reformulating the service life in the building codes could have positive effects for value preservation in the long term.
- **More detailed guiding factors:** only three cases were examined (two industrial functions and one casino), therefore, it was difficult to truly make the distinction between the service life and residual value. Research into more building functions could be beneficial for identifying guiding factors in more detail.

References

A. Best, D. B. (2008). *Potential of the Ecological Footprint for monitoring environmental impacts from natural resource use.* DG Environment: Report to the european commission.

ABN AMRO. (2017, 10 3). *Utiliteitsbouw.* Retrieved from Insights ABN AMRO: https://insights.abnamro.nl/branche/utiliteitsbouw/

Anderson, J. E., & Silman, R. (2009). The role of the structural engineer in green building. *International Association for Bridge and Structural.*

ASCE, J. M. (2011). Sustainable Structural Design Methodologies. *Practice Periodical on Structural Design and Construction*, 186-190.

Atieno, O. (2009). An Analysis of the Strengts and Limitations of Qualitative and Quantitative Research Paradigms. *Problems of Eduction in the 21th Century.*

Baarda, B. (2010). Research. This is it! Guidelines for setting up, doing and evaluating quantitative and qualitative research. *Noordhoff Uitgevers B.V.*

Best, A., Blobel, D., Cavalieri, S., Giljum, S., M. Hammer, S., Lutter, C., . . . Lewis, K. (n.d.). *Potential of the Ecological Footprint for monitoring environmental impacts from natural resource use.*

Birgisdóttir, H., Houlihan-Wiberg, A., Malmqvist, T., Moncaster, A., & Rasmussen, F. N. (2016). *Strategies for Reducing Embodied Energy and Embodied GHG Emissions: Guideline for Designers and Consultants - Part 2.* International Energy Agency.

Blok, R., & Herwijnen, F. v. (2005). Flexibility of Building Structures. *Improvemnt of Buildings Structural Quality by New Technologies*, 73-79.

Bragança, L., Mateus, R., & Koukkari, H. (2010). *Building Sustainability Assessment.* 2010-2023: Sustainability.

Bragança, L., Vieira, S. M., & Andrade, a. J. (2014). Early Stage Design Decisions: The Way to Achieve Sustainable Buildings at Lower Costs. *The Scientific World Journal.* doi:http://dx.doi.org/10.1155/2014/365364

Brand, S. (1994). *How buildings learn: What happens after They're Built.* London: Penguin Books.

Braungart, M., McDonough, W., & Bollinger, A. (2006). Cradle-to-cradle design: creating healthy emissions - a strategy for eco-effective product and system design. *Journal for Cleaner Production*, 1-12.

BRE. (2017). *BREEAM-NL Nieuwbouw en Renovatie: Keurmerk voor duurzame vastgoedobjecten.* Building Research Establishmet.

Buckley, & Chiang. (1976). *Research Methodology and Business Decisions.* Cananda: National Association of Accountants.

Buitelaar, E. M., van den Berge, F., van Dongen, A., Maarseveen, R., & Weterings, A. (2017). *De toekomst van kantoren Een scenariostudie naar de ruimtebehoefte.* Den Haag: PBL en CPB.

Buyle, M., Braet, J., & Audenaert, A. (2012). LCA in the construction industry: a review . *RenewableandSustainableEnergyReviews.*

Caruso, M. C., Menna, C., Asprone, D., & Prota, A. (2018). LCA-Based Comparison of the Environmental Impact of Different Structural Systems. *IOP Conference Series: Materials Science and Engineering.*

CE Delft. (2017). *Handboek Milieuprijzen 2017.* Delft: Ministerie van Infrastructuur en Milieu.

Circle Economy. (2015). *Circular Construction: the foundation under a renewed sector.* Circle Economy & ABN AMRO. Retrieved from https://www.slimbreker.nl/downloads/Circle-Economy_Rapport_Circulair-Construction_05_2015.pdf

Cole, R. (2010). Building Environmental Assessment in a Global Market. *International Conference of Sustainable Building Asia.*

Cole, R. J. (2011). Transitioning from green to regenerative design. *Building Research & Information*, 39-53. doi:10.1080/09613218.2011.610608

Consoli, F., Allen, D., Boustead, I., Fava, J., Franklin, W., Jensen, A., . . . Vigon, B. (1993). *Guide Lines for Life-Cycle Assessment: A 'Code of Practice'.* Florida, U.S.A.

Crotty, M. (1998). *The Foundations of Social Research: Meaning and Perspective in the Research Process.* Thousand Oaks: SAGE publications.

Curran, M. (2014). Strengths and Limitations of Life Cycle Assessment. In *Challenges in Life Cycle Assessment: An Overview of Current Gaps and Research Needs* (pp. 189-206).

Danatzko, J. M., & Sezen, H. (2011). *Sustainable Structural Design Methodologies*, 186–190.

Danatzko, J. M., Sezen, H., & M.ASCE. (n.d.).

DeSimone, L., & Popoff, F. (1997). *Eco-efficiency: The Business Link to Sustainable Development.* Massachusetts: World Business Council for Sustainable Development 2000.

Dhillon, B. (1989). *Life cycle costing.* New York.

Dias, W. P. (2003). Useful life of Buildings. *University of Moratuwa.*

Ding, G. (2007). SUSTAINABLE CONSTRUCTION – THE ROLE OF ENVIRONMENTAL ASSESSMENT TOOLS. *School of the Built Environment.*

Dodge Data & Analytics. (2018). *World Green Building Trends 2018: Smart Market Report.* Bedford: Dodg Data & Analytics.

Dossche, C., Boel, V., & Corte, W. D. (2017). Use of Life Cycle Assessments in the Construction Sector: Critical Review. *Elsevier: Procedia Engineering*, 302-311.

Durmisevic, E. (2006). *Building Structures: Design for assesmbly as a way to introduce sustainable engineering to building design & construction.* Delft: Delft University of Technology.

Durmisevic, E., & Noort, N. (2003). RE-USE POTENTIAL OF STEEL IN BUILDING CONSTRUCTION .

Eisenhardt , K. (1989). Building theories from case study research. *Academy of Management Review*, 532-550.

Elkington, J. (1997). *Cannibals with Forks: The Triple Bottom Line of 21st Century Business.* Oxford: Capstone Publishing Ltd.

Fay, R., & Treloar, G. (1998). Life cycle energy analysis – a measure of the environmental impact of buildings. *Environment Design Guide*, 31-41.

Geissler, S., Larsson, N., Henriksen, C., Schuler, M., & Balcomb, D. (2000). Examples of Integrated Design: Five low energy buildings created through integrated design. *IEA Solar Heating and Cooling Task 23* .

Gijsbers, R. (2006). Towards adaptability in structures to extend the functional. *International Conference of Adaptable Building Structures.*

Graham, P. (2003). *Building Ecology: First Principles for a Sustainable Built Environment.* Oxford, U.K.: Blackwell.

Guinée, J. (2002). *Handbook on Life Cycle Assessment.* Eco-Efficiency in Industry and Science.

Guinée, J. (2016). Life Cycle Sustainability Assessment: What Is It and What Are Its Challenges? *Taking Stock of Industrial Ecology*, 45-68.

Gummesson, E. (2000). *Qualitative Methods In Management Research.* SAGE Publications.

Häkkinen, T. (2011). Barriers and drivers for sustainable building. *VTT Technical Research Centre of Finland, Espoo, Finland* .

Hammond, G. P., & Jones, C. I. (2008). Embodied energy and carbon in construction materials. *Proceedings of the Institution of Civil Engineers - Energy*, 87-98.

Hayes, R. (2013). Embodied Energy Calculations within Life Cycle Analysis of Residential Buildings.

Hermans, M. (1999). BUILDING PERFORMANCE STARTS AT HAND-OVER: THE IMPORTANCE OF LIFE SPAN INFORMATION - Performance-over-time and life span information. *Durability of Building Materials and Components 8*, 1867-1873.

Holton, J. A. (2010). The Coding Process and Its Challenges. *The Sage handbook of grounded theory.* , 265-289.

Huang, L., Krigsvoll, G., Johansen, F., Liu, Y., & Zhang, X. (2018). Carbon emission of global construction sector. *Elsevier*, 1906-1916.

Hultgren, A. (2011, June 1). *Global Buildings and Construction: Energy and Environmental Impacts.* Retrieved from Kleiwerks: http://www.kleiwerks.org/wp-content/uploads/2012/11/Buildings-Energy-and-Carbon.pdf

Hussain, A. (2012). Sustainable Structural Design. *International Journal of Research in Engineering & Applied Sciences.*

Ilhan, B., & Yobas, B. (2019). Measuring construction for social, economic and environmental assessment. *Engineering, Construction and Architectural Management.*

IPCC. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Geneva, Switzerland: IPCC.

IPCC. (2014). *Fifth Assessment Report .*

Itard, L. (2009). Embodied and operational energy use of buildings. *CMS 2009 - Life cycle design of buildings, systems and materials, University of Twente, The Netherlands*, 77-84.

Johnson, R., Onwuegbuzie, A., & Turner, L. (2007). Toward a Definition of Mixed Methods Research. *Mixed Methods Research International Research Association.*

Jolliet, O., Brent, A., Goedkoop, M., Itsubo, N., Mueller-Wenk, R., Peña, C., . . . Stewart, M. a. (2003). *Final Report of the LCIA Definition study, Life Cycle Impact Assessment Programme of the UNEP/SETAC Life Cycle Initiative.* Lausanne: Life Cycle Initiative.

JW, B., & H., C. (1976). *Research Methodology and Business Decisions.* Canada: National Association of Accountants.

Kaethner, S. a. (2012). Embodied CO2 of structural frames. *The Structural Engineer*, 33-40.

Kajikawa, Y., Toshihiro, I., & Goh, T. N. (2011). Analysis of building environment assessment frameworks and their implications for sustainability indicators. *Sustainability Science*, 233-246.

Kemp, R., & Martens, P. (2017). Sustainable development: how to manage something that is subjective and never can be achieved? *Sustainbility: Science, Practice and Policy*, 5-14.

Kesik, T. J. (2016). Building Enclosure Design Principles and Strategies. *National Intitute of Building Sciences*, http://www.wbdg.org/resources/building-enclosure-design-principles-and-strategies.

Khareen, M., Banfill, P., & Menzies, G. (2009). Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. *Sustainability*.

Klöpffer, W. (2008). Life cycle sustainability assessment of products. *Int J Life Cycle Assess 13(2)*, 89–95.

Kudryashova, A., Genkov, A., & Mo, T. (2015). Certification Schemes for Sustainable Buildings: Assessment of BREEAM, LEED and LBC from a Strategic SustainableDevelopment Perspective. *Master Thesis*.

Lee, W., & Burnett, J. (2008). Benchmarking energy use assessment of HK-BEAM, BREEAM and LEED. *Building and Environment*, 1882-1891.

Lima, C. (2017, 05 29). *Triple Bottom Line: Sustainability and Energy Efficiency*. Retrieved from Viridis: https://viridis.energy/en/blog/triple-bottom-line-sustainability-and-energy-efficiency

Lindner, S., Braungart, M., & Essig, N. (2019). Comparison of eco-effectiveness and eco-efficiency based criteria for the construction of single-family homes., (p. IOP Conf. Series: Earth and Environmental Science).

Logistic Management Institute. (1965). *Life cycle costing in equipment procurement*. Washington D.C.: U.S. Secretary of Defense.

Løkke, A.-K., & Sørensen, P. (2014). Theory Testing Using Case Studies. *The Electronic Journal*, 66-74.

Luca, N. I. (2018). Why social life cycle assessment is struggling in development? *The International Journal of Life Cycle Assessment*, 201–203.

Malmqvist, T., Nehasilova, M., Moncaster, A., Birgisdottir, H., Rasmussen, F. N., Wiberg, A. H., & Potting, J. (2018). Design and construction strategies for reducing embodied impacts from buildings – Case study analysis. *Energy & Buildings*, 35-47.

Markelj, J., Kuzman, M., Grošelj, P., & Zbašnik-Senegačnik, M. (2014). A Simplified Method for Evaluating Building Sustainability in the Early Design Phase for Architects. *Sustainability* , 8775-8795.

Mebratu, D. (1998). Sustainability and sustainable development: Historical and conceptual review. *Environmental Impact Assessment Review*, 493-520.

Mehta, P. K. (2002). High performance, high volume fly ash concrete for sustainable development. *International Workshop on Sustainable Development and Concrete Technology*.

Moon, K. S. (2008). Sustainable structural engineering strategies for tall buildings. *Structural Design Tall Special Buildings*, 895–914.

Mora, E. (2007). Life cycle, sustainability and the transcendent quality of building materials. *Building and Environment*, 1329–1334.

Murguía, D., Ruiz-Conejo, L., & Brioso, X. (2017). Process Integration Framework for the Design Phase of a Residential. *Procedia Engineering*, 462 – 469.

Oldfield, P. (2012). Embodied Carbon and High-Rise. *CTBUH 2012 9th World Congress*, (pp. 614-622). Shanghai.

Ortiz, O., Castells, F., & Sonnemann, G. (2007). Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials*, 28-39.

Peters, P., & Westenbrugge-Bilardie, E. v. (2014). *Duurzaam Construeren: Ontwikkelingen op het gebied van duurzaamheid.* IMd Raadgevende Ingenieurs.

Pinder, J., Schmidt, R., Austin, S., Gibb, A., & Saker, J. (2016). What is meant by adaptability in buildings? *School of Civil and Building Engineering.*

Piracha, T. C. (2013). Effective contribution of structural engineers to green buildings. *Can. J. Civ. Eng*, 97-100.

Pongiglione, M. a. (2016). Sustainable Structural Design : Comprehensive Literature Review. *Journal of Structural Engineering*, 1-15.

Poveda, C. A., & Lipsett, M. G. (2011). A Review of Sustainability Assessment and Sustainability/Environmental Rating Systems and Credit Weighting Tools. *Journal of Sustainable Development.* doi:10.5539/jsd.v4n6p36

Puskas, A., & Moga, L. (2016). Sustainability of Masonry and Reinforced Concrete Frame Structures. Case Studies. *Procedia Technology* , 304-311.

Ramesh, T., Prakash, R., & Shukla, K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings, 42*(10), 1592-1600.

Rijkswaterstaat. (2013). *Nederlands afval in cijfers, gegevens 2006-2010.* Utrecht: Ministry of Infrastructure and Environment.

Robert Adam Architects. (2008). A study of the energy performance of two buildings with lightweight and heavyweight facades: energy and environmental assessment. *Sustainable Architecture Today.*

Rønning, A., & A.Brekke. (2014). Life cycle assessment (LCA) of the building sector: strengths and weaknesses. *Eco-efficient Construction and Building Materials*, 63-83.

RVO. (2010). *GPR-gebouw.* Den Haag: Agentschap-NL.

RVO. (2017). *MIA \Vamil: Brochure & Milieulijst.* Ministerie van Infrastructuur en Milieu.

RVO. (2018). *Duurzaam gerenoveerd of zeer duurzaam nieuw gebouw volgens GPR Gebouw 4.3.* Den Haag: RVO.

RVO. (2018). *MilieuPrestatie Gebouwen - MPG.* Den Haag: RVO.

