Design and material selection for lowering the environmental impact of Dutch office buildings

INVESTIGATING THE IMPACT OF CLIENTS' INITIAL AND FUTURE REQUIREMENTS ON THE FINAL DESIGN AND MATERIAL COMPOSITION OF A BUILDING'S LOAD BEARING STRUCTURE

8 NOVEMBER

Anouk van der Ree

TU Delft

Witteveen + Bos

Illustration title page: (BOSCO VERTICALE)

Design and material selection for lowering the environmental impact of Dutch office buildings

investigating the impact of clients' initial and future requirements on the final design and material composition of a building's load bearing structure

Written by

A. L. van der Ree

to obtain the degree of Master of Science in Structural Engineering
at Delft University of Technology.

To be defended publicly on November 30th, 2022.

Colophon

Author

Name	Anouk Louise van der Ree
Studentnumber	4571142

University

Delft University of Technology
Faculty of Civil Engineering and Geosciences
Master Structural Engineering
Specialization in Structural Mechanics

Graduation committee

Prof. dr. H.M. (Henk) Jonkers	TU Delft **(chair)**
Ir. S. (Sander) Pasterkamp	TU Delft
Dr. M.C.M. (Maarten) Bakker	TU Delft
MSc M.S. (Maartje) Dijk	Witteveen+Bos

Preface

This thesis is the final deliverable of my graduation research for the Master of Science in Structural Engineering at Delft University of Technology. This research was carried out in collaboration with Witteveen+Bos, which enabled me to use some of their past projects as a case study. The final goal of this research is to develop and propose a MCA that shows which building materials might result in the lowest environmental impact of an office building's supporting structure. At the same time, this MCA can be carried out for different design strategies, all optimizing for different principles of the Circular Economy.

Experts in the field of research that are mostly interested in the different design strategies that are proposed, can find all information regarding them in chapter 4. An overview of the used building materials in this research and the reasoning behind the selection of these materials can be found in chapter 6. The criteria that were included in the MCA and the various steps it is composed of, can be found in chapters 5 and 8. Finally, the conclusions, discussion of the results and recommendations for further research are placed in chapters 10, 11 and 12. All relevant background information was added in the Appendices.

Furthermore, I would like to thank everyone who contributed to the content of this research and helped me in the process of writing it. First of all, I would like to thank my graduation committee. Henk Jonkers, acting as the chair of this committee, helped a great deal in the demarcation of this research and always motivated me to keep in mind the final product I wanted to deliver. My other two supervisors, Maarten Bakker and Sander Pasterkamp, always gave honest feedback and I learned a great deal from them, especially on the field of sustainability, the Circular Economy and their application in practice. Finally, I want to thank my supervisor from Witteveen+Bos, Maartje Dijk, for making the time to guide me during my research and her suggestions regarding the building materials that are included in this thesis. Besides my graduation committee, I would like to thank my family, friends and colleagues for always keeping me motivated and giving me the moral support I needed during this research. It means a great deal to me!

Delft, October 6th, 2022
Anouk van der Ree

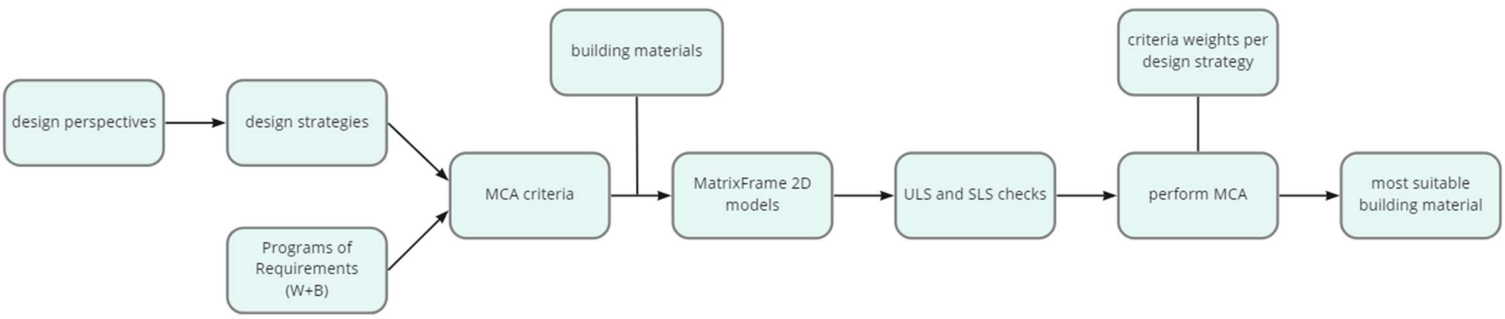
Summary

The following sections give a quick summary of the performed research. First, a brief motivation is given, followed by the used methodology. The different design strategies are mentioned, together with the varying weights of all the criteria of the Multi Criteria Analysis (MCA) that correspond with them. The results of the application of the proposed MCA on a case study from Witteveen+Bos are included, resulting in the final conclusions and recommendations. The final section of this summary gives a brief outline of the different parts this research is divided in.

In order to help the building and construction sector move towards a Circular Economy and lower its environmental impact, a better founded choice regarding the design and selection of building materials for a building's load bearing structure is required. Especially office buildings can help in this transition, as a relatively large percentage of their total floor area is not used up to their full potential. This often has to do with changing requirements of the clients that use the building, which results in vacant buildings as clients move towards a new building that better fits the company's current wishes.

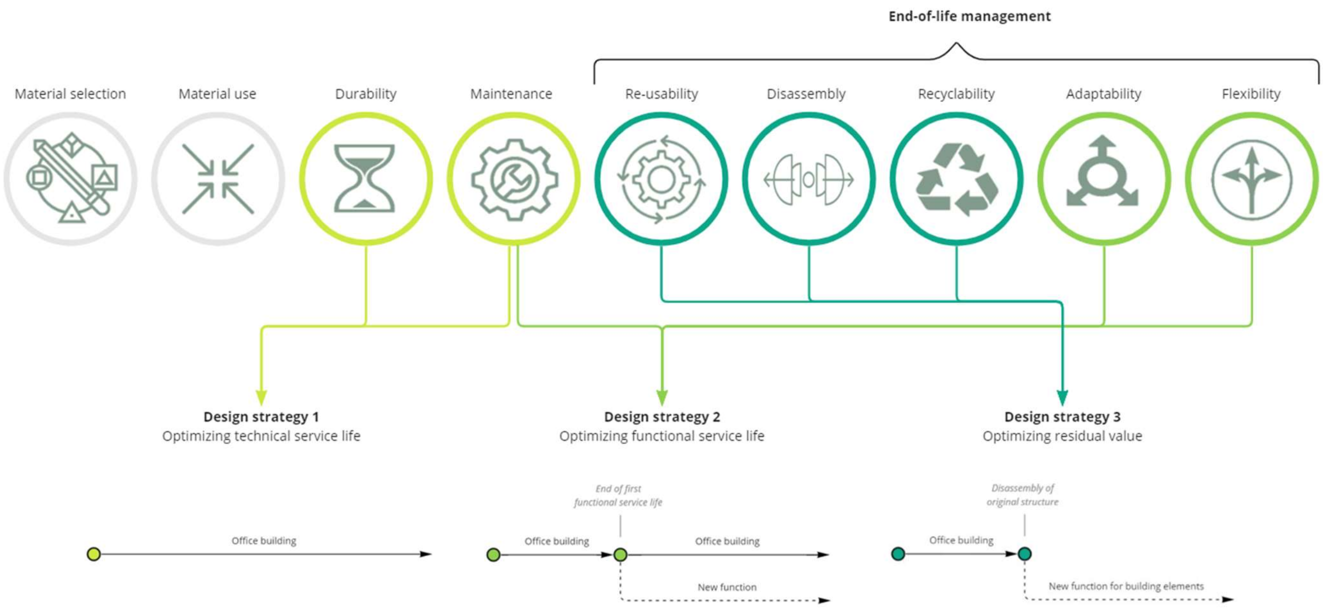
By investigating different design strategies that focus on optimizing various aspects of the Circular Economy, an office building can be designed in such a way that it matches both the initial client's requirements as well as possibly changing future needs. Different design strategies then lead to varying layouts of a building's load bearing structure and the building material it's made of. By matching a client to one design strategy, an optimal design for the office building can be made, which might be considered as the solution with the lowest environmental impact for that specific combination of current needs and the building's future perspective.

The following figure shows a simple flow diagram of the different steps that were performed in this research. Each topic will be discussed further in the following sections.



Design perspectives and design strategies

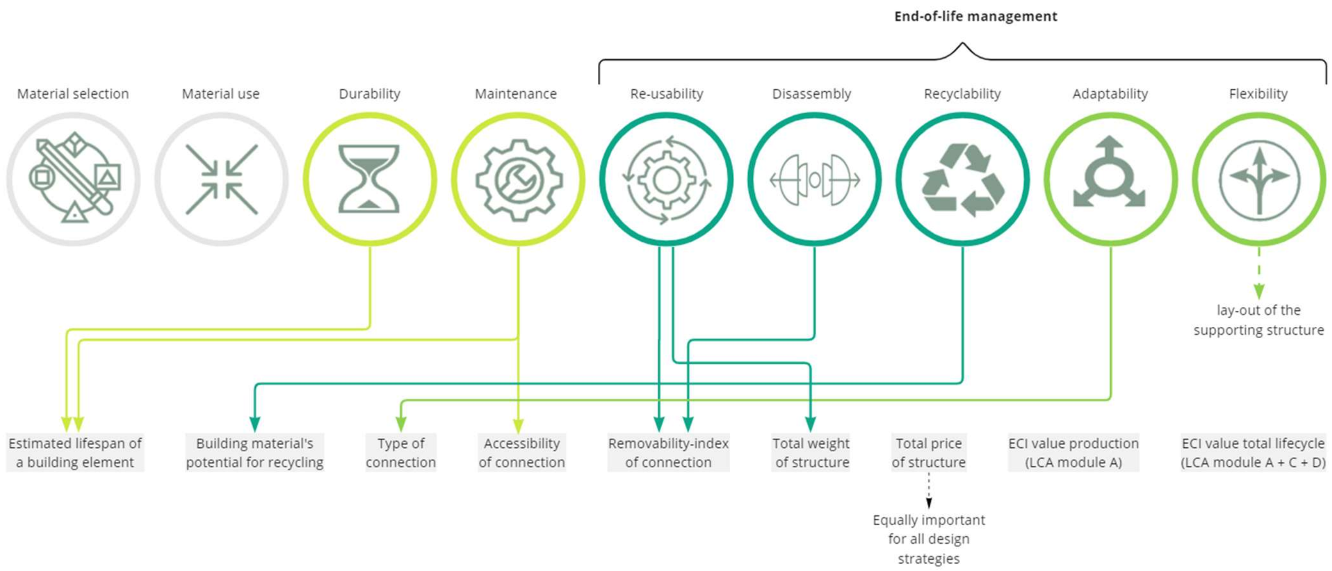
In his thesis, Tim Vonck introduced ten design perspectives from which each one contributes to reaching a more sustainable structure, however some of them contradict with each other and as a result of that, not all aspects can be fully optimized in a design. By ranking the design perspectives in varying orders, each time prioritizing one over the other, specific design strategies are formed. The first one aims to optimize a structure's technical service life while limiting the used amount of resources needed for maintenance during its functional lifespan. The second strategy focuses on maximizing a structure's functional service life which enables a building to follow possible changes in requirements regarding space and its internal layout. As it's expected that a structure will be in use for a long time, the needed amount of maintenance still needs to be limited. The final design strategy aims to maximize a structure's residual value at its end-of-life stage by making elements fit for re-use in other projects. The link between a design strategy and the corresponding design perspectives is given in the figure below, together with possible timelines for a building per design strategy. A more detailed explanation of these strategies is given in chapter 4.



Note that the objective of this research is to gain better insight in the selection of a suitable design strategy (including the lay-out of a building's supporting structure) and building material, which excludes the design perspectives material selection and material use from further investigation in the design strategies.

MCA criteria

As the final goal of this research is to create a MCA that analyses which building material best fits a specific design strategy per project, it's necessary to select criteria for this MCA. The most suitable and transparent solution would be to use the same design perspectives as criteria, as these were already prioritized per design strategy. However, these design perspectives are still quite abstract and thereby hard to quantify using scores in the MCA. As it's desired to use actual numbers in the MCA, which creates a clear difference between various results, already existing studies and scoring methods were selected and linked to the design perspectives. These MCA criteria are the result of analysing different programs of requirements for office buildings from Witteveen+Bos, combined with principles of the Circular Economy linked to the design perspectives. The following figure shows the design perspectives (top of the figure) and their link with the MCA criteria (bottom of the figure). Again, material selection and material use are not included here.



The following table gives a short explanation of the relation between the MCA criteria and the linked design perspectives. At the same time, this functions as the foundation of the proposed weights that are assigned to the criteria for each design strategy. The corresponding scoring methods for these criteria are included in chapter 5.

1	Estimated lifespan of a building element	An ESL that is higher than the RSL is assumed to be an indication of high durability (caused by work execution, material characteristics, etc.). It might also result in less deterioration, resulting in lower maintenance needs.
2	Building material's potential for recycling	In case re-use of building elements in not possible for some reason, the most residual value can still come from recycling the building material. This is specifically useful when optimizing a structure's residual value at its end-of-life stage.
3	Type of connection	This criterium focuses on the possibility of adjusting a connection in case additional future elements have to be added in case of expansion of the building. For example, a bolted connection seems easier to adjust than a cast in-situ one.
4	Accessibility of connection	Besides the type of connection, also its accessibility needs to be adressed. Here, a high level of accessibility means little to no damage to connected elements when performing maintenance or replacing deteriorated elements in the worst case.
5	Removability-index of connection	The two criteria mentioned above can also be combined into one removability-index of a connection. A high removability-index shows that a connection has great potential for easily removing it and thereby demounting a structure.
6	Total weight of structure	This criterium is specifically focused on the final weight of the total structure. Lower self-weight of the elements is considered to be beneficial for their transportability, which is important when elements can be re-used in new projects.
7	Total price of structure	In practice, the total price of a structure is always something that is included in the decision making. This criterium enables one to show which building material might result in the cheapest structure (based on early design checks).
8	ECI value production (LCA module A)	Finally, ECI values are included in the MCA. First, the ECI value for the production process only is considered. This is specifically relevant when assuming the building will last a long time as its functional service life matches its technical one.
9	ECI value total lifecycle (LCA module A + C + D)	Also a structure's ECI value over its full lifecycle is included. This one becomes more relevant when a structure is being optimized for a high residual value, as LCA module D might result in benefical aspects at a materials end-of-life stage.

Note that criterium 5 depends on criteria 3 and 4 (more information regarding this can be found in chapter 5). In order to prevent 'double counting scores' in the MCA, it's recommended to only include one of these three criteria in the MCA (this was done by only assigning a non-zero weight to the most important criterium of these three in one design strategy and setting the weights for the other two to zero). This can also be seen in the table at the end of this page.

Design of the load bearing structure

After selecting the most suitable design strategy, one can start the design process of the load bearing structure. This requires information regarding strength, costs and ECI values for all building materials that are being considered (more information on the selected building materials can be found in chapter 6). In the context of this thesis, MatrixFrame was used to create 2D frames of governing cross sections of a building. After selecting the appropriate floor loads, wind load and including the self-weight in the model, basic USL and SLS were performed in order to calculate the necessary cross sectional dimensions of the load bearing elements (more information on this process can be found in chapter 7 and the appendices). The final results of this design function as the input of the MCA.

Weights of MCA criteria per design strategy and the final results

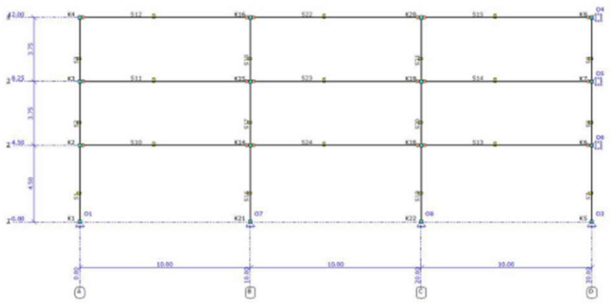
For each design strategy, the weight of all MCA criteria is changed in order to match each design strategy's specific goal (the proposed weights of the criteria per design strategy based on the arguments as explained in chapter 5, are shown in the table below). The previous table and figures emphasize the links between the design perspectives, corresponding design strategies and the MCA criteria that are particularly important for each strategy. However, note that the weights as shown in the table below are still somewhat open for adjustments. As the MCA criteria are based on already existing studies, its variety might be limited. The benefit of this method, is its high potential for keeping it up to date (this means that future users can easily add building materials and criteria to the MCA, as well as they might want to change the weights per criteria in case new studies or motivations become available).

	Weights of MCA criteria per design strategy		
	Design strategy 1 *(max. technical service life)*	Design strategy 2 *(max. functional service life)*	Design strategy 3 *(max. residual value)*
1. Lifespan of a building element	5	3	0
2. Material's potential for recycling	0	0	2
3. Type of connection	0	4	0
4. Accessibility of connection	2	0	0
5. Removability-index of connection	0	0	4
6. Total weight of structure	0	0	2
7. Total price of structure	1	1	1
8. ECI value (LCA module A)	2	2	0
9. ECI value (LCA module A + C + D)	0	0	1
Total	**10**	**10**	**10**

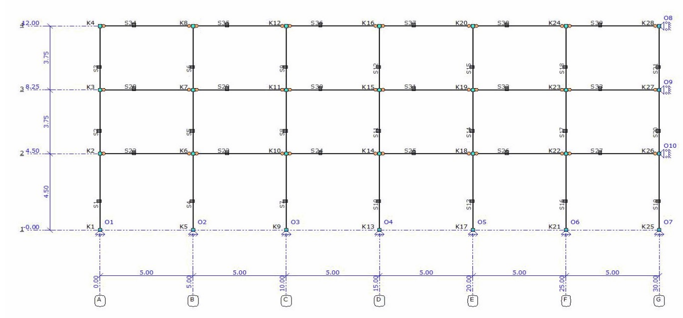
The final MCA score of a building material per design strategy can be calculated by multiplying the score per MCA criterium (which is always an index between 0 and 1, as explained further in chapter 5) by the corresponding weight of that criterium and then summing the scores for all nine MCA criteria. Two examples of the MCA's that were performed on a case study can be found in the appendices.

Application on case study Witteveen+Bos

Now the performed research and proposed set up of the MCA can be applied on an actual project that was selected from Witteveen+Bos. This enables the opportunity to investigate to which extent varying requirements and wishes regarding sustainability, result in different designs of an office building. Based on the case study's program of requirements, both design strategy 1 and 2 seemed suitable, which made it interesting to compare the results for both strategies. First, the following figures show the different lay-outs of the load bearing structure for both strategies.

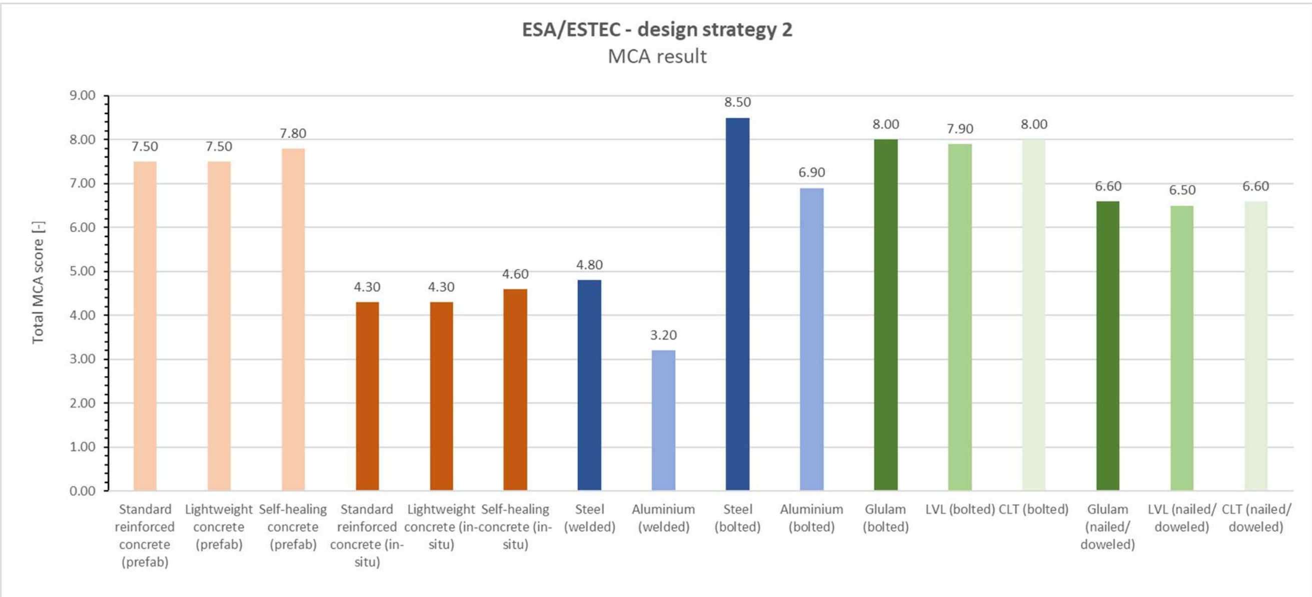


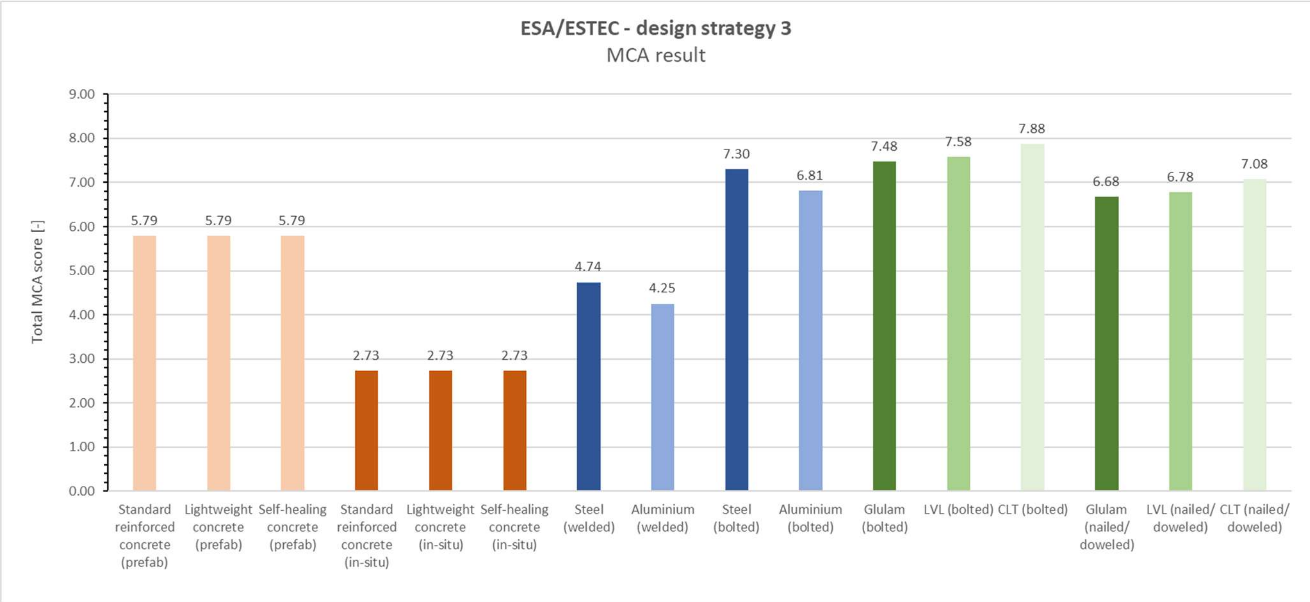
Lay-out for ESA/ESTEC design strategy 2



Lay-out for ESA/ESTEC design strategy 3

These figures clearly show the influence of a selected design strategy on the lay-out of the supporting structure. Design strategy 2 aims for high internal flexibility, resulting in open spaces and large spans. Design strategy 3 aims for potential re-use of building elements, which results in smaller, standardized elements that are already designed for future use in buildings with a different function. The figures below show the final MCA results for both design strategy 2 and 3 that were applied. Note that the complete MCA for this case study can be found in the appendices, including scores for each criterium.





These results show that when following different design strategies that optimize for different aspects of the Circular Economy, indeed influences the final outcome regarding which building material seems to be most suitable and might result in the lowest environmental impact. However, for the results of both strategies on this case study, the difference between a bolted steel structure and a bolted CLT structure is very limited. Therefore, it might be advised to take these two building materials to the next design step, where a more detailed design can result in the final material selection. This means, that for this case, the MCA more functions as a tool to exclude a list of building materials from being investigated further, and more results in one, two or maybe more building materials that show great potential for lowering a building's environmental impact. Furthermore, it can function as a foundation for well-considered decision making when selecting a building material and design strategy.

However, in order to verify the conclusions from this research, it's advised to apply the proposed MCA approach on more case studies or past projects from Witteveen+Bos, in order to analyse whether the MCA focuses on the right topics. At the same time, this can give more insight into which aspects are still missing in the MCA and might have a great influence on the final results.

The verification of the MCA method as mentioned above, is considered to be the most important recommendation for further research and the future MCA users. One of the main advantages of the proposed MCA, is the fact that new criteria and building materials can quite easily be added to the MCA, as all scoring methods are clearly explained in the report. Therefore, it's advised to keep adding new building materials and floor systems to the current MCA, as this helps in keeping the analysis relevant and up to date. Only then, it can help in comparing more traditional building materials to relatively new ones.

Besides keeping the proposed MCA up to date and adding new materials and criteria, it's evenly important to find more reliable methods with regard to calculating ECI values of building materials. In this research, ECI data from the Nationale Milieudatabase (NMD) was used. However, this database lacks a lot of important background information and doesn't give clear insight in which aspects are being considered in the ECI calculation.

Finally, as mentioned in the PhD thesis 'The Sustainable Office', combining different building materials in one supporting structure shows great potential for lowering the structure's environmental impact. It's highly advised to perform future research into the possibilities of these combinations and how that would affect the types of connections that can be made between different materials.

Outline of this report

In order to divide all information into logical, smaller pieces, this thesis is divided into four parts:

1. The research foundation (containing background information, the research questions and used methodology)
2. Information and data gathering (where first different design strategies are introduced and different programs of requirements are analysed, then there will be elaborated on a selection of building materials that apply for implementation in the MCA and finally, the criteria and set up of the MCA is explained in further detail)
3. Results and final remarks (here the proposed MCA is used to analyse the case studies from Witteveen+Bos, which results then can be used to form conclusions and answer the main research question)
4. Appendices.

A more detailed outline of this thesis is given in section 2.5.