SAIC. (2006). *Life Cycle Assessment: Principles and Practice.* Reston: U.S. Environmental Protection Agency.

Sartori, I. a. (2007). Energy use in the life cycle of conventional and low-energy buildings: A Review Article. *Building and Energy*, 249-257.

Schiermeier, Q. (2018). Droughts, heatwaves and floods: How to tell when climate change is to blame. *Nature - International journal of science - Feature*, Volume 560 - 20-22 .

Schmidt, R., Eguchi, T., Austin, S., & Gibb, A. (2010). What is the meaning of adaptability in the building industry? *Proceedings of the 16th International Conference on Open and Sustainable Buildings*, 227-236.

Schweber, L., & Haroglu, H. (2014). Comparing the fit between BREEAM assessment and design processes. *Building Research and Information*, 300-317.

Schweber, L., & Haroglu, H. (2014). Comparing the fit between BREEAM assessment and design processes. *Building Research & Information*, 300-317.

Shelbourn, M. A., Bouchlaghem, D. M., Anumba, C. J., Carillo, P. M., Khalfan, M. M., & Glass, J. (2006). Managing knowledge in the context of sustainable construction. *ITcon*, 57-71.

Shoubi, M., Bagchi, A., & Barough, A. (2015). Reducing the operational energy demand in buildings using building information modeling tools and sustainability approaches. *Ain Shams Engineering Journal*, 41-55.

Spence, R., & Mulligan, H. (1995). Sustainable development and the construction industry. *Elsevier: Habitat International*, 279-292.

Sridhar, K., & Jones, G. (2013). The three fundamental criticisms of the Triple Bottom Line approach: An empirical study to link sustainability reports in companies based in the Asia-Pacific region and TBL shortcomings. *Asian Journal of Business Ethics*, 91–111.

Stichting Bouwkwaliteit. (2011). *Bepalingsmethode Milieuprestatie Gebouwen en GWW-werken.* Rijswijk: SBK.

Strauss, A. (1990). *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory.* San Jose State University: SAGE publications.

Then, K., Rankin, J., & Ali, E. (2014). Focus group research: what is it and how can it be used? *Can J Cardiovasc Nurs.*, 16-22.

Thormark, C. (2000). Environmental analysis of a building with reused building materials. *International Journal of Low Energy and Sustainable Buildings*.

UN Environment. (2017). *Global Status Report 2017.* Global Alliance for Building and Construction & International Energy Agency.

USGBC. (2016). *LEED v4: Impact category and point allocation development process.* USGBC.

Verschuren, P., & Doorewaard, H. (2013). *Designing a Research Project.* The Hague: Eleven International Publishing.

W, K. (2008). Life cycle sustainability assessment of products. *Int J Life Cycle Assess 13(2)*, 89–95.

W/E Adviseurs. (2013). *Richtsnoer 'Specifieke gebouwlevensduur': Aanvulling op de Bepalingsmethode Milieuprestatie.* Utrecht: W/E Adviseurs.

W/E Adviseurs. (2018). *Geschiedenis W/E Adviseurs*. Retrieved from https://www.w-e.nl/over-w-e-adviseurs/geschiedenis/

WCED. (1994). *Brundtland Report: Our Common Future.*

Webster, M. (2004). Relevance of structural engineers to sustainable design of buildings. *Structural engineering international*, 181-185.

Webster, M., Gumpertz, S., & Costello, D. (2005). Designing Structural Systems for Deconstruction: How to Extend a New Building's Useful Life and Prevent it from Going to Waste When the End Finally Comes. *Greenbuild Conference*.

Wells, J. (1985). The role of construction in economic growth and development. *Habitat International*, 55-70.

Wolf, C. D. (2014). *Material quantities in building structures and their environmental impact.* Massachusetts : Massachusetts Institute of Technology.

WRAP. (2010). *Designing out Waste: A Design Team Guide for Civil Engineering.* Branbury, UK: WRAP.

WRAP. (2011). *Applying the waste hierarchy: A guide to business.* England, Oxon: Waste and Resources Action Programme.

Yin, R. (2003). *Case Study Research Design & Methods.* SAGE Publications.

Zamagni, A. (2012). Life cycle sustainability assessment. *The International Journal of Life Cycle Assessment*, 373–376.

Zareaian, S., & Zadeh, K. A. (2013). The Role of Climate Factors on Designing and Constructing Buildings (From Urbanization Architecture Approach). *Bull. Env. Pharmacol. Life Sci*, 197-200.

Zhonghua, G., & Xiaohuan, X. (2017). Evolving green building: triple bottom line or regenerative design? *Journal of Cleaner Production*, 600-607.

Zimin, P. (2018). Low-Carbon Concrete: Reducing the Embodied Energy of a Notorious Emitter . *Energy Efficiency, Green Living, On-Site with SWA.*

Zorn, T. (2018). Designing and Conducting Semi-Structured Interviews for Research . *Waikato Management School.*

Appendices

I. Literature Review Demarcation

A. Breakdown of a building

Before this thesis dives into the notion of structural environmental impact, first a comprehension is given of what features a building comprises of and what the structure itself entails; its functions, aspects, systems, elements and materials. In short, the structure of a building could be defined as: "The means to translate external forces into internal loads carrying mechanisms in order to support and reinforce an architectural concept". By demarcating the structure and identifying its influence on other features of a building this Chapter aims to answer the first sub-question.

a. Main disciplines in a building

For a building to be fully functional, a variety of disciplines have to partake in the design. As the disciplines vary enormously, the involvement of different fields of expertise is essential. Each discipline has its own role, issues and responsibilities. In Figure 39 the relationships between the stakeholders that are involved in the design of a building are portrayed. Although this thesis does not consider the stakeholders, it gives a good understanding of which disciplines are utilized to technically complete the design of a building and where the overlaps occur.

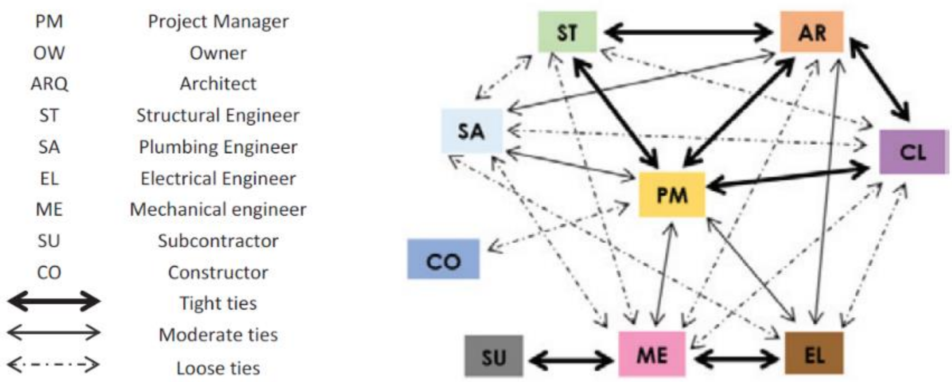


Figure 39: Stakeholder's Relationship Network in the Design Phase (Murguía, Ruiz-Conejo, & Brioso, 2017)

A building can be dissected and isolated into four technical inquiries in which several disciplines reoccur. To what extent a discipline is involved differs per project, however the following disciplines are recurring regardless of its function: architecture, structural engineering, building services engineering – mechanical, electrical and plumbing (MEP or HVAC) - and building physics engineering – insulation and fire safety to name of few. Together these four disciplines are essential for an integrated design as they are closely linked (Geissler et al., 2000).

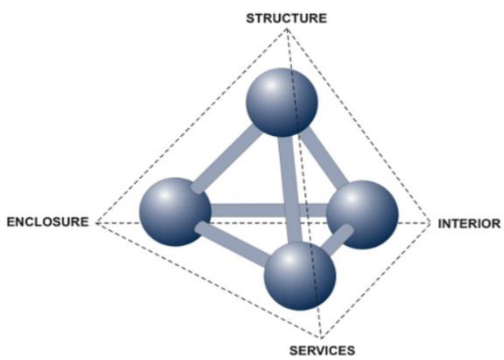


Figure 40: Integration of a building involves the structure, the enclosure, the interior elements and the building services. In which the four disciplines: architecture, structural engineering, service engineering and building physics play a crucial role (Kesik, 2016)

b. Functional building layers

A building comprises of multiple functional layers; each of those layers has its own function and technical lifespan. In Figure 41, the multiple layers are depicted with its accompanying lifetime. These layers are known as the Shearing layers, based on the premise that in traditional buildings alterations to "fast" layers – stuff - is not hindered by "slow" layers – structure (Brand, 1994). For example, placement of inventory such as desks (stuff) could be changed without the structure being altered, the other way around, however, is not the case. The structure of a building has a technical lifetime in the range of 30 to 300 years depending on a variety of factors, such as materials of construction, quality and degree of maintenance, the environment of the location and socio-economic considerations amongst other things (Dias, 2003).

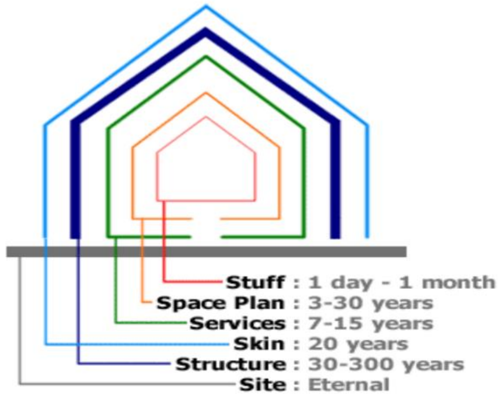


Figure 41: The 6 Shearing Layers (Brand, 1994)

The theory of Brand states that changes made in the structure will, in turn, change the lower echelons of the layers; skin, services, and space plan in which architecture, service engineering and building physical engineering are the fields of expertise. So, the structure gives shape to or facilitates those layers, i.e., to those fields of expertise. Each of those layers should be optimized according to their own service life. However, as stated earlier, the different disciplines, and thus, the functional layers, are interconnected, which entails that they could be an obstacle or be facilitative.

c. The structural system

A structure of a building can be dissected into two parts, as is shown in Figure 42, namely the superstructure and the substructure. The superstructure is the segment that is above the surface, ground level, in its entirety. This section generally serves as the purpose for which the building is intended. Below the superstructure and, thus, below ground level is the substructure. The substructure consists of the foundation and if applicable to the basement. The loads incurred in the super- and substructure are transmitted via load-bearing systems to the foundation.

When looking at the superstructure in more detail, certain elements could be identified which are of importance for the structure to withstand any external or internal force. The structural load-bearing elements could be gathered under the following statement:

"All elements that are part of the structural design which is either necessary for resisting the imposed internal and external forces or for transmitting the load to the foundation on which the building is established."

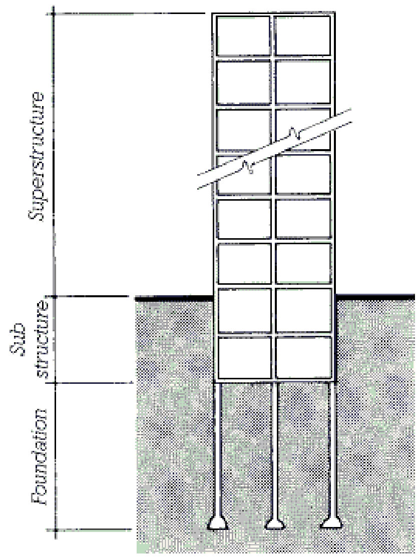


Figure 42; Global breakdown of a building's structure.

There are three types of traditional building structures for vertical loads: structures with load-bearing walls, structures that consist of frames and a composite structure, which is a combination of load-bearing and a frame structure. Within the load-bearing structure the load distribution is as follows; slabs to walls and walls to the foundation. This entails that the majority of inner walls bear the weight of the building. Load-bearing structure is solely used if the building will not exceed a certain amount of storeys. The conventional materials used for this type of structure is concrete, blockwork and/or steel. With a frame structure, the load distribution goes from slabs to beams, beams to columns and from columns to foundation. The amount of storeys in a frame structure is to a certain extent limitless and inner walls do not bear the weight of the structure, therefore, changing the positions of the walls is possible if desirable or necessary. Typical materials used for frame structures are steel, timber and reinforced concrete (Dias, 2003).

The super- and substructure can be further dissected into the following structural features based on Bepalingsmethode Milieuprestatie Gebouwen en GWW-werken (Stichting Bouwkwaliteit, 2011):

Foundation

Soil services: fill sand and dampproofing on soil

Foundation construction: foundation piles, beam grid foundation, the foundation on steel

Shell

Interior walls: bearing walls

Roofs: supporting structure flat roof, supporting structure sloping roof

Loadbearing structure: beams, columns, and supporting beams

Floors: ground floor, the floor on solid soil, and storey floors

d. Structural limiting conditions/requirements

The structure ought to be **reliable** for its services and users to utilise the building and should, in turn, be reliable for its surroundings. Folic (2009) defines reliability as follows: the probability that the function is fulfilled in its service lifetime. Fulfilment of the function entails that failure of the structure should be eluded by staying within limit states. Reliability of a structure could be dissected into three components – safety, serviceability and durability. All three components together make a structure reliable.

Firstly, for a structure to be **safe**, the structure should procure **stability** and **strength**. A structure is stable when it remains in its equilibrium whence affected by extraneous forces (Colorado Uni, Basic Concepts, 2018). Stability entails that a structure should be able to transmit all the loads to the ground, e.g. its foundation. Subsequently, the strength of the structure is defined as in what capacity the structure can withstand stresses generated by loads in structural elements (Constructor, 2018). The two mentioned aspects are affected by a range of different loads, i.e. the forces imposed on the structure. Beginning with the dead load: the load of the structure itself, e.g. the roof, the walls, the floors.

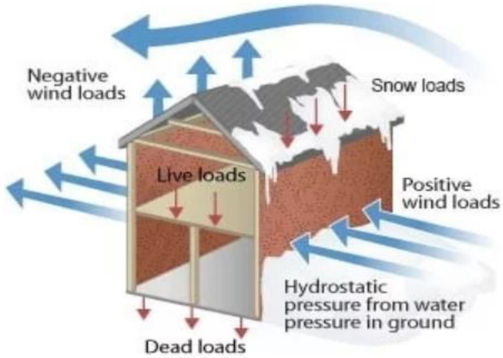


Figure 43 Variety of loads which are imposed on the structure (Constructor, 2018)

These loads are transferred via load-bearing entities to the foundation. Additionally, the live loads are forces that are incorporated in the structural design. Live loads are divided in loads on the roof; snow and water, and on the floors; people and movable equipment. Next to the aforementioned gravitational loads, lateral loads have an impact on the structure which is wind, soil and water pressures. In Figure 43, a visualisation is depicted.

Secondly, the structure should be able to fulfil the functions for which it is designed and constructed related to experience, which entails that the structure should be fit for humans to live carefree, safety features such as fire and corrosion resistant and also the experience of the user should be taken into account. For instance, if the top floor of a building is moving back and forth due to the sheer wind forces or floors are made of a material that is elastic, both technically feasible. However, it will make the occupant feel unsafe resulting in an inadequate living environment. The aspect is called **serviceability**.

Thirdly, the **durability** of a structure is an essential requirement as it touches on multiple other requirements, such as safety, serviceability and longevity. Durability, also found in the literature as lifetime, longevity or service life, can be defined from two perspectives; on the one hand, the serviceability of a structure needs to be conserved over a specified time (Folic). A structure has different individual durability's which overlap with one another. The above-mentioned technical lifetime which has a maximum of 300 years according to Brand (1994). The economic lifetime, the functional lifetime and also the cultural life could be seen as trade-offs to either extend the life or to demolish the building. Below the lifetimes are addressed (Voordt & Heijer, 2004):

- **Technical lifetime:** The lifespan in which the technical and physical features of a building can deliver sufficient performance to be occupied by its users while ensuring the safety and health of its users.
- **Economic lifetime:** The lifespan in which the current and future benefits outweigh the current and future costs from the owners' perspective.
- **Functional lifetime:** the lifespan in which the building gratifies all the functional demands and wishes of the user, which could be altered if the structure allows.
- **Cultural lifetime:** the lifespan in which the building represents the historical and aesthetic value of society.

The requirements differ for which **function** the building was intended. Design of a structure is dependent on what kind of function the building should pertain. Firstly, the spatial design of a building is closely linked to the structure; the spatial plan of a structure for industrial purposes is dissimilar to a structure designed for schools. Secondly, the live loads differ per intended use, which entails that the function affects what kind of loads should be incorporated in the design. Furthermore, the particular function of a building prescribes the "fictional" service life the building will be designed for.

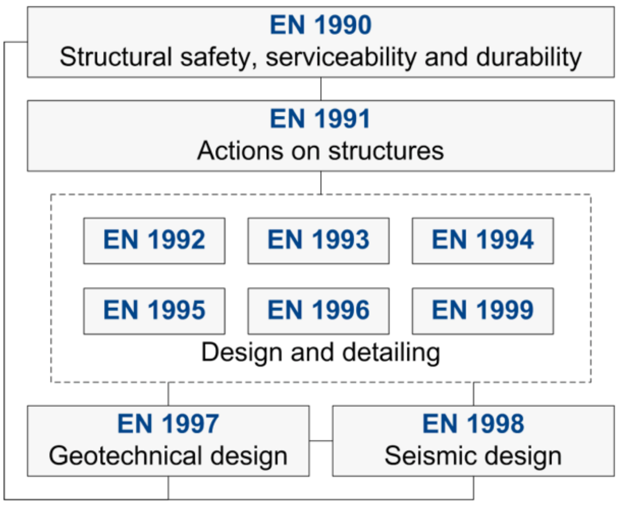


Figure 44: Euro codes for structural engineering (NEN-EN 1990 – 1999)

The requirements the structure must adhere to is secured in regulations and norms, such as the Bouwbesluit and the Eurocodes. The Bouwbesluit is a collection of building regulations to which every building built in the Netherlands, regardless of its function, should conform to. In the Bouwbesluit specific for structural purposes, regulations such as minimal floor-to-floor height, the maximum height of a building depending on the function and location, minimum service life amongst other things. From these regulations no diversion is possible, hence these prerequisites functions as its system boundaries. The Bouwbesluit often refers to the Eurocodes for technical inquiries in which it contains guidelines, (calculation)methods and norms described in detail that are composed by (structural) experts. As described in this paragraph and is seen in Figure 44, the highest virtues of a structure of a building are to be safe, serviceable and durable. These requirements are attained by using the subsequent codes accordingly. The codes NEN-EN 1992 to NEN-EN 1999 are material specific; concrete, steel, steel-concrete, timber, masonry and aluminium respectively.

e. Conclusion building structure

This chapter produced insight in what disciplines are present in the design of a building, what the structural system entails, what influences are present on other building components and what conditions a design of a structure must adhere to. This leads to the answer of the following sub-questions, which will be summarized in this paragraph:

What does a building structure comprise of?

The structure is the skeleton of a building. The structure consists of both above- and underground features. The foundation, substructure, is crucial for the stability of a building. The heavier or taller the building, the more strength is needed in the foundation. The superstructure is the part that is above ground and facilitates the intended function. There are different forms of superstructures; structures in which the walls are loadbearing and structures which consist of frames, also composition is possible. Although there are more possibilities in shapes of the structure these traditional forms are applied most often.

The purpose and the primary function of structural elements of a building can be merged in the following sentence:

"All elements that are part of the structural design which is either necessary for resisting the imposed internal and external forces or for transmitting the load to the foundation on which the building is established."

Basic components of the structure consist of the foundation, columns, load-bearing walls, beams, floors, roofs, as well as joints to attach components depending on the material. Furthermore, stability measures can be implemented such as trusses or stability cores such as staircases or lift shafts. The material for structural purposes is most often reinforced concrete, steel or timber.

The structure should provide safety, as in stability and strength, it should provide serviceability so that the inhabitants or tenants are able to utilize the building care-free and it should be durable for the considered service-life. Incorporating measures for the dead and live loads, both vertical and horizontal in the design of the structure and choosing and implementing the structural materials according to the standards results in a technically feasible design of a structure. Notably, besides the structure being an entity on its own, it facilitates other disciplines in the building, such as the envelope or skin, the services, and the spatial lay-out. The structure, however, should be optimized according its own service life. Notwithstanding, the structure should not interfere with layers that are more prone to replacement. Better yet, the structure could facilitate "faster" functional layers.

B. Environmental impact of the structure

This paragraph gives the notion into what areas the structure affect the environment. First, the definition of sustainability will be addressed in a broad sense, followed by an explanation of the life cycle approach and the role of the structure in it. Subsequently the different parameters of structural environmental impact are put forward. Resulting in the answer of the second sub-question of what the environmental impact entails of a structure of a building.

a. From sustainability to environmental impact

Ever since the introduction of the 'Our Common Future' report by the World Commission on Environment and Development in 1987 the awareness and popularity of sustainable development have skyrocketed. In this report the following often-cited phrase captures the essence of sustainable development:

"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Sustainable development can be achieved when economic development is intertwined with meeting the growing demand of human needs and desires, the conservation of natural resources and the capacity of Earth's environment to absorb stress (Kajikawa, 2008).

Environmental impact does not cover the whole spectrum of sustainability. Ever since Elkington (1997) coined the notion of the triple bottom line (TBL), sustainability is regarded from three perspectives, namely, social, environmental and economic also known as the 3P's: people, planet, and profit. A significant development, as by broadening the definition, the private sector was incentivised to contemplate and implement environmental and social aspects, thus, changing projects and policies sector wide. Unfortunately, the TBL is broad, vague and ambiguous and leaves room for many different interpretations (Mebratu, 1998). Moreover, the triple bottom line has been criticized in the past due to its measurements approach, its lack of integration across all three dimensions and its function as a compliance mechanism (Sridhar & Jones, 2013). One aspect the TBL fails to examine thoroughly is the whole life cycle of a material, product, component.

To achieve sustainable development, all three pillars should be contemplated and used; however, before the three could be integrated the depth of each pillar should be closely examined. Therefore, this thesis will emphasise the environmental pillar. Notwithstanding that environmental aspects could be overlapping with economic and societal tendencies.

b. The life cycle perspective

The conception of lifecycle thinking began with a report from the U.S. Secretary of Defence: "Life Cycle Cost in Equipment Procuration" (Logistic Management Institute, 1965). It was used to compare operational and maintenance costs. In 1960s awareness rose about the limitations of raw materials and energy resources. This ignited the motivation to uncover the cumulative material and energy consumption from source to the *grave* to predict what will happen with finite raw materials and energy resources in the future. This paved the way for analysing the environmental impact on the whole life cycle of a material, product and/or systems. The term “life cycle” specifies all the dominant activities during the lifespan, this includes mining for raw materials, manufacturing the materials, use, renovating and maintenance, to its final disposal, also known as the “Cradle to Grave” assessment, excluding the benefits beyond the system boundary (SAIC, 2006). In Figure 45 the system boundaries are depicted in which the stages and its activities are named. By including the benefits beyond the system boundary, waste is re-entered in the product stage transforming the “Cradle to Grave” principle into “Cradle to Cradle”.

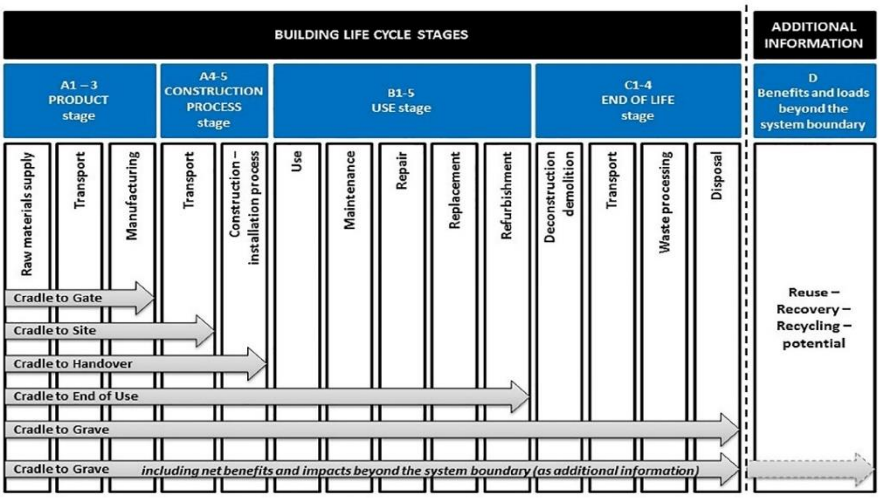


Figure 45: Building life cycle stages (EN 15978:2011)

In the norm of EN 15978:2011 the life cycle is defined as follows: *“consecutive and interrelated stages of a product system, from the acquisition of raw materials or generation of natural resources until its final elimination”*. Through an environmental life cycle assessment of a building, every stage is assessed on the basis of the collection of input and output variables. The inputs being material and energy and the outputs being pollution and waste. By assessing the whole life cycle, an overview is given on environmental impact per stage, resulting in a comparable means for improving the decision-making and, thus, avoiding problem shifting (Guinée, 2002). What is meant by problem shifting is that by lowering the environmental impact in the product stage (A3), by manufacturing a structural beam with a material that is environmentally friendly but lacks the technical properties, could lead to more maintenance and repairs during the use-phase or even decrease the lifetime of a building. Thus, alleviating the environmental burden at some place does not necessarily entail that it is more environmentally friendly as a whole: the environmental impact does not disappear, it is only reallocated (Mora, 2007).

The LCA methodology consists of four distinct analytical steps: (1) defining of the goal and scope, (2) creating the life-cycle inventory, (3) assessing the impact and ultimately (4) interpreting the results [ISO 14040]. These steps are iteratively conducted which entails that previous steps could be altered while continuing the assessment. By delineating the life cycle, it could help in understanding the multifaceted chain and, thus, result in more tenable decision-making. Therefore, the first step of defining the goal and scope is a critical step, as it sets the boundaries, purpose and other aspects so that in the end the decision-making is justifiable (EPA, 2006).

The life cycle approach could be assigned on more than only environmental decision-making (E-LCA). The life cycle approach, as it was intended, could also be focused on economic decision-making (LCC). To obtain the TCO, or the total cost of ownership, life cycle costing plays a crucial role and is inseparable with the project finance nowadays. Moreover, the life cycle approach can even be conducted for social issues (S-LCA). All three take on the whole life cycle but focus on different aspects. Combining these three gives the hybrid tool: life cycle sustainability assessment (LCSA) developed by (Klöpffer, 2008). The integration of the TBL with the life cycle perspective gives a good starting point for sustainable development. However, the quantification of social indicators is still too immature for this method. The same applies to the LCSA as for the TBL, the three indicators are difficult to integrate. More research has to be conducted before the LCSA could become operational (Zamagni, 2012; Guinée, 2016).

In the LCC, given the fact that the goal and scope are clearly defined, the costs are comparable throughout the life cycle. As also could be said of the LCA. Where the LCA and the LCC are mature in the norms, literature and practical usage, the S-LCA is still struggling in its development, affecting, in turn, the development of life cycle sustainability assessment (Luca, 2018). Therefore, in practice, the life cycle approach is conducted separately. Notably, this does not mean that there are no limitations to the LCA and LCC.

Conducting an LCA can be resource and time intensive. To alleviate the burden, a great variety of databases are constructed. However, converting the impact in a single score, i.e. environmental costs requires value judgment, which inherently is not solely based on natural science. The credibility of underlying data and calculations methods of the LCA could be imprecise as it could depend on input from actors that are difficult to monitor. This could produce erroneous outcomes, resulting in inaccurate decision-making (Rønning & Brekke, 2014; EPA, 2006).

However, despite these shortcomings, LCA still is a reliable tool for environmental assessment for striving towards more sustainability (Curran, 2014).

c. Environmental structural parameters

The environmental impact of a structure can be dissected into two main areas. The environmental criteria and in what stage of the LCA the criteria manifest itself. The life cycle stages were explained in the previous chapter. Thus, the focus of this paragraph lies on the environmental impact. NIBE, het Nederlands Instituut voor Bouwbiologie en Ecologie, has set up indicators to give an overview of what areas the structure impacts the environment (NIBE, 2008).

No single environmental indicator is in the position to comprehensively monitor and account for the totality of human impact on the environment (Best, 2008). The environmental impact of the structure of a building could be ascribed to the type, quantity and quality of used materials, the realization process, service period, maintenance needs and end-of-life processes (Puskas & Moga, 2016). Underlying to this enumeration several indicators could be identified and are used in practice, which is explained below.

Natural resources

- Depletion of scarce resources

- Depletion of non-renewable resources
- Total use of depleted resources
- Excavation location

Depletion of natural resources affects the first two stages A1 and A2 of the life cycle (raw material supply and transport).

Pollution

- Acidification
- Eutrophication
- Global warming potential
- Ozon depletion
- Summer smog
- Winter smog
- Heavy metals
- Pesticides

The environmental cost is a monetised parameter in which the social value is calculated of environmental and human health impact indicators per kg. Social costs are quantified for GPW, ozone layer depletion, acidification, human toxicity amongst others. Environmental cost indicates the amount of damage created if one extra kg is released in the environment. In Table 11, the impact categories and its shadow pricing are depicted.

Table 11: Impact categories with environmental cost per kg eq (Nationale Milieudatabase, 2018)

Impact Category	Environmental Costs per kg eq	Unit
Abiotic depletion	€0.16	kg Sb eq
Global warming potential	€0.057	kg CO_2 eq
Ozone layer depletion	€30.00	kg CFC-11 eq
Human toxicity	€0.16	kg 1.4-DB eq
Fresh water aquatic ecotox.	€0.03	kg 1.4-DB eq
Marine aquatic ecotoxicity	€0.0001	kg 1.4-DB eq
Terrestrial ecotoxicity	€0.06	kg 1.4-DB eq
Photochemical oxidation	€0.06	kg C_2H_4
Acidification	€5.4	kg SO_2 eq
Eutrophication	€9.00	kg PO_4 eq

The environmental costs can be used as a calculation tool whence performing a life cycle assessment (LCA). Researchers can weigh the environmental costs into a single score, so that it can be determined which structural material damages the environment the least or is the costliest for intervention. Every material or component has a specific single environmental cost based on the activities in its life cycle (CE Delft, 2017). The final environmental costs of a building are an accumulation of all materials incorporated in the building and expressed as follows: environmental costs per m^2 GFA per year. Consequently, the surface area and the estimated service lifetime are important factors.