Table of contents

Colophon v

Preface vii

Summary viii

List of figures xx

List of tables xxi

Definitions xxiii

Abbreviations xxv

PART I | Research foundation 1

Chapter 1 – Introduction 2

1.1 Background information 2

1.1.1 Increase of the built environment 2

1.1.2 Current practice in the application of building materials 3

1.1.3 Application on office buildings in The Netherlands 4

1.2 Problem analysis 5

1.3 Knowledge gap 5

Chapter 2 – Research design 6

2.1 Research objective 6

2.2 Research questions 7

2.3 Research scope 9

2.4 Methodology 10

2.5 Outline 13

Chapter 3 – Theoretical framework 15

3.1 Sustainability and the circular economy 15

3.1.1 Linking sustainability to CE 15

3.1.2 Principles of the CE 16

3.2 Quantifying a product's environmental impact 18

3.2.1 Life Cycle Assessment (LCA) 18

3.2.3 Environmental Cost Indicator (ECI) 18

3.2.4 Dutch 'Nationale Milieudatabase' 19

3.3 Design perspectives 19
3.4 Link with PhD report 'The Sustainable Office' 21

PART II | Information and data gathering 23
Chapter 4 – Design strategies 24
4.1 Contradicting design perspectives 24
4.2 Forming design strategies 27
4.2.1 Optimizing a structure's technical service life 27
4.2.2 Optimizing a structure's functional service life 29
4.2.3 Optimizing a structure's residual value 32
4.2.4 Making a design with re-used building elements 34
4.3 Summary of design strategies 35
Chapter 5 – Program of requirements 36
5.1 Suitable projects 36
5.1.1 APM Terminals, Maasvlakte 36
5.1.2 Ørsted, Vlissingen 37
5.1.3 ESA/ESTEC, Noordwijk 38
5.2 Criteria to include in the MCA 40
5.2.1 Lifespan of a building element 40
5.2.2 Building material's potential for recycling 42
5.2.3 Type of connection 43
5.2.4 Accessibility of connection 43
5.2.5 Removability-index of a connection 44
5.2.6 Total weight of used building material 44
5.2.7 Total price of used building material 45
5.2.8 ECI value for production process (LCA module A) 45
5.2.9 ECI value at end-of-life stage (LCA module A, C and D) 46
5.3 Relation between MCA criteria and design perspectives 47
5.4 Weights of MCA criteria 49
Chapter 6 – Building materials 51
6.1 Load bearing elements 51
6.1.1 Beams and columns 52
6.1.2 Floors 52
6.1.3 Roofs 53

6.2 Reinforced concrete ... 54
6.2.1 Standard reinforced concrete ... 54
6.2.2 Lightweight reinforced concrete ... 55
6.2.3 Self-healing reinforced concrete ... 55
6.2.4 Prefabricated concrete vs. cast in-situ concrete elements ... 55
6.2.5 Hollow-core slab ... 56
6.2.6 Composite floor system ... 56
6.3 Metal ... 57
6.3.1 Steel ... 57
6.3.2 Aluminium ... 58
6.3.3 Steel deck structure ... 58
6.3.4 Aluminium deck structure ... 59
6.4 Timber ... 59
6.4.1 Glulam ... 60
6.4.2 LVL ... 60
6.4.3 CLT ... 61
6.5 Summary of used building materials ... 61
Chapter 7 – Design of the load bearing structure ... 63
7.1 Design loads ... 63
7.1.1 Design service life ... 63
7.1.2 Consequence class ... 64
7.1.3 ULS and SLS design loads ... 64
7.1.4 Imposed floor loads ... 66
7.1.5 Wind loads ... 66
7.1.6 Snow loads ... 68
7.2 Strength and deformation checks ... 68
Chapter 8 – MCA decision making ... 69
8.1 Steps for completing the MCA ... 69
8.2 MCA scores per building material ... 72
8.2.1 Lifespan of a building material ... 72
8.2.2 Building material’s potential for recycling ... 74
8.2.3 Type (TC), accessibility (AC) and removability-index of a connection ... 74

PART III | Results and final remarks 77
Chapter 9 – Application on case study 78
9.1 Linking PoR's to design strategies 78
9.1.1 Focus points per case study 78
9.1.2 Linking design aspects to a design strategy per case study 79
9.2 Design for ESA/ESTEC 80
9.2.1 Design strategy 2 81
9.2.2 Design strategy 3 85
9.2.3 Comparing design strategy 2 and 3 90
9.3 MCA sensitivity analysis 91
9.3.1 Sensitivity analysis for design strategy 2 92
9.3.2 Sensitivity analysis for design strategy 3 93
Chapter 10 – Conclusions 95
Chapter 11 – Discussion of the results 99
11.1 Validity of the data and research 99
11.1.1 ECI values for used building materials 99
11.1.2 Costs of used building materials 100
11.1.3 Generalization of this research 101
11.2 Interpretation of the results 101
11.2.1 Expected benefits of innovative building materials 101
11.2.2 Expanding case study results for in-situ concrete to design strategy 1 102
11.2.3 Link between MCA results and further design steps 102
11.3 Limitations of this research 103
11.3.1 Limited number of criteria in MCA 103
11.3.2 Limited number of building materials 103
11.3.3 Use of standardized cross sections 104
11.3.4 Simplification of wind bracings 104
Chapter 12 – Recommendations 106
12.1 Recommendations for Witteveen+Bos 106
12.1.1 Verification of the MCA on past projects 106
12.1.2 Use design strategies to actively work together with clients on sustainability 106
12.2 Recommendations for future research 107
12.2.1 Combining and adding new building materials and floor systems 107
12.2.2 ECI values and their sources 108

Bibliography 109

PART IV | Appendices 113

Appendix A – Additional background information 114

A.1 Climate change 114

A.2 Resource depletion 115

A.3 Emissions per sector 116

A.4 Life cycle stages 118

A.5 Lansink's Ladder 120

A.6 Cramer's 10R model 121

A.7 Methods for measuring the environmental impact 122

Appendix B – Environmental impact categories 124

Appendix C – Assessing materials for recycling 126

Appendix D – Calculation of ECI values 129

Appendix E – Calculation of costs per building material 130

Appendix F – Peak velocity pressure for wind loads 131

Appendix G – Concrete strength classes 133

Appendix H – Steel properties and profiles 135

Appendix I – Timber properties and profiles 141

Appendix J – Formulas used for wind loads 146

Appendix K – Formulas used for ULS checks 147

Appendix L – Design ESA/ESTEC – design strategy 2 149

Appendix M – Design ESA/ESTEC – design strategy 3 149

Appendix N – Overview MCA scores 150

List of figures

Chapter	Figure title	
1	1.1	Average material intensity per building type
2	2.1	Flowchart for performing the proposed research
4	4.1	Timeline for design strategy 1
	4.2	Timeline for design strategy 2
	4.3	Timeline for design strategy 3
	4.4	Overview of design perspectives linked to design strategies
5	5.1	Design perspectives linked to MCA criteria
6	6.1	Schematization of a steel deck structure
	6.2	Examples of dry connections between prefab concrete elements
	6.3	Example of a predal
7	7.1	Building parameters and wind zones
8	8.1	Different steps for performing the MCA for this research
9	9.1	Floorplan ESA/ESTEC for design strategy 2
	9.2	2D frame ESA/ESTEC for design strategy 2
	9.3	Total volume and weight per building material for ESA/ESTEC design strategy 2
	9.4	ECI values per building material for ESA/ESTEC design strategy 2
	9.5	MCA results per building material for ESA/ESTEC design strategy 2
	9.6	Floorplan ESA/ESTEC for design strategy 3
	9.7	2D frame ESA/ESTEC for design strategy 3
	9.8	Total volume and weight per building material for ESA/ESTEC design strategy 3
	9.9	ECI values per building material for ESA/ESTEC design strategy 3
	9.10	MCA results per building material for ESA/ESTEC design strategy 3
	9.11	Comparing MCA results for ESA/ESTEC for design strategy 2 and 3
	9.12	MCA results for five adjusted weights of the MCA criteria for design strategy 2
	9.13	MCA results for five adjusted weights of the MCA criteria for design strategy 3
11	11.1	Schematization of wind bracings in Matrixframe at nodes K6, K7 and K8
Appendix A	A.1	Natural and enhanced greenhouse effect
	A.2	Global greenhouse gas emissions by sector
	A.3	Consumed energy and energy-related CO2 emissions for buildings and construction sector
	A.4	Life cycle stages of a (half) product
	A.5	Life cycle stages in LE
	A.6	Life cycle stages in CE
	A.7	Lansink's Ladder
	A.8	10R model

List of tables

Chapter	Table title	
1	1.1	Material content in Dutch office buildings
2	2.1	Research scope
3	3.1	Principles of the CE
	3.2	Ten design perspectives
4	4.1	Brief explanation of the ten design perspectives
	4.2	Contradicting design perspectives
	4.3	Ranking of design perspectives for design strategy 1
	4.4	Ranking of design perspectives for design strategy 2
	4.5	Ranking of design perspectives for design strategy 3
5	5.1	Key features of APM Terminals
	5.2	Key features of Ørsted
	5.3	Key features of ESA/ESTEC
	5.4	Factor values for determining ESL
	5.5	Scores based on ESL compared to RSL
	5.6	Scores for different types of connections
	5.7	Scores for different levels of accessibility of connections
	5.8	Scores for the total weight of used building material
	5.9	Scores for the total price of used building material
	5.10	Brief explanation per MCA criteria and their link with design perspectives
	5.11	Weights of MCA criteria
6	6.1	Selected building materials and their application
	6.2	Flat roof structure
	6.3	Product specifications hollow-core slab
	6.4	Product specifications composite floor system
	6.5	Material specifications 6061-T6 aluminium
	6.6	Layers of a steel deck structure
	6.7	Layers of an aluminium deck structure
	6.8	Wood species used for timber products and their natural durability
	6.9	Natural durability linked to different use classes
	6.10	Possible dimensions CLT panels
	6.11	Overview floor systems
	6.12	Overview beams and columns
7	7.1	Design service life per building category
	7.2	Consequence classes
	7.3	Values for load factor γ
	7.4	Values for combination factor ψ_0, ψ_1 and ψ_2
	7.5	Building categories based on their specific use
	7.6	Imposed floor loads per building category
	7.7	Force coefficients for different wind zones

8	8.1	Values used for factor method
	8.2	MCA scores for lifespan of a building material
	8.3	MCA scores for building material’s potential for recycling
	8.4	MCA scores for TC, AC and removability-index of connection
9	9.1	Design perspectives for each project
	9.2	Optimizing design perspectives for each design strategy
	9.3	Dimensions, volume and weight per building material for ESA/ESTEC design strategy 2
	9.4	Dimensions, volume and weight per building material for ESA/ESTEC design strategy 3
	9.5	Original weights of the MCA criteria for design strategy 2 and 3
	9.6	Five adjusted options for the weights of design strategy 2
	9.7	Five adjusted options for the weights of design strategy 3
10	10.1	Weights of MCA criteria

Definitions

Circular construction	Developing, using and re-using buildings, areas and infrastructure without unnecessarily depleting natural resources, polluting the living environment and affecting ecosystems. Carrying out construction such that it is economically justifiable and contributes to the welfare of people and animals. Here and there, now and later.
Circular economy	An economic system that optimises the use and value of resource flows without hampering the functioning of the biosphere and the integrity of society. This means endeavouring to protect biological and technical stocks of materials, avoiding environmental impact and preserving existing value.
Durable	Capable of withstanding chemical, physical and mechanical actions which occur in specific applications to such an extent that functionality is guaranteed for a long period of time.
Environmental impact	Unfavourable or favourable change in the environment fully or partly resulting from an organisation's activities or products.
Future value	The extent to which a structure has a positive long-term usage value and is therefore capable of meeting the needs of its users and social developments during several life cycles.
Life cycle	Consecutive and interlinked stages of a product or service in its current function and location: design, acquisition of raw materials, production, distribution, use and end-of-life management.
Lifespan	Economic lifespan: Period of time during which the object or sub-object is depreciated after having been constructed. Functional lifespan: Lifespan of an object or sub-object during which it remains suitable for its current function and is used at its current location. Technical lifespan: Period during which an object can continue to perform the functions desired sufficiently reliably. Reference lifespan: Known lifespan of a construction product under certain circumstances or conditions of use.
Non-renewable resource	Raw material of abiotic or biotic origin which is not grown, naturally replenished or naturally cleansed, on a human time scale.
Recycle	Recovering materials and raw materials from discarded products and reusing them to make products.
Renewable resource	Resource that is grown, naturally replenished or naturally cleansed, on a human time scale. A renewable resource is capable of being depleted, but may last indefinitely with proper stewardship.

	Examples include: trees in forests, grasses in grassland, fertile soil. A renewable resource can be of abiotic or biotic origin.
Residual value	Value assigned to a structure at the end of the analysis period.
Re-use	Re-use of construction products, components or elements in the same function, possibly after they have undergone treatment.
Sustainable	Produced in line with sustainable development principles. *(see 'sustainable development')*
Sustainable development	Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

All definitions as given above, are retrieved from the lexicon on Circular Construction as published by Platform CB'23 (Platform CB'23, 2020). *As Platform CB'23 is one of the organizations that continuously monitors recent developments in the field of circularity in the building and construction sector, the definitions as presented in their lexicon can be considered as the most recent and accurate ones to use in the context of this research.*

Abbreviations

AC	Accessibility of Connection
BR	Index for Benefits from Recycling
CE	Circular Economy
CLT	Cross Laminated Timber
EJ	Exajoule
ECI	Environmental Cost Indicator
EPD	Environmental Product Declaration
GluLam	Glued Laminated Timber
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Analysis
LE	Linear Economy
LVL	Laminated Veneer Lumber
MCA	Multi criteria analyses
MCDM	Multi criteria decision making
NMD	Nationale Milieudatabase
PCR	Product Category Rules
PoR	Program of Requirements
SR	Index for Suitability for Recycling
TC	Type of Connection

PART I Research foundation

Chapter 1
Introduction

Before starting the core research of this thesis, it is important to explain relevant background information that forms the cause of performing this research. Note that this chapter is directly linked to Appendix A, which contains brief explanations on the two main crises that form the core motivation and relevance for this research, namely climate change and resource depletion. In this chapter, the current use of building materials and the link to the increase of the built environment is elaborated on. Also the potential of improving the design process and material selection especially for Dutch office buildings is explained. The aim of this chapter is to emphasize the relevance and importance of this research and how it can contribute to lowering the environmental impact of the building and construction sector.

1.1 Background information

As explained in Appendix A, the transition from a linear economy (LE) towards a more circular economy (CE) is crucial in lowering the environmental impact of the building sector. The use of raw building materials worsens the crisis related to resource depletion, while at the same time, the production process that is needed to fabricate (half) products from the extracted materials enhances the current climate crisis. Therefore, the background information given in the following sections acts as a bridge between these two major problems and the to be performed research in this thesis.

1.1.1 Increase of the built environment

Lowering the environmental impact of the building and construction sector depends on multiple factors, varying from the extraction and transportation of raw materials and (half) products to lowering the energy and water consumption for a building during its use stage. As if the challenge of making the building and construction sector more sustainable isn't big enough, the problem becomes even bigger when looking at future needs regarding the built environment. In 2020, 56,2% of the entire global population lived in cities (World Economic Forum, 2020). It is expected that by 2050, this share will increase to over two-thirds of the population, namely 68% (Ritchie & Posner, Urbanization, 2019). More people living in urban areas also calls for more floor area in the built environment. On top of this, the world's population keeps growing at a rate of 1,05% per year, which further increases the need for new buildings (Posner, Ritchie, & Ortiz-Ospina, 2019). In total, this globally growing demand for more buildings means that by 2060 the floor area of the building sector is expected to double. This requires an addition of 230 billion square meters of new floor area to the current available area. This is equivalent to adding an entire New York City to the world for every month for the next 40 years (Carbon Equity, 2021). This emphasizes the need for action in lowering the building and construction industry's environmental impact, not only in the design phase of a structure, but throughout all its life cycle stages.

1.1.2 Current practice in the application of building materials

As of today, there are a few most commonly used types of building materials, mainly concrete, bricks, steel and wood. In 2021 a study was performed in order to obtain average material intensities per building type. This was done by investigating all the materials that were found in demolition projects. In the category of utility buildings, the total floor area that was investigated for office buildings, is 148.329 m^2. This data was gathered from 25 different demolition project in The Netherlands (Sprecher, et al., 2021).

The following figure shows the material intensity per building type that was investigated in the study and the different materials that were distinguished.

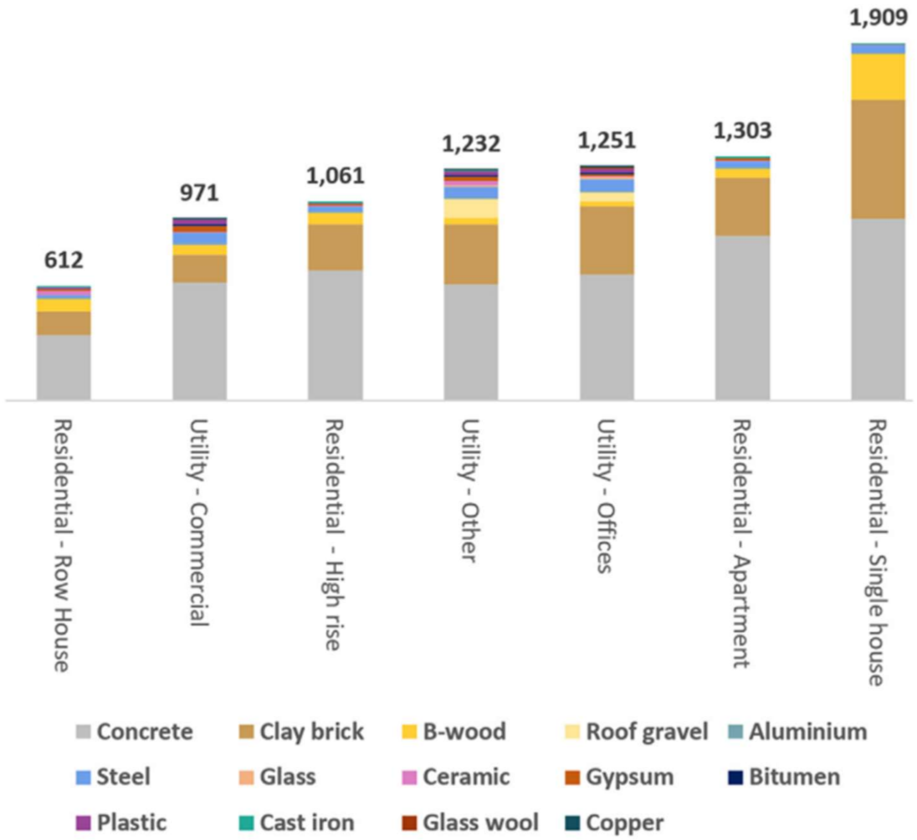


Figure 1.1: Average material intensity per building type $[kg/m^2]$ (Sprecher, et al., 2021)

Specifically for office buildings, the following table lists the contribution per building material to the total material intensity.

Material	Material content $[kg/m^2]$
Concrete	671
Brick	392
Steel	56,2
Wood	37,6
Glass	23,8
Aluminium	5.2
Other	65.2
Total average material intensity	*1.251*

Table 1.1: Material content in Dutch office buildings (Sprecher, et al., 2021)

Figure 1.1 shows that the material content of Dutch office buildings is quite similar to the one of apartment buildings. There is only a slight increase of the used amount of concrete and a small difference in the contribution of the lesser used materials. These similarities show great potential for possible future functions of an office building as residential space, as the material decomposition shows that the materials used for the load bearing structure is almost the same. Therefore, based on the composition of these building's load bearing structures, there might be a relatively high potential for a possible change in function in the future.

1.1.3 Application on office buildings in The Netherlands

In January 2021, 10,2% of all office buildings in The Netherlands was empty and without any registered users (Bos, Geertjes, & Pennings, 2021). At the end of 2020, so just before the percentages of empty office buildings were released, there were in total 15.005 office buildings in The Netherlands (Bak, 2021). This means that in the beginning of 2021, no less than 1.530 office buildings were not in use. These numbers get even worse when taking into account the percentage of office buildings that was already out of use by January 2020, namely 7,6%. So, just a year ago, there were 1.140 office buildings with a floor area of at least 500m2, not in use for at least a period of one year. Looking at different sectors, office buildings relatively have the largest amount of empty buildings, ahead of shops, industrial buildings and houses.

This shows that in many cases, office buildings are designed in such a way that the technical lifespan exceeds the functional lifespan. Looking from an economic perspective, this is quite logical, as office buildings are often designed for one specific company, but when the company is growing or its needs in terms of supply and logistics are changing, that same company often decides to move to a new building, in a new location. Most companies are expected to exist for quite a long time, however they often don't spend all that time in the same building, especially during the developing stage where a company might outgrow its initial building.

Therefore, office buildings show great potential for the investigation of different design strategies and the selection of different building materials. Besides this, most of the office buildings have a quite straight-forward load bearing structure, which often consists of floors, columns, beams and stability elements.

1.2 Problem analysis

To further reduce greenhouse gas emissions in the built environment and limit the extraction of raw materials, the whole building sector needs to develop towards a more circular process. Especially the design and material selection of building elements can have a significant contribution to this shift. In current practice a lot of used building elements are being recycled, but often this is done in the form of downcycling, which holds that elements are being demolished and the left over material is processed into something that has less value than the original building element (Lax, 2018).

To stimulate a process where the re-use of building elements or complete structures is encouraged, a dialog needs to be established between client, designer and engineer to not only focus on the primary function of a structure, but also on possible future applications. By including this vision into an early design stage, better choices regarding the design and material selection can be made, contributing to a final design with the lowest environmental burden possible in a specific situation.

1.3 Knowledge gap

In the context of this research, the knowledge gap mainly exists in the field between the designer or engineer and the client for which the office building has to be designed. This has to do with the fact that the building is in most cases designed especially for the specific wishes of the client that will use the building in its first functional service life. During the design process, this client often has no clue about the timespan that the company will use the office building or how possible future development of the company may affect the expectations regarding the performances of the building, which often results in a design where the technical lifespan well exceeds the functional lifespan. By activating and encouraging the client to think beyond the to be designed building's first functional lifespan and the clients current needs, this problem of not meeting a building's technical service life can be avoided or at least be limited, by including possible changes in lay-out or function of the building in the future in the first design.

One of the key aspects that can help in closing this gap, is starting a discussion between designer and client on what the technical and functional requirements of the building are for the initial use phase, but also, and maybe even more importantly, what the clients expectations are regarding growth or development of its company and how that might affect their expectations of their office building. When a client understands that especially future changes in their company and thereby changes in how they use their space and building highly effect the design of the initial structure, only then the designer and client can work together on selecting the design and building material that is most sustainable in their specific case.

Chapter 2

Research design

This chapter will further explain the goal of this research and will state the main research question that needs to be answered. Also various sub-questions that will function as a foundation for answering the main research question are elaborated on. The scope of this thesis is defined, which gives clear outlines on which aspects are or are not included in the research. Finally, an extensive methodology is explained, in order to give an overview of the steps that need to be taken to complete the research and be able to answer the main research question.

2.1 Research objective

Based on the problem analysis as presented in the previous chapter, the following research objective for this thesis is determined.

To gain insight into a spectrum of design strategies for Dutch office buildings based on specific present needs and sustainability wishes of a client and to encourage client, designer and engineer to include possible future applications of structural elements into the early design process, which may lead to a better founded and more suitable selection of building materials.

With this primary goal, this thesis aims to be of added value for further research into the topic of sustainable material selection and adjusting the design of a load bearing structure in such a way that it is better fitted for possible future re-use or re-design for new purposes.

Furthermore, the research done in this thesis can help colleagues at Witteveen+Bos to activate clients to think about possible future values of a structure, after its primary functional service life has come to an end. This can also be done in close cooperation with municipalities or other governing organizations, in order to align possible future functions with new area development and spatial planning.

2.2 Research questions

To fulfil the objective of this thesis as presented above, the following research question is formulated.

'Based on different design perspectives, which design strategies (all aiming for lowering the structure's environmental impact) for office buildings in The Netherlands can be formed and to what extent does a selected design strategy influence the selection of a building material for a building's load bearing structure?'

This question focuses mainly on three parts, namely different design strategies for Dutch office buildings, different types of wishes and requirements that are formulated in a project's program of requirements for an office building and finally, the most suitable combination of design and building material for a building's load bearing structure that results in the building's lowest environmental impact.

Those topics are related to each other and influence the final result of the design stage of a structure. First of all, there are multiple technical, functional and economical requirements for every structure (like a building's technical and functional service life, its flexibility, possible new functions in the future, etc.) that influence the best possible design strategy for a building. The selection of one specific strategy has to do with future expectations of a structure as well of the future expectations of the company that will use the building and has to be agreed on by the client. In current practice, most clients are only interested in the lifespan of a structure that matches the duration of the primary chosen functional lifespan that meets the client's needs. However, in order to move the building industry towards a more circular sector, this short term-thinking needs to prevented and a structure's possible future value to society needs to be considered earlier in the design stage.

This shows that exactly knowing the client's most important requirements of a structure and its elements, can highly influence which design strategy is best suitable for a structure. For example, structures with only a short technical lifespan may have other possible design outcomes than buildings that are meant to last for a very long time, and the same can be said regarding a structure's functional service life.

Finally, the design of the load bearing structure and the building material it's made of, can be chosen based on the requirements as listed in a project's program of requirements and by discussing the importance of different principles of the CE with the client. When a structure or its building elements have specific needs regarding for example strength, flexibility, service life, waste production or demountability, not every design or building material might be suitable for application. Therefore the various material properties of a selection of building materials need to be listed, which then can be used in a MCA that results in the most sustainable selection of a building material per design strategy.
To help answering the research question, multiple sub-questions are presented below.

1. *Which different design strategies can be used in the design process of an office building and how do they match with different clients?*

   Different companies and clients may result in different specific wishes and needs for their new office building. Especially a company's future perspective on growth and the expectations of their new building that come with this growth have a huge impact on which design strategy might be the best for them. Using the ten design perspectives as presented by Tim Vonck and dividing them into groups, each group prioritizing different perspectives over the others, can lead to forming specific design strategies. Design strategies may differ in the duration of the technical service life and functional service life and the potential for re-use of building elements. Each design strategy comes with its own aspects that need to be optimized, for example the level of demountability, a structure's durability or its flexibility.

2. *What are the most important requirements for an office building (resulting from analysed programs of requirements and the design strategies as described in sub-question 1) that can be used as criteria in the MCA?*

   One of the first things to investigate from the selected case studies is what the most relevant technical (mostly linked to building regulations) and functional (often the result of a client's specific wishes) requirements of a Dutch office building can be, as they highly influence the important input needed for the MCA that will later on select the best design and building material. Before it's possible to perform this MCA, all relevant criteria that contribute to the final result must be listed. These criteria can be the result of delivered programs of requirements as these documents contain all the wishes and needs of the client for their new office building. To narrow down the research and limit the list of possible requirements, three specific cases from Witteveen+Bos will be used.

3. *Which building materials apply for implementing in the MCA (based on criteria resulting from sub-question 3) and what are their relevant specifications?*

   To make a well-founded choose in selecting the best suitable building material, the relevant material properties (from a technical, economic and environmental point of view) for a variety of building materials need to be listed. The materials that can be considered, can be a mix of traditional and relatively new building materials and there has to be enough information available for each building material in order to fill in the MCA for all criteria that result from sub-question 2.

4. *How to compare different materials for building elements when using a Multi Criteria Decision Making method and which approach is best suitable for this specific purpose?*

   This final sub-question focuses on the comparison of building materials. Possibly the best way of doing this is by using a Multi Criteria Decision Making method, but this also requires developing a system that rates the building materials based on criteria that follow from the aspects that need to be optimized per design strategy. This rating can be done relatively, but also quantitatively using scores, depending on the type of criteria and possible units.

   It's important to state that performing this Multi Criteria Analysis should result in different designs (consisting of different internal layouts and building materials) for each design strategy. As each design strategy prioritizes different sustainability aspects by ranking the design perspectives in different orders, these strategies will most likely result in different designs and selected building materials.

2.3 Research scope

For the following subjects, a clear description is given of the sub-domains that are or are not included in the performed research. By doing so, the precise field of application of this thesis is determined and the search for information gets limited.

Building type	To prevent an infinitely long list of technical and functional requirements, three cases from Witteveen+Bos have been selected where the client asked for the design of a new office building. One case is considered as a more traditional and conservative one, as sustainability is not clearly mentioned in the program of requirements. Another case is considered as a more modern one, as this program of requirements highly focusses on flexibility and possible future applications. The last case is considered as more of an intermediate case between the traditional and modern program of requirements. While the selected type of structure in each case is an office building, some design strategies may also look at possible new functions for future application.
Structural elements	Every building consists of a wide variety of elements, from the foundation to facades and from technical installations to interior decoration. To limit the endless amount of possible elements that can be considered in this thesis, only the horizontal and vertical load bearing building elements will be discussed. By doing so, many aspects like aesthetics or acoustics, become less relevant when selecting a building material. Although the foundation is part of a building's load bearing structure, this building part lies out of the scope of this research, as in most cases concrete remains the most logical and widely used material for this application.
Building materials	As it would be too extensive to include all types of building material in this research, a selection of materials is made. The following materials are considered: - Standard reinforced concrete (prefab and in-situ) - Self-healing concrete (prefab and in-situ) - Lightweight concrete (prefab and in-situ) - Steel - Aluminium - Glulam - LVL

	- CLT
LCA modules	When looking at the amount of waste products that is produced in a structure's lifespan, it needs to be specified which life cycle stages are included in this analysis. In the context of this research two ECI values are used. Each ECI value includes different LCA modules: - ECI value for the production process only (LCA module A1-3) - ECI value for full life cycle (LCA module A1-3, C1-4 and D)
Re-use and recycling	In the context of this research, both the terms re-use and recycling will be discussed. In this case, the re-use of complete structural elements will be most important, as it can be stated that one-on-one re-use of elements has a lower environmental impact than demolishing a building element and using the left over material for a new purpose. Recycling can be divided into two groups, namely upcycling and downcycling. Most materials are nowadays suitable for downcycling, which means that they can be processed into something that can be used again in a different setting, but has less value than the original product. In the light of this thesis, upcycling is far more interesting to consider, as only a few materials apply for this form of recycling.
Target audience	In order to fully use the performed research, the target audience is set as the building sector as a whole. As explained in the previous chapter, the knowledge gap that comes with the main topic of this research, exists between the client (a company in this specific case) and the team of designers and engineers. Hopefully, this research can help in closing this gap, resulting in a structural design that fits a client's initial requirements, while also limiting the environmental impact of the building. In the end, to complete building sector can benefit from closing this gap.
Geography	The research done in this thesis will mainly be focused on application in The Netherlands, as this enables the use of national statistics and Dutch building codes.

Table 2.1: Research scope

2.4 Methodology

The flowchart below shows the steps that will be performed in order to answer the sub-questions and main research question. All the different steps as shown there, will be explained in further detail below.

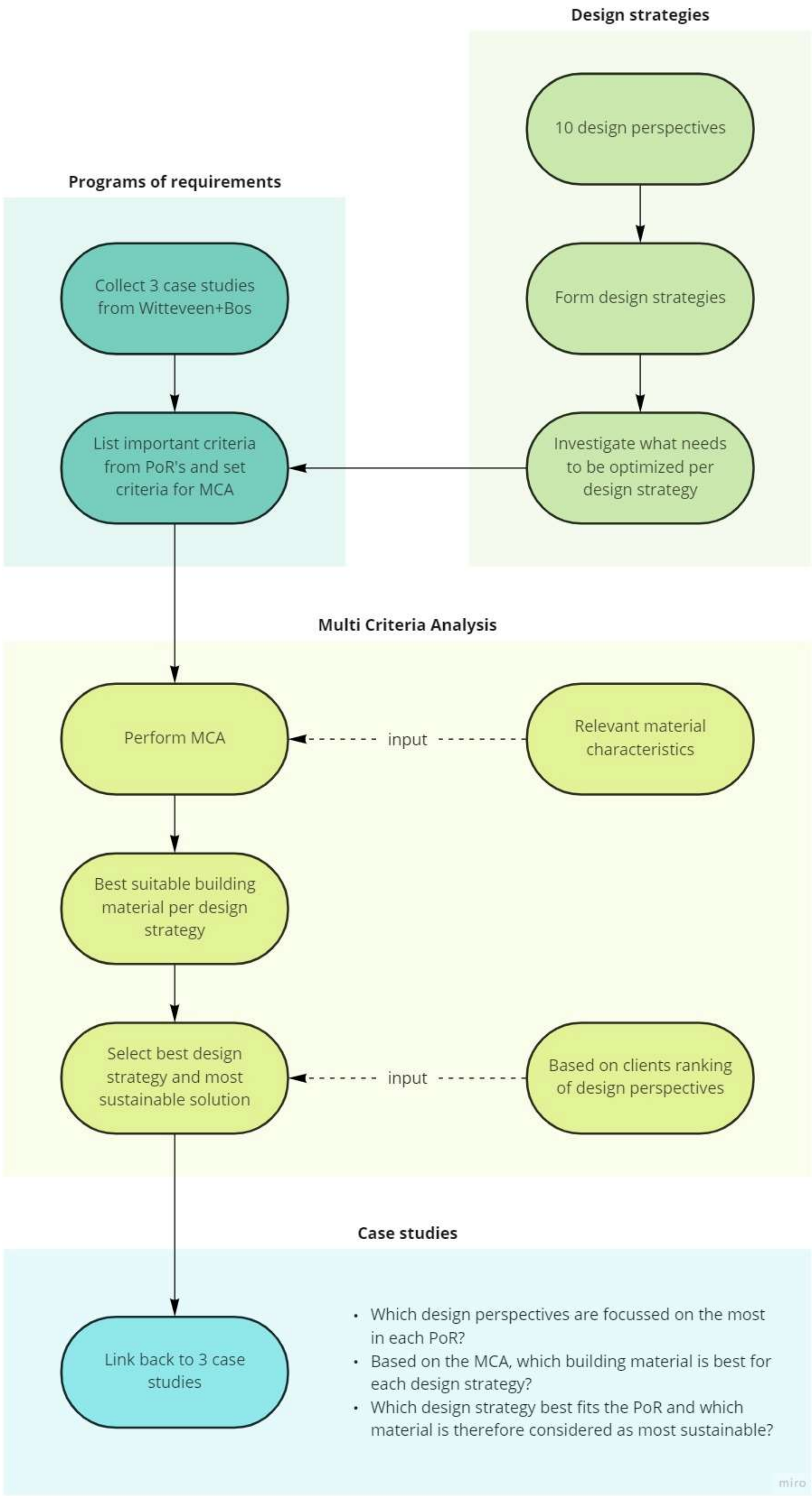


Figure 2.1: Flowchart for performing the proposed research

Programs of requirements

The first step is to collect different programs of requirements used for office buildings from Witteveen+Bos. As there is a wide variety of requirements for each specific project, it is interesting to select two most extreme cases and one more averaged case in the middle of these two. By analysing different programs of requirements, especially with different wishes from clients regarding sustainability, it can be investigated what the impact of those requirements is on the possible design strategies and the final outcome in terms of material selection.

From the three selected programs of requirements, all kinds of criteria can be subtracted and listed as criteria for the Multi Criteria Analysis (MCA).