Waste

- Waste prior to processing
- Waste End of Life (EoL)
- Dangerous Waste

Waste is conceived in the product stage, construction stage and the end of life stage. Also, structural alterations such as renovations or refurbishments during the in-use phase could conceive waste.

Nuisance

- Stench
- Noise
- Light

Nuisance is an indicator that could be ascribed to all life stages. However, this indicator is mostly focused on construction, in-use and demolition phase. Consequently, it can be stated that it is mostly focused on the local environment. From a structural point of view, the nuisance is mostly attributed to the construction phase (A4-5).

Degradation of nature

- Land surface use
- Degree of recoverability
- Degree of disruption

The areas in which nature is degraded by structural purposes are two; the excavation site for the raw materials (A1) and the land surface upon which the structure is constructed (A4-D).

Reusability or Recyclability

- Reuse on product level – reusing products for the same purpose, without changing the product.
- Further use on product level – reusing products for other purposes, almost without changing the product.
- Recycling on resource level – repeatedly use of collected construction- and demolition waste and product waste into a similar production process; the waste will be utilized for identical products.
- Downcycling on resource level – repeatedly use of collected construction - and demolition waste and product waste for products that are lower in value.

Repairability (or maintenance sensitivity)

- Maintenance cycle
- Replacement percentage – quantity of resources used for maintenance.

Service life (estimation)

- Technical lifespan
- Economic lifespan
- Functional lifespan

The length of the service life determines the duration of the use phase (B1-5). The lengthier the use phase, the lower the environmental impact per year is of the embedded energy and materials form the prior phases.

Energy

Energy consumption does not have an impact on the environment itself. The environmental consequences mostly come from the production of energy, such as emissions from electricity plant generated by coal or gas. Energy could also be from a source with very low environmental impact, such as energy produced by renewable sources. The literature proposes a lot of environmental impact analyses of structures by (embodied) energy consumption (Puskas & Moga, 2016). A list of the life cycle energy consumption of a building is depicted below.

- **Operational Energy (OE)** is the energy requirement of the building throughout its service life from commissioning to demolition (with the exemption of maintenance and renovations) also known as the use phase. This also covers HVAC – heating, ventilation and air conditioning.
- **Embodied Energy (EE)** is the energy that is required for all the stages prior to and after utilising a building. All the energy that is needed for extracting raw materials, transportation, construction and demolition, see Figure 46. Furthermore, also recurring embodied energy is present in the form of maintenance and renovation.
- **Demolition Energy (DE)** is the embodied energy that is needed to demolish and transport waste materials to landfill sites or recycling plants.
- **Life Cycle Energy (LCE)** is the total energy that is required for the whole life cycle of a building. LCE is the sum of the three parameters mentioned above (OE + EE + DE).

- **Embodied Carbon (EC)** is the emitted carbon from all the stages prior to and after utilising a building: the carbon produced by the embodied energy. The emitted carbon depends on what kind of primary energy is used, Figure 46. This entails that the amount of embodied energy and carbon could vary. Consequently, embodied carbon is a better environmental impact estimator. Unfortunately, carbon emissions are more difficult to estimate and are subject to more variability (Hayes, 2013).

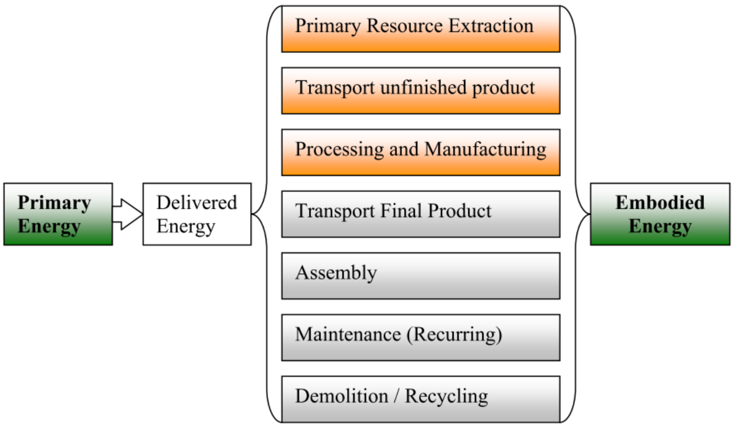


Figure 46: Breakdown of Embodied Energy (Hayes, 2013)

d. Conclusion structural environmental impact

This paragraph provided an insight into what different areas, levels and life stages the structure has an environmental impact. Furthermore, it gave an indication of what different indicators are present. The answer of the following sub-question is stated in this paragraph:

What is the environmental impact of a building's structure?

The environmental impact of a structure could be brought back to its building life cycle stages. The life cycle consists of the *product stage* in which the materials are excavated, transported and manufactured (A1-3), the *construction process stage* in which the materials or manufactured products are transported to the site and assembled on site (A4-5), the *use stage* in which structure is utilized, maintained, repaired, replaced and/or refurbished over a certain lifespan (B1-5), the *end of life stage* in which the structure is deconstructed or demolished and processed and disposed accordingly (C1-4). These subsequent building life cycle stages are known as the system boundary of "Cradle to Grave". However, the building life cycle can be extended, insofar that the materials or products yielded from deconstruction and demolishing could be reused, recovered or recycled resulting in lowering the share of the product stage of the building life cycle stages for subsequent structures.

In the building life cycle stages the input and the output are materials and energy, and pollution and waste respectively. Thus, to lower the environmental impact of the structure both the input and the output should be minimized. Minimizing the material and energy input, minimizing the pollution and waste output whilst prolonging the lifespan of the use stage results in lowering the environmental impact of a structure on the whole life cycle. In addition, waste should be treated as a resource, this entails that waste could be utilized for subsequent purposes. Below an inventory is put forth in what areas the environmental impact could be lowered:

- Minimize material usage (or: choose materials with low environmental costs, or: choose materials that have surpassed a cycle)
- Minimize overall energy input (or: maximize renewable primary energy)
- Minimize pollution (or: choose materials with low environmental costs)
- Minimize waste
- Maximize service life
- Maximize reutilisation of waste

II. Analysis Sustainability Assessment Methods

A. Analysis of BREEAM-NL

Breeam-NL	What?	Detail	Credits (Max)	Mandatory (amount of Stars)	Exemplary Performance	Structural (direct)	Structural (indirect)
Management							
MAN 1	Performance security	Stimulation of securing performance installation	3	1	-	No	No
MAN 2	Construction Site & Surrounding	Stimulation of responsible management of the construction site and its influence on its surroundings	2	4	-	No	No
MAN 3	Environment Impact Construction Site	Stimulation of responsible management of the construction site from a environmental point of view (e.g. environment friendly material usage)	4	-	1%	No	Yes
MAN 4	User Manual	Stimulation to provide manuals of the building for non-technical users	1	4	-	No	No
MAN 6	Consultation	Involving relevant interested parties in the design process (users, companies, tentants and local government) - Enhancing local involvement for optimizing building function	1	-	-	No	May be
MAN 8	Safety	Identifying and stimulation of effective design measures for safety purposes (e.g. vandalism)	1	-	-	No	No
MAN 9	Transfer of Knowledge	Stimulation of providing information to users and visitors about sustainable construction	1	5	-	No	No
MAN 11	Maintainability	Stimulation of designing a building and its installations which could be maintained effortless	1	-	-	Yes	Yes
MAN 12	LCC	Stimulation of a LCA in the design phase	2	-	-	Yes	Yes
Health							
HEA 1	Daylight	Provide sufficient daylight for in areas of the building for the purpose of visual performance and well-being	1	-	1%	May be	May be
HEA 2	View	Stimulation that important workplaces have access to a view to outside	1	-	-	May be	May be
HEA 3	Remediation light nuisance	Remediation of nuisance in areas as a consequence of reflection or blinding by light	1	-	-	No	No
HEA 4	High Frequency Lighting	Increase of visual comfort by application of high frequency lighting	1	1	-	No	No
HEA 5	Artifical lighting in- and outside	Guaranteeing the visual comfort of artificial lighting in- and outside	1	-	-	No	No
HEA 6	Light regulation	Guaranteeing the accesibiltiy of regulation of lighting by buildingusers in areas where work takes places	1	-	-	No	No
HEA 7	Ventilation	Providing extra possibility for users to (temporarly) ventilate directly to outside air, in addition to the basis ventilation	1	-	-	No	May be
HEA 8 (?)	Internal air quality	Promoting a healthy life- and stayclimate through sufficiently refreshing the air without contamination of sources in- and outside	2	-	-	No	May be
HEA 9 (?)	Volatile organic compounds	Good quality of inside air by choosing for building and surface finish material that have a low emission of harmful volatile organic compound	1	-	-	No	May be
HEA 10	Thermal comfort	Ensuring thermal comfort in the building	2	-	-	No	May be

HEA 11	Temperature regulation	Provide sufficient possibilties to regulate the temperature by buildingusers	1	-		-	No	No
HEA 13	Acoustics	Lowering noise nuisance inside a building with isolation and noise protection	1	-		-	No	No
HEA 14 (?)	Private outside area	Improving living standard by procuring outside area with privacy for building occupants	1	-		-	No	May be
HEA 15	Accessibiltiy	Stimulation of accessibility for as many target groups as possible (e.g. wheelchair accessibility and eldery)	2	-		-	No	May be
Transport								
TRA 1a	Supply of PT - offices, schools, industry							
TRA 1b	Supply of PT - shopes, loges, meetingplaces							
TRA 1c	Supply of PT - residential							
TRA 2	Distance to basic needs							
TRA 3a	Alternative transport (other functions)							
TRA 3b	Alternative transport (residential)							
TRA 4	Pedestrians and cyclists safety							
TRA 5	Transportplan and parking policy							
TRA 7	Transport information point							
TRA 8	Subcontracting and manoevering							
Energy								
ENE 1	Energy-efficiency	Stimulation of designing and realising buildings with the lowest CO2-emission of primary operational energy usage of the building	15		4	2%	No	May be
ENE 2a	Submetering energy use (other functions)	Applying submetering of both areazones inside the building as of large electricty consuming groups	2		3	-	No	No
ENE 2b	Submetering energy use (residential)	Applying a monitor system for energy usage	2		3	-	No	No
ENE 4	Low energy outside lighting	Stimulation of saving energy en reducing CO2 by implementing energy efficient outside lighting	1	-		-	No	No
ENE 5	Application of renewables	Stimulation of implementation of renewable energy in the immediate surroundings	3		4	1%	No	Yes
ENE 6	Minimalisation of air infiltration loadhandling platforms	Stimulation of energy saving and CO2-reduction by implementation and desiging load handling platforms	1	-		-	No	Yes
ENE 7a	Low energy refrigeration and freezer	Stimulation of energy saving and CO2-reduction by implementation of energy efficient storage facilities where product could be cooled and frozen	1	-		-	No	No

	storage (other functions)							
ENE 7b	Low energy refrigeration and freezer storage (shops and loges)	Stimulation of energy saving and CO2-reduction by implementation of energy efficient storage facilities where product could be cooled and frozen	2	-		-	No	No
ENE 8	Low energy elevators	Stimulation of energy saving and CO2- reduction by implementation of energy saving elevators (by type: personell or goods)	2	-		-	No	May be
ENE 9	Low energy escalators	Stimulation of energy saving and CO2-reduction by implementation of energy efficient escalators and passenger conveyors	1	-		-	No	No
ENE 26	Guarantee thermal quality building envelope	Stimulation the construction of buildings as they are designed and realised with the least CO2-footprint	2	-		-	No	May be
Energy								
WAT 1a	Water consumption (other functions)	Minimalizing usage of water for sanitary purposes by implementation of water saving or waterless provisions	3		2		No	No
WAT 1b	Water consumption (residential)	Minimalizing usage of water for sanitary purposes by implementation of water saving or waterless provisions	2		2	-	No	No
WAT 2	Water meter	Securing monitoring and managing of water usage, so that the consumption of drink- and groundwater is reduced	1		2	-	No	No
WAT 3	Leak detection main water connection	Limiting the consequences of large waterleakages	1	-		-	No	No
WAT 4	Selfclosing water supply sanitation	Limiting the consequences of large waterleakages	1	-		-	No	No
WAT 5	Water recycling	Applying of collection and reuse of grey wastewater or rain water for flushing and reducing usage of drinkwater	1	-		-	No	No
WAT 6	Irrigation systems	Reducing the use of drinkwater for green provisions	1	-		-	No	No
WAT 7	Vehicle washing service	Reducing the use of drinkwater through vehicle washing services	2	-		-	No	No
Materials								
MAT 1	Building materials	Identification and stimulation of the use of materials with a low environmental impact during the whole life cycle of the building	8		3	1%	Yes	Yes
MAT 5	Substantiated origin of materials	Stimulation of the implementation of materials with sustantiated/responsible origin of the main construction parts	4	-		1%	Yes	Yes
MAT 7	Robust Design	Identification and stimulation of measures for protection purposes of exposed construction parts whereby replacement frequency is minimized	1	-		-	Yes	Yes
MAT 8	Building flexibility	Stimulation of realizing buildings with a high degree of flexibility	4	-		-	Yes	Yes
Waste								
WST 1	Waste management	Promoting efficient use of raw materials on the construction site meaningful waste management	3		3	1%	No	May be

	on the construction site							
WST 2	Use of secondary material	Stimulation of recycled or secundary aggregates in stone constructions, so that the demand falls for new raw materials and materials are used more efficiently	1	-		1%	Yes	Yes
WST 3a	Storagespace for reuse waste (other functions)	Facilities that are specifically designed for storage of recycable waste during exploitation/use of the building	1		4	-	No	Yes
WST 3b	Storagespace for reuse waste (residential)	Facilities that are specifically designed for storage of recycable waste during exploitation/use of the building	1		4	-	No	Yes
WST 5	Compost	Stimulation of provisions for composting organic waste	1	-		-	No	Yes
WST 6	Inrichting	Stimulation of co-ordinating with the user of the building about the completion and interior design, so that waste of material is minimized	1	-		-	No	Yes
Land-use and ecology								
LE 1	Reuse of land	Stimulation of project developers, municipalities, housing associations and other building parties to realize building projects on a location with low ecologic and landscape value and stimulation of reuse of developed soil	5	-		-	No	No
LE 2	Contaminated soil	Realizing of projects on location with contaminated soil instead of location with healty soil	2	-		-	No	No
LE 3	Presence of plants and animals on the building location	Stimulation of measures to protect and conserve plants and animals during construction	1	-		-	No	No
LE 4	Plants and animals as other users in the plan area	Stimulation of measures to develop sustainable use of a realizing buildings and open spaces with plant- and animalspecies	2		3	-	No	No
LE 6	Sustainable use of plants and animals for the long-term	Stimulation of nature friendly management, maintenance and nature friendly monitoring of buildings and open spaces (guarantee use of certain plants and animals)	1	-		-	No	No
LE 9	Efficient land-use	Promoting efficient land use by limiting the building on the designated surface	2	-		-	Yes	Yes
Pollution								
POL 1	GWP of refrigerants for climate control	Reducing the contribution of climate change by stimulating the use of refrigerants with a low GWP	1	-		-	No	No
POL 2	Preventing leakages of refrigerants	Prevention of emissions of refrigerants to the atmosphere caused by leakages in the refrigeration (for climate control and warehouse cooling)	2	-		-	No	No
POL 3	GWP of refrigerants for warehousecooling	Reducing the contribution of climate change by stimulating the use of refrigerants with a low GWP	1	-		-	No	No

POL 4	Spatial warming related Nox-emission	Stimulation of measures of heatingsystem where Nox-emissions is minimized, with the result of lower air pollution	3	-	1%	No	No
POL 6	Rainwater runoff	Prevention, minimization and delaying of drainage of rainwater to public sewages as environmental damages will be minimized	3	-	-	No	Yes
POL 7	Minimilisation of light nuisance	Guaranteeing outside lighting only enluminate the right areas while minimizing energy use and light nuisance for surrounding lots	1	-	-	No	No
POL 8	Noise nuisance	Reducing the possibility that sound causes nuisance in the surrounding areas during the operational phase	1	-	-	No	Yes

Material 1 (MAT 1): Building materials – environmental costs (8 credits with 1 innovation credit)

This credit has to goal to identify and stimulate the use of materials with a low environmental impact during the whole life cycle of the building. The environmental costs are based on the whole life cycle of a material and are calculated and published in the NMD (Nationale Milieu Database). The environmental costs are based on the 11 indicators depicted in Table 11 in paragraph c, the number of square feet of the building, and lifespan (euro/m2/year). To attain all 8 credits the environmental burden of the used materials should at least be 60% lower than the reference value, which is based on the function a building pertains. MAT 1 incorporates all materials, thus it does not only encompass the structural materials, also services and finishing and the likes are included. For the innovation credit, it has to be demonstrated that at least 3 materials that have a severe impact in lowering the environmental costs are contemplated. Design for material and design for materials minimization could be attributed to MAT 1.

Material 5 (MAT 5): Substantiated origin of materials (4 credits)

The aim of this credit is to stimulate the implementation of materials with the substantiated/responsible origin of the main construction parts. As the origins of raw materials are difficult to monitor construction materials have to be certified. For example, timber should have a certification that the trees are cut down responsibly. To attain the 4 credits a minimum of 80% of the total volume of the used materials in every building component has to have a substantiated origin, and more than 20 points in the MAT 5-calculator (based on the amount and level of certifications), and that all timber used is 100% sustainably produced which is mandatory despite the level of ambition.

Material 7 (MAT 7): Robustness (1 credit)

This credit's goal is the identification and stimulation of measures for protection purposes of exposed construction parts whereby replacement frequency is minimized. To obtain the MAT 7 credit protection needs to be implemented in areas in which the risk of damage is high.

Material 8 (MAT 8): Building flexibility (4 credits)

Through this credit realizing buildings with a high degree of flexibility is stimulated. BREEAM constructed a tool to calculate the level of flexibility in a building. Flexibility is determined by more factors than the structure alone, also the skin, services, and spatial layout dictates the level of flexibility as is depicted in Appendix D. Flexibility is structured on the basis of three key performance indicators: subdivisible (interior level), versatility (unit level) and multifunctionality (building level). In this tool, the following aspects determine the flexibility of a building from the point of view of the structure.

Column placement (structural grid)
Movable internal walls
Non-bearing function separating walls
Building accessibility
Non-bearing facades
Sufficient bearing capacity
Floor-to-floor height

Waste 2 (WST 2): Use of secondary material (1 credit)

This credit's goal is the stimulation of recycled or secondary aggregates in stony constructions so that the demand falls for new raw materials and materials are used more efficiently. This is done by setting a mandatory minimal percentage of recycled or secondary material. For the structure, it is 30% and for the foundation, it is 35%.

Management 3 (MAN 3): Environmental Impact Construction Site (4 credits)

Stimulation of responsible management of the construction site from an environmental point of view (e.g. environmentally friendly material usage). This credit is subdivided into 6 paragraphs of which one is focused on environmentally material usage on the construction site. The following criteria could be brought back to the usage of materials: use local materials (where possible), responsible purchase of materials (MAT 5), reusage of materials, use of materials that can be recycled adequately, waste minimizing and recycling, material use with low environmental impact, and sustainable material use.

Management 11 (MAN 11): Maintainability (1 credit)

In this credit, a plan has to be constructed how the building is going to be maintained over its service life. A design guide should be constructed so that other parties (such as an inspector) have an overview of what the maintenance strategy is. Although the structure is not mentioned specifically in MAN 11, other than stating abstractly; reliability requirements, consideration of resource use and building life span, it is an important aspect of the structure.

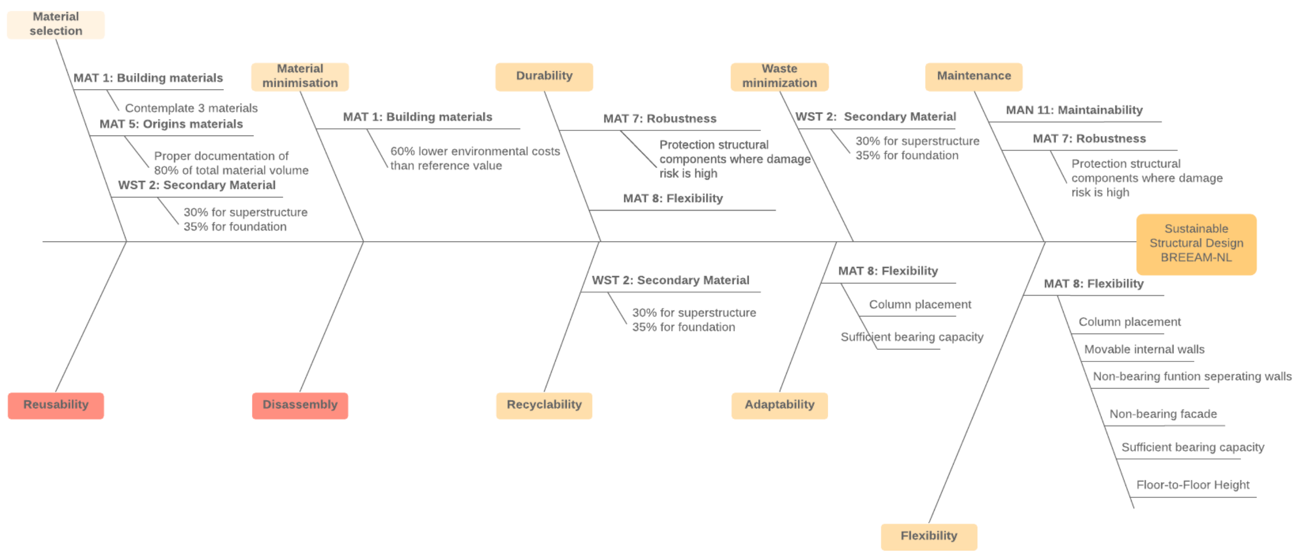


Figure 47: Ishikawa diagram of sustainable structural design strategies and their contribution (and operationalisation) to a sustainable structural design derived from BREEAM-NL (Own Figure)

B. Analysis of LEED

LEED	What?	Detail	Credits (Max)	Structural influence (direct)	Structural influence (indirect)
Integrative Process					
Integrative Process	Early analysis of the interrelationships among systems		1	Yes	
Location and Transportation					
L&T 1	Sensitive Land Protection	Avoiding development of environmental sensitive lands and reduce environmental impact from the location of a building site	1	No	No
L&T 2	High priority sites	To encourage project location in areas with development constraints and promote the health of the surrounding area.	2	No	No
L&T 3	Surrounding density and diverse uses	Conserving land and protecting farmland and wildlife habitat by encouraging development in areas with exisiting infrastructure	5	No	No
L&T 4	Access to quality transit	Encouraging development in locations shown to have multimodal transportation choices or otherwise reduced motor vehicle use	5	No	No
L&T 5	Bicycle facilities	Promoting bicycling and transportation efficiency and reduce vehicle distance traveled	1	No	No

L&T 6	Reduced parking footprint	Minimizing environmental harms associatied with parking facilities, including automobile dependence, land consumption and rainwater runoff	1	No	No
L&T 7	Green vehicles	Promoting alternatives to conventionally fueled automobiles	1	No	No
Sustainable Sites					
SS 1	Construction activity pollution prevention	Reducing pollution from construction activities by controlling soil erosion, waterway sedimentation and airborne dust	Required	No	No
SS 2	Site assessment	Assessment of site conditions before design to evaluate options and inform related decisions about site design	1	No	Maybe
SS 3	Site development	Conserving existing natural areas and restoring damaged areas	2	No	No
SS 4	Open space	Creating exterior open space that encourages interaction with the environment, social interaction, passive recreation, and physical activities	1	No	Yes
SS 5	Rainwater management	Reducting runoff volume and improving water quality	3	No	Maybe
SS 6	Heat island reduction	Minimizing effects of microclimates and human and wildlife habitats by reducing heat islands	2		Maybe
SS 7	Light pollution reduction	Increasing night sky access, improving nightime visibility and reducing the consequence of development for wildlife and people	1		
Water Efficiency					
WE 1	Outdoor water use reduction	Reducing outdoor water consumption	Required	No	No
WE 2	Indoor water use reduction	Reducing indoor water consumption	Required	Maybe	Maybe
WE 3	Building-level water metering	Supporting water management and identifying opportunities for additional water savings by tracking water consumption	Required		
WE 4	Outdoor water use reduction	Reducing outdoor water consumption	2		
WE 5	Indoor water use reduction	Reducing indoor water consumption (further reduce than baseline)	6		
WE 6	Cooling tower water use	Conserving water used for cooling tower makeup while controlling microbes, corrosion, and scale in the condenser water system	2		
WE 7	Water metering	Supporting water management and identifying opportunities for additional water savings by tracking water consumption	1		
Energy and Atmosphere					
E&A 1	Fundamental commissioning and verification	Supporting design, construction, and eventual operation of a project	Required	No	Yes
E&A 2	Minimum energy performance	Reducing environmental and economic harms of excessive energy use by achieving a minimum level of energy efficiency for the building and its systems	Required	No	No
E&A 3	Building-level energy metering	Supporting energy management and identifying opportunities for additional energy savings by trackings building-level energy use	Required		

E&A 4	Fundamental refrigerant management	Reduce stratospheric ozone depletion	Required		Maybe
E&A 5	Enhanced commissioning	Supporting design, construction, and eventual operation of a project	6	No	Yes
E&A 6	Optimize energy performance	Achieving increasing levels of energy performance	18		
E&A 7	Advanced energy metering	Supporting energy management and identifying opportunities for additional energy savings by trackings building-level energy use	1		
E&A 8	Demand response	Increasing participation in demand response technologies and programs	2		
E&A 9	Renewable energy production	Reducing environmental and economic harms associated with fossil fuel energy by increasing self-supply of renewable energy	3		Yes
E&A 10	Enhanced refrigerant management	Reducing ozone depletion and supporting early compliance with the Montreal Protocol	1	No	No
E&A 11	Green power and carbon offsets	Encouraging reduction of greenhouse gas emissions through the use of grid-source, renewable energy technologies and carbon mitigation projects	2		
Materials and Resources					
M&R 1	Storage and collection of recyclables	Reducing waste that is generated by building occupants and hauled to and disposed of in landfills	Required	No	No
M&R 2	Construction and demolition waste management planning	Reducing construction and demolition waste disposed of in landfills and incineration facilities by recovering, reusing and recycling materials	Required	Yes	Yes
M&R 3	Building life-cycle impact reduction	Encouraging adaptive reuse and optimize the environmental performance of products and materials	5		
M&R 4	Building product disclosure and optimization - environmental product declarations	Encouraging the use of products and materials for which life-cycle information is available and that have environmentally, economically and socially preferable life-cycle impacts	2		
M&R 5	Building product disclosure and optimization - sourcing of raw materials	Encouraging the use of products and materials for which life-cycle information is available and that have environmentally, economically and socially preferable life-cycle impacts	2		
M&R 6	Building product disclosure and optimization - material ingredients	Encouraging the use of products and materials for which life-cycle information is available and that have environmentally, economically and socially preferable life-cycle impacts	2		
M&R 7	Construction and demolition waste management	Reducing construction and demolition waste disposed of in landfills and incineration facilities by recovering, reusing and recycling materials	2		
M&R 8	Design for flexibility	Conserve resources associated with the construction and management of buildings by designing for flexibility and ease of future adaptation and for the service life of components and assemblies.	1		
Indoor Environmental Quality					
IEQ 1	Minimum IAQ performance	Contributing to the comfort of well-being of building occupants by establishing minimum standards for indoor air quality	Required	No	No

IEQ 2	Environmental tabacco smoke control	Preventing or minimizing exposure of building occupants, indoor surfaces and ventilation air distribution systems to environmental tabocca smoke	Requ ired	No	No
IEQ 3	Enhanced IAQ strategies	Promoting occupants' comfort, well-being and productivity by improving indoor air quality	2		
IEQ 4	Low-emitting materials	Reducing concentrations of chemical contaminants that can damage air quality, human health, productivity and the environment	3	No	Yes
IEQ 5	Construction IAQ management plan	Promoting well-being of construction workes and building occupants by minimizing indoor air quality problems associated with construction and renovation	1		
IEQ 6	IAQ assessment	Establishing better quality indoor air in the building after construction and during occupancy	2		
IEQ 7	Thermal comfort	Promoting occupants' comfort, well-being and productivity by providing thermal comfort	1		
IEQ 8	Interior lighting	Promoting occupants' comfort, well-being and productivity by providing high quality lighting	2		
IEQ 9	Daylight	Connecting building occupants with the outdoors, reinfore circadian rhythms and reduce the use of electrical lighting by introducing daylight into the space.	3		
IEQ 10	Quality views	Giving building occupants a connectioon to the natural outdoor environment by providing quality views	1		
IEQ 11	Acoustic performance	Providing workspaces and classrooms that promote occupants' well-being, productivity and communications through effective acoustic design	1		
Innovati on					
INN 1	Innovation	Encouraging project to achieve exceptional or innovative performance	5	No	No
INN 2	LEED Accredited Professional	Encouraging the team intergration required by a LEED project and to streamline the application and certification process	1	No	No

Integrative process (1 credit)

For this credit, an early analysis should be performed into the interrelationships between systems in a building. The systems are energy- and water-related. In the energy-related systems, the building form and geometry are specifically mentioned. However, the structure is not specifically mentioned.

Materials and Resources 3 – Building lifecycle impact reduction (MR3 – 5 credits)

The intent of MR3 is to encourage adaptive reuse and optimize the environmental performance of products and materials. This should be done by demonstrating the reduced environmental effects during initial project decision-making by reusing existing building resources or demonstrating a reduction in materials uses through life-cycle assessment. This can be achieved by the subsequent option:

Option 1: Historic building reuse – usage of an already existing building without demolishing it. (5 credits)
Option 2: Renovation of an abandoned or blighted building – usage of an existing building and maintaining at least 50% surface area. (5 credits)
Option 3: Building and materials reuse – re-usage or salvaging building materials as a percentage of the surface area. This includes; structural elements such as; floors, roof decking, but also enclosure materials and permanently installed interior elements. (max 4 credits)
Option 4: Whole-building life cycle assessment – conducting of a life cycle assessment for new construction

based on the environmental costs indicators to demonstrate a minimum reduction of 10%. In which, unlike BREEAM-NL (50 years), a service life of at least 60 years is asserted. There are no specified databases which are used, solely the notion of using the same life cycle assessment tool for both the reference case and the design case is mentioned. (3 credits)

Materials and Resources 4 – Building product disclosure and optimization - EPD (MR4 - 2 credits)

In this credit, the importance of the source of the materials is emphasized. The intention of MR4 is to encourage the use of products and materials for which life-cycle information is available with trustworthy certifications in which the environmental, economic and social impact is secured. Environmental product declarations (EPD) are required to attain the 2 credits.