Design strategies

In the context of this research, a client can be seen as the company that will use the newly constructed office building. Different clients and therefore different companies require different designs. A relatively young company with great ambitions to grow and develop, is likely more interested in an office building for only a limited amount of time, as it will move towards a better location or larger building when the company has grown bigger in a few years time. On the other hand, a company that is already developed and is mainly focussing on maintaining its current performances, is likely more interested in a building that they can stay in for a longer period of time. Both approaches might result in different designs and building materials and can lead to varying solutions that will be considered as the one with the lowest environmental impact in the specific context of each client.

To link those future ambitions and current needs of a company to the best solution regarding design and material selection, the ten design perspectives as described by Tim Vonck can be used. By placing these design perspectives in different orders, each time prioritizing one over the other, different 'groups' of design perspectives can be formed. The goal of these groups is to combine design perspectives that don't contradict with each other, but rather work together towards one specific goal for that group. These groups of design perspectives can then be linked to design strategies, which are all ways of contributing to the transition towards a CE, but each design strategy does that by optimizing for a different aspect. Finally, the aspects that need to be optimized for in each design strategy can, together with the criteria as selected from the programs of requirements, be used in and linked to the criteria for the MCA.

Multi Criteria Analysis

Now that all criteria for the MCA are selected, the necessary input information needs to be combined. For all building materials that will be considered in this thesis, the relevant material characteristics like strength, robustness, information regarding its environmental impact and ways of connecting elements need to be listed. In this step, it's important to make sure that this information is expressed in the same units or at least relative to other materials in order to make a fair comparison.

With this input, the MCA can be performed. The result of this is the best design and building material for every design strategy. The last step is now to select the best design strategy for the client and thereby the solution with the lowest environmental impact. Of course, this step needs close contact between the engineer or designer and the client. By asking the client to rank the ten design perspectives from most to least important, the client is activated to think about in which ways it can or wants to contribute to a more circular building process. A very important aspect of this process is a client's future perspective. The engineer's job in this step is to emphasize that it's of no use when a client simply states it wants a sustainable building, but that the client needs to think ahead and give directions in which aspects of the CE are most important or desired in his or her specific situation. Only in this way a result with a minimal environmental impact can be established for this client's specific office building.

Case studies
Now, the performed research and proposed MCA can be used to further investigate the three selected case studies from Witteveen+Bos. By analysing the client's wishes in the delivered programs of requirements and by performing the MCA on a project, the best design and building material can be found for each design strategy. By looking at the programs of requirements and investigating which design perspectives are marked as most important, the best design strategy for each project can be found (purely based on the programs of requirements). This results in the final design and selection of the best suitable building material for a case study.

Especially in this step, it can be investigated to what extent the priorities from a project's program of requirements influence the final selection of a design and building material, by comparing the results for different design strategies. At the same time, comparing these different results for various design strategies can give a client some insight in why a specific design and building material can be considered as the solution with the lowest environmental impact in their specific case.

2.5 Outline

In order to follow the methodology as explained above in a logical order, this thesis is divided into four parts. The goal of each part and the topics that are discussed in the different chapters will be explained below.

Part I – Research foundation
The first part of this thesis starts with an introduction to the topic of sustainable material selection by briefly describing relevant background information (partly in the first chapter and partly in Appendix A) and emphasizes the relevance of this research. Then, the research design is described, including research questions, its scope and the used methodology. Finally, a theoretical framework is presented, including some basic theories on sustainability and the CE, the quantification of those topics and an introduction into the ten design perspectives that will be used extensively throughout this research.

Part II – Information and data gathering
This part focuses on the formulation of new design strategies, using already existing research. In chapter 4, the design perspectives are analysed and used to form design strategies. Each design strategy is then also linked to a specific type of client and their future perspective. In the next chapter, three case studies from Witteveen+Bos are introduced. The programs of requirements of these projects, together with the formed design strategies, result in a list of criteria that will be used in the MCA. In chapter 6, different building materials are investigated and relevant information that is needed for the design and MCA is

listed. Finally, in chapter 7 the approach that is used for the MCA is explained in further detail, from the different steps that need to be taken in order to come to the final result, to the variation in weights of the criteria for each design strategy.

Part III – Results and final remarks

The third part of this thesis mainly consists of application of all performed research so far on the three selected case study projects. This means that the proposed MCA will be applied on test projects and the results will be analysed. Following these results, the main research question can be answered and possible recommendations for further research are described.

Part IV – Appendices

The final part consists of all information that was used for this research, but considered too extensive to use in the main part of this report.

Chapter 3
Theoretical framework

The goal of this chapter is to elaborate on already existing theories regarding sustainability. Starting with the famous definition from the Brundtland report, politicians and experts in the field of sustainability developed new theories, often continuing on existing studies. Not only recycling of materials is considered, but also the complete re-use of elements or products as a whole. The next step is to look at ways of quantifying sustainability, which can be done in many different ways and can be quite complex, as sustainability is not always tangible. Finally, ten different design perspectives are introduced. These design perspectives are the result of a thesis written by Tim Vonck and clearly show different ways of contributing to a sustainable outcome, while some of them contradict with each other.

3.1 Sustainability and the circular economy

3.1.1 Linking sustainability to CE

The first international thoughts on sustainability where published in 1987 in the Brundtland report. As of today, the formulation as presented in that report is one of the most well-known definitions on the topic of sustainability: ''Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs'' (United Nations, 1987). This can be seen as the most broad and basic principle of sustainability, but at the same time, the definition is rather vague due to this broadness and therefore hard to implement for policymakers. Over the years, many 'new' definitions of sustainability and CE where developed, all aiming to clarify the concept in light of a more specific application per sector.

A few years later, in 1994, John Elkington introduced the Triple Bottom Line (TBL), better known as People, Planet, Profit (which was later adjusted to Prosperity). He explained that sustainability and thereby sustainable development, should not only be measured in economic profits or losses, but also in the impact on society and the environment. This theory forms a framework for businesses and organizations to help them move towards a more sustainable future and shows that on the long term, all three aspects need to be taken into account, rather than only the profit margins (University of Wisconsin, n.d.).

In the context of this research, the focus mainly lies on the Planet aspect of the TBL, as the goal of this thesis is to minimize the environmental impact of a structure. Thereby, the People and Prosperity aspects become less relevant. Within the Planet aspect, especially the transition from LE to CE becomes important (see Appendix A) as this lowers the extraction or raw materials and thereby the burden on the environment. In the light of this report, it is therefore better to speak of the circular economy and its principles, rather than using the term sustainability in general.

Specifically for the transition from LE towards CE within the building and construction sector, a group of companies and organizations working in this sector is formed, called CB'23. This group focuses on developing and implementing guidelines for a circular building industry. Platform CB'23 consists of two parts, on one hand there is a team with people from various companies acting in the construction sector for civil engineering works (including hydraulic structures, infrastructure works, housing projects and the construction of utility buildings), who are involved in selecting and prioritizing subjects to be discussed within the platform, thereby acting as a link between ambitions (for example ambitions regarding circularity as presented by the government) and practice. This part of the organization includes parties like Rijkswaterstaat, the ministry of infrastructure and NEN. On the other hand, the platform consists of a team that is more focused on implementing proposed regulations into the building sector. This team represents the more practical side and deals with the problems of implementing a regulation into the existing pattern, without making things unnecessary complex. In order to give readers a clear understanding of the meaning of different words related to sustainability and CE, Platform CB'23 developed their own lexicon. As sustainability is a word that is so widely used throughout the years and to prevent any misunderstanding with regards to other related words, it's necessary to give a clear definition of sustainability and CE specifically within the context of this research. Important terms regarding these topics are presented in the beginning of this report, in the section Definitions.

3.1.2 Principles of the CE

One of the politicians that was concerned about the amount of new materials that was required for the rapid economic growth of The Netherlands, was Ad Lansink. His theory, Lansink's Ladder, was one of the first introductions on the topic of circularity. Instead of landfilling waste or burning it, products or materials could be recycled or re-used after their first functional service life. Ideally, the amount of produced waste should be reduced and kept to a minimum. A more detailed view on Lansink's Ladder can be found in Appendix A.

More than thirty years later, another Dutch politician, Jacqueline Cramer, went a step further than Lansink's theory. She made a distinction between using waste as a useful product (using it for energy production or recycling it), increasing a product's lifespan in order to minimize waste and adjusting a design of a product in order to prevent waste. She used the same principles as Ad Lansink did, but also introduces more 'intermediate' steps, within a category. Finally, this resulted in Cramer's

10R model, which is explained in more detail in Appendix A. Here, all the names of the ten steps start with re- (for example re-use, refurbish, re-purpose, recycle), which emphasizes the link to CE.

The CE (as also explained in Appendix A), is based on seven principles, according to a study performed at the University of Vigo (Suárez-Eiroa, Fernández, Méndez-Martínex, & Soto-Onate, 2019). All seven principles contribute to transforming the current LE towards the desired CE. The following table shows the different principles and some brief examples.

	CE principle	Examples
1	Adjusting inputs to the system to regeneration rates	- Substituting non-renewable by renewable inputs - Substituting renewable inputs with low regeneration rates by renewable inputs with high regeneration rates - Saving energy and materials
2	Adjusting outputs from the system to absorption rates	- Substituting processes with high waste generation rates by processes with low waste generation rates - Adjusting taxes and subsidies of technology, products and materials based on their waste generation rates
3	Closing the system	- Properly separating biological and technical waste - Promoting and improving recycling systems
4	Maintaining resource value within the system	- Increasing durability (for example through preventive and corrective maintenance or repurposing)
5	Reducing the system's size	- Adjusting selling doses to consumer doses - Promoting sharing economy (for example collective mobility)
6	Designing for circular economy	- Eco-design (for example optimizing packaging and improving durability) - Designing reproducible and scalable products to build the same products in other places with local resources
7	Educating for circular economy	- Adjusting educational curricula to current challenges - Promoting habits and individual actions in favor of the circular economy

Table 3.1 : Principles of the CE (Suárez-Eiroa, Fernández, Méndez-Martínex, & Soto-Onate, 2019)

In the context of this thesis, the focus mainly lies on minimizing the used amount of resources for a building's load bearing structure (CE principle 1 – adjusting inputs). This can be achieved by using the least amount of building material, while still designing a save structure that meets the client's needs. Furthermore, the re-use of complete structures or building elements (CE principle 4 – maintaining resource value within the system) is highly important in this research, as this requires less extraction of raw materials in new projects. In cases where re-use is not an option, recycling becomes more relevant (CE principle 3 – closing the system), as this results in a higher residual value at a structure's end-of-life stage.

3.2 Quantifying a product's environmental impact

A material's, product's or structure's environmental impact has always been a difficult topic to quantify. An environmental impact can occur in many different ways, which automatically creates a very wide spectrum of effects that need to be investigated. As all these environmental impacts are different and have varying results, it is hard to evenly compare them, especially when they are not expressed in the same units. The following paragraphs describe methods that aim to make a fair comparison and quantification of environmental effects of a product.

3.2.1 Life Cycle Assessment (LCA)

As explained in section 1.1 Background information, a product's or structure's life consists of multiple life cycle stages, which can be assessed individually in a LCA. Performing a LCA is a way of measuring the effects of a product or structure on the environment, so it is a way of quantifying the environmental impact. To accurately perform a LCA, it is important to state the used methodology which specifies the life cycle stages and impact categories that are being considered and the used calculation rules. This includes for example choosing between cradle-to-gate, cradle-to-grave, cradle-to-cradle or other variants, like Well-to-Wheel (mostly applicable to transport and vehicles) or Economical Input-Output LCA (EIO-LCA) (can be used for averaged data to fill in gaps that might occur in the analysis) (Ecochain, 2021). A more detailed explanation of the different steps that need to be taken in order to accurately perform a LCA is included in Appendix A, section A.7.

3.2.3 Environmental Cost Indicator (ECI)

An Environmental Cost Indicator (ECI) is a single-score indicator that expresses all relevant environmental impacts together in Euros (Ecochain, 2021). It is often referred to as shadow costs, which indicates that these costs are not accounted for in the design or budget of the manufacturer, but later on become the problem of society as a whole. For calculating an ECI value, the same environmental impact categories are used as explained in section 3.2.1 and Appendix B. All these different impact categories have their own units, which makes it hard to compare them. In order to convert these units to one monetary value (often Euros), multiplication factors are available for every unit of the environmental impact categories, the so called unit equivalent values. This factor is based on how much money would be necessary in order to compensate for the damage that is done to the environment for each specific impact category. Appendix B shows an overview and explanation of all the possible impact categories and corresponding unit equivalent values. During a LCA, it is already determined exactly how much inputs and outputs are necessary for a product or structure. Now, for each environmental impact category, the total amount of CO2 and other units can be multiplied by the corresponding unit equivalent values and by adding these values, the final ECI value of a product or structure is calculated in Euros.

3.2.4 Dutch ’Nationale Milieudatabase’

Nowadays, a lot of specific products or materials are listed in the Dutch ’Nationale Milieudatabase’. This is an online tool where manufacturers can enter their products, including all the necessary inputs and (harmful) by-products. They specify a functional unit (for example kg, m2 or m3) and an expected technical lifespan of the product, which enables the user to convert the ECI value per functional unit to a total ECI value (for example when the user knows exactly how much material is needed) or to an ECI value per year. Furthermore, a manufacturer can specify the input or output of different environmental impact categories per LCA module. This shows a clear distinction between the negative environmental impact during the production process (LCA module A) and the possible positive impact after a product’s end-of-life stage (LCA module C and D).

In the context of this research, the use of this Dutch ’Nationale Milieudatabase’ is considered to be the most convenient way of retrieving necessary ECI values, as it allows the user to easily calculate a total ECI value for a structure when the exact amount of building material is known. It also partially eliminates the problem of comparing ECI values from different sources that include different LCA modules. As this database offers the user insight in which LCA modules are included in the calculation, a clear ECI value per LCA module can be obtained. Only in this way, a fair comparison between ECI values for different materials and products can be made.

More information on ways of quantifying a material’s or product’s environmental impact can be found in Appendix A, section A.7.

3.3 Design perspectives

In his Master’s Thesis, Tim Vonck developed ten design perspectives that can be distinguished during the design process of a structure. Every perspective focusses on a different aspect of the CE when the design is optimized for that perspective. However, some of these perspectives contradict each other, as will be explained in further detail below.

1. Material selection
The use of materials has a huge influence on for example the ECI value and environmental footprint of a structure. The environmental burden caused by the materials used in a structure, could be limited by selecting more eco-friendly materials.

2. Material use
Minimizing the used amount of building material could result in more slender structures that are less harmful to the environment, as lesser resources are needed.

3. Durability

Durability can indicate to which level a structure maintains its original requirements from both technical and functional point of view. High durability might therefore indicate that a structure has a very long service life. Durability can be created on both material and structural level. In the context of this research, durability will especially refer to the technical life span of a building element.

4. Maintenance

The proper maintenance on a structure could increase its service life and thereby contribute to the durability of a structure. Not properly maintaining a structure could even result in extensive deterioration and preliminary demolition of a structure or building element.

5. End-of-life management

As the construction sector is one of the biggest contributors to the globally produced amount of waste, it is important to limit the waste resulting from a structure's end-of-life phase. The design of a structure can have a large impact on the redirection of waste. The next design perspectives all contribute to this end-of-life management and are all ways of managing and limiting the produced amount of waste at a structure's or element's end-of-life stage.

6. Re-usability

The design solution that creates almost no waste, is completely re-using the structure as a whole. This can be done by implementing a new function into the same building, hereby elongating a structure's functional lifespan until it matches its technical lifespan.

7. Disassembly

If a structure can not be re-used as a whole, it can be disassembled into smaller parts that can individually be used in other projects. The design of a structure has an enormous effect on the level of disassembly that can be reached in a structure. Furthermore, designing a structure for disassembly also increases its level of transportability. In cases of temporary structures that will be moved to a new location after a few years, a high level of transportability and thereby disassembly is preferred, as the structure can than easily be divided into smaller parts that are more practical to transport.

8. Recyclability

In case parts of a structure can not be re-used, for example when the elements have experienced too much deterioration (for example as a result of a fire) or are no longer meeting the current design standards, it might be the best solution to recycle the left over materials.

9. Adaptability

To make a structure more fit for future use, it may be wise to design it in such a way that it can easily expand in horizontal and vertical direction (referring to the first icon). Another way of making a structure more adaptable, is by designing it in a more modular way, which enables individual modules to be moved internally or towards other projects (referring to the second icon).

10. Flexibility
Although flexibility is often confused with adaptability, it can be a design perspective of its own. By designing a structure in such a way that the internal layout can be modified easily, the way towards implementing new functions in a building is opening up.

Table 3.2: Ten design perspectives (Vonck, 2019)

As stated above, some of these design perspectives contradict with each other. For example, minimizing the used amount of material for a structure could in most cases result in using in situ concrete, however, this material usually isn't fit for disassembly and isn't very flexible either. This shows that aiming to increase a structure's level of circularity is all about finding a balance between optimizing the ten design perspectives.

The ten design perspectives as stated by Tim Vonck will be used extensively throughout this research, as they form a clear basis of the different aspects that contribute to increasing a structure's level of circularity and as they clearly show that this can be done via various routes. For this reason, they come in very handy when describing different design strategies by ranking these design perspectives in various orders, which will be explained later on in this report.

3.4 Link with PhD report 'The Sustainable Office'

In 2004, Andy van den Dobbelsteen published his PhD thesis 'The Sustainable Office'. In his research, he investigated the potential of a factor 20 reduction of the environmental load caused by offices. This was done by looking at a wide variety of solutions that showed potential for actively contributing to this factor 20 environmental improvement.

To start with, he analysed twelve functionally comparable government offices (all where constructed after 1985) in The Netherlands. Looking at the annual environmental load of these offices, he concluded that 77.5% was related to energy consumption during a building's use phase, 19.5% was linked to the use of building materials (of which a building's load bearing structure is accountable for 60% of this load) and only 3% was related to water consumption during the use phase of the building. This shows the great potential for lowering a building's total environmental impact by making an efficient design for its supporting structure.

However, it is emphasized that the biggest potential environmental improvement lies in the use of an integral approach, combining several aspects (efficient and intensive use of space, application of sustainable and renewable energy solutions, applying appropriate life time strategies and making an efficient design for a building's supporting structure). So, besides the selection of the best suited building material for a load bearing structure, also the so-called time-factor needs to be considered. Already in his study, Andy states that for the design of an office, one can either choose for one of these two design strategies: the first one meaning to design a long-lasting over-sized structure, while the second one focusses on making a more demountable and short-cyclic structure. In this current research, these two design strategies also follow as a result from combining the previously explained design perspectives. However, also a third design strategy is proposed, which lies in the middle of the two strategies as proposed by Andy. In his research, Andy stated that a factor 2.8 environmental improvement could be achieved by simply matching a building's functional service life with its technical one. Further investigating the three different design strategies in this thesis, could help in reaching this improvement, or even enlarge its effect.

Finally, Andy makes use of a structure's or building element's estimated service life, which is related to its reference service life. By doing so, various (technical) aspects that could influence a building element's lifespan are considered. This method (referred to as the factor method in NEN-ISO 15686, part 8: Reference service life and service-life estimation (NEN-ISO 15686-8, 2008)) will also be used in this thesis.

PART II

Information and data gathering

Chapter 4

Design strategies

As shown in the theoretical framework, the design perspectives introduced by Tim Vonck can be used as individual ways of reaching the CE principles, as each design perspective optimizes a different aspect of a design. As explained, the perspectives sometimes contradict with each other. Aiming to increase a structure's level of circularity, the design perspectives could be placed in different orders, every time prioritizing one perspective over the other. Each ranking can then be used to form a design strategy consisting of design perspectives that work together on reaching one specific goal per strategy, instead of contradicting with each other.

4.1 Contradicting design perspectives

The table below briefly lists the design perspectives as explained earlier in the theoretical framework.

	Design perspective	Goal
1	Material selection	Selecting the best material possible for the structure from an environmental point of view.
2	Material use	Minimizing the amount of used resources or energy by intelligent use of structural materials
3	Durability	Designing a structure in such a way that it remains serviceable without severe damage or unexpected maintenance during its expected service life.
4	Maintenance	Limiting, simplifying or targeting the amount of required maintenance, as this reduces the needed material or energy during its service life.
5	End-of-life management	Minimizing the amount of waste produced by a structure at its end-of-life stage.
6	Re-usability	Designing a structure in such a way that it's already prepared and fit for re-use of the complete structure or structural elements.

7	Disassembly	Using structural elements that could easily be dismantled at a building's end of service life for re-use in a new structure.
8	Recyclability	Selecting building materials that have a high potential for recycling once a structure has reached the end of its service life.
9	Adaptability	Designing a structure that has the possibility to be expanded horizontally or vertically. *(In context of this research, use of the modular building concept is not considered, however, this could be seen as the highest possible level of adaptability.)*
10	Flexibility	Enabling the user of the building to make changes to the internal spatial layout without interfering with the load bearing structure.

Table 4.1: Brief explanation of the ten design perspectives (Vonck, 2019)

The previous table shows ten design perspectives, however, from this point onwards, only nine design perspectives will be considered. Design perspective 5 Waste effectiveness is left out, because perspectives 6 Re-usability, 7 Disassembly, 8 Recyclability, 9 Adaptability and 10 Flexibility are all forms of minimizing waste at the end of a structure's service life and can therefore be seen as subcategories of 5 End-of-life management.

As described earlier, some of these design perspectives contradict with each other. The following table shows for which design perspectives this is the case.

	1 Material selection	2 Material use	3 Durability	4 Maintenance	6 Re-usability	7 Disassembly	8 Recyclability	9 Adaptability	10 Flexibility
1 Material selection			x	x		x	x	x	
2 Material use					x				x
3 Durability	x								
4 Maintenance	x								
6 Re-usability		x							
7 Disassembly	x								x
8 Recyclability	x								
9 Adaptability	x								x
10 Flexibility		x				x		x	

Table 4.2: Contradicting design perspectives

Material selection might contradict with **durability** and **maintenance**, as selecting a material that looks like the best option from an environmental point of view (for example wood, as this material contains a lot of captured CO2), might not always be the most durable solution (wood is often more prone to deterioration as a result of changes in the environment where it's used, like fire, changing humidity levels that might cause rotting or damage done by insects (Caitlin, 2020)). Of course, to some extent these durability issues can be prevented or limited by regular maintenance of the material and for example the application of additional conservations, but this contradicts with the design perspective of limiting the necessary amount of maintenance in order to save on required resources and energy needed for the maintenance activities.

Furthermore, material selection can also be in contradiction with the design perspectives **disassembly** and **adaptability**. When a building material is selected, this often influences the type of connections that can be used for assembling the structure. As not every connection is fit for easy demounting (for example in the case of a 3D printed concrete structure, horizontal and vertical load bearing elements may be directly bound together, which makes it very hard to take these elements apart without damaging them), this may affect the level of demountability of the final structure as a whole. As for increasing a structure's level of adaptability, it's preferred to use connections between load bearing elements that can rather easily be adapted in order to connect additional elements in case of horizontal or vertical expansion of the structure, this design perspective may also be conflicting with material selection, for the same reason as why it contradicts with disassembly.

Finally, material selection can also be in contradiction with the level of **recyclability** of a structure. Not every building material is a good option for recycling, especially when only upcycling is considered (again taking wood as an example, this material can in most cases only be downcycled, especially due to its high susceptibility for deterioration). While on the opposite, steel might a be a very good option for designing a structure with a high potential for recycling, this building material might not be the best solution with regard to selecting an environmental friendly material, as it requires a lot of energy in the production process.

The design perspective **material use** can be in contradiction with **re-usability**, as minimizing the used amount of material in a structure can lead to very specific dimensions of load bearing elements for each individual project. When aiming to reach a high level of re-usability, the designer should seek for dimensions of load bearing elements that are standardized as much as possible, as this increases the possibility that a building element can later on be applied in a new structure. To even further increase the potential of re-usability, load bearing elements should optimally be designed for application in buildings with another function and higher load cases than their primary one, which often results in oversizing these elements for their first life cycle. Of course, this is highly conflicting with the design perspective of using as little building material as possible.

Furthermore, minimizing the used amount of building materials also conflicts with increasing a structure's level of **flexibility**. It's to be expected that optimizing for material use results in limited spans, as this saves a lot of material in horizontal load bearing elements like beams. As a result of this, the structure will probably have one or more vertical load bearing elements in the middle of its floor plan. This affects a structure's level of flexibility, as the presence of these elements makes the user of the building less free in self choosing or later on changing the internal layout of a building's floor plan.

Finally, **flexibility** is also in contradiction with the design perspectives **disassembly** and **adaptability**. As aiming for the highest possible level of flexibility of a structure, optimally results in an open floor plan with load bearing elements only directly behind the facades, so at the edges of a floor, the spans to create this type of open space will become quite large. As a result of this, the horizontal load bearing elements will reach larger dimensions, which at the same time might complicate the connection between horizontal and vertical load bearing elements. These more complex connections are often harder to adapt in case additional elements need to be connected later on and at the same time they might also be harder to disassemble.

4.2 Forming design strategies

Now it's clear which design perspectives contradict with each other, it's important to prevent combining these design perspectives in the same design strategy. Design strategies can be formed by prioritizing specific principles of the CE over the others and thereby selecting design perspectives that all work together on reaching that specific goal. This group of design perspectives is then what needs to be optimized to reach that goal, which can then be called a design strategy.

It can be argued that one of the design strategies can be formed by prioritizing material selection and material use over the other design perspectives. However, this can be seen as the general goal of this research. This thesis aims to find the best suitable design with the lowest environmental impact possible, based on a client's program of requirements and its future perspectives. Therefore a design is already made in such a way that the environmental burden is kept to a minimum for each specific project. In that way, it can be said that the type and used amount of building material is a result of the to be performed MCA, and not a specific design strategy that will be discussed in this chapter.

4.2.1 Optimizing a structure's technical service life

The first and most straightforward goal that can be reached by ranking the design perspectives is maximizing a structure's technical service life. The key aspect in this case is making a design in which the structure maintains able to fulfil the services that are required of it without extensive repairs or other forms of maintenance, however long that structure's functional service life may be. Keeping this in mind, the nine design perspectives can be placed in the following order.

High importance	3	Durability
	4	Maintenance
Medium importance	1	Material selection
Low importance	2	Material use
	6	Re-usability
	7	Disassembly
	8	Recyclability
	9	Adaptability
	10	Flexibility

Table 4.3: Ranking of design perspectives for design strategy 1

The duration of a structure's technical service life mainly depends on the ability of a structure to limit the amount of deterioration and therefore remain able to fulfil its technical requirements. This means, designing the building in such a way that is has a high level of durability. Another important aspect of this design strategy is making sure that maintenance is limited, in order to limit disturbance for the users, and rather easy, which means that maintenance could be done in a short period of time without interfering with or affecting the jobs of the users. Optimizing for these two aspects results in limiting all possible resources, meaning new materials and energy, that might be necessary for any possible repairs in case a structure undergoes deterioration.

Material selection can be marked as medium important in this design strategy, as selecting a more robust material might result in a longer technical service life. However, as stated in the previous section, this design perspective may contradict with increasing a structure's durability and limiting its maintenance, and therefore can't be optimized for in this design strategy.

Possible timeline and stakeholders for a structure using design strategy 1

The following figure shows what could be a possible timeline for a structure that is designed following the principles and optimizations of design strategy 1.

Figure 4.1: Timeline for design strategy 1

This timeline shows that the office building is designed especially for the client who requested it and it's assumed that this client will use it as long as its company exists.

Types of companies that might be suitable for the application of design strategy 1, might for example be companies working in the industrial sector. In this case, companies often have a factory or other facility or industrial part and need an office building nearby on that same terrain in order to manage and control the factory or facility. As a result of this, it can be assumed that as long as the company operates the factory or industrial facility, their office building will be in use. Therefore, the office building and industrial part can't be separated and the office building will never have to adapt to a new function or different type of company. Of course, there is a possibility that the factory or industrial facility is taken over by a different company, but this will most likely not change anything with regard to the technical and functional requirements of the new company, as they will still have the same tasks, namely managing all operations regarding the industrial business of the company.

Furthermore, this design strategy can also be useful for companies that don't work in the industrial sector but are already fully developed and its future perspective is mostly focused on maintaining its current performances. This means that they are not planning to expand anymore with regard to their number of employees and it's expected that the company is considered stable enough and financially healthy to be continuing its current work and will therefore use their to be constructed office building for a long period of time (meaning that the functional service life (the period the initial client uses the building) will match the structure's technical service life).

While the following two design strategies come with more specific requirements regarding the lay-out of a building's load bearing structure, this is not so much the case for this first design strategy. Here, the priority lies more on the selection of a durable material and a connection type that is rather robust. This design strategy doesn't result in specific wishes or restrains with regard to dimensions of the building elements, which means that the design of the structure can be fully based on the clients wishes.

4.2.2 Optimizing a structure's functional service life

Besides a structure's technical service life, also its functional service life can be maximized. The most important aspect in achieving this, is to make sure that the building can always fulfil the functional requirements of its users, whether this means changing the existing spaces or creating new ones by expanding the building. The following table shows how the nine design perspectives can be ranked in order to meet these goals.

High importance	10	Flexibility
	9	Adaptability
Medium importance	4	Maintenance
Low importance	1	Material selection
	2	Material use
	3	Durability
	6	Re-usability
	7	Disassembly
	8	Recyclability

Table 4.4: Ranking of design perspectives for design strategy 2

In order to elongate a structure's functional service life, it's important to ensure that the building is designed in a flexible way, which enables the user to make changes to the layout of the available floor area. Often, this means that it would be ideal if the structure is designed in such a way that no large vertical load bearing elements are present and spans are made as long as possible, ideally from one façade to the opposite one. Using light-weight and non-loadbearing wall elements, the users can make their own internal layout of the floor plan, which can be changed and adapted in case the needs of the users change, for example when a company is expanding and needs to make room for more employees.

Besides using this principle to make a building very flexible, it's also possible to design the loadbearing structure in such a way that future horizontal or vertical expansion of the building can easily be constructed, which makes the building more adaptable. Adaptability thereby also increases the ability of a structure to fit into possible future needs of the user, in case the whole building is too small and internal changes in the layout don't result in the desired space.

Furthermore, also limiting the needed amount of maintenance can be considered important here, as this also limits the use of new resources and the level of disturbances for users of the building.

Note that this design strategy focuses on maximizing the functional service life of the complete structure, rather than the individual building elements it's composed of. This implies the assumption that this design strategy is only applicable in cases where it's to be expected that the to be designed building will stay intact after its first service life has ended (so when the initial client for which the building was designed leaves and new users enter the building). These new users can also use the structure for different purposes than the original function it's designed for, for example making apartments for residential purpose in the existing structure. Other options are using the building as a new shopping centre or facilitating cultural activities like museums, of course depending on its location and surroundings. During the initial design of the building, it's important for the engineer and designer to think about these possible future functions in case the building loses its initial one as an office building. These changes in function can affect the expected floor loads on the structure and might therefore require larger dimensions for the load bearing elements.