Materials and Resources 5 - Building product disclosure and optimization – sourcing of raw materials (MR5 - 2 credits)

The intention of the prior credit MR4 is identical for MR5. What sets it apart is that it is not merely an EPD, but in MR5 the reports of manufacturers are required in which excavation locations, long-term responsible land-use and the like is secured and proven to be tenable. Another credit can be obtained by using products with the following criteria (only criteria are mentioned that could be contributed to structural elements):

Bio-based materials
Wood products
Materials reuse
Recycled content

Materials and Resources 6 - Building product disclosure and optimization – material ingredients (MR6 - 2 credits)

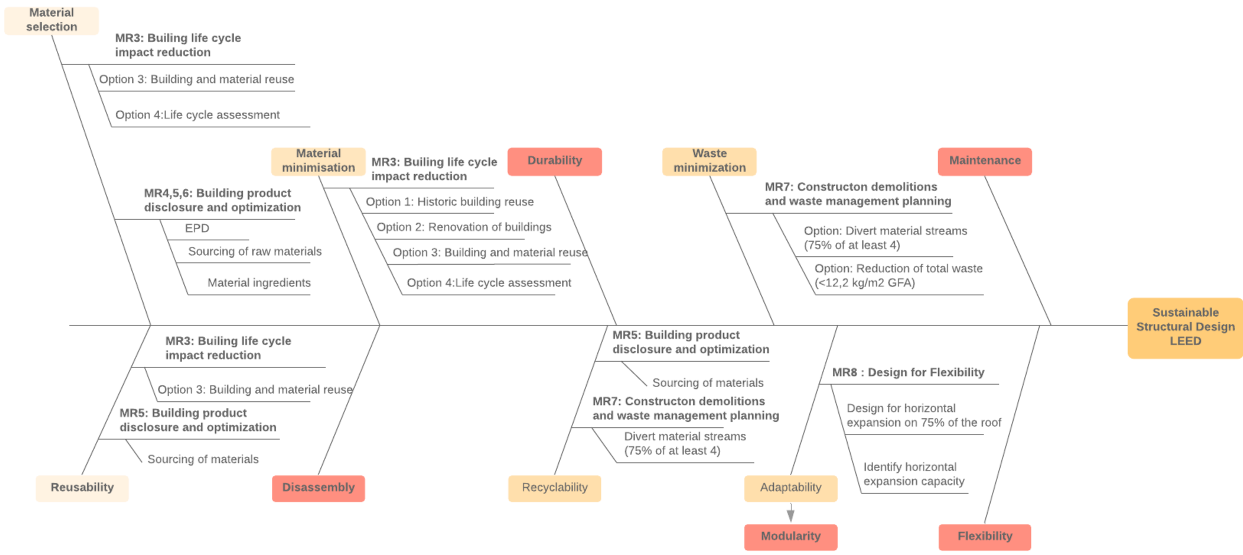
The intention of MR6 is the same as for both MR4 and MR5. In this credit, however, the focus is on the ingredients of the materials. The credits can be obtained either by sufficiently reportage of the materials (manufacturer's inventory, health product declaration, cradle-to-cradle certificated, and USGBC approval); or by optimization of the material ingredients also obtained through documentation prove, or by optimization of the product supply chain of the manufacturer.

Materials and Resources 7 – Construction and Demolition Waste Management (MR7 - 2 credits)

Reducing both construction and demolition waste by diverting it from landfills and incineration facilities to recovering, reusing, and recycling of materials. Two options are given to attain the 2 credits of MR7, either by diverting 75% of the waste streams of at least 4 materials or by reducing the total waste material in which no more than 2.5 pounds (1,1 kg) of waste is generated per square foot of the GFA of the building.

Materials and Resources 8 – Flexible Design (MR8 – 1 credit)

LEED contributes this credit solely to healthcare buildings resulting in measures that could predominantly be attributed to healthcare buildings. However, there are several indicators that are of a generalizable nature. Both flexible and adaptable indicators are identified. The intention of this MR8 is to conserve resources that are associated with construction and management of buildings by designing for flexibility and ease of future adaptation and for the service life of components and assemblies. The indicators that could be seen as generic are the following; for flexibility: use of demountable partitions for 50% of applicable areas, use of interstitial space for flexibility of services; and for adaptability: designing for future vertical expansion on at least 75% of the roof, and movable or modular casework for at least 50% of casework and custom millwork.



C. Analysis of GPR Gebouw

Environment - Environmental performance building (Milieu Prestatie Gebouw (MPG) – max rating: 500/5000)

For this score the environmental costs (euro/m2/year) are calculated of all the embedded materials in the building. The environmental costs of the materials are based on the life cycle of the materials and the data upon which the costs are based is extracted from the NMD, as is also done with MAT 1 in BREEAM-NL. The components in which the materials are embedded comprises of the foundation, floors, loadbearing structure, façade, roofs, installations (services) and encased components. Other than with BREEAM-NL, the estimated service life of the building is not set in stone. It is prone to change. This is crucial as the environmental costs heavily depend on the estimated service life. The estimated service life could be prolonged on the basis of the following criteria (W/E Adviseurs, 2013):

High internal amenity value – high functionality, special daylight and/or view, high comfort
High external amenity value – a landmark and powerful identity
High accommodating value – future-oriented, layout flexibility, flexible subdivisible and adaptable building volume

Environment – Circular material usage (max rating: 300/5000)

With this score the implementation of reusable, bio-based, secondary products and materials is stimulated. Also, the usage of sustainably cut down timber is incentivized. Besides the emphasis on materials, this credit also focuses on building methods; special design solutions for thin construction (a reduction of material in building systems due to design decisions), robust design or detailing of susceptible building elements, and easily adaptable building elements. Moreover, the building method also should be adjusted for multiple cycles for which the following indicators are put forward; 2 or more building systems should be entirely manufactured, separation of the structure and afbouw/inbouw, and demountable building components/systems.

User Quality – Functionality (max rating: 28/5000)

The score user quality is divided into four categories; accessibility, functionality, technical quality and social safety. The structure only plays a minor role in the category of functionality. The following aspects are referred to: free span (structural grid) and floor-to-floor height.

Future Value – Future-oriented facilities (max rating: 27/5000)

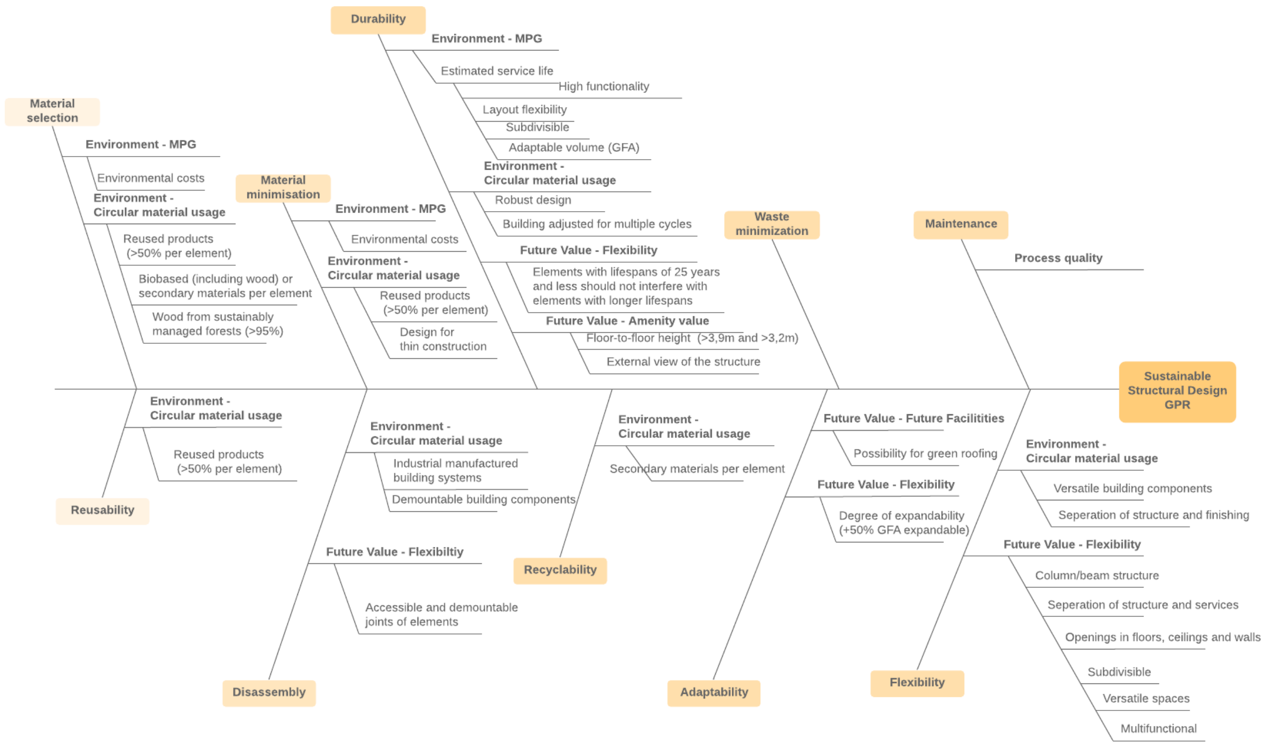
In this category, there are two aspects which coincide with the structure, namely; the bearing capacity of the structure itself that should be above 5 kN/m2 (18) and that the roof is designed for 'green roofing' (9).

Future Value – Flexibility (max rating: 162/5000)

In GPR, flexibility is an important feature of the future value of a building. In this score the emphasis is put on structural features in the building. For a building to be flexible in GPR the building should be *adaptable in size*, particularly the structure has to withstand enlargement in user surface (27). Furthermore, the *structural type* should be a column-/beam structure, or a frame structure, so that internal flexibility is possible (27). Also, an important feature in GPR is that the building should comprise of *modifiable elements*. Meaning, the structure and the façade should be separated from internal walls and services (27); in loadbearing walls (9) and floor/roofs (9) possibilities should be incorporated for future passages, and elements should be easily accessible and demountable (9). Finally, the *possibility of altering the spatial layout* should be incorporated through easily modifying the size of a room (18), the building should be subdivisible (18), and different functions inside the shell should be possible (18). Also, negative points can be scored if there is no possibility of adaptability in size (-9), if loadbearing walls are based on "schijf werking" (-27), service components are difficult to adapt and replace (-9), and elements with lifespans of 25 years and less should not interfere with elements with a longer lifespan (-9).

Future value – Amenity value (max rating: 50/5000)

The amenity value of a building is dissected into four areas: amenity of the direct surroundings (within 400 meters), the amenity of the outside of the building, amenity within the building and the educative value. The amenity of the direct surroundings does not have a link with the structure, as it does not focus on the building. The amenity of the outside of the building is focused on the façade in which the structure could have a facilitating/shaping value. If the structure of a building is linked to the façade in the design, it both supports it as it gives shape to the outline of the building. The internal amenity of the building is linked to the structure only on the basis of floor-to-floor height.



D. Flexibility calculation tool – BREEAM-NL

Rekentool Gebouwflexibiliteit

Verkaveling (inrichting)			0	1	2	3	WEGING	
1.	Kolomplaatsing	Casco	○	○	○	●	1	
2.	Verplaatsbare binnenwanden	Binnenafbouw	●	○	○	○	1	
3.	Voldoende aansluitpunten E-installaties	Installaties	●	○	○	○	1	
4.	Klimaat, E-installaties en W-installaties apart in te delen per stramien	Installaties	●	○	○	○	1	
								4%
Aanpasbaarheid (unitniveau)			**0**	**1**	**2**	**3**		
5.	Niet dragende functiescheidende wanden	Casco	○	○	○	●	2	
6.	Gebouwontsluiting	Casco	○	○	○	●	2	
7.	Niet dragende gevel en/of obstakels	Gevel	●	○	○	○	3	
8.	Unitgrootte, mogelijke indeling	Binnenafbouw	○	○	○	●	2	
9.	Zelfstandigheid unit, aanwezigheid pantry, meterkast & sanitair	Installaties	●	○	○	○	2	
								22%
Multi-functionaliteit (gebouwniveau)			**0**	**1**	**2**	**3**		
10.	Capaciteit draagvermogen	Casco	○	○	○	●	3	
11.	Toetreding van daglicht	Gevel	○	○	○	○	3	
12.	Hoogte Bovenkant vloer-Onderkant vloer (netto interne hoogte)	Binnenafbouw	○	○	○	●	3	
13.	Installaties binnen de (juridische) ruimte van de gebruiker	Installaties	○	○	○	○	3	
								22%
		Casco			100%			
		Gevel			0%			
		Binnenafbouw			83%			
		Installaties			0%			
Totaal								48%

1. Kolomplaatsing	Score
Kolommen binnen de gevel, stramien < 5400 mm	0
Kolommen binnen de gevel , stramien 5400 mm < 8100 mm	1
Kolommen binnen de gevel , stramien > 8100 mm	2
Geen kolommen binnen de gevel, vrije overspanning	3

2. Verplaatsbare binnenwanden	Score
Binnenwanden niet verplaatsbaar en niet afbreekbaar, meerdere functies	0
Binnenwanden niet verplaatsbaar; afbreekbaar maar niet herbruikbaar	1
Binnenwanden verplaatsbaar, demontabel en opnieuw op te bouwen	2
Binnenwanden eenvoudig verplaatsbaar, systeemwand	3

3. Voldoende aansluitpunten E-installaties	Score
Geen aansluitpunten	0
Aansluitpunt/goot in 1 richting in vloer, plafond of wand	1
Aansluitpunt/goot in 2 richtingen in vloer, plafond of wand	2
Holle vloer of computervloer	3

4. Apart in te delen installaties per stramien	Score
Geen indeling per stramien mogelijk	0
Alleen E-installaties mogelijk	1
E-installaties en W-installaties mogelijk, zonder ventilatie	2
E-installaties en W-installaties mogelijk, met ventilatie	3

5. Niet dragende functiescheidende wanden	Score
FS-wanden niet verplaatsbaar en niet afbreekbaar, meerdere functies	0
FS-wanden niet verplaatsbaar; afbreekbaar maar niet herbruikbaar	1
FS-wanden verplaatsbaar, demontabel en opnieuw op te bouwen	2
FS-wanden eenvoudig verplaatsbaar, systeemwand	3

6. Gebouwontsluiting	Score
Decentraal gecombineerde entree en kern	0
Centraal gecombineerde entree en kern	1
Gebouw verdeeld in 2 vleugels vv centrale gecombineerde entree en kern	2
Gebouw verdeeld in > 2 vleugels vv centrale gecombineerde entree en kern	3