It can be argued that the best strategy for making a building as flexible and adaptable as possible, is by applying the modular building concept. This means that a building consists of individual modules, each with their own function and layout, which can easily be combined, both in horizontal and vertical direction, into a complete building. This allows the users to easily adapt and change the modules in order to make the building fit for a new function. However, for the purpose of this research, the modular building concept is not investigated any further, as these modules have a very specific design approach of their own. As the main goal of this thesis is to gain insight into the best selection of a design and building material, and modules as applied in the modular building concept often consist of a combination of multiple materials, this design approach becomes less relevant in this context.

Possible timeline and stakeholders for a structure using design strategy 2
The following figure shows what could be a possible timeline for a structure that is designed following the principles and optimizations of design strategy 2.

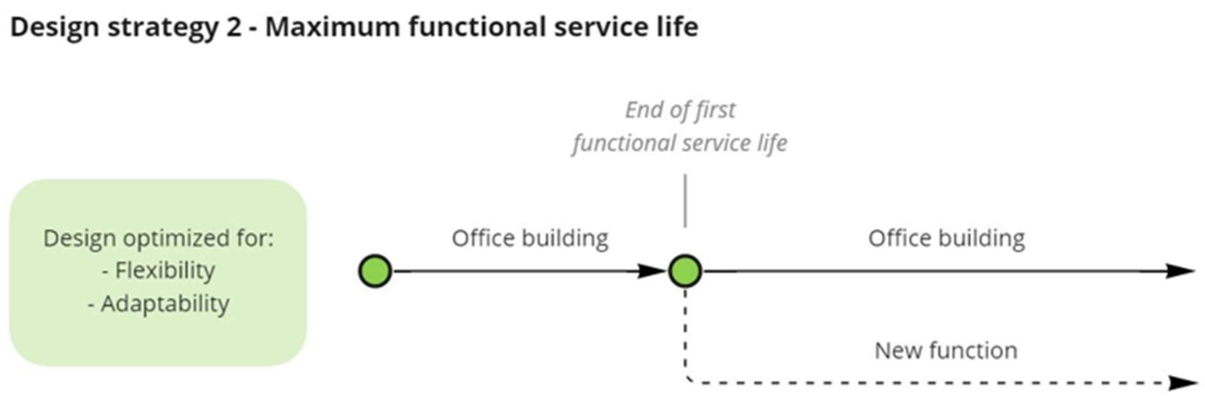


Figure 4.2: Timeline for design strategy 2

This timeline shows that the office building is designed to fully utilize a structure's technical service life by expanding its functional service life. This prevents an office building from becoming empty after the first user left, while it's still perfectly functioning from a technical point of view. This timeline shows that when the client for which the building originally was designed has left, the building can again function as an office building or it can be used for a new function.

Whether this design strategy is applicable, highly depends on the building's location and the type of company for which it's originally designed. In contradiction with design strategy 1, this second design strategy is best applicable for companies that don't require any additional facilities besides their office building. This means that when the first company leaves the building, it can easily be used again by another company with approximately the same amount of employees. Another possibility in cases where the originally designed building is quite big, is to split it into smaller parts and use them as individual spaces for separate companies (for example by using each floor for a separate company). This requires very little to no changes in the load bearing structure, but can quite easily be done by changing the internal layout of the building. Due to the flexible nature of the design, each company that will use the building can adjust the internal design according to its own needs. This enables free shifting from large meeting rooms to smaller individual offices or even an open plan office area.

The type of function that the structure will fulfil after its first service life as an office building has ended, depends on its location and surroundings. When its situated on a business park, it can be assumed that the next function will again be an office building. However, when the building is placed in a more dynamic environment where residential buildings are combined with shopping areas, cultural activities and work environments, it's already much more likely that at the ending of the structure's first functional service life, another function might be assigned to the building.

Again, the flexible and adaptable design of the structure makes it possible to change the internal layout of the structure in order for the building to fit its new functional requirements. Also in this case of changing the building's function, it's possible to split floors in order to enable multiple functions happening at the same time in the existing structure.

While the first design strategy might be best applicable to longer existing and financially stable companies (in case the company is not bound to any industrial facilities like explained in the previous section), this doesn't have to be the case for this second design strategy. Due to its flexible and adaptable design, this type of structure can also be used by companies that are still growing and developing. First, throughout the years they can change their building according to their changing needs regarding the internal layout. When this no longer matches their functional requirements, the users can either expand the structure horizontally or vertically to create extra space, or leave the building and move to a new one. This leaves the existing building empty and open for new companies or other functions to use it.

4.2.3 Optimizing a structure's residual value

A third and last design strategy can be one where there's aimed for designing a structure which residual value at the end of its functional service life as an office building is as high as possible. After the original client for which the building was designed leaves and it's expected that no new company will use the building and the structure is not particularly fit for a new function, it might be best to demolish the existing structure and use its building elements for new projects. The nine design perspectives could be ranked in the following order to achieve this goal.

High importance	6	Re-usability
	7	Disassembly
Medium importance	8	Recyclability
Low importance	1	Material selection
	2	Material use
	3	Durability
	4	Maintenance
	9	Adaptability
	10	Flexibility

Table 4.5: Ranking of design perspectives for design strategy 3

This design strategy essentially focusses on minimizing the amount of waste that could be produced when a building reaches the end of its functional service life, holding that a company has left the building and no other company or new function is fit to use the existing building (which means that the previous explained design strategy is not applicable here). This holds that the primary function for which the building was designed is now ending, but the structure is still performing well from a technical point of view. The best solution in this case is to find a new project where building elements from this existing structure can be re-used, ideally one-on-one, so without making any changes to the elements. This requires that the building elements designed in the original structure are standardized as much as possible, as this increases the chances of finding a project where they can be re-used. When a structure has very special and rare dimensions, it will be hard to find a new structure for it and to one-on-one re-use the elements in a new project. Making such a standardized element includes taking into account possible higher load cases that may occur in cases where elements are re-used in structures with a different function than an office building.

Besides making elements as standardized as possible, this design strategy also requires to design the structure in such a way that it can easily be demounted at the end of its functional service life. The used connections between load bearing elements need to be easy to disassemble and the elements should not be damaged during the process of disassembling the connections.

The level of recyclability of a structure is marked as medium important in this design strategy. Recycling building materials or elements that could not be re-used in new projects does contribute to a structure's residual value, however one-on-one re-using complete building elements is considered as a more sustainable solution, as this requires less energy (recycling a material often requires heavy machinery, like furnaces for melting scrap metal or crushers for separating parts of a concrete element). Therefore, in this design strategy a structure is optimized for re-usability and disassembly.

Note that in this design strategy, the design perspective regarding maintenance is not so much considered. This has to do with the fact that it's expected that a structure that was designed following design strategy 3 probably won't last a long time (at least not the originally constructed building). Therefore, it's assumed that deterioration during this short period of time is limited and no maintenance is needed. Of course, when a structure is disassembled, experts can easily asses the building elements and check whether maintenance is required before re-use in a new structure.

Possible timeline and stakeholders for a structure using design strategy 3

The following figure shows what could be a possible timeline for a structure that is designed following the principles and optimizations of design strategy 3.

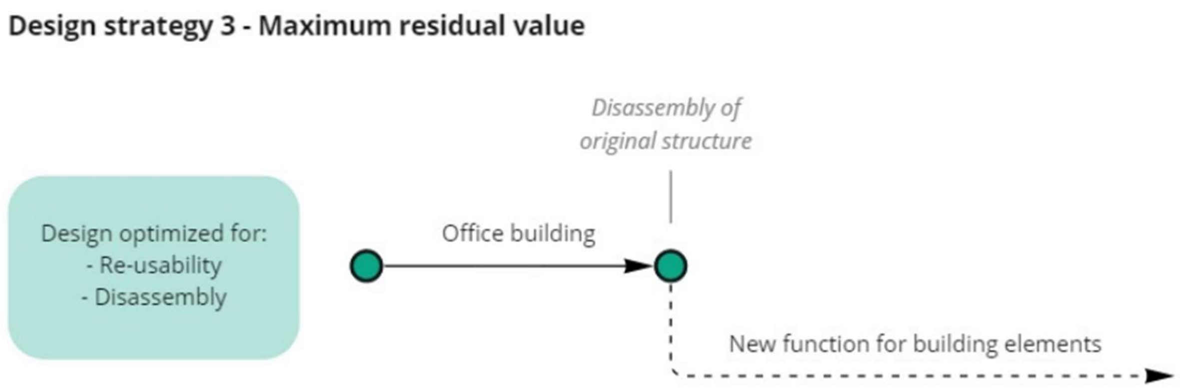


Figure 4.3: Timeline for design strategy 3

This timeline shows that after a structure's functional service life has ended, it can be demolished and (part of) the load bearing elements can be re-used in new projects. Ideally, one-on-one re-use of building elements in new projects can be used and in the best scenario this is possible for all load bearing elements. In cases where not all elements can be re-used, it's still best to re-use as much elements as possible and try to recycle the material of the elements that can't be re-used. Again, upcycling would result in a higher residual value, but this can't always be done for every building material. Therefore, this design strategy won't be optimized for recycling.

The type of company that might benefit most from this design strategy is the one that already knows they will not use the building for an extensive period of time and the building will for some reason not be attractive for other companies to use (for example due to a more uncommon location that met the clients specific requirements). Fast developing companies that are already planning on expanding their business and growing their number of employees and services in the (nearby) future might choose for this design strategy as this will result in a higher selling price when they leave the building. Either, there might be found another company that can use the building (again for a relatively short period of time) that is willing to pay a good price for the building (hereby also partly paying for and later on benefiting from the structure's high residual value) or there is no next user, which results in demolition and selling the building elements that can be re-used, again earning back a part of the initial investment costs to give the building its high level of re-usability and disassembly.

Furthermore, this design strategy can also be followed in case of temporary structures. This might be the case when an area is reserved for a specific function, like houses and apartment buildings, in five or ten years time, but governing organizations have agreed on the temporary use of the area for office buildings. In this case, it's known on beforehand that the to be designed structure will only be used for a short period of time. Often, structural elements are designed for a much longer technical service life, so in order to limit the amount of waste at the end of the temporary structure's lifespan, the structure can be designed in accordance with this specific design strategy which enables the re-use of these structural elements.

4.2.4 Making a design with re-used building elements

Finally, nowadays more and more companies start to explore the possibility to design a new structure with already existing elements that became available from a different project. Of course, this is in line with the CE principles and can be a very good method of lowering the a building's environmental impact. In the context of this research, it is not preferred to create an additional design strategy for this movement, as it could theoretically be applied on all three design strategies as explained in previous sections. However, in order to account for the re-use of elements, the ECI-values for a structure in LCA module A should be adjusted (or even set to zero).

For example, when the designer needs to select a floor system, thereby choosing between a steel deck structure that needs to be newly constructed or a concrete hollow-core slab that becomes available from another project, the ECI-value for the steel deck variant remains unchanged (taking the values for LCA module A that correspond with the production of a new floor system). On the other hand, the ECI-value for the hollow-core slab can be significantly lowered (no need of raw building materials, but still taking into account transport etc.). In this way, the re-use of building materials is still rewarded in the MCA.

4.3 Summary of design strategies

To conclude this chapter, the following figure shows a clear overview of all the design perspectives that are linked to the three design strategies.

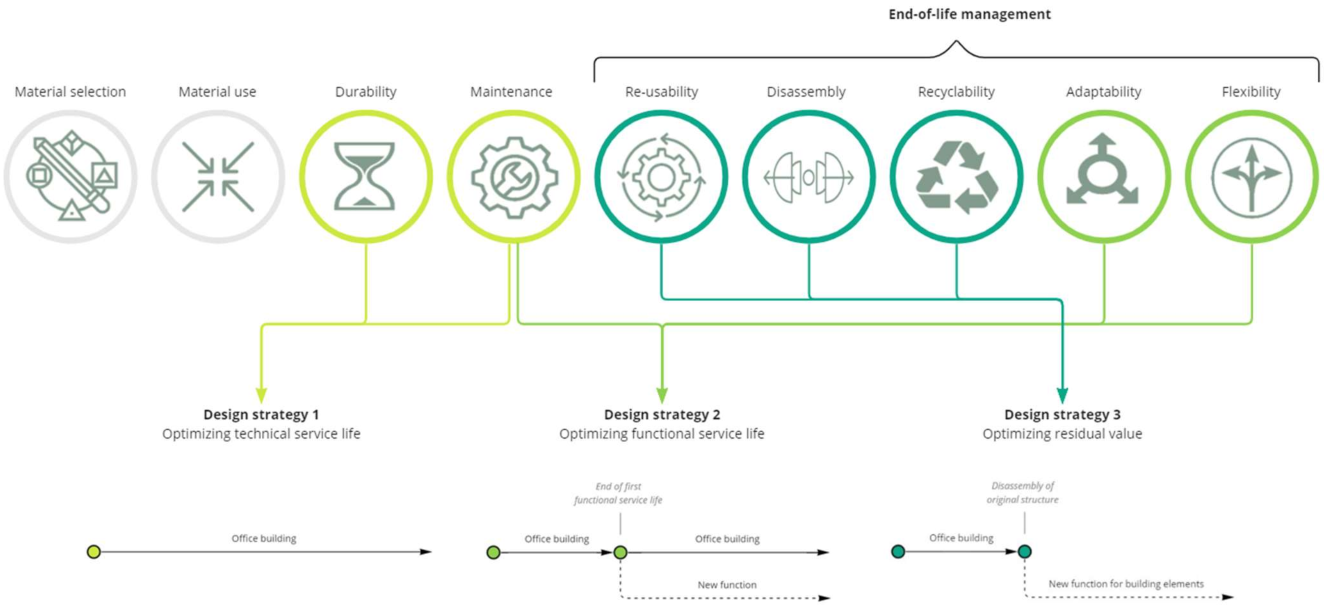


Figure 4.4: Overview of design perspectives linked to design strategies

Chapter 5

Program of requirements

This chapter focuses on the selection of three suitable projects from Witteveen+Bos based on their program of requirements. One project is chosen as a baseline project, where no additional requirements or wishes regarding sustainability are mentioned. Another project is selected as a more modern or futuristic one, as this program of requirements is highly focused on the structure's flexibility and end-of-life value. A third project is chosen as a more intermediate case.

Furthermore, as a result of the three analysed programs of requirements, different criteria that can be used in the MCA are listed and explained, including a way of quantifying and rating each criteria.

5.1 Suitable projects

As it would be interesting to investigate how big the impact of variations in programs of requirements is on the final outcome regarding material selection, three different projects from Witteveen+Bos are selected for further use in this research. These projects were selected based on their program of requirements only. While searching for suitable projects to use in the context of this research, the main goal was to find two extreme cases with very different programs of requirements and one intermediate case. This search resulted in the following three projects: a new terminal building on Maasvlakte II, an office and operating building that will serve as a new base for sustainable energy company Ørsted and finally an addition to the already existing ESA campus that will function as a general meeting centre. The three different projects are briefly explained below.

5.1.1 APM Terminals, Maasvlakte

The first selected project is APM Terminals, which program of requirements was made by Witteveen+Bos after studying other terminal buildings in the harbours of Rotterdam and Hamburg.

Witteveen+Bos acted as the engineering consultant for the new APMT MVII terminal on the second Maasvlakte. This project includes the design of a new terminal building, from which all operations on the terminal will be managed and directed. This program of requirements is quite basic and mainly gives a clear insight in the required functions that need to be fulfilled and the spaces that need to be present in order to enable those functions Additional topics, like sustainability goals and future plans for the terminal building are not discussed. Therefore, this program of requirements serves as a baseline case, in which functionality of the building is the first and foremost goal of the design.

Building envelope for APM Terminals	
Available building area	*50,4 x 28,8 m*
Number of floors	*5 (excluding basement)*
Gross floor area	*4666 m^2*
Net floor area	*3608 m^2 (equals 77% of gross floor area)*

Building structure and spaces for APM Terminals	
Primary structure	*The program of requirements does not specify anything regarding the structural layout of the building.*
Functional spaces	*The building should provide small offices (1 person) where people can work in silence and an open office area. The building should also include a control room from where the terminal can be operated. Besides office areas, there should also be space for meeting rooms and rooms for educational purposes, like job trainings and simulators. Furthermore, the building should provide changing rooms, showers and rooms where employees can sleep or relax. Finally, there should be enough space for a reception, technical facilities and other services and circulation of the people that use the building.*

Additional goals and requirements for APM Terminals	
Future perspective	*As the office building will be placed on a newly constructed terminal on the second Maasvlakte, it is assumed that this office building will be operational as long as the terminal is fulfilling its function. However, as there is limited space reserved for the building on the terminal area, it is assumed that expansion of the building in the future is not an option.*
Sustainability goals	*The program of requirements does not specify anything regarding sustainability of the building.*

Table 5.1: Key features of APM Terminals

5.1.2 Ørsted, Vlissingen

The second selected project is the design of a new base for Ørsted in Vlissingen. Ørsted is one of the global market leading companies with a specialization in renewable energy, such as wind energy. In the Netherlands, the company is mostly known from the offshore windfarms Borssele 1 & 2. Besides employees of Ørsted, also people from DONG Energy will use the new building as a base from which they can carry out maintenance activities for Borssele 1 & 2. Due to the background of Ørsted, futureproofing and sustainability are clearly mentioned in the delivered program of requirements. The company asks the engineering company to include future-proof concept drawings in the design. These concept drawings should indicate how the office building could be expanded in the future, within the site boundaries. When making the concept drawings, especially disruption or disturbance of building users and ongoing operations should be kept to a minimum, as the operation and maintenance program for Borssele 1 & 2 should not be influenced by construction works for a possible expansion of the building. These requirements show that Ørsted is already partially incorporating sustainability wishes for their new office building in the design phase. However, these requirements seem to be more optional for possible future application than a strict requirement for the primary design. Therefore, this program of requirements acts as a more intermediate case, as it is already much more focussed on lowering its environmental impact than the program or requirements of APM Terminals.

Building envelope for Ørsted	
Available building area	*60,0 x 22,2 m*
Number of floors	*2*
Gross floor area	*2664 m^2*
Net floor area	*2007 m^2 (equals 75% of gross floor area)*

Building structure and spaces for Ørsted	
Primary structure	*The primary grid structure for the building must allow for a big open plan office from where multiple employees can work, as well as smaller individual offices and meeting rooms.*
Functional spaces	*The building should provide small offices (1 person) and a large open plan office (at least 20 persons). There should also be meeting rooms of different sizes (6, 10 and 20 persons). Besides these office spaces, the building should also contain room for the technicians facilities, like changing rooms, lockers and showers. Finally, there should be space for a reception, technical facilities and other services and the building should provide sufficient space for circulation of its users.*

Additional goals and requirements for Ørsted	
Future perspective	*As stated above, it is desired to take possible future expansion of the building into account during the design phase.*
Sustainability goals	*The design of the building shall include 'future-proof' site concept drawings showing how the facilities could be expanded within the site boundaries. The designer shall prepare proposals and a life-cycle business case for achieving an energy neutral facility, which should include renewable energy (e.g. solar panels).*

Table 5.2: Key features of Ørsted

5.1.3 ESA/ESTEC, Noordwijk

The final and most future orientated program of requirements, belongs to the design of a new meeting facility for ESA/ESTEC. The European Space Agency (ESA) has multiple business locations throughout Europe, of which the biggest is located in Noordwijk, The Netherlands. The European Space Research and Technology Centre (ESTEC) is a campus consisting of multiple offices, labs and other facilities. In 2018 a Site Evolution Plan was released, which shows future developments of the campus up to the year 2040. At the heart of all facilities, an ellipse-shaped building will connect multiple departments and labs via so-called building fingers. The to be constructed Building B to which this program of requirements applies, will primary function as a general office building, offering shared and individual workplaces, together with meeting rooms for employees and visitors of the ESTEC campus.

As there is yet no specific department of ESA that will use Building B, it is designed as a general office building, but as it is possible that in the future a more specific function for this new building is found, flexibility in the design is highly important. Furthermore, ESA has set the goal to design Building B in accordance with the requirements for achieving a BREEAM Excellent certificate. Finally, the program of requirements also mentions that it is desired that Building B is not only flexible, but also demountable and adaptive. In this way, the building can easily be redesigned for a new purpose in the future or building elements can be re-used in a new project. This shows that the incorporation of CE principles like flexibility and re-usability are required from the beginning of the design phase, while this is seen more as a future option in the program of requirements of Ørsted. Therefore, the program of requirements for the design of Building B, is chosen as the final one for further use in the context of this thesis and functions as the most future-oriented one regarding circularity.

Building envelope for ESA/ESTEC	
Available building area	*37,8 x 30,6 m*
Number of floors	*3*
Gross floor area	*3470 m^2*
Net floor area	*2700 m^2 (equals 78% of gross floor area)*

Building structure and spaces for ESA/ESTEC	
Primary structure	*The primary grid structure for the building must allow for a flexible reconfiguration of spaces within the building over its lifecycle to accommodate changes in use.*
Functional spaces	*The building should provide focus offices (1 person), standard offices (1-2 persons) and shared offices (3-6 persons), as well as meeting rooms for larger groups. Besides these primary spaces, the building should also contain room for service, storage and technical facilities and provide sufficient space for circulation of its users.*

Additional goals and requirements for ESA/ESTEC	
Future perspective	*It is desired to apply the principles of a demountable, adaptive and flexible structure, such that in the future the building can be redesigned if necessary and its elements re-used.*
Sustainability goals	*BREEAM Excellent is a desired goalpost for this project, which means that it is desired from the engineers to design in accordance with the guidelines that belong to this certificate. However, the BREEAM Excellent certificate itself is not a requirement.*

Table 5.3: Key features of ESA/ESTEC

5.2 Criteria to include in the MCA

As a result of different programs of requirements from Witteveen+Bos especially for office buildings, different types of requirements that apply to this building type can be found. Together with the design perspectives that can be optimized for in different design strategies, a list of criteria to include in the MCA can be made.

One might want to just use the design perspectives as criteria in the MCA. On one hand, this seems the logical thing to do, as they were already used in chapter 4 when forming design strategies. However, these design perspectives are quite abstract and hard to quantify. As this thesis aims to perform a MCA based on actual numbers (in this case it's chosen to use indexes between 0 and 1 for all criteria), the criteria for the MCA are chosen in such a way that a scoring systems is already available in existing literature.

The sections below list the different MCA criteria and their corresponding ways of assigning scores to them. After this, it will be shown what the relation is between these criteria and the design perspectives.

5.2.1 Lifespan of a building element

Especially when trying to improve a structure's durability, the selection of a building material that has a long expected lifespan without extensive deterioration over time, is important. Using such a type of building material limits the required amount of maintenance and therefore prevents the use of additional materials and resources.

One way of estimating a building element's expected service life, is by applying the factor method as described in NEN-ISO 15686-8 on reference service life and service life estimation (NEN-ISO 15686-8, 2008). In this method, a building element's service life is estimated by multiplying the reference service life (RSL) by factors A, B, C, D, E, F and G. These factors are all related to specific building material characteristics, indoor and outdoor conditions and the execution method. The table below shows the different factors and how a distinction can be made between poor, normal or good conditions. A poor condition holds that the reference service life is multiplied by a factor smaller than one, meaning that the estimated service life of that element is reduced. On the other hand, good conditions mean that the reference service life is multiplied by a factor larger than one, thereby elongating the building element's estimated service life.

Aspect of interest	Factor		To consider	Conditions		
				Poor (factor 0,9)	Normal (factor 1)	Good (factor 1,1)
Inherent quality characteristics	A	Inherent performance level	*Material type/ grade*	Concrete strength class C20/25 or lower	Concrete strength class between C25/30 and C50/60	Concrete strength class C55/67 or higher (high strength concrete)
				Lower grade steel	Mild steel	Stainless steel/ heavy duty steel
				Non-durable sapwood	Sapwood, carpenter quality	Durable heartwood
			Durability, e.g.	No additional curing	Surface curing	Curing and self-healing bacteria

			protection system	Not galvanized and coated	Pre-galvanized and coated	Post-galvanized
				Dipped/ immersed (surface only)	Impregnated, some cutting after preservation	Impregnated, no cutting after preservation
	B	Design level	*Construction details*	External exposed surfaces, inadequate weatherproofing	Adequate protected external exposed surfaces	Additional coating/ weatherproofing to prevent external exposing
	C	Work execution level	*Site work or prefabricated*	Site work with little control over quality	Some small site alterations, site coated	Site work avoided, coated in factory
Environment	D	Indoor environment	*Special features, e.g. condensation*	Possible exposure to aggressive internal agents, high risk of condensation	No aggressive internal agents, occasional risk of condensation	Low risk of condensation
	E	Outdoor environment	*Special features, e.g. marine/ polluted*	Regular cycling between wet and dry, polluted industrial/ marine environment	Occasional cycling between wet and dry, urban environment with little risk of pollution	Sheltered from exposure to wet and dry cycles, rural environment with low risk of pollution
Operation conditions	F	Usage conditions	*Special features, e.g. vandalism*	Not applicable	Not applicable	Not applicable
	G	Maintenance level	*Cyclical, including quality*	Irregular maintenance without proper quality control	Regular maintenance	Regular maintenance and optional replacement of elements
Additional properties*	H	Fire resistance	*Deterioration due to fire*	Low resistance, possibility that the structure collapses during/ after the fire	Medium resistance, structure will probably survive fire but might not be reliable afterwards	Good resistance, meaning the structure can still be reliable after a fire

Table 5.4: Factor values for determining ESL (NEN-ISO 15686-8, 2008)

In addition to the method as proposed by NEN, category H is introduced. This factor elaborates on a building material's fire resistance.

The estimated service life (ESL) of a building element can now be calculated as:

(eq. 1) $$ESL = RSL * A * B * C * D * E * F * G * H$$ (NEN-ISO 15686-8, 2008)

In the case of office buildings, the design service life is set to 50 years, according to Annex A from the Eurocode (NEN-EN 1990, 2021). The reference service life for office buildings can often be set to 20 years, as A. van den Dobbelsteen explained in his research 'The sustainable office' (Dobbelsteen, 2004), following realistic values for modern office buildings. However, one of the goals of this research is to design an office building in such a way that the functional service life of the structure (or its individual elements) matches its technical service life. Therefore, the reference service life is set equal to the design service life of 50 years.

In case the ESL as calculated with equation 1 turns out to be higher than the RSL, it can be stated that certain material properties have a positive effect on a building element's lifespan. This also works the other way around. One way of converting this to an index between zero and one in presented in the table below.

ESL vs RSL	Explanation	Score
$ESL > 110\%\ of\ RSL$	Material properties are likely to have a positive influence on estimated lifespan of building element	1,00
$ESL = 100\% - 110\%\ of\ RSL$	Material properties might have a small positive impact on estimated lifespan of building element, but not significant	0,90
$ESL = RSL$	Material properties don't influence estimated lifespan of building element	0,80
$ESL = 90\% - 100\%\ of\ RSL$	Material properties might have a small negative impact on estimated lifespan of building element, but not significant	0,70
$ESL < 90\%\ of\ RSL$	Material properties are likely to have a negative influence on estimated lifespan of building element	0,60

Table 5.5: Scores based on ESL compared to RSL

5.2.2 Building material's potential for recycling

Especially when considering a structure's residual value, a building material's potential for recycling can be important to include in the decision making. Of course, one-on-one re-use of building elements is preferred here, however in cases where this is not possible or when a building element has reached its technical lifespan, the highest residual value that can be reached then is by recycling it.

In a materials potential for recycling, it's important to consider whether the material has a high possibility for upcycling, rather than downcycling, as upcycling results in a higher residual value. Furthermore, the process that is required for recycling a specific material needs to be considered as well. This results in seeking for an optimum between the quality or benefits of a recycled product and the suitability of a material to be recycled. Therefore, a building material's potential for recycling can be divided in two part: an **index for benefits from recycling (BR)** and an **index for suitability for recycling (SR)**.

These two indexes are introduced and listed for a variety of building materials by P. Sassi. The complete overview of indexes and ratings can be found in Appendix C (Sassi, n.d.). Note that this overview gives indexes for both re-using the entire element and for reprocessing the element. In the context of this criterium, only the indexes for the reprocessing of a building material will be considered, as complete re-use of elements is being covered in other criteria.

The index for the benefits from recycling and the index for a building material's suitability for recycling can be combined into one index: a building material's recycling index (I_recycling). This can be done by simply taking the average of the two indexes, using the following equation:

(eq. 2) $$I_{recycling} = \frac{BR+SR}{2}$$

5.2.3 Type of connection

As each building material comes with its own specific types of connections, it's important to take this into account in the MCA, as connections highly differ in the level of ease to adjust it, for example when an expansion of a building is planned and additional load bearing elements have to be connected to the existing structure. In 2021, Alba Concepts released a study on the quantification of a structure's level of demountability (Vliet, Grinsven, & Teunizen, 2021). This report introduces a way of assessing a connection based on the type of connection and its accessibility. The type of connection can vary from a solid chemical connection to a dry connection without any additional mounting material. The following table shows a rating system based on the type of connection, according to the report of Alba Concepts.

Type of Connection (TC)	Examples	Score
Dry connection	Loose (no mounting material) Click connection Magnetic connection	1,00
Connection with additional mounting material	Bolted connection Spring connection Screw connection	0,80
Direct integral connection	Doweled connection Nail connection	0,60
Soft chemical connection	Polyurethane foam (PUR) Sealed connection (kit)	0,20
Solid chemical connection	Glued connection Welded connection Cast-in-situ connection Chemical anchors	0,10

Table 5.6: Scores for different types of connections (Vliet, Grinsven, & Teunizen, 2021)

5.2.4 Accessibility of connection

As stated in the previous criterium, the report of Alba Concepts also provides a table for rating a connection based on its level of accessibility. A high score means that a connection is highly accessible and that no or little damage is done to connected elements when working on that connection. A low score implicates that a connection is not very well accessible and that doing so causes (irreparable) damage to connected elements. The following table shows the scores for each level of accessibility.

Accessibility of Connection (AC)	Score
Freely accessible without any additional actions	1,00
Accessible with additional actions that don't cause any damage	0,80
Accessible with additional actions that cause fully repairable damage	0,60
Accessible with additional actions that cause partially repairable damage	0,40
Inaccessible (unrepairable damage on connected elements)	0,10

Table 5.7: Scores for different levels of accessibility of connections (Vliet, Grinsven, & Teunizen, 2021)

5.2.5 Removability-index of a connection

The type of connection and its accessibility, as explained in the previous two criteria, can also be combined into a general removability-index (I_connection_removability) of a connection, using the following formula:

(eq. 3) $$I_{connection\_removability} = \frac{2}{\frac{1}{TC}+\frac{1}{AC}}$$ (Vliet, Grinsven, & Teunizen, 2021)

Filling in this equation results in a value between 0 and 1, where a low score means that the connection is not fit for disassembly without damaging the elements that are connected, while a high score means that a connection is very removable and that connected elements can quite easily be disassembled without extensive damage.

5.2.6 Total weight of used building material

As the general goal of this research is to design a structure with a minimal amount of used resources over its complete lifespan, also the used amount of material for the initial design needs to be optimized.

Note that this criterium only focuses on the total amount of building material that is used for the initial design, so excluding any additional materials that might be needed during maintenance activities, and only considers building material that is used for a building's load bearing structure, which holds that all materials used for example for facades, internal ceiling systems and flexible non-load-bearing walls that can be used for the separation of spaces are not included in this calculation.

Furthermore, the total used amount of building material can be expressed in the total weight of the structure and the total volume of used building materials. In this case, the total weight is considered more important, as this might have a beneficial effect on the dimensions that are needed for the foundation of the structure.

The following table shows the method for assigning scores to different designs based on the total weight of the load bearing structure.

Total weight in relation with lightest variant	Score
100% (= lightest variant)	1,00
100% - 125%	0,90
125% - 150%	0,80
150% - 200%	0,70
200% - 300%	0,60
300% - 400%	0,50
400% - 600%	0,40
600% - 800%	0,30
800% - 1000%	0,20
> 1000%	0,10

Table 5.8: Scores for the total weight of used building material

5.2.7 Total price of used building material

Apart from the more environmental-orientated aspects, a client will in the end be mostly interested in the total price that has to be paid for the new office building. Furthermore, it's always interesting to be able to compare differences in costs for various designs.

Note that this criterium only focuses on the total price that has to be paid for the total amount of used building material in a design and that this is not to be compared with the final price of a building.

The following table shows the method for assigning scores to different designs based on the total price of the building material used for the load bearing structure.

Total price in relation with cheapest variant	Score
100% (= cheapest variant)	1,00
100% - 110%	0,90
110% - 125%	0,80
125% - 150%	0,70
150% - 200%	0,60
200% - 250%	0,50
250% - 300%	0,40
300% - 400%	0,30
400% - 500%	0,20
> 500%	0,10

Table 5.9: Scores for the total price of used building material

Appendix E shows a brief overview of the prices that were used or calculated for the building materials that are being considered in this report.

5.2.8 ECI value for production process (LCA module A)

The ECI value of a structure reflects on its negative impact on the environment. The ECI value that can be linked to LCA module A is specifically useful when it comes to the production process of building materials and (half) products. Therefore, a low ECI value in LCA module A is highly appreciated and needs to aimed for in all design strategies.

The data that was used for calculating ECI values for all building materials in this research, was retrieved from the 'Nationale Milieudatabase'. This database separates all available data in to three categories. The first category depends on the product's brand and is mostly owned by the manufacturer of the product. This data has been checked and verified by an external party. Data from the second category mostly doesn't depend on the brand but is often still owned by the manufacturer. This data was also verified by an external party. Finally, the data that isn't owned by a manufacturer or brand, but by the NMD itself, is placed in category 3. However, this data has not been verified by an external party, which comes with uncertainties regarding the validity of the data.

Therefore, data belonging to category 1 and 2 is highly preferred over category 3 data. However, detailed insight in the calculation of a product's ECI value is not publicly available for the first two categories. In these cases, only the final ECI value is presented, without further insight in the contribution of different LCA modules to this final value. The data that was used for this research, mostly comes from category 3, as this data is often publicly available, which was needed for a more detailed insight in the ECI values.

The same scoring table as used for the total costs of a design (previous section) will be used for this criterium.

5.2.9 ECI value at end-of-life stage (LCA module A, C and D)

Besides the ECI value for the production process of building materials and elements, it's also possible to link an ECI value to LCA module D, where the focus lies on a product's end-of-life stage and any possible residual value it has left. In case building elements can be re-used or materials can be recycled, a structure's residual value increases, which is linked to LCA module D. By subtracting the ECI value for module D from the initial ECI value for module A and C, the residual value of a structure can act as a type of discount on its original ECI value caused by the production process. This shows that a structure might have a very high ECI value for module A and C, but when it has a high residual value, the total ECI value can be much lower.

Note that here only LCA module A, C and D are being considered and additional environmental impacts during for example the use-stage of the building are not included here. The ECI value that applies to this phase, mostly has to do with the use of energy, water, thermal insulation and other resources, which lie beyond the scope of this research, as only a building's load bearing structure is being considered.

The same scoring table as used for the total costs of a design (previous section) will be used for this criterium.

5.3 Relation between MCA criteria and design perspectives

As explained in the beginning of section 5.2, the criteria as listed above, can all be linked to design perspectives. In chapter 4, the design perspectives were prioritized in different orders, which emphasized the varying importance of them for each design strategy. In the MCA, it's important that this differing importance per design strategy can be included. In the context of this research, the way to do this, is by assigning varying weights to the nine MCA criteria. As each MCA criteria can be linked to a design perspective (as shown in the figure below), the importance of a design perspective within a design strategy can be expressed by assigning a higher weight to a corresponding MCA criteria.

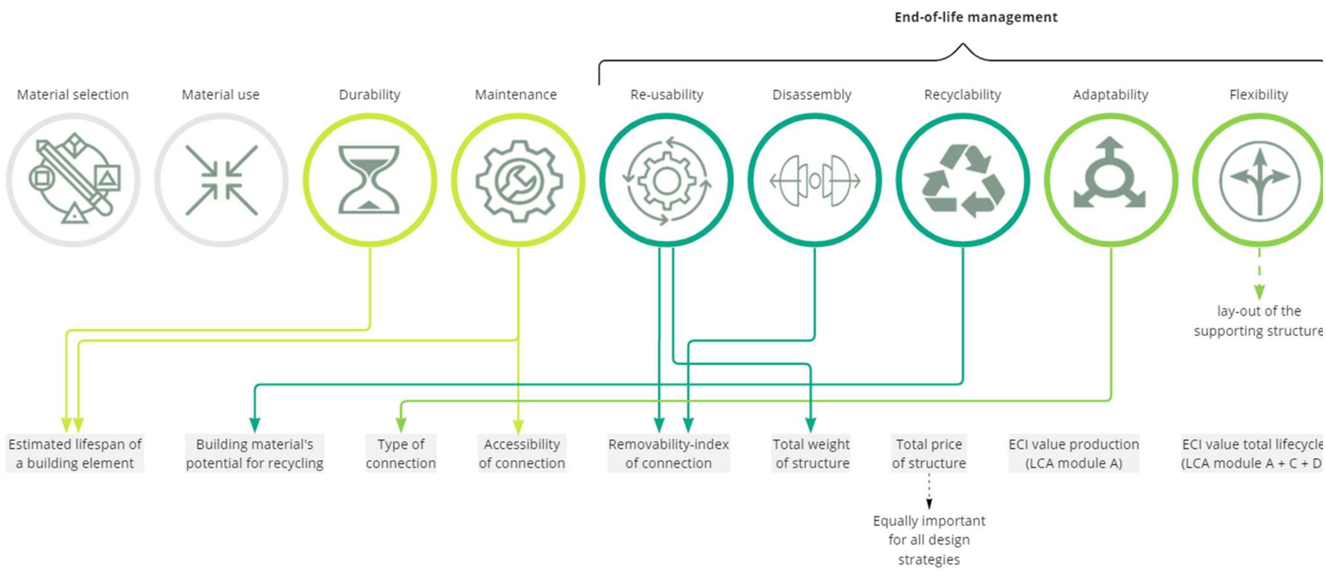


Figure 5.1: Design perspectives linked to MCA criteria

The figure above first shows the nine design perspectives from Tim Vonck on the top of the figure. Note that both material selection and material use are not considered any further here, as these two perspectives are topics that are being optimized in this research by selecting the right design strategy and the best suitable building material.

Both the design perspectives durability and maintenance can be linked to the MCA criterium for the estimated service life of a building element. The longer the ESL, the higher the score for this criterium. A high score here can implicate that little to no deterioration of the material will occur during its technical service life and only a limited amount of maintenance might be necessary. Furthermore, the ease of performing maintenance can be increased by using connections with a high level of accessibility.

The design perspectives re-usability and disassembly can be linked to the MCA criteria of a connection's removability-index and a structure's total weight. A connection with a high removability-index is highly important when building elements need to be disconnected and disassembled before re-use is possible. Furthermore, lightweight building elements are beneficial when looking at its transportability. Obviously, the design perspective recyclability is linked to the MCA criterium for a building material's potential for recycling.

When looking at the level of adaptability of a structure, this can be linked to the type of connection that is being used. Some connections enable the addition of new future elements better than other (for example a bolted connection versus a cast in-situ connection).

Finally, the design perspective flexibility is not linked to one of the MCA criteria. As this design perspective fully focusses on a flexible internal space of a building, mainly the lay-out of the supporting structure and the location of load bearing elements is relevant here.

The table below shows a quick summary of the proposed MCA criteria and their relation with the nine design perspectives. Together with figures 4.4 and 5.1, this can function as the foundation for the assigned weights to each criterium, as can be seen in the next section.

1	Estimated lifespan of a building element	An ESL that is higher than the RSL is assumed to be an indication of high durability (caused by work execution, material characteristics, etc.). It might also result in less deterioration, resulting in lower maintenance needs.
2	Building material's potential for recycling	In case re-use of building elements in not possible for some reason, the most residual value can still come from recycling the building material. This is specifically useful when optimizing a structure's residual value at its end-of-life stage.
3	Type of connection	This criterium focuses on the possibility of adjusting a connection in case additional future elements have to be added in case of expansion of the building. For example, a bolted connection seems easier to adjust than a cast in-situ one.
4	Accessibility of connection	Besides the type of connection, also its accessibility needs to be adressed. Here, a high level of accessibility means little to no damage to connected elements when performing maintenance or replacing deteriorated elements in the worst case.
5	Removability-index of connection	The two criteria mentioned above can also be combined into one removability-index of a connection. A high removability-index shows that a connection has great potential for easily removing it and thereby demounting a structure.
6	Total weight of structure	This criterium is specifically focused on the final weight of the total structure. Lower self-weight of the elements is considered to be beneficial for their transportability, which is important when elements can be re-used in new projects.
7	Total price of structure	In practice, the total price of a structure is always something that is included in the decision making. This criterium enables one to show which building material might result in the cheapest structure (based on early design checks).
8	ECI value production (LCA module A)	Finally, ECI values are included in the MCA. First, the ECI value for the production process only is considered. This is specifically relevant when assuming the building will last a long time as its functional service life matches its technical one.
9	ECI value total lifecycle (LCA module A + C + D)	Also a structure's ECI value over its full lifecycle is included. This one becomes more relevant when a structure is being optimized for a high residual value, as LCA module D might result in benefical aspects at a materials end-of-life stage.

Table 5.10: Brief explanation per MCA criteria and their link with design perspectives

5.4 Weights of MCA criteria

The nine criteria that will be included in the MCA can now be given specific weights for each design strategy. As explained earlier in chapter 4, each design strategy focusses on different design perspectives. This results in varying levels of importance for the MCA criteria as mentioned in the previous sections. These differences in level of importance is included in the MCA as follows: for each design strategy, one can distribute a total of 10 points over the MCA criteria. A criterium that is considered of high importance for that specific design strategy, can get a higher weight by assigning it more points. On the other hand, a criterium that is less or even not relevant for a specific design strategy, can get zero points, thereby excluding it from the MCA. This system results in the following table, where the proposed weights of the criteria for each design strategy are shown.

	Weights of MCA criteria per design strategy		
	Design strategy 1	Design strategy 2	Design strategy 3
	(max. technical service life)	*(max. functional service life)*	*(max. residual value)*
1. Lifespan of a building element	5	3	0
2. Material's potential for recycling	0	0	2
3. Type of connection	0	4	0
4. Accessibility of connection	2	0	0
5. Removability-index of connection	0	0	4
6. Total weight of structure	0	0	2
7. Total price of structure	1	1	1
8. ECI value (LCA module A)	2	2	0
9. ECI value (LCA module A + C + D)	0	0	1
Total	**10**	**10**	**10**

Table 5.11: Weights of MCA criteria

For design strategy 1, the focus mainly lies in designing a structure that has a high durability and therefore using elements with a long estimated service life. Furthermore, the accessibility of a connection is given a high weight, as this might result in easier maintenance if necessary and even enables the possibility of replacing a deteriorated element.

The second design strategy aims for a high level of flexibility (which is achieved by designing a supporting structure with large spans and few load bearing elements) and adaptability (which is achieved by using connections that can relatively easily be adjusted in case a structure is expanded). Besides that, also the estimated service life of building elements is important, as this limits the expected amount of maintenance.

Design strategy 3 focusses on a high removability-index of a connection, as this makes the process of demounting and re-building a structure much easier. Besides that, also the transportability of building elements is important, resulting in the wish to create a structure composed of lightweight building elements. When re-use of elements is not possible, for whatever reason, the most residual value can come from recycling the used building material.

The criterium regarding the estimated price of the supporting structure is given a weight of 1 in all design strategies. In practice, the final costs of a project namely have a large impact on all decision making. Finally, the ECI values have different weights for each design strategy. Design strategy 1 mainly focusses on the functionality of a structure and as it's expected the structure will last a long period of time, the end-of-life stage is not so much considered here. Therefore, in this first design strategy, the ECI value for only the production process is relevant and is given a weight of 2. In the second design strategy, it's expected that the structure might change functions during its technical service life, however it's still expected that the structure will last a long time, so again, the end-of-life stage becomes less important here. This results in the same weight for this criterium as for the first design strategy. Finally, for design strategy 3, the residual value of a structure is of the highest importance, resulting in a higher weight for a material's potential of recycling and a weight of 1 for the ECI value for a structure's full lifecycle (LCA module A, C and D).

The advantage of this scoring system, is that future users of this research and MCA, can easily adjust the weights that are assigned to a certain criterium. It even makes it possible to add a new design strategy if desired. Also, new criteria can be added to the MCA and their relevance can easily be expressed per design strategy by assigning points to it. However, when more criteria are added, it might be useful to increase the total number of points that can be used for one design strategy.

Chapter 6
Building materials

In this chapter, the different load bearing elements that are being considered in this research are listed and explained. Then, the different types of building materials that are included in the MCA will be elaborated on, combined with the various floor types that will be used per building material. Parts of the building material's strength properties are placed in the Appendices, in order to limit the length of this chapter. Finally, a brief overview of all building materials and their application within the context of this thesis is given.

6.1 Load bearing elements

A building's load bearing structure can be divided into three main components, namely the vertical elements, horizontal elements and stability elements. In the context of this thesis, only the vertical and horizontal load bearing elements will be considered. Elements that provide a building's lateral stability, are often incorporated as shear walls into the façade elements or elevator shafts, which are both beyond the scope of this thesis.

The vertical load bearing elements of a building can be columns or walls. Horizontal load bearing elements are beams that are placed on top the columns or walls, and floor elements that are placed on top of the beams. As the general goal of this research is to minimize used resources for a building, it can be stated that the use of columns is more in line with this CE principle than the use of load bearing walls, as this would require much more building material. Therefore, the elements that will be considered in the calculation and MCA are columns, beams and floor elements.

The three main categories of building materials that are most interesting to include in the MCA, are reinforced concrete, steel and timber. First, different types of reinforced concrete, steel and timber are introduced and for each load bearing element it will be explained which building materials can be used.

In the next section, all building materials that will be included in the MCA will be elaborated on in more detail and all necessary information that is needed for the MCA will be listed.

6.1.1 Beams and columns

As of today, reinforced concrete is one of the most commonly used building materials for columns and beams. Due to a lot of recent developments within the concrete sector, new types of concrete are available on the market, each one claiming to be more sustainable than standard reinforced concrete. The types of concrete that will be considered here, are standard reinforced concrete, steel fibre reinforced concrete, lightweight concrete and self-healing concrete. Furthermore, the distinction between prefabricated and in-situ concrete can be made, resulting in a total of eight concrete options for columns.

Next to reinforced concrete, steel is also a very popular building material and can also be used for load bearing elements. A relatively new and less commonly used option for the use of metal as a building material is aluminium. Its strength can be comparable with steel, while its self-weight is significantly lower, resulting in a higher strength-to-weight ratio. This might result in a lower amount of used building material in a structure and aluminium is therefore interesting to include in this research.

Finally, the use of timber as a building material is becoming more and more popular, as it has proven to be a worthy alternative for concrete and steel in specific situations. Especially glued laminated timber (glulam), laminated veneer lumber (LVL) and cross laminated timber (CLT) are fit for usage as load bearing columns and beams, as they usually have higher strength characteristics compared to sawn timber profiles.

6.1.2 Floors

For reinforced concrete floors, two different floor types are being considered in this research. First, hollow-core slabs are included and they function as a prefabricated option for concrete floor elements. A composite floor system ('breedplaatvloer' in Dutch) is considered as a more cast in-situ variant of a concrete floor, as this type of floor can't be fully prefabricated and needs finishing on site.

Steel floors that are being used in steel frame constructions will be considered as one of the options for a metal flooring system. The same type of system (consisting of multiple C-sections with a composite floor on top) can be made using aluminium, instead of steel. This results in one type of floor system, that can be executed in both steel and aluminium. Figure 6.1 shows a schematization of a steel frame deck structure. Note that for the steel or aluminium floor system, only the C-sections and the composite floor on top of them are being considered (supporting beams are not part of the floor system).

The final material option for load bearing floor elements is cross-laminated timer (CLT) panels. Due to the alternating orientation of the lams, CLT panels are specifically fit for usage in floors.

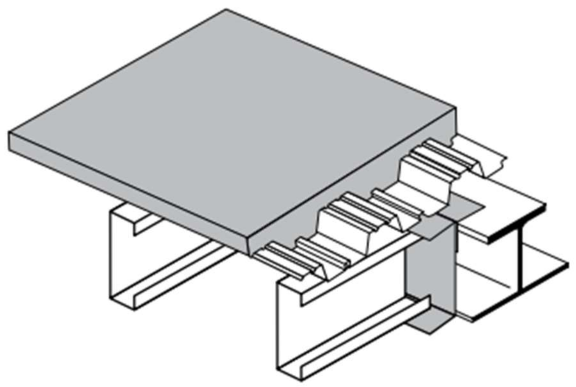


Figure 6.1: Schematization of a steel deck structure (Bouwen met Staal, 2013)

The table below shows a brief overview of the building materials and their application within the context of this research.

Concrete		Metal		Timber	
Beams / columns	Floors	Beams / columns	Floors	Beams / columns	Floors
Standard reinforced concrete	Hollow-core slab	Steel	Steel deck structure	Glulam	CLT
Lightweight reinforced concrete		Aluminium	Aluminium deck structure	LVL	
Self-healing reinforced concrete				CLT	
Standard reinforced concrete	Composite slab				
Lightweight reinforced concrete					
Self-healing reinforced concrete	Prefab In-situ				

Table 6.1: Selected building materials and their application

6.1.3 Roofs

While the roof of a structure is not being considered for further design within the context of this research, its weight should be taken into account as a permanent load on the load bearing structure. According to the categorization as proposed in section 6 of Eurocode 1, roof category H is assumed. This means that the roof is only accessible for normal maintenance and repair (NEN-EN 1991-1-1, 2002).

Assuming a flat roof with a bitumen finish, the roof structure consists of the following layers.

Components of a flat roof with bitumen finish	Self-weight [kN/m^2]
2 layers bitumen	0,42
Felt	0,02
Boarding	0,10
Insulation	0,01
Joists	0,10
Plasterboard	0,15
Total	**0,80**

Table 6.2: Flat roof structure (Steel Beam Calculator, n.d.)

The imposed load on a roof of category H can be set to $q_{imposed,roof} = 0{,}4\ kN/m^2$, according to Eurocode 1 (NEN-EN 1991-1-1, 2002).

6.2 Reinforced concrete

The sections below briefly elaborate on basic characteristics of the different types of reinforced concrete that are being considered in this research. This includes available sizes, which is especially important for floor elements, important strength characteristics and the self-weight of the building material or floor element, in kN/m, kN/m^2 or kN/m^3.

At first, also steel fibre reinforced concrete was considered as a possible building material in this research. However, first calculations showed that the use of steel fibres without additional steel rebars could only be a possible solution for floor systems, but not for beams and columns. Therefore, this building material is not considered any further.

Note, that in cases where a more detailed design shows that crack width control in concrete structures is governing, steel fibre reinforced concrete could be a very good solution, as the steel fibres (especially when present in the concrete cover) significantly lower the crack width.

6.2.1 Standard reinforced concrete

As a sort of baseline, traditional or standard reinforced concrete is selected as one of the building materials that is being considered in this thesis.

As reinforced concrete is one of the most commonly used building materials, it's available in a wide variety of sizes, enabling a lot of different shapes and dimensions for beams and columns.

A full overview of the different concrete strength classes is included in Appendix G. All relevant characteristics, like Youngs modulus, tensile strength and compressive strength are listed for each strength class.

According to Eurocode 1, Annex A, table A.1, the characteristic weight of this building material is $\gamma_{standard\ reinforced\ concrete} = 25{,}0\ kN/m^3$. This value includes $1\ kN/m^3$ for a commonly used amount of steel reinforcement (NEN-EN 1991-1-1, 2002). The elastic modulus can be set to $E_{concrete} = 34000\ N/mm^2$.

6.2.2 Lightweight reinforced concrete

Lightweight concrete is made by using lightweight coarse aggregates, like shale, clay or slate (Specify Concrete, 2019). This results in a significantly lowers density, while still remaining a solid building material. Due to this lower density, the loading on a structure as a result of self-weight is reduced, which makes it an interesting alternative to include in this research.

Like standard reinforced concrete, this type of concrete is also available in many different shapes and dimensions.

For lightweight concrete, strength characteristics depending on the concrete class can be derived from standard concrete classes. A table with material characteristics is also included in Appendix G. As can be concluded from this table, lightweight concrete class LC40/44 is relatively comparable with standard concrete from section 6.2.1. The Elastic modulus needs to modified using the formula as given in the table in Appendix G, resulting in $E_{lightweight\ concrete} = 18000\ N/mm^2$.

According to Eurocode 1, Annex A, table A.1, the characteristic weight of this building material is $\gamma_{lightweight\ concrete} = 17{,}0\ kN/m^3$, hereby assuming density class LC 1,6. This value includes $1\ kN/m^3$ for a commonly used amount of steel reinforcement (NEN-EN 1991-1-1, 2002).

6.2.3 Self-healing reinforced concrete

Self-healing concrete was introduced in an attempt to limit deterioration of steel reinforcement as a result of concrete cracking. When a crack occurs in the concrete, the steel reinforcement might get exposed to external influences, like rain water. This might cause the steel reinforcement to corrode, which results in progression of the crack. In order to prevent the crack from reaching the reinforcement bars, a mixture of bacteria can be applied in the concrete. This can be done by directly mixing the bacteria with the concrete mixture or by combining the bacteria in capsules that crack open when a crack reaches a capsule (Nodehi, Ozbakkaloglu, & Gholampour, 2022).

Like standard reinforced concrete, this type of concrete is also available in many different shapes and dimensions.

For self-healing concrete, the same concrete strength classes can be used, thereby again referring to Appendix G.

For self-healing concrete, the same characteristic weight as standard reinforced concrete is assumed, resulting in $\gamma_{self-healing\ concrete} = 25{,}0\ kN/m^3$. This value includes $1\ kN/m^3$ for a commonly used amount of steel reinforcement.

6.2.4 Prefabricated concrete vs. cast in-situ concrete elements

All types of concrete as described in the previous sections, can be made as prefab elements or can be cast in-situ. The difference between these two execution methods is the type of connections between different load bearing elements in a building. While in-situ elements are often cast together, resulting in solid chemical connections, prefab elements are often connected differently. Using modern techniques, it’s even possible to create completely loose connections, as shown in the figure below. Of course, this type of connection is probably far more expensive than a simple cast in-situ connection, but in the context of this research, this type of connection can significantly increase the level of demountability of a structure.

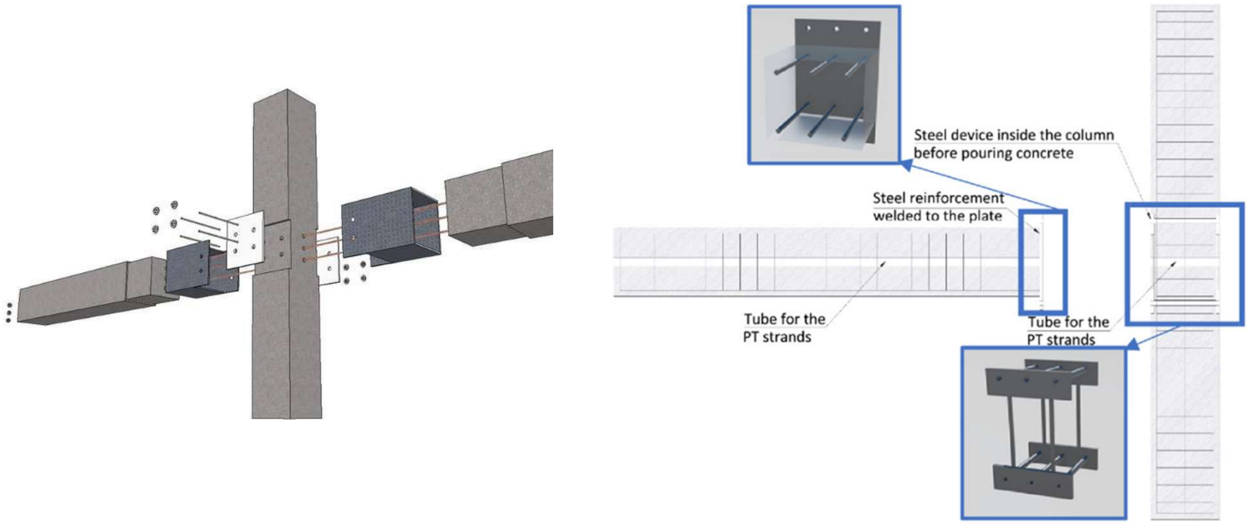


Figure 6.2 : Examples of dry connections between prefab concrete elements (Cao, Xiong, Feng, & Wu, 2021) (left) (Navarro-Rubio, Pineda, & García-Martínez, 2018) (right)

It is assumed that for both cast in-situ and prefab concrete elements, the same strength characteristics apply as described in the previous sections.

6.2.5 Hollow-core slab

As stated in the beginning of this chapter, hollow-core slabs are included in this research as a prefab option for concrete flooring. Due to the hollow spaces within the slab, the floor elements have a relatively small self-weight in comparison with normal concrete slabs. This saving can be as much as 50%, which means that the complete load bearing structure can be made considerably lighter (Wagemans, 2014). When making a design using hollow-core slabs, the following principles are important to consider: free supports and a maximum deflection under variable loading of 0.003 L, with L being the span of the slab.

In the context of this research, the following type of hollow-core slab is being considered:

VBI isolation slabfloor A320	
Weight (including joint mortar)	4,5 kN/m^2
Fire resistance	90 – 120 minutes
Slab height	0,32 m
Maximum slab length	14,70 m
Slab width	1,20 m
Strength class	C45/55

Table 6.3: Product specifications hollow-core slab (Wagemans, 2014)

6.2.6 Composite floor system

In order to also include a more cast in-situ alternative for a concrete floor, a composite slab ('breedplaatvloer' in Dutch) is also discussed in this research. This floor system consists of a thin prefab concrete slab including the reinforcement (predal), which is installed on site and then finished with in-situ cast concrete. An example of a predal (before finishing it with in-situ cast concrete) is shown below.

Figure 6.3: Example of a predal (PredalCo, n.d.)

Assuming the same total thickness as the hollow-core slab, the following table with product specifications apply for the composite floor system. This floor consists of a precast slab with a thickness of 80 mm. The finishing top layer consists of 240 mm cast in-situ concrete, resulting in a total thickness of 320 mm.

Dycore precast concrete slab (thickness precast slab = 80 mm, total thickness = 320 mm)	
Weight (including top layer)	$8{,}0\ kN/m^2$
Slab height	0,32 m
Maximum slab length	10 m
Strength class	C45/55

Table 6.4: Product specifications composite floor system (Wagemans, 2014)

6.3 Metal

The sections below briefly elaborate on basic characteristics of the different types of metal that are being considered as building material in this research, namely steel and aluminium. This includes available sizes, important strength characteristics and the self-weight of the building material or floor element, in kN/m, kN/m^2 or kN/m^3.

6.3.1 Steel

As explained in the beginning of this chapter, steel profiles will be used for both columns and beams in this research. For load bearing columns, H-sections are preferred, due to their high compressive resistance. For load bearing beams, I-sections are more useful, as they are relatively light and have a high resistance against bending due to the larger webs when compared to H-sections (Wagemans, 2014).

A full overview of the different steel classes and used H- and I-sections is included in Appendix H. All relevant characteristics, like Youngs modulus, yield stress, tensile stress and specifications for different profiles are listed there.

According to Eurocode 1, Annex A, table A.1, the characteristic weight of steel is $\gamma_{steel} = 78{,}5\ kN/m^3$ (NEN-EN 1991-1-1, 2002).

6.3.2 Aluminium

An interesting alternative for steel, might be the use of structural aluminium for load bearing elements. Due to its higher strength to weight ratio, the dimensions of the load bearing structure can be significantly smaller. There is a wide range of aluminium alloys, all with different fields of application. In the context of this research, aluminium alloy 6061-T6 will be considered, which is used mostly for structural purposes. Here, 6061 refers to the elements and the amounts of it that are being used in this alloy. T6 refers to the temper or heat treatment of the material, where T6 means that the solution is heat treated and artificially aged.

The following table lists a few important material characteristics of 6061-T6 aluminium.

6061-T6 aluminium alloy	
Elastic modulus	$E = 69000\ N/mm^2$
Shear modulus	$G = 26000\ N/mm^2$
Yield stress	$f_y = 276\ N/mm^2$
Tensile stress	$f_t = 310\ N/mm^2$

Table 6.5: Material specifications 6061-T6 aluminium (ASM Aerocpace Specification Metals, n.d.)

According to Eurocode 1, Annex A, table A.1, the characteristic weight of aluminium is $\gamma_{aluminium} = 27{,}0\ kN/m^3$ (NEN-EN 1991-1-1, 2002).

For aluminium beams and columns, the same profiles are considered as for steel, meaning that all sections properties (except for the mass, due to aluminium's different density) as shown in Appendix H also apply for aluminium structural elements.

6.3.3 Steel deck structure

As explained in the beginning of this chapter, a steel deck consists of multiple layers (from top to bottom): finishing layer (anhydrite), plate material which functions as the formwork of the anhydrite floor layer, C-sections, purlins ('veerregels' in Dutch) and plasterboard finishing.

	Self-weight $[kN/m^2]$	Thickness [mm]
Finishing layer (anhydrite)	0,70	35
Plate material	0,10	20
C-sections (h = 300 mm)	0,50	300
Purlins ('veerregels' in Dutch)	0,05	20
Plasterboard	0,25	25
Total	**1,60**	**400**

Table 6.6: Layers of a steel deck structure (Bouwen met Staal, 2013)

** According to the Quick Reference, the mass of a C-section with dimensions 300x100 mm and a thickness of 10 mm is 46,2 kg/m, which is equivalent to approximately 0,453 kN/m. Therefore, it can be concluded that Bouwen met Staal assumed approximately 1 C-section per meter width.*

The type of floor as shown in the table above is fit for use in residential buildings (as a separation floor between apartments) and in utility buildings, like offices. It has a fire resistance of 60 minutes and can be made with spans up to 7,2 meters (Bouwen met Staal, 2013).