7. Niet dragende gevel en/of obstakels	Score
Dragende gevel	0
Dragende gevel, 50% open oppervlakte of obstakels	1
Dragende gevel, 75% open oppervlakte of obstakels	2
Niet dragende gevel, geen dragende obstakels	3

8. Unitgrootte	Score
Groter dan 600 m2 BVO	0
Tussen 400 en 600 m2 BVO	1
Tussen 200 en 400 m2 BVO	2
Minder dan 200 m2 BVO	3

9. Zelfstandigheid unit	Score
Eén voorziening aanwezig	0
Twee voorzieningen aanwezig	1
Drie voorzieningen aanwezig	2
Vier voorzieningen aanwezig	3

10. Capaciteit draagvermogen	Score
Veranderlijke 1,75 kN/m2	0
Veranderlijke 2,50 kN/m2	1
Veranderlijke 4,00 kN/m2	2
Veranderlijke 5,00 kN/m2	3

11. Toetreding daglicht	Score
Minder dan 70%	0
Tussen 70% en 85%	1
Tussen 85% en 95%	2
Tussen 95% en 100%	3

12. Hoogte bovenkant vloer-onderkant vloer	Score
Netto interne hoogte ≤ 2700 mm	0
Netto interne hoogte 2700-3000 mm	1
Netto interne hoogte 3000-3500 mm	2
Netto interne hoogte 3500- 4000 mm	3

13. Installaties binnen de (juridische) ruimte van de gebruiker	Score
Installaties/leidingen ingestort in de vloer	0
Installaties/leidingen over 2 bouwlagen verdeeld	1
Installaties/leidingen in één bouwlaag, boven of onder	2
Installaties/leidingen onder computervloer of in holle vloer	3

III. Empirical Research Results

A. Survey: design criteria for structural design perspectives

Design for materials

Design criteria for selection of materials extracted from the surveys is depicted below:

- Strength. The strength in structural material, products, components, elements and system is essential is choosing the appropriate material.
- Stiffness.
- Thermal bridge. The magnitude of the thermal bridge of materials is dependent on the kind of material chosen. Moreover, the structural component has to be in contact with the exterior for a thermal bridge to occur. A thermal bridge has an impact on the indoor climate of a building.
- Fire safety. Steel, concrete and timber react differently when in contact with fire. Both the speed of ignition as the time for reaction differs. By coating the structural materials, the risk of fire decreases.
- Dimensions of a building. Most high-rises are constructed with steel or concrete.
- User requirements
- Service life
- Robustness
- Transport, deliver time, construction time
- The weight of the material.
- Minimal carbon footprint
- Local environment, such as soil properties, weather conditions, or earthquake risks.
- Total score on the life cycle
- Type of building
- Aesthetics
- Costs
- Early in the design, it is the selection of materials that is important, in the execution phase the origin and composition of the material are important.

Design for material use

Design criteria for minimizing the material usage derived from the survey are presented below:

- Light superstructure. By designing the structure with a light material the volume of the foundation could be lowered.

- Maximal squeezing of structural components. By designing the structure as thin as possible with no spare capacity, within the compounds of the EU-codes, the material quantity is lowered.
- Open structure. As more material is needed for the structure with loadbearing walls a structure with columns and beams results in lessening of material necessity.
- Limiting the loads on the structure. By designing the structure as such that the loads are minimized in certain areas.
- Schematization optimization. By efficiently designing the structure as such that the schematization results in a lower need for materials.

Important to note:

- Variant research. In a variant research, different materials are contemplated for the same structure so that the different structures can be compared.
- Optimisation of the structure through parametric design.

Design for durability

The design criteria for increasing durability of the structure, which is derived from the survey, is presented below:

- Design flexible. By incorporating flexibility in the design, the service life of a structure increases.
- An increase in the safety factor. As a structure is designed for a longer lifespan the structure is subjected to more stresses resulting in a higher risk of failure and therefore the safety factor increases. Which entails that structural components are required to be oversized.
- Material durability. Apply materials that do not deteriorate over time.
- Accessibility of critical junctions.

Important to note:

- Design of the architect and budget of the client play an essential role.

Design for waste effectiveness

The design criteria for reducing waste of the structure, which is derived from the survey, is presented below:

- Prefabrication of structural materials. By prefabricating structural material the waste is lowered during construction and demolition.
- Reduce finishes of materials.
- Sortation on the construction site.
- Optimal design. Material usage is minimized and, thus, EoL waste is lowered.

Design for maintenance

The design criteria for reducing maintenance which is derived from the survey are presented below:

- Durable structural materials. By incorporating structural materials that are durable the frequency of maintaining these elements is reduced. The level of cement in concrete influences the durability or the type of steel (stainless steel rather than zinc). Concrete requires less maintenance than steel.
- Accessibility of structural components. Structural components should be accessible so that maintenance is possible.

Protection from external influences. Structural materials deteriorate faster when in contact with open air. Humidity and temperature shifts are detrimental for structural materials. By averting structural materials being in contact with open air maintenance is reduced. One respondent said that maintenance of the structure is only is done when structural components are exposed to open air.

Design for reusability

Below the design criteria are presented for increasing the reusability of structural components:

- The durability of the structural components. For a structural component to be reusable for future structures the lifespan of a component is an important criterion as it is insurmountable that it deteriorates.
- Demountable structural components. The structural components should be easily dismantlable to the extent that they could be reused in future structures. Thus, simple joints or connections are crucial.
- Designing with reused structural components. By knowing what structural components are available in the market the structure could be designed accordingly.

Important issues when contemplating reusability:

- Structural donor. With a structural donor, structural components from an old structure could be utilized. This can be taken into account in the design of a new structure if a structural donor is present and meets the quality standards.
- Unknown what structural components are reusable in the future as the structure could incur damage.
- How much effort is needed to dismantle a structural component and to reassemble it.
- Transport of prefabricated structural components.

Design for disassembly

The design criteria to simplify disassembly of the structure consist of the following elements:

- Easily detachable structural components. The structural components should be connected via easily dismantlable joints or connections. By incorporating universal connections and bearings the structure could be easily dismantled. The details should be designed as such that structural components could be adequately dismantled. All structural components that are connected with screws, bolts, nails, hinges and clamps are beneficial for disassembly.
- Loose structural components. By administering more loose structural components instead of a monolithic structure or dry connections the potential of deconstruction without demolition increases. When designing for disassembly it is beneficial to build with structural elements, thus the go-to structural components are prefabricated concrete and steel.
- Incorporation of structural stability components. As the structure should be designed with loose structural components the stability of the building could be reduced, so implementation of stability components is essential such as wind braces or concrete stability cores.

Important to note:

- Transportation of the structural components
- Contemplation of the service life

Design for recyclability

The design criteria for recyclability which are derived from the survey are presented below:

- Separation possibilities. To recycle materials, materials should be able to be separated on an elementary level, insofar concrete is concrete, steel is steel and so forth. Thus, the potential should be incorporated to be able to simplify separation of materials, so that materials are isolated and can be recycled. Preferably no mixing of materials.
- Percentage of recycled content.

Design for adaptability

Important to note is that design for adaptability differs from design for flexibility as it focuses on alternating the structure itself instead of the design of the structure facilitating internal alterations as is the case with flexibility. Adaptability could be approached in two manners: expansion or modularity. The design criteria for incorporating adaptability in the structure obtained from the survey consist of the following elements:

- Redundancy in loadbearing elements. Sufficient capacity should be embedded in loadbearing elements for the extension in both horizontal and vertical loads. Also, sufficient capacity in the foundation is essential for expanding the structure as the loads' increases.
- Prior established expansion. The structure should be fully designed for the future possibility of expansion. Therefore, it should be known by the structural engineer through the client, as expedient measures should be incorporated so that horizontal or vertical expansion is made possible.
- Modularity.

Important to note:

- How much effort does it cost to add another floor?
- Transference of loads should be known prior to an operation such as adapting a structure.

Design for flexibility

The design criteria for incorporating flexibility in the structure derived from the surveys consists of the following elements:

- Open structure. Thus, incorporating a column and beam structure instead of implementing loadbearing walls or minimizing loadbearing elements. So that the use of space or spatial plan could easily be altered.
- Redundancy in the loadbearing elements. By implementing an overcapacity in loadbearing elements of the structure (or parts of it) building openings could be applied more easily. Furthermore, by incorporating redundancy in the loadbearing elements the structure could withstand higher loads allowing for a potential to change to a different user function. Also, it gives the possibility to adapt or enlarge the structure
- Take into account future openings. By contemplating future openings, the potential of reforming the spatial plan is increased. Next to that, the services or installation could be adjusted more effortlessly.
- Demountable dry connections.

Notable elements that do not directly affect the design of a structure but are important aspects when contemplating flexibility in the design.

- Prolonging the service-life
- A vision for the future
- Location
- Costs

B. Survey: interrelationships of structural design perspectives

Relations of material selection

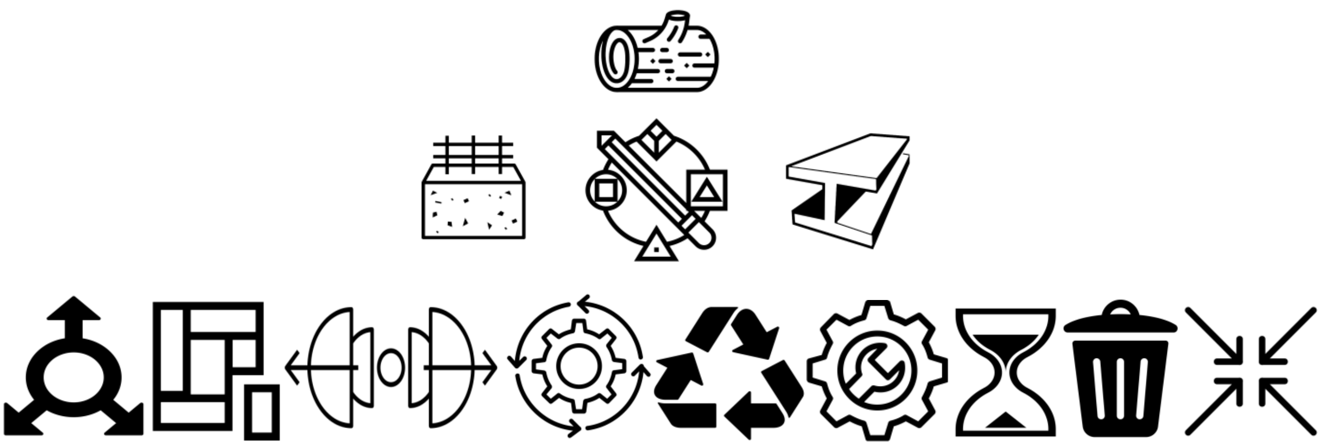
The traditional materials in building structures are steel, reinforced concrete and timber. Each of these materials follows their own path from the excavation site to construction to end of life, thus, differentiating from one another in the environmental impacts incurred in certain life cycle stages. Apart from the direct environmental impact, the structural go-to materials also encompass properties which influences structural design approaches.

Reinforced concrete

Concrete is a rather fixed and rigid material, therefore, when in place it is difficult to alter it. Thus, when designing for modularity, disassembly, and reusability concrete is an untenable option. Furthermore, concrete is a heavy material, which entails that the foundation needs to be designed accordingly resulting in an increase in material usage. When protecting the concrete structure from humidity and temperature shifts, little to no maintenance is needed depending on the quality of the concrete, the same goes for the concrete's durability. Although a concrete structure is not reusable in the same state after its End of Life phase, the material still has value; as concrete granulate, which could be recycled in future concrete batches.

Steel

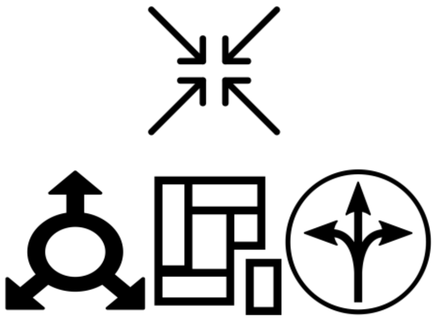
Steel positively influences multiple design focus areas. It is a valuable choice for an adaptable structure, as it is more easy to disassemble and can be reused if properly dismantled. If not properly dismantled, it could be recycled. Thus, the choice of steel reduces the amount of waste in the EoL, but also during construction as structural components are supplied prefabricated. The maintenance of a steel structure is also fairly low when not in contact with open air, however, protective paint is often used for reducing fire hazard. Also, it is more difficult to repair than concrete.



Relations of material use

When the objective of the design is to incorporate the minimal needed material as possible, it affects the flexibility in several ways. By exhausting the material usage, the structural elements are calculated for a specific function for a specific spatial layout, from that perspective the flexibly of a structure is decreased dramatically. However, as one respondent remarked, for a flexible design one opts for an open loadbearing structure (frame structure) which is beneficial for internal flexibility.

Squeezing the material quantity to its limits has an adverse effect on future changes of the structure. As mentioned above, an increase of live loads is not possible, but also an increase in dead loads is unfeasible. Thus, expansion of a building is not an option when minimizing the material input.



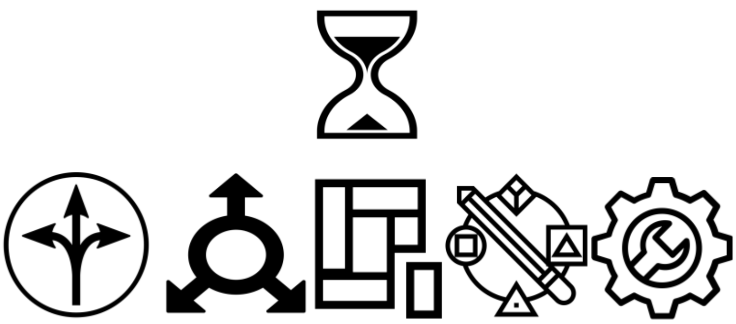
Relations of durability

Designing for a longer life span can be approached from two angles, either be conserving the technical properties of the structure or by incorporating the potential of extending its functional life by either changing the internal spatial layout or adapting the structure.

Designing the structure flexible, insofar a change in demand of the building user could result in a functional shift after its service life or a change in the building's internal, prolonging the service life, thus, increasing durability.

For a structure to incorporate properties to expand the structure, the notion of a longer life span is taken into account. By designing the structure with more material than is necessary in the structural components, the technical lifespan of the structure is increased.

Designing for long service life, inquiries of maintenance should be contemplated in the design of the structure. Inherently, more maintenance is required with longer lifespans.



Relations of waste effectivness

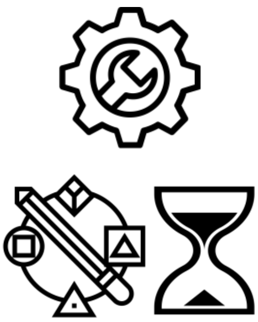
The quantity of waste is highly correlated with the quantity and type of structural materials used. Minimizing waste is focused on both the reduction of the waste output as it is focused on transforming the waste into valuable resources.

Prefabricated materials produce less waste than materials that have to be moulded during construction. By selecting the structural material the quantity of waste that is generated during construction and demolition should be taken into account. Consequently, by designing for reusability prefabricated structural components are applied which result in a reduction of waste as they could be utilized for future structures.