6.3.4 Aluminium deck structure

For an aluminium deck structure, the same layers as for a steel deck are assumed. The only difference here is the weight of the C-sections. The self-weight of aluminium is $\frac{\gamma_{steel}}{\gamma_{aluminium}} = \frac{78{,}50\ kN/m^3}{27\ kN/m^3} = 2{,}9$ times lower than that of steel. Assuming the same C-profile for both steel and aluminium results in a self-weight of this C-profile made out of aluminium of approximately $\frac{0{,}50\ kN/m^2}{2{,}9} = 0{,}20\ kN/m^2$. This result is included in the table below.

	Self-weight $[kN/m^2]$	Thickness [mm]
Finishing layer (anhydrite)	0,70	35
Plate material	0,10	20
C-sections (h = 300 mm)	0,20	300
Purlins ('veerregels' in Dutch)	0,05	20
Plasterboard	0,25	25
Total	**1,30**	**400**

Table 6.7: Layers of an aluminium deck structure, based on a steel deck structure from (Bouwen met Staal, 2013)

6.4 Timber

The sections below briefly elaborate on basic characteristics of the different types of timber that are being considered as building material in this research, namely Glulam, LVL and CLT. This includes available sizes, important strength characteristics and the self-weight of the building material or floor element, in kN/m, kN/m^2 or kN/m^3.

First of all, for timber structural elements, it's important to state the use class of the elements. In the context of this research, all structural elements are covered (for example by façade elements) and not exposed to the weather. However, in some cases and under extreme circumstances (for example during extreme rainfall or driven rain that might cause leakage), wetting can occur. This means that all elements considered in this research fall within use class 2.

In the context of this research, the following wood species are assumed for different timber products:

Product	Wood specie(s)	Natural durability	Source
Glulam	Spruce	D4	(Brettschichtholz, n.d.)
LVL	Larch, pine	D3 – D4	(Naturally:Wood, n.d.)
CLT	Spruce, pine	D4, D3 – D4	(Wigo Group, n.d.)

Table 6.8: Wood species used for timber products and their natural durability (Wagemans, 2014)

The following table gives an overview of the relation between the use class as explained above and the material's natural durability. Here, D1 means a very high natural durability, while D5 means a relatively low natural durability.

use class	natural durability				
	D1	D2	D3	D4	D5
1	O	O	O	O	O
2	O	O	O	(O)	(O)
3	O	O	(O)	(O)-(X)	(O)-(X)
4	O	(O)	(X)	X	X
5	O	X	(X)	X	X

Table 6.9: Natural durability linked to different use classes (Wagemans, 2014)

In the table above, O means that the material's natural durability is always sufficient. (O) shows that the material's natural durability should be sufficient, but in some circumstances wood treatment might be required. This might be the case for the timber products being considered in this research and should be taken into account when making a detailed design (it is therefore advised to order timber products with additional treatment in order to prevent deterioration as a result of weather influences).

6.4.1 Glulam

Just like concrete and steel profiles, glulam is available in a wide variety of dimensions. A complete overview of all possible strength classes, material properties and cross sections, including section properties, is included in Appendix I. In order to limit the amount of options for the design of a structural element, the strength class is set to GL32h. This results in a characteristic weight of $\gamma_{glulam} = 4{,}6\ kN/m^3$.

6.4.2 LVL

In this research, glulam, LVL and CLT are all considered as building materials that can be used for the production of load bearing columns and beams. Within the context of this thesis, it is assumed that all these timber elements can have approximately the same sizes in width and height, however the span of LVL beams is limited compared to glulam ones (Canadian Wood Council, n.d.).

For simplicity, the same cross sections that are possible for glulam beams are used for LVL, limiting the height of the beam to 600 mm and the width of the beam to 160 mm. This is also shown in Appendix I.

Furthermore, Appendix I gives an overview of the different LVL strength classes and the corresponding material properties. As was also done for glulam, in order to limit the amount of possible options in the design phase, the strength class of LVL considered in this research is set to LVL50P. This results in a characteristic weight of $\gamma_{LVL} = 6{,}0\ kN/m^3$.

6.4.3 CLT

In the context of this research, CLT is used as a building material for beams and columns, but CLT panels are also considered here as a timber alternative of a flooring system. The following table gives an overview of possible and commonly used dimensions for CLT floor panels.

Parameter	Available	Commonly used
Thickness (t)	60 – 500 mm	80 – 300 mm
Width (w)	max. 4,80 m	1,20 – 3,00 m
Length (l)	max. 30 m	16,00 m
Number of layers	max. 25	3, 5, 7 or 9

Table 6.10: Possible dimensions CLT panels (Borgström & Fröbel, 2019)

The characteristic strength values of a CLT panel depend on the strength properties of the timber boards that were used for the production of CLT. Assuming CLT panels made with only timber boards from strength class C14, the density can be set to $\rho_{CLT} = 420\ kg/m^3$, resulting in a characteristic weight of $\gamma_{CLT} = 4{,}12\ kN/m^3$. Assuming a commonly used floor thickness in residential and office buildings of 140 mm, this results in the self-weight being approximately $0{,}60\ kN/m^2$ for CLT panels (Borgström & Fröbel, 2019). Further specifications regarding the strength characteristics for CLT as a building material can be found in Appendix I. The cross sections that will be used for CLT beams and columns in the context of this thesis are assumed to be equal to the ones used for glulam and LVL.

6.5 Summary of used building materials

In order to give a clear overview of the most important material properties as discussed in the sections above, the tables below show a brief summary per building material and structural element.

Floor system	Thickness [mm]	Width [m]	Length [m]	Self-weight [kN/m^2]
Hollow-core slab	320	max. 1,20	max. 14,70	4,5
Composite slab	320	max. 3,00	max. 10,00	8,0
Steel deck	400	*made on site*	max. 7,20	1,6
Aluminium deck	400	*made on site*	max. 7,20	1,3
CLT panel	140	max. 3,00	max. 16,00	0,6

Table 6.11: Overview floor systems

Material	Width [mm]	Height [mm]	Span [m]	Self-weight $[kN/m^3]$
Prefab concrete - Standard reinforced - Lightweight - Self-healing	max. 800	max. 800	max. 15,00	 25,0 17,0 25,0
In-situ concrete - Standard reinforced - Lightweight - Self-healing	max. 800	max. 800	max. 15,00	 25,0 17,0 25,0
Steel (S355) - Beams - Columns	 *I-profiles* *H-profiles*	 *I-profiles* *H-profiles*	 max. 30,00	78,5
Aluminium (6061-T6) - Beams - Columns	 *I-profiles* *H-profiles*	 *I-profiles* *H-profiles*	 max. 30,00	27,0
Glulam (GL32h)	max. 205	max. 950*	max. 30,00	4,6
LVL (LVL 50 P)	max. 205	max. 950*	max. 20,00	6,0
LCT (CL28h)	max. 205	max. 950*	max. 20,00	4.1

Table 6.12: Overview beams and columns (Wagemans, 2014)

** As can be seen in Appendix I, timber beams are available with a height up to 1800 mm. However, in order to limit the total height of the beam and floor system, a maximum height of 950 mm is applied.*

Chapter 7

Design of the load bearing structure

Now that all the building materials that will be considered in the MCA are listed, the next step is designing a governing 2D frame in Matrixframe. Before doing so, the various permanent and variable loads need to be explained, together with the relevant partial safety factors and combination factors. Note that the imposed variable floor load varies per type of building (residential, public or office building for example). The value of this load also depends on the selected design strategy, as a change in function of the building or re-use of building elements in new projects is also being considered here.

7.1 Design loads

In order to be able to calculate necessary dimensions for columns, beams and floor elements, it is necessary to summarize relevant information before starting the design process for each strategy. This contains setting specific values for the lifespan a building needs to be designed for and selecting the right loads that act on a structure.

7.1.1 Design service life

The design service life of a structure holds the technical service life, so the period of time over which the structure should fulfil all requirements regarding strength, stiffness and stability. The Eurocode specifies this design service life as: ’’assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary’’ (NEN-EN 1990, 2021). The following table shows the design service life per building category.

Category of buildings	Design service life [years]
Monumental building structures	100
Building structures not covered by another category	50
Agricultural, industrial and similar structures	25
Replaceable structural parts	25
Temporary structures	≤ 10

Table 7.1: Design service life per building category (NEN-EN 1990, 2021)

This table shows that, according to Annex A.1.3 of the Eurocode, the design service life for office buildings is set to 50 years. This holds for the complete structure, but also for individual components of the load bearing structure, even in the case of a demountable design where components could potentially be re-used in a new project later on. By setting this same design service life for all case study projects and building components, comparing different design strategies and outcomes will be easier at the end of this research.

7.1.2 Consequence class

The following table shows three different consequence classes, depending on the type and use of the to be designed building.

Consequence class	Description	Examples	k_f
CC1	Low consequence for loss of human life, and economic, social or environmental consequences small or negligible.	- *Agricultural buildings* - *Greenhouses*	0,9
CC2	Medium consequence for loss of human life, and economic, social or environmental consequences considerable.	- *Residential buildings* - *Office buildings* - *Some public buildings*	1,0
CC3	High consequence for loss of human life, and economic, social or environmental consequences very big	- *Grandstands* - *Concert halls*	1,1

Table 7.2: Consequence classes (Wagemans, 2014)

Based on this table, the consequence class that can be selected for the design of structure's within the scope of this research is CC2. This includes office buildings, but also possible future functions of office buildings (depending on the selected design strategy), like residential buildings and public spaces like shops or restaurants.

Factor k_f is a consequence factor that needs to be multiplied by the load factor γ, which will be explained later on. As stated in the previous table, for CC2 it holds that $k_f = 1{,}0$.

7.1.3 ULS and SLS design loads

For the design of a structure, two different situations should be considered: Ultimate Limit State (ULS) and Serviceability Limit State (SLS). ULS uses the least favourable and most extreme load combinations, thereby using load factor γ. This results in designing a building with sufficient structural resistance. SLS focusses on preventing large deformations within the structure, thereby enabling the users of a building to optimally use the building for the function is was designed for.

The Quick Reference gives the following formula for determining the design load on a structure for both ULS and SLS

(eq. 4) $$F_{d,ULS} = \gamma_G \cdot G_k + \gamma_{Q,1} \cdot Q_{1,k} + \sum(\gamma_{Q,i} \cdot \psi_{0,i} \cdot Q_{i,k})$$ (Wagemans, 2014)

(eq. 5) $$F_{d,SLS} = G_k + Q_{1,k} + \sum(\psi_{0,i} \cdot Q_{i,k})$$ (Wagemans, 2014)

As can be seen in equation 4, ULS includes load factors γ_G (permanent loads), $\gamma_{Q,1}$ (leading variable load) and $\gamma_{Q,i}$ (other variable loads). As stated in the Quick Reference, the values of these load factors depend on the design situation, as shown in the table below.

Design situation	Permanent loads (γ_G)		Variable loads ($\gamma_{Q,1}$, $\gamma_{Q,i}$)	
	Unfavourable	Favourable	Leading	Other
1	1,35 $\cdot k_f$	0,9 $\cdot k_f$	0	1,5 $\cdot k_f$
2	1,2 $\cdot k_f$	0,9 $\cdot k_f$	1,5 $\cdot k_f$	1,5 $\cdot k_f$

Table 7.3: Values for load factor γ (Wagemans, 2014)

As stated in the previous section, the consequence factor k_f is set to 1 for CC2. The design situation resulting in the highest design load can be considered as the governing load combination.

Equation 4 and 5 also include combination factor ψ for variable loads. The following table shows the relevant values of this combination factor based on the building category or type of load, as given in table A.1.7 from the Eurocode.

Category/ type	ψ_0 *	ψ_1 **	ψ_2 ***
A	0,7	0,5	0,3
B	0,7	0,7	0,6
C	0,7	0,7	0,6
D	1,0	0,9	0,8
Imposed loads	0,7	0,5	0,3
Snow loads	0,5	0,2	0
Wind loads	0,6	0,2	0

Table 7.4: Values for combination factor ψ_0, ψ_1 and ψ_2 (NEN-EN 1990, 2021)

* ψ_0 = factor for combination value of a variable action
** ψ_1 = factor for frequent value of a variable action
*** ψ_2 = factor for quasi-permanent value of a variable action
(Wagemans, 2014)

7.1.4 Imposed floor loads

The design floor loads for different types of buildings depend on the classification of the use of that building. Eurocode 1, section 6 on imposed loads on buildings specifies four categories, as can be seen in the next table.

Category	Specific use	Examples
A	Areas for domestic and residential activities	*- Rooms in residential buildings* *- Bedrooms in hospitals* *- Bedrooms in hotels*
B	Office areas	
C	Areas where people may congregate (with the exception of areas defined under category A, B and D)	*- C1: Areas with tables (e.g. restaurants)* *- C2: Areas with fixed seats (e.g. theatres)* *- C3: Areas with obstacles for moving (e.g. museums)* *- C4: Areas with possible physical activities (e.g. dance halls)* *- C5: Areas susceptible to large crowds (e.g. concert halls)*
D	Shopping areas	*- D1: Areas in general retail shops* *- D2: Areas in department stores*

Table 7.5: Building categories based on their specific use (NEN-EN 1991-1-1, 2002)

Clearly, the offices as required in the selected case study projects, all belong in category B. However, possible future functions of office buildings also need to be considered here. This shows the relevance of category A as residential buildings, category C1 as restaurants or cafés, category C3 as museums and category D as shops.

The imposed loads on floors for each category as presented above, can be found in the table below.

Category	Uniformly distributed load [kN/m^2]	Concentrated load [kN]
A	2,5	3,0
B	3,0	3,0
C	5,0	7,0
D	4,0	7,0

Table 7.6: Imposed floor loads per building category (Wagemans, 2014)

7.1.5 Wind loads

Wind loading on a structure can be simplified as a combination of a horizontal distributed load on the façade of the building and a vertical distributed load on the roof. The following equation from the Quick Reference can be used for the calculation of these distributed loads.

(eq. 6) $$q_{wind} = c_s c_d \cdot c_f \cdot q_p(z_e) \cdot b_{ref}$$ (Wagemans, 2014)

For buildings with a height below 15 meters, it holds that the structural factor $c_s c_d = 1{,}0$.

The force coefficient for a structure or structural element depends on its shape. For simplicity, only wind loads perpendicular to the façade elements and the roof (which is assumed to be flat) are being considered. The figures below show some basic dimensions and zones being considered in the calculation of wind loads.

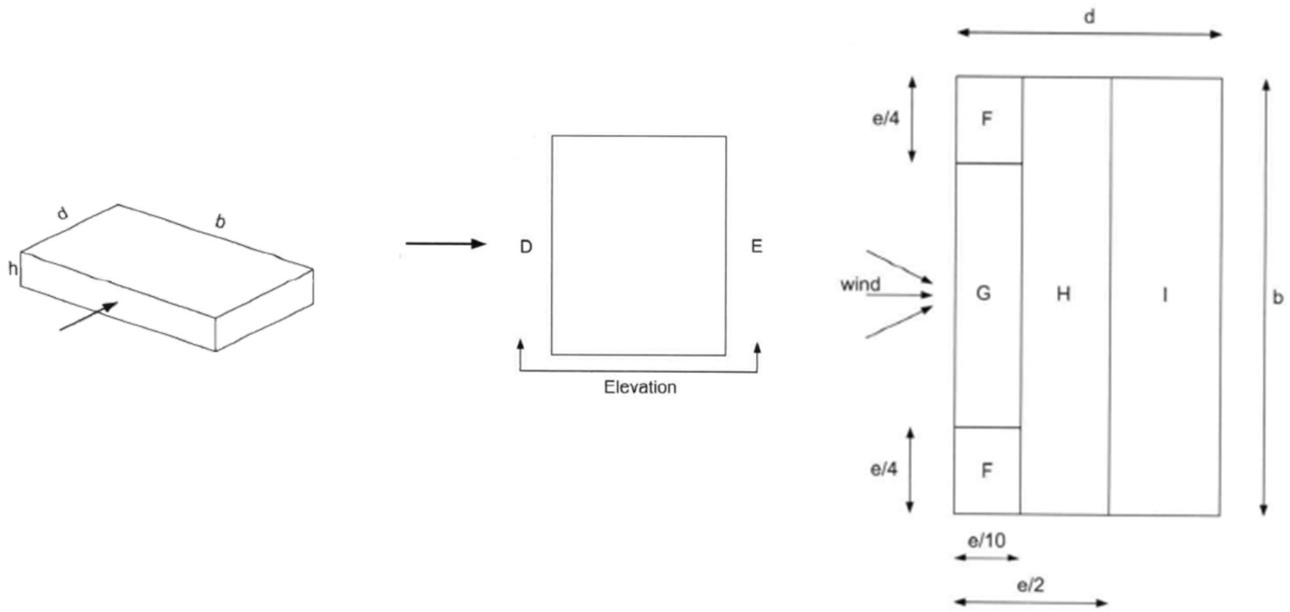


Figure 7.1 : Building parameters and wind zones (Wagemans, 2014)

h = height of building [m]
d = dimension in wind direction [m]
b = dimension in crosswind direction [m]
e = minimum of b or 2h [m]

h/d	c_f zone D	c_f zone E
≥ 5	+ 0.8	- 0.7
1	+ 0.8	- 0.5
≤ 0.25	+ 0.7	- 0.3

c_f zone F	c_f zone G	c_f zone H	c_f zone I
- 1.8	- 1.2	- 0.7	- 0.2

Table 7.7: Force coefficient for different wind zones (Wagemans, 2014)

The values for force coefficient c_f can be interpolated between the points as given in the table above. When necessary, this is done for the case study projects in an additional Excel sheet especially made for calculating wind loads on the structure.

The peak velocity pressure $q_p(z_e)$ depends on the reference height z_e of a structure. The Quick Reference includes a table with all values for q_p, depending on the region where a specific structure will be located and the type of landscape it will be placed in. The full table is available in Appendix F.

Finally, the reference width b_{ref} represents the width of the part of the façade that will transfer the wind forces to one load bearing column. Of course, this value varies for each case study project and design strategy.

The Excel sheet that was used to calculate the resulting wind loads per case study is included in Appendix J.

7.1.6 Snow loads

The snow load on a structure can be determined using the following formula from the Quick Reference.

(eq. 7) $q_{snow} = \mu \cdot C_e \cdot C_t \cdot s_k \cdot b_{ref}$ (Wagemans, 2014)

In this formula, the shape coefficient μ depends on the roof angle. Again assuming a flat roof, it holds that $\mu = 0.8$. Furthermore, in this case it also holds that exposure coefficient $C_e = 1.0$ and thermal coefficient $C_t = 1.0$. Finally, the characteristic value of the snow load in the Netherlands is $0.7\ kN/m^2$.

Combining these parameters, results in $q_{snow} = 0.8 \cdot 1.0 \cdot 1.0 \cdot 0.7 \cdot b_{ref} = 0.56 \cdot b_{ref}\ kN/m$, where b_{ref} again represents the distance between two load bearing beams in the roof structure of a building.

7.2 Strength and deformation checks

All formulas that are used for the strength checks in ULS conditions, are included in the Excel sheets in Appendix K.

Besides the checks that need to be done in ULS, also the deformations in SLS need to be limited. According to the Quick Reference, the maximum deflection under a combination of permanent and variable loads in SLS, should have a maximum value of $w_{max} = 0.004 \cdot l$, where l is the span of the beam (Wagemans, 2014).

Chapter 8

MCA decision making

The final chapter of the second part of this report, involves setting up the MCA and listing the scores for criteria that are linked to building material properties and the type of connections that can be used. First, an overview of the different steps that need to be taken when performing the MCA is given. After this, the scores for the MCA criteria that are linked to a building material and their type of connection only are explained. Note that this involves only the first five criteria, as the other four depend on the final design of the supporting structure (this results in a structure's total weight, price and ECI value).

8.1 Steps for completing the MCA

The following figure shows all the different steps for performing the MCA in the context of this research for the three selected projects from Witteveen+Bos. First of all, each design strategy leads to a basic layout of the building's floor plan. For example, in the design strategy where a structure's flexibility is optimized, the ideal design consists of spans that are made as long as possible, as this increases the possibilities of the users to create and change their own internal layout of the building's floors.

The second step is to further specify the basic design from step 1 into a more detailed design for every building material that is being considered in the MCA. In order to limit the amount of work that needs to be done in this step, it's important to average building material's characteristics like strength. In case that multiple types of concrete are being considered, it simplifies this step when it can be stated that their strength can be taken as one average value. By doing this, each type of concrete will then lead to the same design with regards to spans and dimensions of beams and columns. Of course, this makes the final outcome of the MCA less accurate, but it can be assumed that slight changes in a building material's strength will not completely change the spans and dimensions of the design.

Next, the characteristics of each specific design can be used as input for the MCA. This holds information like the total amount of used building material, the costs of the design, the expected lifespan of a building material and the environmental impact of the design (for example the ECI value) for different LCA modules.

In the MCA, each design strategy will focus on different criteria. For the design strategy where a structure is optimized for its technical service life, the criteria regarding lifespan of a building material and the expected amount of maintenance will weigh heavier than other criteria. When optimizing for a structure's demountability, especially the types of connections that can be used for a building material will be important. As a result of the MCA, the best suitable building material can now be selected for each design strategy.

In the final step, the best suitable design strategy for the project and client is chosen (in the context of this research, this results from the delivered PoR). Based in the design strategy that best fits the company's future expectations, the final building variant (consisting of a specific design and building material) is selected.

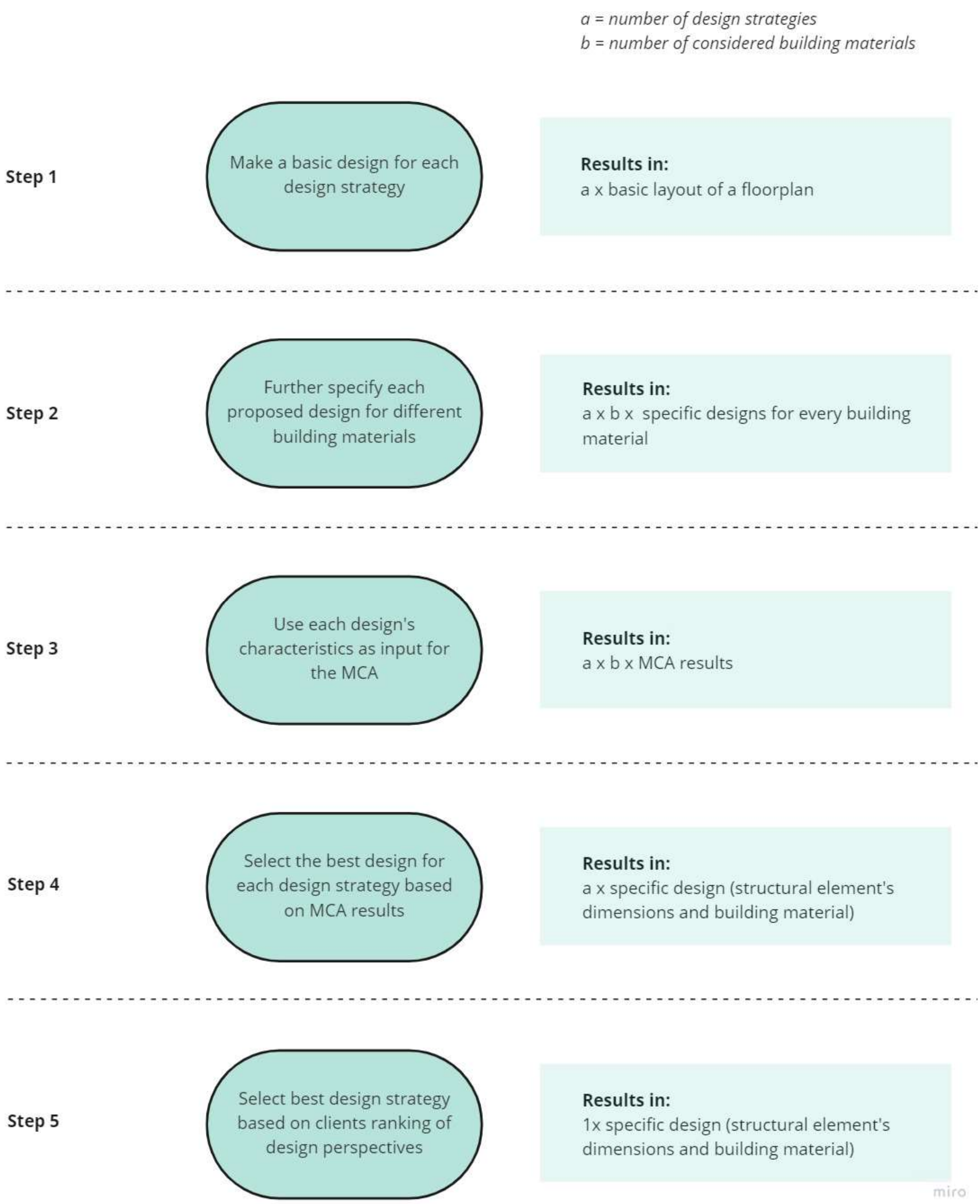


Figure 8.1: Different steps for performing the MCA for this research

8.2 MCA scores per building material

All MCA criteria scores for different building materials are explained in the sections below. A complete overview of the scores (applied on one of the case studies provided by Witteveen+Bos) is included in Appendix N.

8.2.1 Lifespan of a building material

The following table explains different scores per building material for factors A1 to G of the factor method, including an additional factor H regarding a building material's fire resistance.

Explanation per building material			Score
Factor A.1	-	For all types of concrete, metal and timber, a normal quality is assumed. This means that the concrete strength class will be a commonly used one somewhere between C25/30 and C50/60 (in this case C35/45 is used).	**1.00**
	-	For metals, this means standard steel (S355) and aluminium (6061-T6) classes are selected.	**1.00**
	-	As explained in section 6.4, usually sapwood with a relatively low natural durability is used. Therefore, a lower score will be used for timber.	**0.90**
	*	*In case a client or designer wants a higher material quality, like high strength concrete or steel or hardwood instead of sapwood, factor A.1 can be adjusted to a value of 1.2 instead of the standard value of 1.*	
Factor A.2	-	As this factor focusses on typical durability features for each building material, there are two materials that score higher than the others here. All other materials have a standard value of 1.00 in this category.	**1.00**
	-	First, self-healing concrete is given a score of 1.10, as it has the potential to 'heal' small cracks in the concrete before they become bigger and expose the reinforcement.	**1.10**
	-	Also aluminium is considered a bit better than steel in this case, as it is less prone to corrosion due to the layer of aluminium oxide on the surface.	**1.10**
Factor B	-	For the design level, normal conditions are assumed, meaning a standard value of 1.00 for all building materials.	**1.00**
	*	*However, in case a designer wants to improve the expected lifespan of a structure or building element, additional measures can be taken in order to minimize the possibility of deterioration due to external exposing of the material. Applying additional material/ coating might increase an element's expected service life, but at the same time also increases its environmental impact. In cases like this, it's always important to compare the increase in the environmental impact with the possible elongation of the estimated service life, in order to decide whether or not it's wise to upgrade factor B.*	
Factor C	-	This factor makes it possible to account for the differences between prefabricated elements and elements that are adjusted on site. Typically, prefab concrete is produced in a controlled environment in the	**1.10**

	factory, thereby ensuring a certain quality level. On site, alterations on prefab concrete elements are avoided and not needed.	
	- In-situ cast concrete is more prone to external influences on site, for example the humidity, temperature and quality of the formwork. This results in a lower value for factor C.	**0.90**
	- For metal structures, welded connections are more prone to external influences, resulting in a lower value.	**0.90**
	- For metal structures that are connected with bolts, no site alterations are necessary and boltholes etc. are already coated in the factory.	**1.10**
	- For timber structures, nailed or doweled connections have a lower score compared to bolted connections.	**0.90**
Factor D	- As the indoor environment where all building materials are applied is the same, namely an office building, this factor is set to 1.00. * *Of course, when designing a different type of structure, this value might need to be changed.*	**1.00**
Factor E	- Here, the same reasoning as for factor D applies. In this case, normal conditions regarding the outdoor environment are assumed. * *In case a building is designed in a more polluted environment, this value might need to be changed from 1.00 to 0.90. On the other hand, when a structure is designed in a rural area, this might have a positive effect on a building element's estimated service life.*	**1.00**
Factor F	- As this research focusses on an office building's load bearing structure, it assumed that normal usage conditions apply. Therefore, this category will not be considered.	**1.00**
Factor G	- It is assumed that the required maintenance will always be performed and that this will be done by professionals, thereby guaranteeing a good quality of the performed maintenance/ repair. Therefore, the standard value of 1.00 is applied.	**1.00**
	- In this category, bolted metal and timber connections have slightly higher scores than the different types of concrete. This has to do with the fact that in case of bolted connections, building elements can quite easily be removed and replaced by new ones, in case of extensive deterioration.	**1.10**
Factor H	- According to the Quick Reference, the following can be stated regarding a building material's fire resistance. For all other materials, the standard value of 1.00 is applied.	**1.00**
	- In-situ is assumed to have a slightly higher fire resistance, as long as sufficient concrete cover is applied (this also holds for prefab concrete elements).	**1.10**
	- As metal starts to yield under high temperatures, this fire resistance is slightly lower compared to other building materials.	**0.9**

Table 8.1: Values used for factor method

As explained in chapter 5, the reference service life is set to 50 years for all building elements. This results in the following estimated service lives and corresponding final scores for this criterium. A more detailed overview is included in Appendix N.

Building material	Estimated vs. reference service life		Score
Prefab concrete			
- Standard reinforced concrete	55 years	110%	**0.90**
- Lightweight concrete	55 years	110%	**0.90**
- Self-healing concrete	61 years	122%	**1.00**
In-situ concrete			
- Standard reinforced concrete	50 years	100%	**0.80**
- Lightweight concrete	50 years	100%	**0.80**
- Self-healing concrete	54 years	108%	**0.90**
Steel			
- Welded connections	41 years	82%	**0.60**
- Bolted connections	54 years	108%	**0.90**
Aluminium			
- Welded connections	45 years	90%	**0.70**
- Bolted connections	60 years	120%	**1.00**
Glulam			
- Bolted connections	50 years	100%	**0.80**
- Nailed/ doweled connections	41 years	82%	**0.60**
LVL			
- Bolted connections	50 years	100%	**0.80**
- Nailed/ doweled connections	41 years	82%	**0.60**
CLT			
- Bolted connections	50 years	100%	**0.80**
- Nailed/ doweled connections	41 years	82%	**0.60**

Table 8.2: MCA scores for lifespan of a building material

8.2.2 Building material's potential for recycling

Based on a study from P. Sassi, the following values for a building material's suitability for recycling and the benefits from recycling. These two factors are then combined into one final score.

Building material	Suitability for recycling	Benefits from recycling	Score
Concrete	0.72	0.47	**0.595**
Steel	0.67	0.63	**0.650**
Aluminium	0.71	0.70	**0.705**
Timber	0.69	0.49	**0.590**

Table 8.3: MCA scores for building material's potential for recycling (Sassi, n.d.)

8.2.3 Type (TC), accessibility (AC) and removability-index of a connection

According to a study done by Alba Concepts, the scores as presented in table 5.6 apply for the various types of connections that are being considered in this research.

Again using the study performed by Alba Concepts, the scores for the level of accessibility of a connection are also included in table 5.7. Accessibility hereby refers to what extent a connection can undergo repair or maintenance without damaging connected building elements.

Finally, also the removability-index of a connection is included in this table.

		Score		
Building material	**Type of connection**	**TC**	**AC**	**RI**
Concrete				
- Prefab	Assuming dry connection using steel plates for beam-column connections (see figure 6.2)	**0.80**	**0.80**	**0.80**
- In-situ	Solid chemical connection	**0.10**	**0.40**	**0.16**
Metal				
- Welded connection	Solid chemical connection	**0.10**	**0.40**	**0.16**
- Bolted connection	Connection with additional materials	**0.80**	**0.80**	**0.80**
Timber				
- Bolted connection	Connection with additional materials	**0.80**	**0.80**	**0.80**
- Nailed/ doweled connection	Direct integral connection	**0.60**	**0.60**	**0.60**

Table 8.4: MCA scores for TC, AC and removability-index of connection (Vliet, Grinsven, & Teunizen, 2021)

All criteria as explained in de sections above, fully depend on a building material's characteristics and the types of connections that are commonly used per building material. The other criteria that are being considered in the MCA (total weight, price and ECI values of a building variant) depend more on the design and layout of the supporting structure. For these criteria, the scoring systems as explained in section 5.2 are used. As stated earlier, a full overview of the scores (based on the application of the MCA on one of the case studies) is included in Appendix N.

PART III

Results and final remarks

Chapter 9

Application on case study

Now a complete list of building materials and criteria for the MCA is proposed, the whole analysis can be applied on a project from Witteveen+Bos. In this chapter, three case studies are selected, based on their programs of requirements only. Each case study is linked to a design strategy and for each design strategy the aspects that need to be optimized are shown. Finally, one case study is selected as a test project to apply the MCA on. The results of the design strategies and the corresponding MCA are shown at the end of this chapter.

9.1 Linking PoR's to design strategies

9.1.1 Focus points per case study

As explained in chapter 5, each of the three selected projects and their PoR has its own requirements regarding sustainability. In every project, the point of focus lies on a different aspect and each client has different aspirations regarding reaching a more sustainable building variant. In order to make this clear, again the design perspectives can be used to emphasize where the focus regarding sustainability lies in each project.

The following table shows the nine design perspectives and the three selected case studies from Witteveen+Bos. For every program of requirements, the table shows which design perspectives the client seems to be focussed on most in its program of requirements.

Design perspective	APM Terminals	Ørsted	ESA/ESTEC
Material selection			
Material use			
Durability	✓		
Maintenance	✓	✓	
Re-usability			✓
Disassembly			✓
Recyclability			
Adaptability		✓	✓
Flexibility		✓	✓

Table 9.1: Design perspectives for each project

For APM Terminals, functionality of the office building is of the highest importance, as all operations on the terminal are managed from this facility. In order for the building to match the functional service life of the whole container terminal, the building must be durable and the necessary amount of maintenance should be limited, as these maintenance operations may not influence ongoing terminal operations, as this might directly influence profit margins and the terminals tight schedule.

For Ørsted, including plans for expansion of the building and making sure that the users can later on change the structure's internal layout in order for it to match their needs, is clearly wished for in the delivered program of requirements. This goal can be achieved by designing a structure with large spans and a minimum number of load bearing elements in the middle of a floor plan, which results in a flexible internal layout. Furthermore, the type of connections that comes with different building materials, highly affect the structure's ability to be adaptive and enable possible future expansions.

Finally, the program of requirements for the new Building B for ESA/ESTEC is highly orientated on possible future functions, as well for the existing structure as for individual building elements in case they are re-used at the buildings end-of-life stage. As there is yet no specific department selected for the use of this building, it is being designed as a generic office building and meeting facility. However, the building must be fit to fulfil possible different functions in the future, in case a more specific department wishes to use this facility. In case building elements are being re-used in new projects with a different function than an office building, the loads acting on these elements might be higher, which means that in the original design, already possible future functions and loads need to be taken into account.

9.1.2 Linking design aspects to a design strategy per case study

The following table gives a quick summary of the design perspectives that are most important for each design strategy as explained above.

Design perspective	Design strategy 1	Design strategy 2	Design strategy 3
Material selection			
Material use			
Durability	1		
Maintenance	2		
Re-usability			1
Disassembly			2
Recyclability			3
Adaptability		2	
Flexibility		1	

Table 9.2: Optimizing design perspectives for each design strategy

Comparing this table with the table as presented in the previous section, where design perspectives are linked to the three programs of requirements, immediately similarities can be found. Based on table 9.1 and table 9.2, the program of requirement belonging to APM Terminals, best fits design strategy 1. The program or requirements for APM Terminals was quite simple and focused mainly on designing a functional office building, which corresponded to focusing on durability and limiting the amount of maintenance. This is in accordance with design strategy 1, in which optimization of the building's technical service life and limiting disturbance as a result of maintenance, is prioritized over the other design perspectives.

The program of requirement for Ørsted focuses on adaptability and flexibility, hereby enabling possible changes in the number of employees working in the building and enabling the building to follow its users' needs regarding space and internal layout, and is thereby mostly similar to design strategy 2, where a design is optimized for its functional service life.

Finally, the program of requirements for ESA/ESTEC highly prioritizes the potential re-use of building elements and at the same time aims for a flexible configuration. These requirements match both design strategy 2 and 3. As stated earlier, these design strategies ask for the optimization of different design aspects, and optimizing all of them might not be possible as some of them contradict with each other. Therefore, ESA/ESTEC has some kind of contradiction in its PoR, making it the most interesting project to use as a test case for the MCA.

9.2 Design for ESA/ESTEC

In the PoR that was used for ESA/ESTEC, it's stated that *'in the design, it is desired to apply the principles of a demountable, adaptive and flexible structure, such that in the future the building can be redesigned if necessary and its element re-used*'. Especially within the context of this thesis, this is an interesting statement, as it implies the use of both design strategies 2 and 3. Design strategy 2 focuses on a flexible and adaptive structure with an open floor plan and internal layout. On the other hand, design strategy 3 is more focused on the use of standardized building elements that can easily be re-used, even in buildings with other functions, which may result in higher floor loads. As the delivered PoR aims for two different design strategies, it's a very interesting case study to investigate. As stated in the beginning of this report, both design strategies result in optimizing different aspects of the design. The following sections apply design strategy 2 and 3 on this project. In the end, both results can be compared and this can be used to show how big the influence of certain wishes in a PoR is on the final design.

9.2.1 Design strategy 2

The following figure shows the layout of load bearing elements for a floor plan for ESA/ESTEC in case design strategy 2 is followed. Here, the floor spans (between two load bearing beams) are set to a distance of 7 meters. The spans of the beams (between two load bearing columns) are set to a relatively large distance of 10 meters. This results in a grid of columns as shown below. In this figure, also the direction in which the floors are spanning is shown.

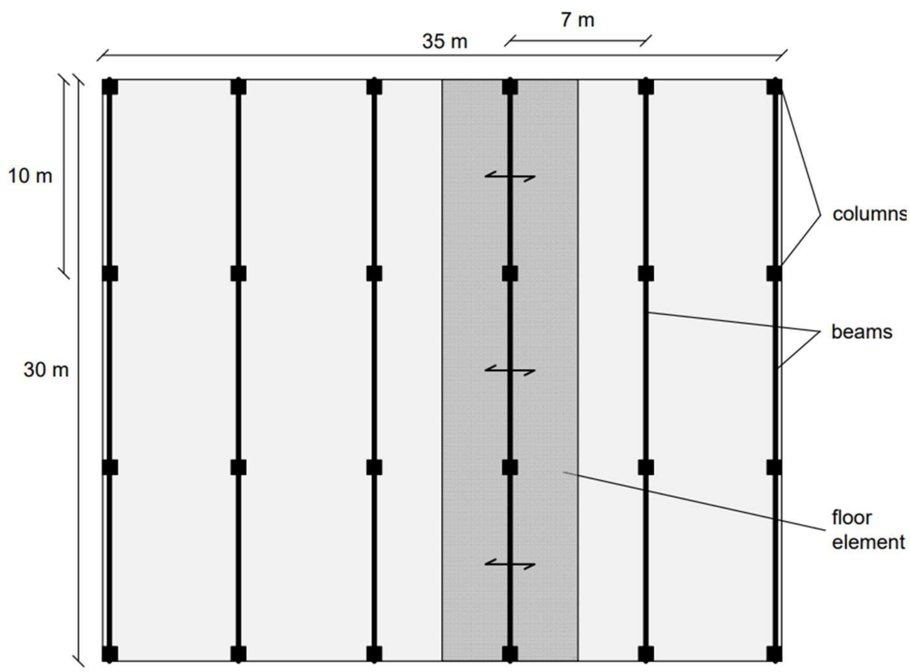


Figure 9.1: Floorplan ESA/ESTEC for design strategy 2

The design is made in MatrixFrame, using a governing cross section (a 2D frame in the middle of the structure) of the figure above. The same heights for the storeys are used as in the design drawings from Witteveen+Bos (ground floor: 4,5 m ; first floor: 3,75 m ; second floor: 3,75 m). The 2D frame from MatrixFrame is shown below.

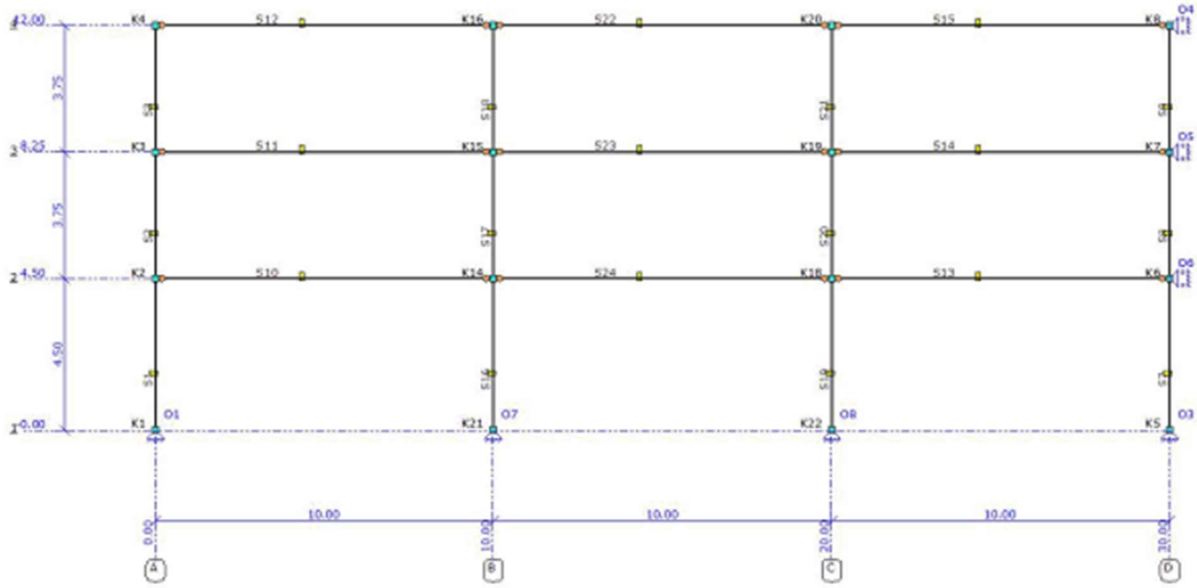


Figure 9.2: 2D frame ESA/ESTEC for design strategy 2

The 2D frame as shown above, was designed for the building materials as listed in the table below. All strength (ULS) and deformation (SLS) checks are performed in Excel (an overview of the Excel maps is included in Appendix L). In order to limit the length of this report, all the formulas that were used in these Excel sheets are included in Appendix K.

The table below shows an overview of the types of floor system and the dimensions of the beams and columns that are the result of the ULS and SLS checks.

	ESA/ESTEC – design strategy 2				
	Building material			**Total volume [m3]**	**Total weight [kg]**
1	Prefab concrete C35/45				
	Floor	Beams	Columns		
	Hollow core slab	450 x 650 mm	300 x 300 mm	749	1.908.028
2	Prefab lightweight concrete LC40/44				
	Floor	Beams	Columns		
	Hollow core slab	400 x 750 mm	250 x 250 mm	746	1.754.281
3	Prefab self-healing concrete C35/45				
	Floor	Beams	Columns		
	Hollow core slab	450 x 650 mm	300 x 300 mm	749	1.908.028
4	In-situ concrete C35/45				
	Floor	Beams	Columns		
	Composite slab	600 x 700 mm	300 x 300 mm	1.259	3.207.339
5	In-situ lightweight concrete LC40/44				
	Floor	Beams	Columns		
	Composite slab	550 x 750 mm	300 x 300 mm	1.255	2.995.991
6	In-situ self-healing concrete C35/45				
	Floor	Beams	Columns		
	Composite slab	600 x 700 mm	300 x 300 mm	1.259	3.207.339

7	Steel S355				
	Floor	Beams	Columns		
	Steel deck	IPE 550	HE 200 A	200	474.363
8	Aluminium 6061-T6				
	Floor	Beams	Columns		
	Aluminium deck	IPE 750	HE 220 A	206	347.606
9	Timber (GL32h + CLT)				
	Floor	Beams	Columns		
	CLT panels	205 x 850	135 x 400	549	243.467
10	Timber (LVL50P + CLT)				
	Floor	Beams	Columns		
	CLT panels	205 x 750	135 x 350	536	251.070
11	Timber (CL28h + CLT)				
	Floor	Beams	Columns		
	CLT panels	205 x 900	160 x 350	555	240.712

Table 9.3: Dimensions, volume and weight per building material for ESA/ESTEC design strategy 2

The total volume and weight per building material is also summarized in the following graph.

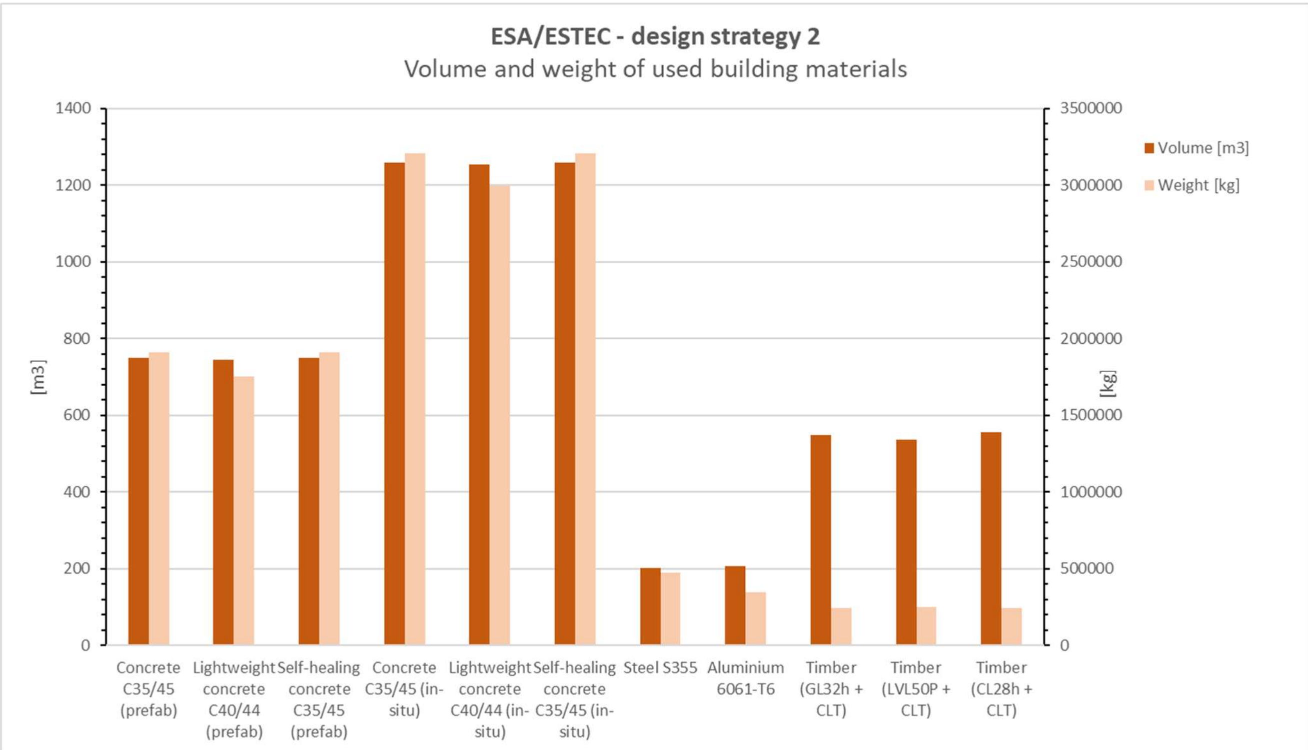


Figure 9.3: Total volume and weight per building material for ESA/ESTEC design strategy 2

This figure clearly shows the benefits regarding the total weight of a steel or timber structure compared to a concrete one. Especially the in-situ cast concrete structures result in a significantly heavier structure due to the higher self-weight of the solid composite slab, which then results in larger dimensions for the load bearing beams and columns. Due to the efficient use of material in metal I- and H-sections, the total weight of steel and aluminium structures is limited. The very low self-weight of timber compared to the other building materials, also results in a very lightweight structure, despite the fact that relatively large cross sections are necessary for the timber beams.

Apart from the total weight of a supporting structure, also the ECI values that result from the use of building materials are interesting to compare. The following figure shows the ECI values for all building variants for design strategy 3. Also the difference between the ECI values for only LCA module A and the full life cycle (combining LCA module A, C and D) is clearly visible here.

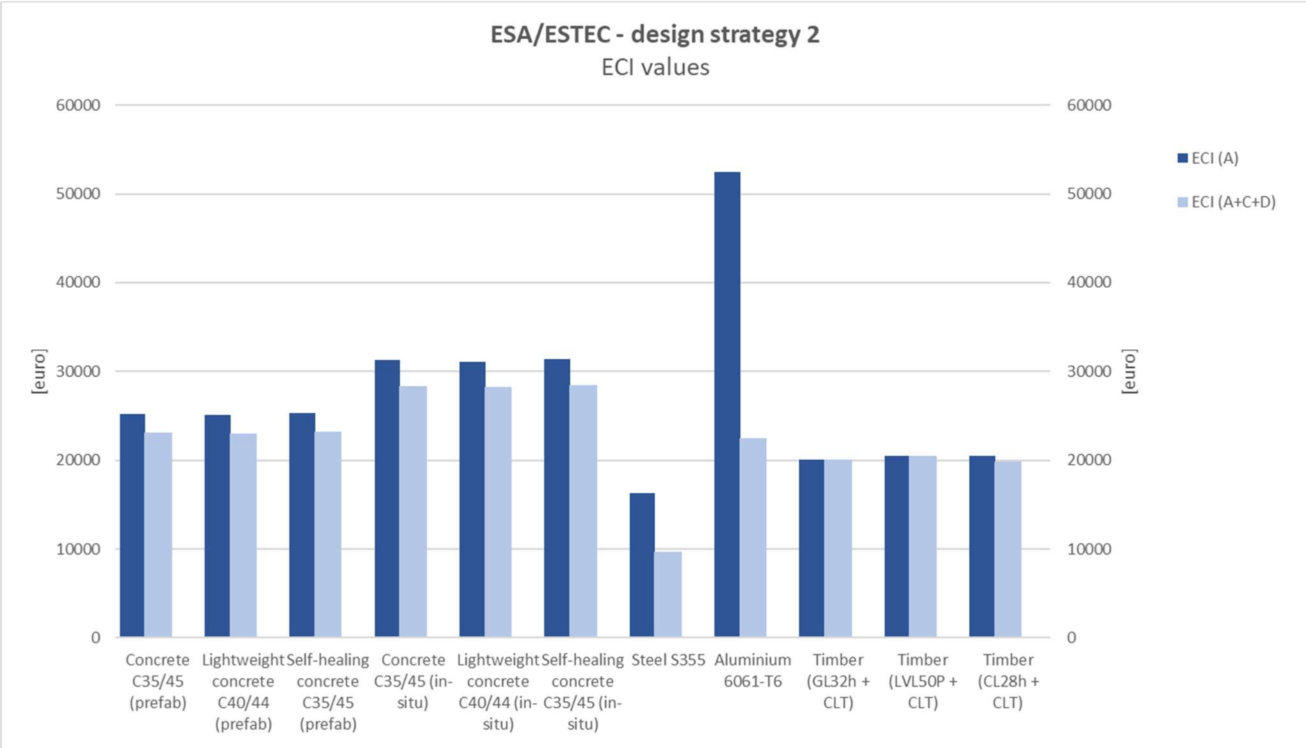


Figure 9.4: ECI values per building material for ESA/ESTEC design strategy 2

Finally, all the information for the building variants for ESA/ESTEC for design strategy 2 can be combined in the MCA. The nine criteria (consisting of 5 criteria purely focusing on the material and the connections, and 4 criteria focusing on the results of the design regarding weight, price and ECI values) are multiplied with their corresponding weights for design strategy 3. Summation of the nine scores results in a final MCA score per building variant. The MCA scores are shown in the figure below.

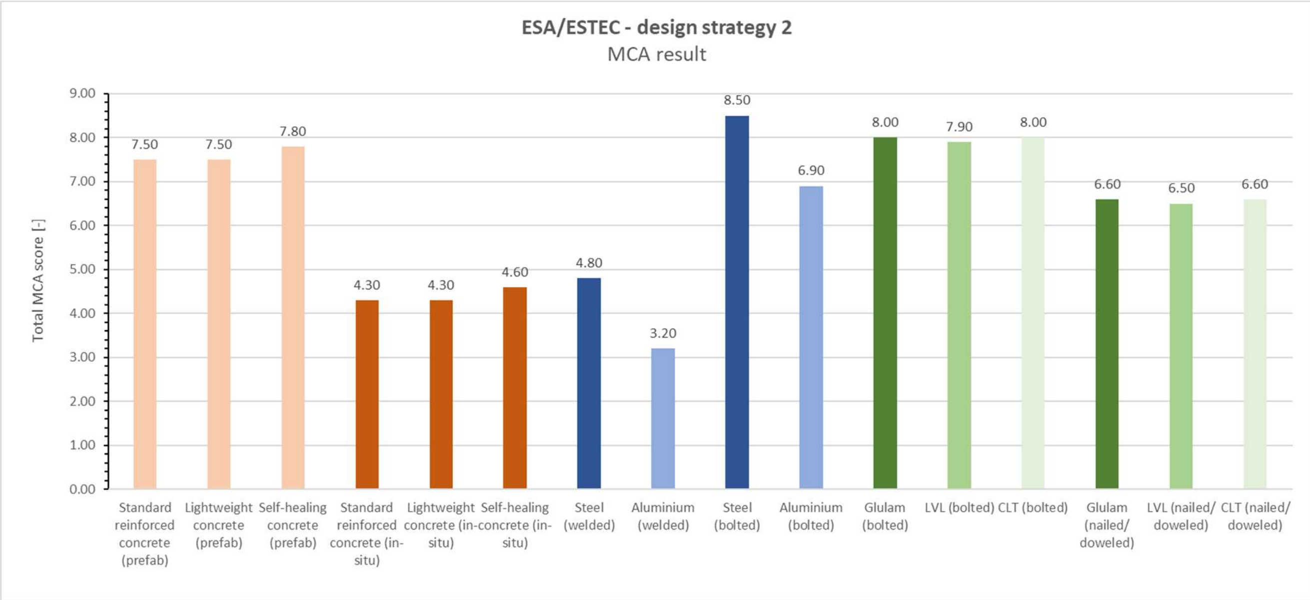


Figure 9.5: MCA results per building material for ESA/ESTEC design strategy 2

This figure shows that, when the MCA is applied on the test project for ESA/ESTEC, for design strategy 2, a steel structure with bolted connections is the best suitable solution. Most likely, this is due to the much more efficient use of material in metal I- and H-sections, compared to solid rectangular cross sections as were used for concrete and timber. Metal has a high strength to weight ratio, which enables large beam spans and a relatively lightweight structure. Aluminium seems to be a good alternative for steel, however due to its lower Young's modulus, deflections become governing in stead of the member strength. As a result of this, the expected benefits of aluminium (being able to use smaller cross sections due to its higher strength to weight ratio than steel) can not be fully achieved. A bolted timber structure also has quite high final MCA scores, however, due to its slightly lower estimated life span, its final result is lower than the one for steel.

9.2.2 Design strategy 3

The following figure shows the layout of load bearing elements for a floor plan for ESA/ESTEC in case design strategy 3 is followed. Here, the floor spans (between two load bearing beams) are set to a standard distance of 5 meters. Also the spans of the beams (between two load bearing columns) are set to 5 meters. This results in a grid of columns as shown below. In this figure, also the direction in which the floors are spanning is shown.

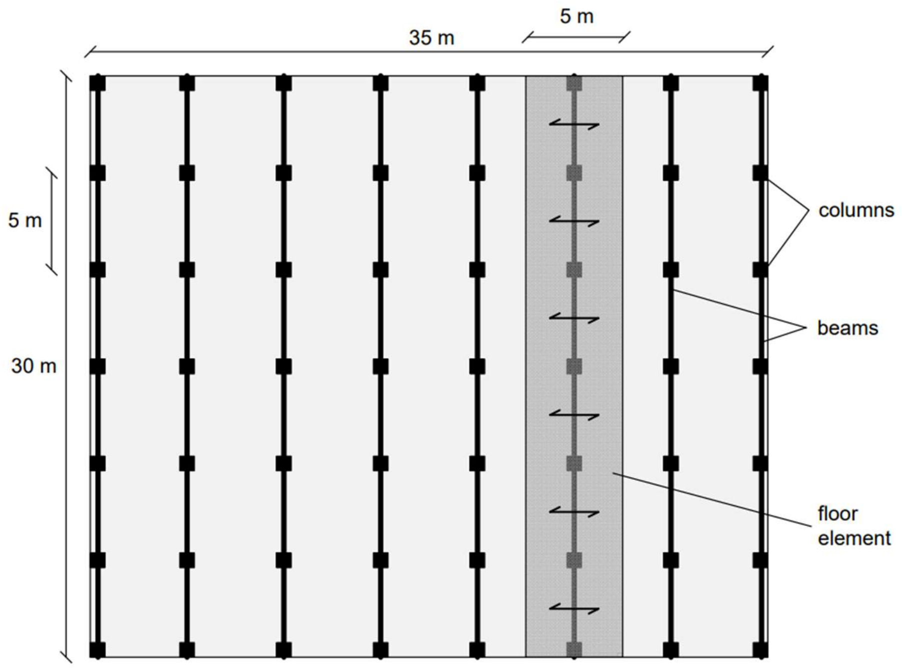


Figure 9.6: Floorplan ESA/ESTEC for design strategy 3

The design is made in MatrixFrame, using a governing cross section (a 2D frame in the middle of the structure) of the figure above. The same heights for the storeys are used as in the design drawings from Witteveen+Bos (ground floor: 4,5 m ; first floor: 3,75 m ; second floor: 3,75 m). The 2D frame from MatrixFrame is shown below.

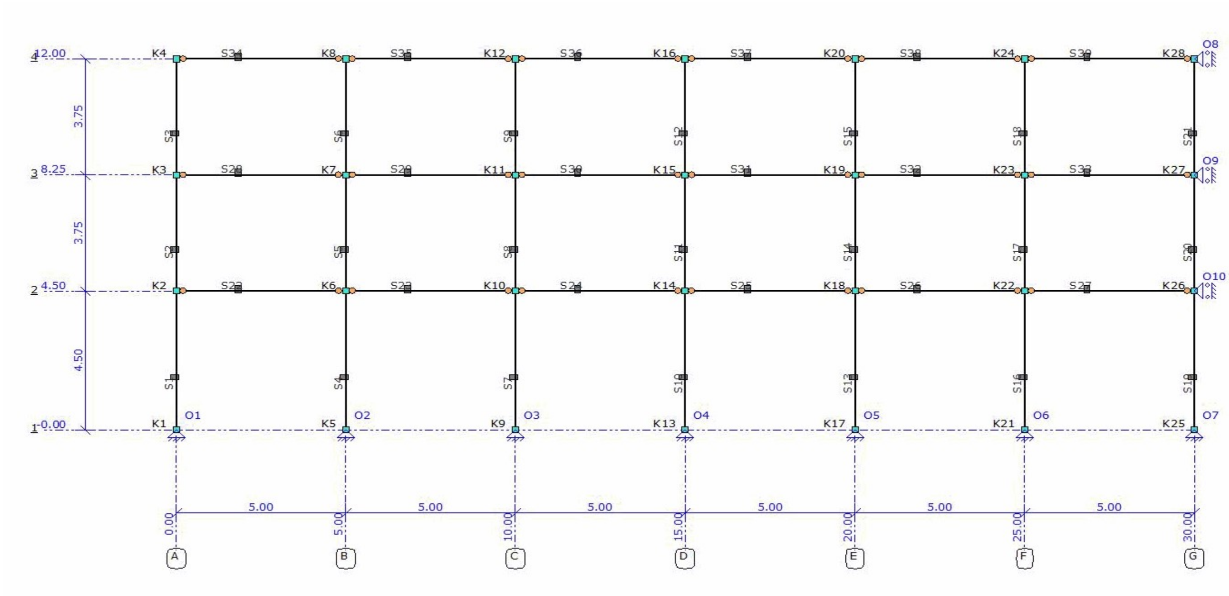


Figure 9.7: 2D frame ESA/ESTEC for design strategy 3

The 2D frame as shown above, was designed for the building materials as listed in the table below. All strength (ULS) and deformation (SLS) checks are performed in Excel (an overview of the Excel maps is included in Appendix M). In order to limit the length of this report, all the formulas that were used in these Excel sheets are included in Appendix K.

The table below shows an overview of the types of floor system and the dimensions of the beams and columns that are the result of the ULS and SLS checks.

	ESA/ESTEC – design strategy 3				
	Building material			**Total volume [m3]**	**Total weight [kg]**
1	Prefab concrete C35/45				
	Floor	Beams	Columns		
	Hollow core slab	300 x 400 mm	200 x 200 mm	678	1.727.931
2	Prefab lightweight concrete LC40/44				
	Floor	Beams	Columns		
	Hollow core slab	300 x 400 mm	200 x 200 mm	678	1.637.378
3	Prefab self-healing concrete C35/45				
	Floor	Beams	Columns		
	Hollow core slab	300 x 400 mm	200 x 200 mm	678	1.727.931
4	In-situ concrete C35/45				
	Floor	Beams	Columns		
	Composite slab	350 x 400 mm	200 x 200 mm	1.133	2.888.481
5	In-situ lightweight concrete LC40/44				
	Floor	Beams	Columns		
	Composite slab	300 x 450 mm	200 x 200 mm	1.133	2.786.186
6	In-situ self-healing concrete C35/45				
	Floor	Beams	Columns		
	Composite slab	350 x 400 mm	200 x 200 mm	1.133	2.888.481
7	Steel S355				
	Floor	Beams	Columns		
	Steel deck	IPE 300	HE 160 A	198	455.217
8	Aluminium 6061-T6				
	Floor	Beams	Columns		
	Aluminium deck	IPE 450	HE 180 A	202	335.118
9	Timber (GL32h + CLT)				
	Floor	Beams	Columns		
	CLT panels	185 x 500	110 x 250	525	231.833
10	Timber (LVL50P + CLT)				
	Floor	Beams	Columns		
	CLT panels	165 x 550	85 x 300	519	240.455
11	Timber (CL28h + CLT)				
	Floor	Beams	Columns		
	CLT panels	160 x 550	85 x 350	523	226.967

Table 9.4: Dimensions, volume and weight per building material for ESA/ESTEC design strategy 3

The total volume and weight per building material is also summarized in the following graph.