Relations of maintenance

Generally, concrete requires less maintenance than steel or timber as concrete is more resistant to external influences, especially in outdoor environments. Steel and timber need to be preserved during its service life by applying coating/varnish as both materials are more susceptible to fire hazard than concrete is. When choosing steel as the structural material, stainless steel is the preferred option when requiring less maintenance.

The more durable the structural components are designed, the less maintenance is required for those materials. By maintaining the structure, the quality will be conserved, thus, resulting in higher technical durability.

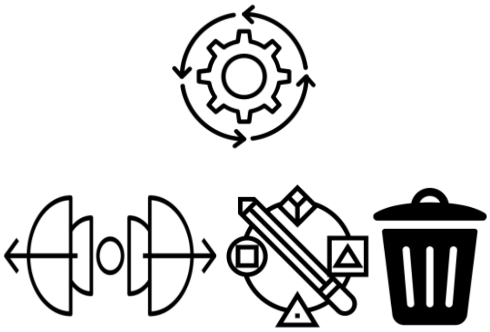


Relations of reusability

Designing for reusability is inherent to simplifying dismantlement of structural components. Consequently, when designing for reusability, the structure ought to be designed for disassembly, and vice-versa.

Structural components of the materials steel and timber are delivered prefabricated to the construction site, therefore, no modifications during construction are necessary. The components have to be connected, thus, increasing the extent to which they can be reused. An important aspect to consider for prefabricated components is the transport from the manufacturer or storage to the construction site as the weight and dimensions are variables that impact the transport.

A goal of designing for reusability is to eliminate or reduce waste during construction and after the service life of the building. As a building has a fairly long lifespan, which makes it difficult to foresee if the structural components are still valuable after usage as they could deteriorate or be damaged during its long lifespan. Furthermore, it is possible that the effort of dismantling the structure outweighs the added value of dismantling the components, if it is not to be reused, recycling is also an option.



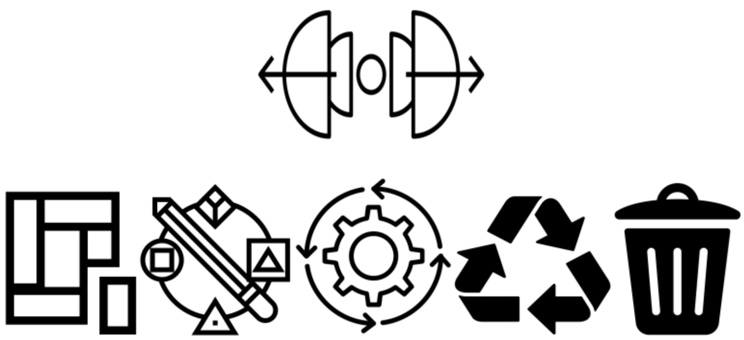
Relations of disassembly

The objective of designing for disassembly is that structural components could be easily detached. This makes a structure inherently more adaptable. By incorporating more connections and joints that are beneficial for the level of dismantlement, and designing with loose structural components instead of fixed, the structural component can be changed, removed, or added.

The structural materials that could be selected are reduced when designing for disassembly. Monolithic concrete is a fixed structural material and, therefore, no option if dismantled is preferred. In particular, steel and timber are the material of choice.

Designing for disassembly increases the potential of reusing the structural components as the structural components are easily detached from one another in the same state. Thus, the structural components can be utilized for future structures.

Disassembly of the structure influences the quantity of waste in a positive manner; reducing waste. During the EoL of the structure the structural components are not transported to landfills or incinerated, they are reused, therefore, waste is lowered.



Relations of recyclability

The quantity of recycled content in the structure or the potential of recycling at the end of the service life of the structure depends on the chosen material. For instance, concrete consists of multiple materials; cement, sand, gravel, and water. Also, concrete granulate could be added in the mix. The compound can be modified depending on which properties are demanded. Steel is a material that can be recycled in high-quality, and increasingly more structural steel has a recycled nature.

If the chosen structural materials can be recycled on an elementary level, waste during construction could be salvaged. Also, this is the case after the service life of the structure. For both protection of the materials is needed so the materials do not degenerate.

Relations of adaptability (expansion or modular)

An adaptable structural design has the goal to prepare a structure of a building to make alterations *to* the structure. Adaptability comprises of expansion either by vertically adding another floor or horizontally by adding another building section. Adaptability could also entail modular units in which the building surface could be enlarged or reduced by adding extra units or taking the structure apart.

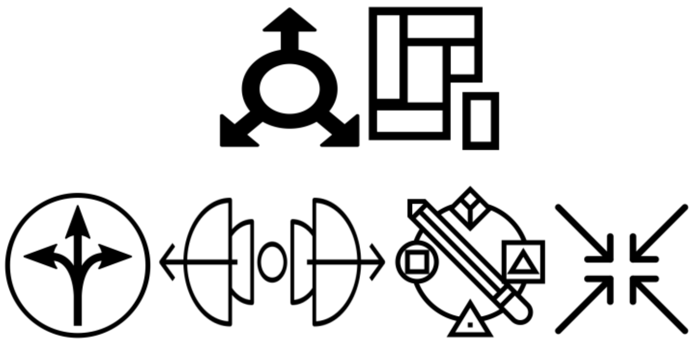
When taking the potential vertical expansion of the structure into consideration, structural load-bearing elements ought to be designed to bear the extra weight. The design, therefore, has to be calculated as if the extra floor is already incorporated. This results in a design in which the structural elements could withstand a significant increase in loads, thus, embedding also the potential of increasing live loads which is beneficial when contemplating user or function changes. However, it could have an adverse effect on the flexibility as the necessity of more loadbearing elements, for instance applying more or wider columns, could increase. Resulting a decrease in potential of altering the spatial layout.

For modular adaptability, the structure should be designed as such that it could be disassembled easily in which building units can be either added or removed. The design of the connections between structural components is, therefore, important.

When approaching the design from the perspective to increase the adaptability, there are certain structural materials that are preferred over others. For modular buildings, the preferred structural material is steel, as it is, in contrast with reinforced (in-situ) concrete, easy to replace and take apart given the fact that connections and joints are designed accordingly. Also, timber is preferred over concrete.

By designing the structure to be able to be expanded, altered or reduced more material has to be incorporated in contrast when adaptability is not an issue. Thus, the same that goes for a flexible design can be said for an adaptable design: it creates a precondition for the embedded material quantity.

Different statements can be made and different relations can be identified when looking to either expand the structure or modular construct the building. The same goes for the relation with durability. When designing for an addition of another floor, the structure is designed for a relatively long lifespan and, therefore, designed accordingly. For modular buildings, durability can be seen in two manners; building durability and material durability. When contemplating modular buildings, the building as a whole is designed for a relatively short lifespan as the goal of modular buildings is to dismantle and reuse the structure. As modular systems will be reused, the material durability should be high as it will re-enter another building's life cycle.



Relations of flexible design

When contemplating flexibility in the design of the structure the future use of the building has to be taken into account. By implementing higher capacity in the loadbearing structural elements, it increases both the potential of designing for flexibility as it does for the possibility of expanding the structure. The structure can withstand more stresses over its lifespan, thus, enabling internal alterations within the structure and expansion of the structure. Moreover, when regarding flexibility, the design should facilitate adjustment for internal services.

By designing for flexibility, as is mentioned frequently, the strength of the structure should be enlarged. This negatively affects the quantity of material input. It is not possible to optimize material input of the structure if the live loads on the structure change. Designing for flexibility, therefore, creates a precondition by raising the minimum material input.

An objective of flexibility in the structure is to prolong the lifespan of a building by giving the potential to alter the spatial plan or function of the building, therefore, by the implementation of flexibility in the structure it positively affects the functional service life. Furthermore, as more material is put into the structure it positively affects the strength and, therefore, the technical durability.

IV. Example Survey

Flexibel Ontwerp

Een flexibel ontwerp houdt in dat de capaciteit van de draagconstructie om intern verandering aan te brengen zonder dat de draagconstructie zelf aangepast dient te worden.

5. **Flexibiliteit in het ontwerp moet in de volgende fase(s) worden beschouwd?**
   Vink alle toepasselijke opties aan.
   - ☐ Schematisch Ontwerp (SO)
   - ☐ Voor Ontwerp (VO)
   - ☐ Detail ontwerp (DO)
   - ☐ Bestek
   - ☐ Uitvoerend Ontwerp (UO)
   - ☐ Anders: ____________________

6. **Wat zijn design criteria in de draagconstuctie voor een flexibel ontwerp?** *

   ____
   ____
   ____
   ____
   ____

7. **Op welke andere SDSS heeft flexibiliteit invloed? (meerdere antwoorden mogelijk - per ingevuld vakje graag de open vraag beantwoorden)**
   Vink alle toepasselijke opties aan.
   - ☐ Adaptief ontwerp
   - ☐ Demontabel ontwerp
   - ☐ Materiaal selectie
   - ☐ Materiaal minimalisatie
   - ☐ Herbruikbaarheid
   - ☐ Recyclability
   - ☐ Onderhoud vermindering
   - ☐ Durable ontwerp
   - ☐ Afval vermindering
   - ☐ Anders: ____________________

8. **Wat is de relatie met het ontwerpen voor adaptiviteit?**

   ____
   ____
   ____
   ____
   ____

9. **Wat is de relatie met demontabel ontwerp?**

   ____
   ____
   ____
   ____
   ____

10. **Wat is de relatie met materiaal selectie?**

   ____
   ____
   ____
   ____
   ____

11. **Wat is de relatie met materiaal minimalisatie?**

   ____
   ____
   ____
   ____
   ____

12. **Wat is de relatie met ontwerpen voor herbruikbaarheid?**

   ____
   ____
   ____
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   ____

13. **Wat is de relatie met het ontwerpen voor recyclability?**

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   ____
   ____
   ____
   ____

V. Interview Protocol

This appendix established the interview protocols used to interview the structural engineers (Explore A) and the sustainable structural design experts (Explore B). The interview protocols are derived from Baarda and van der Hulst (2012). As said both interviews follow the semi-structured approach.

a. Interview Explore A with structural engineers

Prior to the interview:

- Send introduction of the researcher and the research

Bring to the interview:

- Recording equipment
- Interview Protocol
- Note block
- Pen

Interviewer

Create an open and friendly environment, be critical, ask the right questions, don't be afraid to , ask for real life examples and clarifications, keep the focus on the subjects at hand, don't get distracted on topic that doesn't concern the research and keep an eye on the clock. Write down during or after the interview, important findings, but don't let it be of a distracted nature.

Introduction

- Thank the interviewee for cooperation.
- Give a concise introductory of the graduation subject.
- Research that is in collaboration with Arcadis B.V. and Delft University of Technology.
- The answers are used with care: confidentially.
- Ask permission from the interviwee to record the interview.
- Ask the interviwee if he/she is willing to give feedback on the transcribed interview as well as validating it.

Questions/subjects

1. Influence of the structural engineer

   a. Role
   b. Activities
   c. Focus
   d. Opportunities
2. Design phase
   a. Phases
   b. Information availability
   c. Trade-offs
   d. Alterations, why?
3. Structure
   a. Material
   b. Elements
   c. Components
   d. Systems
   e. Criteria
   f. Goal
   g. Overlap
4. Sustainability assessment methods
   a. Usage of BREEAM-NL, GPR and LEED
   b. Life cycle assessment
   c. Influence of the structure on health aspects
   d. Relation between structure and operation energy
   e. Contemplation of waste
5. Additional information (Opinions)
   a. What do you see as the most important hurdle for increasing sustainability in structure's
   b. What is the overall feeling about sustainability within the structural department?
   c. What do you think is the added value of the structure from an environmental point of view?
   d. What do you think is the added value of the structure from an economic point of view?

e. What do you think is the added value of the structure from an social point of view?

Closing interview

- Thank the interviewee for his/her time and useful responds.
- Transcription of the interview will be send.

b. Interview Explore B with sustainable structural design experts

Prior to the interview:

- Send introduction of the researcher and the research
- Provide the goal of the interview

Bring to the interview:

- Recording equipment
- Interview Protocol
- Note block
- Pen

Interviewer

Create an open and friendly environment, be critical, ask the right questions, don't be afraid to , ask for real life examples and clarifications, keep the focus on the subjects at hand, don't get distracted on topic that doesn't concern the research and keep an eye on the clock. Write down during or after the interview, important findings, but don't let it be of a distracted nature.

Introduction

- Thank the interviewee for cooperation.
- Give a concise introductory of the graduation subject.
- Research that is in collaboration with Arcadis B.V. and Delft University of Technology.
- The answers are used with care: confidentially.
- Ask permission from the interviewee to record the interview.
- Ask the interviewee if he/she is willing to give feedback on the transcribed interview as well as validating it.

Questions/subject

1. Environmental impact of structure

   a. Materials

b. Waste

c. Emissions

d. Longevity

e. Life cycle

f. Measurability

g. Comparability

2. Life cycle assessment

3. Sustainable structural design

a. Design strategies

b. Influence on other strategies

c. Dependencies

d. Advantage and disadvantages

e. Real-life examples

Closing interview

- Thank the interviewee for his/her time and useful responds.
- Transcription of the interview will be send.

C. Case study Interviews

Prior to the interview:

- Send introduction of the researcher and the research
- Provide the goal of the interview
- Send the list of sustainable structural design strategies with explanation

Bring to the interview:

- Recording equipment
- Interview Protocol
- Note block
- Pen

Interviewer

Create an open and friendly environment, be critical, ask the right questions, don't be afraid to , ask for real life examples and clarifications, keep the focus on the subjects at hand, don't get distracted on topic that doesn't concern the research and keep an eye on the clock. Write down during or after the interview, important findings, but don't let it be of a distracted nature.

Introduction

- Thank the interviewee for cooperation.
- Give a concise introductory of the graduation subject.
- Research that is in collaboration with Arcadis B.V. and Delft University of Technology.
- The answers are used with care: confidentially.
- Ask permission from the interviewee to record the interview.
- Ask the interviewee if he/she is willing to give feedback on the transcribed interview as well as validating it.
  1. The goal of the client
     a. What is the objective of the client?
     b. What are their sustainability goals?
     c. What is their vision for the building (service-life)?
  2. How does the structure fit in attaining the stated sustainability goals?
  3. What design decisions were made from initiation till now for the following design strategies (individually handled)?
     a. Material selection
     b. Material minimisation
     c. Flexibility
     d. Adaptability
     e. Disassembly
     f. Reusability
     g. Recyclability
     h. Maintenance
     i. Durability
     j. Waste minimization
     k. Are there any other structural design strategies that is implemented in the structural design?
  4. What was the role of the sustainability assessment methods in the design of the structure?
     a. How was it used?
     b. How does that reflect with the eventual detailed design?
     c. Did you deviate from the methods?
  5. Did the structure influence other disciplines in the building (Services, finishing, insulation, façade, …)?
  6. Were there bottlenecks encountered when designing the structure?
     a. What were the causes?
     b. How was it solved?
  7. Did you have to make concessions in the design of the structure? If yes, what were the implications on the structural design?

8. What kind of lessons were learned from the perspective of structural design?