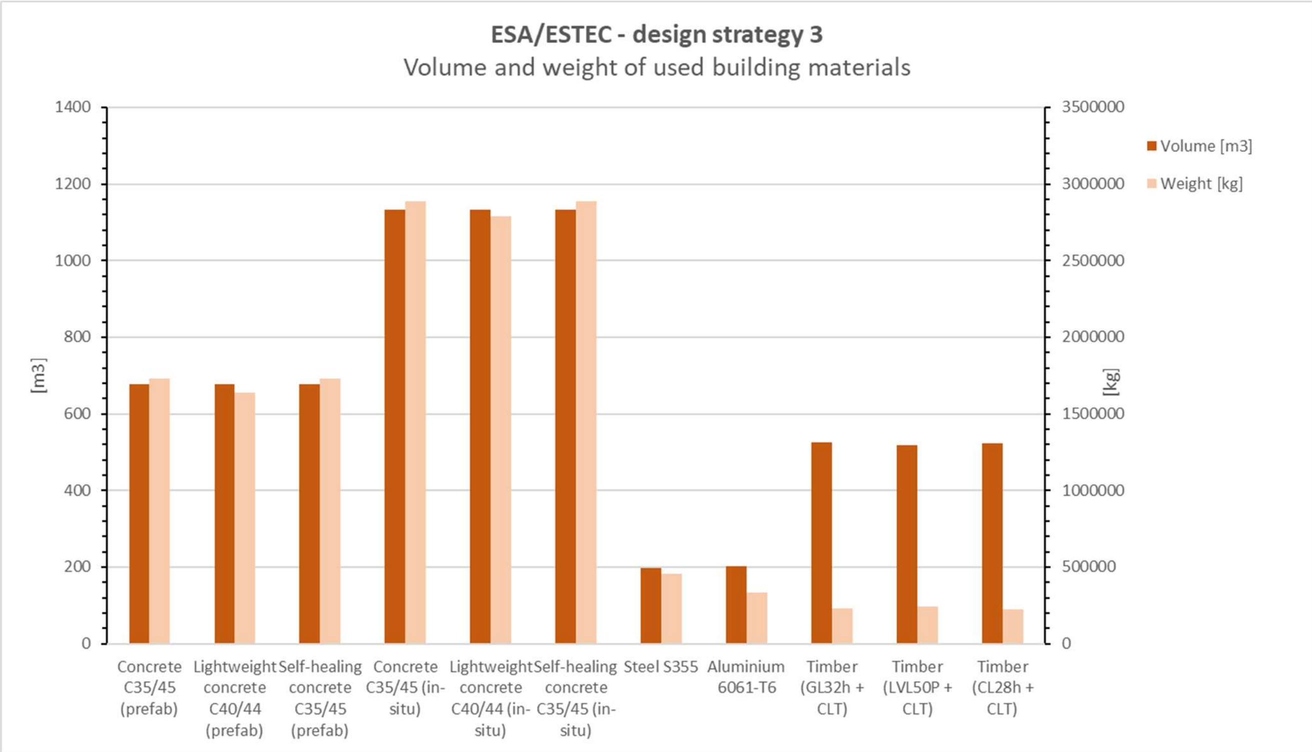


Figure 9.8: Total volume and weight per building material for ESA/ESTEC design strategy 3

Again, this figure clearly shows the differences between the total weight of a concrete structure versus a structure made from metal or timber. While the layout of the supporting structure for design strategy 3 results in many more load bearing elements (compare figure 9.2 to figure 9.7), the total weight of the two different designs doesn't differ that much. Due to the large spans that are used in design strategy 2, all load bearing elements have significantly bigger dimensions than the ones for design strategy 3. The fact that smaller dimensions for load bearing elements are possible in design strategy 3, cancels out the fact that much more supporting elements are present in the design. Of course, this doesn't have to be the case for other projects and is very dependent on the size of the total structure.

Apart from the total weight of a supporting structure, also the ECI values that result from the use of building materials are interesting to compare. The following figure shows the ECI values for all building variants for design strategy 3. Also the difference between the ECI values for only LCA module A and the full life cycle (combining LCA module A, C and D) is clearly visible here.

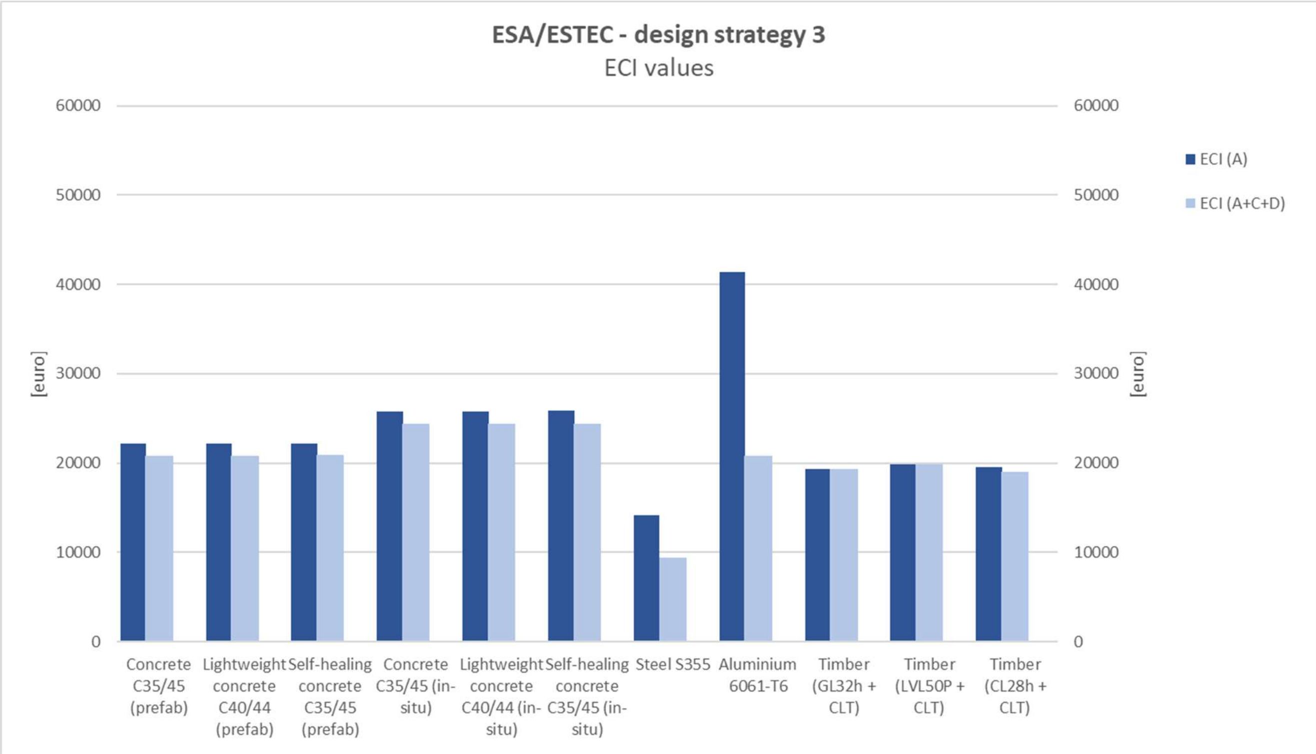


Figure 9.9: ECI values per building material for ESA/ESTEC design strategy 3

Finally, all the information for the building variants for ESA/ESTEC for design strategy 3 can be combined in the MCA. The nine criteria (consisting of 5 criteria purely focusing on the material and the connections, and 4 criteria focusing on the results of the design regarding weight, price and ECI values) are multiplied with their corresponding weights for design strategy 3. Summation of the nine scores results in a final MCA score per building variant. The MCA scores are shown in the figure below.

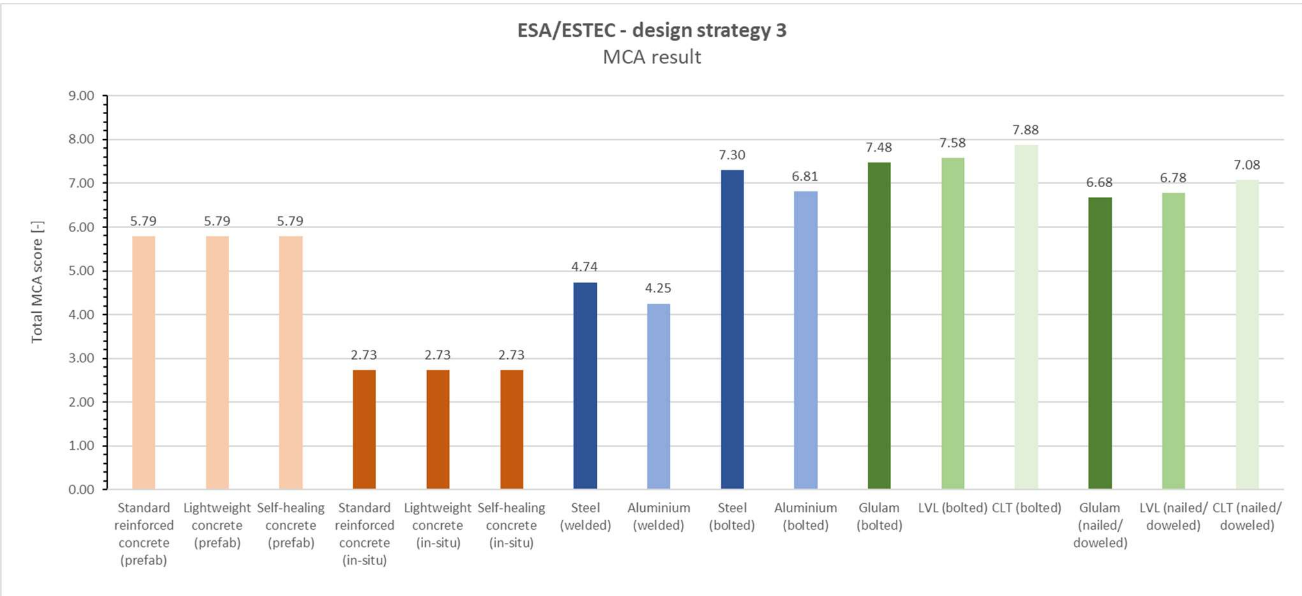


Figure 9.10: MCA results per building material for ESA/ESTEC design strategy 3

This figure shows that, when the MCA is applied on the test project for ESA/ESTEC, for design strategy 3, a timber CLT structure with bolted connections is the best suitable solution. This result is probably due to the fact that a timber structure result by far in the most lightweight building elements, which is highly valued when considering a structure's transportability. Of all timber building materials, CLT proves to be the best solution, due to its lower characteristic weight compared to glulam and LVL. Also, CLT is estimated slightly cheaper than the other timber products. Furthermore, bolted connections have a very high removability-index and thereby make the process of demounting the structure much easier. For this reason, a bolted metal structure also results in a high MCA score.

9.2.3 Comparing design strategy 2 and 3

Now both design strategy 2 and 3 have been applied on the case study, the results for both strategies can be compared. The following figure shows the final MCA scores for all building variants for both design strategies.

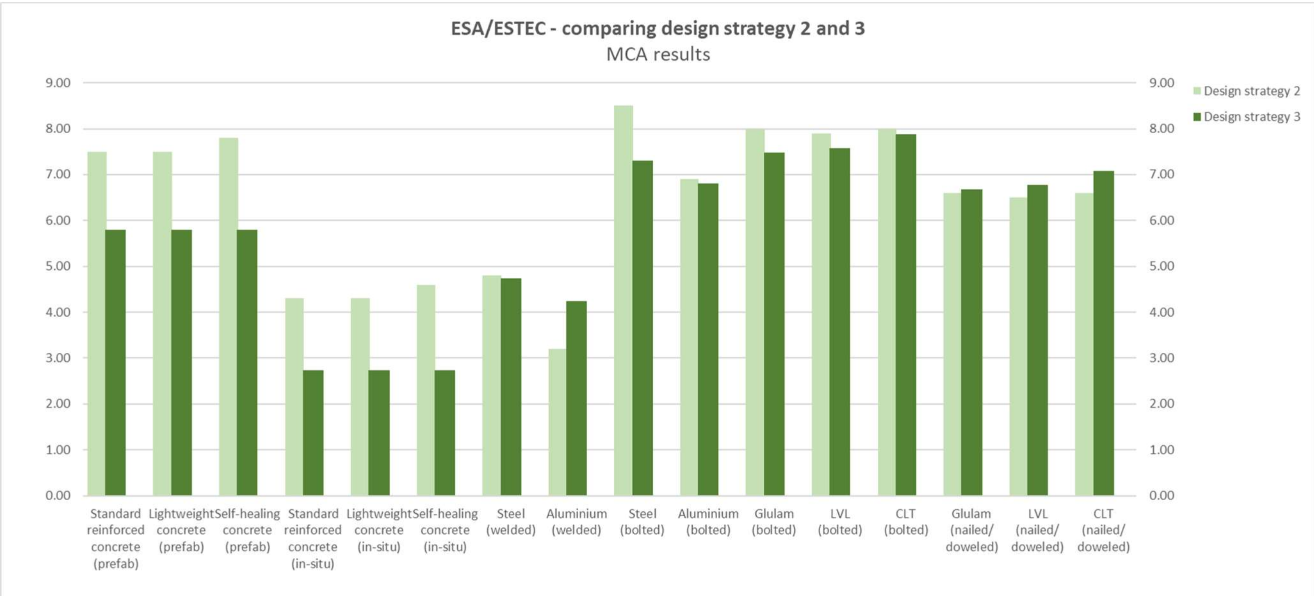


Figure 9.11: Comparing MCA results for ESA/ESTEC for design strategy 2 and 3

The figure above enables one to make a clear comparison of the final MCA scores for all considered building materials for the two applied design strategies. Especially, the concrete variants (both prefab and cast in-situ) show a significant difference in the results between design strategy 2 and 3. For design strategy 2, the estimated lifespan of a building element is considered to be of relatively high importance. As concrete has a high score of 0.80, 0.90 or 1.00 for this criterium, this contributes to a high final MCA score in design strategy 2. However, in design strategy 3, the estimated lifespan of a building element is graded with a weight of zero, which excludes this good property of a concrete structure from the final MCA score.

For all timber building variants, the differences between the MCA results for both design strategies is very limited. In both cases, timber results in a high final MCA score, thereby making it a good option for both strategies. For all timber materials (glulam, LVL and CLT) there is a clear difference between the structures using bolted connections and the ones with doweled or nailed connections. For design strategy 3, the removability-index of a connection is the most important criterium. Bolted connections have a higher score for this criterium than nailed or doweled ones, which explains the difference between the two options. For design strategy 2, the difference between the bolted and nailed/ doweled connections is less obvious. In the factor method that was used for the scoring system for the estimated lifespan of building elements, one of the factors is related to the work execution level. For nailed or doweled connections, this score is a little bit lower than for bolted connections, resulting is a slightly shorter estimated lifespan. As the estimated lifespan of a building element is an important criterium in design strategy 2, the final MCA score for nailed or doweled connections is lower than the one for bolted timber connections.

The same reasoning as stated above for timber structures, also partly applies on metal structures. Again, bolted connections have a higher removability-index than welded connections, which explains the difference between the two types of connections in design strategy 3. Welded connections have a slightly lower score for the work execution level in the factor method (same as for the nailed or doweled timber connections), resulting in a lower MCA score compared to bolted steel connections. This explains the difference between the two types of connections in design strategy 2.

9.3 MCA sensitivity analysis

After comparing the results for both design strategy 2 and 3 that were applied on the case study, the final step is to perform a sensitivity analysis of the proposed MCA. As explained earlier, the differences between the design strategies is included in the MCA by adjusting the weights of the criteria per design strategy. Sections 5.3 and 5.4 focused on the links between the MCA criteria and the design strategies, which explains the weights that are used for all the criteria. However, in case future users of the MCA choose to adjust the proposed weights, it’s important to investigate to what extent this will influence the final MCA results per design strategy.

In order to perform this sensitivity analysis, five different options for weights of the MCA criteria per design strategy are introduced. The first one consists of the original weights that are used in the MCA as explained in chapter 5.4. Besides this original option, two options are included in which the internal differences between the weights are increased. In the final two options, the opposite is done, namely decreasing the internal differences between the weights. First, the average value of the non-zero weights is calculated. This can be seen in the following table.

MCA criteria	Weights for design strategy 2	Weights for design strategy 3
1. Lifespan of a building element	3	0
2. Material’s potential for recycling	0	2
3. Type of connection	4	0
4. Accessibility of connection	0	0
5. Removability-index of connection	0	4
6. Total weight of structure	0	2
7. Total price of structure	1	1
8. ECI value (LCA module A)	2	0
9. ECI value (LCA module A + C + D)	0	1
Average of non-zero weights	**2.25**	**2.00**

Table 9.5: Original weights of the MCA criteria for design strategy 2 and 3

For the two options where the internal differences are increased, the weights that are above the average weight per design strategy are increased and the values below the average are lowered. For the two options where the internal differences are decreased, the weights that are above the average weight are lowered and the weights that are below the average are increased. This process was done under three conditions:

- The average of the non-zero weights stays the same
  This means that the total amount of increased weights equals the total amount of lowered weights.
- The total amount of 10 points that can be distributed over the nine MCA criteria stays the same
  This means that in total, still 10 points are distributed over the criteria for each design strategy.
- Zero weights remain zero
  Sections 5.3 and 5.4 explained why some criteria have a weight of zero depending on the design strategy. The following sensitivity analysis is done under the condition that this reasoning still holds and that some criteria keep their zero weight in the adjusted options following in the next two sections.

9.3.1 Sensitivity analysis for design strategy 2

The following table shows the five options for the weights of the MCA criteria for design strategy 2.

MCA criteria	Increased (extreme)	Increased	Original	Decreased	Decreased (extreme)
1. Lifespan of a building element	4	3.5	3	2.5	2
2. Material's potential for recycling	0	0	0	0	0
3. Type of connection	5	4.5	4	3.5	3
4. Accessibility of connection	0	0	0	0	0
5. Removability-index of connection	0	0	0	0	0
6. Total weight of structure	0	0	0	0	0
7. Total price of structure	0	0.5	1	1.5	2
8. ECI value (LCA module A)	1	1.5	2	2.5	3
9. ECI value (LCA module A + C + D)	0	0	0	0	0
Average	**2.25**	**2.25**	**2.25**	**2.25**	**2.25**
Total	**10**	**10**	**10**	**10**	**10**

Table 9.6: Five adjusted options for the weights of design strategy 2

These five options can now be applied on the MCA, which results in the following figure.

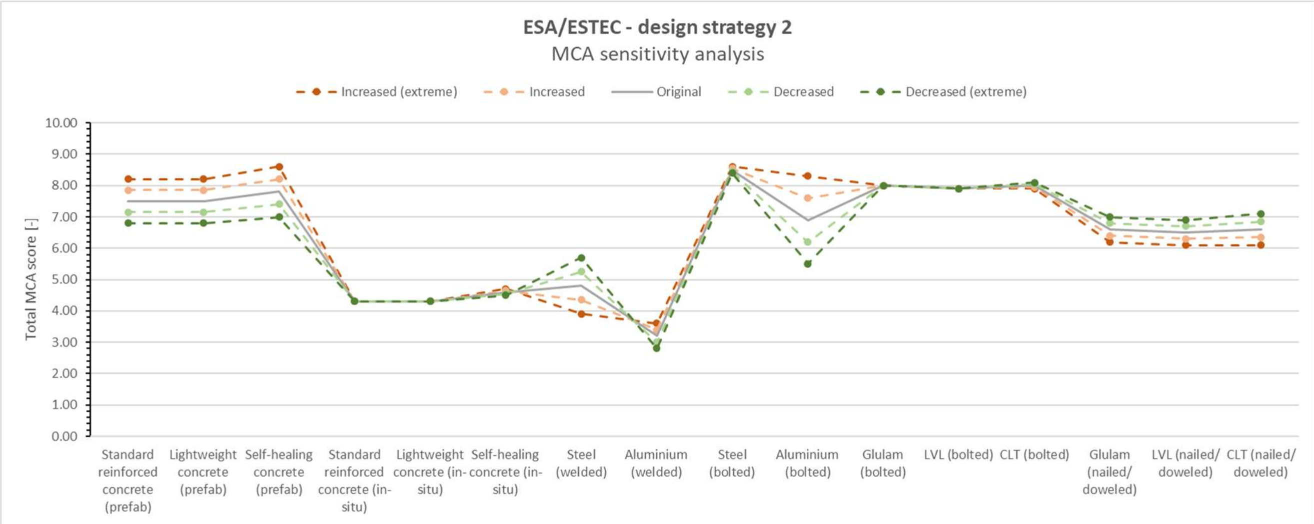


Figure 9.12: MCA results for five adjusted weights of the MCA criteria for design strategy 2

This figure shows that adjusting the weights per MCA criteria has limited influence on the final MCA result. Especially when looking at the three types of in-situ cast concrete, there is almost no difference in the final MCA score. This also holds for the three timber structures with bolted connections, welded aluminium structures and bolted steel structures. However, a clear difference can be seen for the three types of prefabricated concrete. The figure shows for these materials, increasing the internal differences between the weights works favourable for the MCA scores of these structures. This is also true for bolted aluminium structures. The opposite holds for welded steel structures and doweled timber structures. There, increasing the internal differences between the weights of the MCA criteria, works unfavourable for the final MCA scores.

9.3.2 Sensitivity analysis for design strategy 3

The following table shows the five options for the weights of the MCA criteria for design strategy 3.

MCA criteria	Increased (extreme)	Increased	Original	Decreased	Decreased (extreme)
1. Lifespan of a building element	0	0	0	0	0
2. Material's potential for recycling	2	2	2	2	2
3. Type of connection	0	0	0	0	0
4. Accessibility of connection	0	0	0	0	0
5. Removability-index of connection	5	4.5	4	3.5	3
6. Total weight of structure	2	2	2	2	2
7. Total price of structure	0.5	0.75	1	1.25	1.5
8. ECI value (LCA module A)	0	0	0	0	0
9. ECI value (LCA module A + C + D)	0.5	0.75	1	1.25	1.5
Average	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**
Total	**10**	**10**	**10**	**10**	**10**

Table 9.7: Five adjusted options for the weights of design strategy 3

These five options can now be applied on the MCA, which results in the following figure.

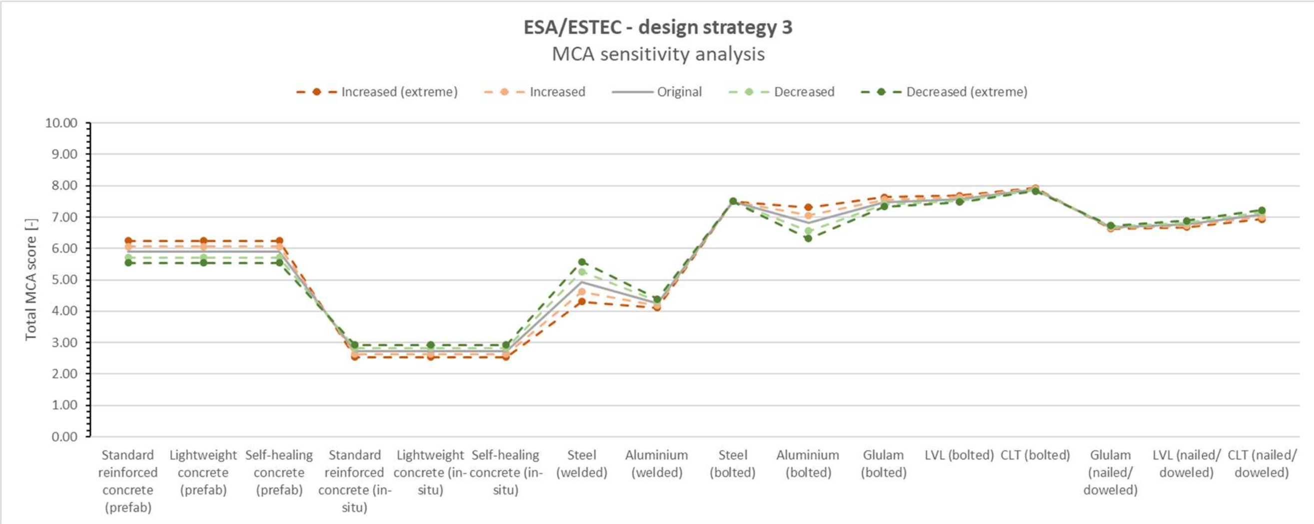


Figure 9.13: MCA results for five adjusted weights of the MCA criteria for design strategy 3

Again, the influence of adjusting the weights of the MCA criteria seems very limited here. The results of figure 9.12 and 9.13 are very similar for prefabricated concrete. Also, the same applies for welded steel structures and bolted aluminium structures, however, the influence seems smaller for design strategy 3 than for design strategy 2.

All in all, changing the weights of the MCA criteria doesn't have a very big influence on the final MCA results for both design strategy 2 and 3. In the case study on ESA/ESTEC, bolted steel resulted in the most suitable building material for design strategy 2, closely followed by bolted timber. When looking at figure 9.12, prefabricated self-healing concrete also becomes a very good option in case the weights are changed to 'Increased (extreme)' as proposed in table 9.6. The material that would benefit the most from these adjusted weights, is a bolted aluminium structure. However, the trend line stays relatively similar to the original one. This statement is even more true for design strategy 3, when looking at figure 9.13. Again, prefab concrete and bolted aluminium structures are the ones to benefit the most from applying the adjusted weights of 'Increased (extreme)', but a bolted CLT structure remains the building material with the highest MCA result.

Chapter 10
Conclusions

The following sections answer the sub-questions as proposed in the beginning of this thesis. Finally, the main research question is answered.

1. Which different design strategies can be used in the design process of an office building and how do they match with different clients?

After completing the research in this thesis, it can be stated that there are three possible design strategies to follow. The first strategy focusses on maximizing a structure's technical service life, resulting in the optimization of its durability and limiting the necessary amount of maintenance. This design strategy matches with a PoR that doesn't give specific guidelines regarding the final structure's level of sustainability. The main focus here lies on functionality of the building and the minimization of disturbance for its users (for example caused by maintenance). For this reason, this type of design strategy can for example be linked to clients within a more industrial sector, where the office building is used mainly as an operational centre for the industrial facilities of the client. Design strategy 1 can also be linked to companies that don't expect any more growth in its number of employees and are beyond the development phase, as this indicates that there will be no big changes regarding the companies needs and wishes with regards to the size of the building.

Design strategy 2 aims for maximizing a structure's functional service life in order to match its technical service life, as this prevents the building from becoming empty and out of use. This can be done by optimizing for a structure's flexibility and adaptability. This design strategy seems more fit for companies that are still in the development phase and might change their number of employees and other wishes in the nearby future. When it's expected that a client will not use the building over its full technical service life, but the building itself shows great potential for other companies or new functions (depending on its location and surroundings), this might be the best design strategy to follow.

Finally, the third design strategy focusses on maximizing a structure's residual value, by making its building elements fit for re-use in future life cycles. This results in optimizing a structure's level of demountability and its potential for recycling in case complete re-use isn't an option. This design strategy is especially useful in case of temporary structures and for clients that know on beforehand that they will not use the building for an extensive period of time.

2. What are the most important requirements for an office building (resulting from analysed programs of requirements and the design strategies as described in sub-question 1) that can be used as criteria in the MCA?

Based the design perspectives as introduced by Tim Vonck and the three different design strategies, the following nine criteria are included in the MCA:

- Lifepan of a building elements
- Building material's potential for recycling
- Type of connection
- Accessibility of connection
- Removability-index of a connection
- Total weight of used building material
- Total price of used building material
- ECI value for production process (LCA module A)
- ECI value at end-of-life stage (LCA module A, C and D)

Each design strategy optimizes for different aspects, thereby resulting in varying importance of the MCA criteria as mentioned above.

3. Which building materials apply for implementing in the MCA (based on criteria resulting from sub-question 3) and what are their relevant specifications?

For a building material to be considered in this research, all information related to the nine MCA criteria mentioned above needs to be available. This includes information on what type of connections are commonly used for each building material. Also strength characteristics need to be available in order to perform the ULS and SLS checks necessary for determining the dimensions of the cross sections of the load bearing elements. Finally, it's important that for the used building materials ECI values are present in the NMD (or other sources if possible or desired), or at least ECI values of a comparable product are available there. These requirements, combined with the proposed materials from Witteveen+Bos, resulted in the following building materials that were included in this research:

- Prefab and cast in-situ concrete
  (standard C35/45, lightweight LC40/44 and self-healing C35/45)
- Steel (S355)
- Aluminium (6061-T6)
- Glulam (GL32h)
- LVL (LVL50P)
- CLT (CL28h)

All relevant material characteristics are included in the Appendices.

4. How to compare different materials for building elements when using a Multi Criteria Decision Making method and which approach is best suitable for this specific purpose?

As mentioned in sub-question 2, the importance of the nine MCA criteria differs per design strategy. In order to enable future users of this MCA to up-date or adjust the weights of the criteria, the following scoring system is proposed: each design strategy gets a total of 10 points that can be distributed over the nine criteria. Irrelevant criteria can thereby get a weight of zero, while very important criteria can get a weight of multiple points. The following table shows the weights for the MCA criteria for the three proposed design strategies.

	Weights of MCA criteria per design strategy		
	Design strategy 1	Design strategy 2	Design strategy 3
1. Lifespan of a building element	5	3	0
2. material's potential for recycling	0	0	2
3. Type of connection	0	4	0
4. Accessibility of connection	3	0	0
5. Removability-index of connection	0	0	4
6. Total weight of structure	0	0	2
7. Total price of structure	1	1	1
8. ECI value (LCA module A)	1	2	0
9. ECI value (LCA module A + C + D)	0	0	1
Total	**10**	**10**	**10**

Table 10.1: Weights of MCA criteria

The largest benefit of this scoring system is the possibility for future users to easily adapt the weights that are assigned to the criteria. In this way, new insights can be incorporated into the MCA, thereby keeping this method up-to-date. It also enables one to add new design strategies to the MCA without having to change the current scoring system. Even new criteria can be added, however, when more criteria are added, one might want to increase the total number of points to a value higher than 10.

The main research question of this thesis is: ***'Based on different design perspectives, which design strategies (all aiming for lowering the structure's environmental impact) for office buildings in The Netherlands can be formed and to what extent does a selected design strategy influence the selection of a building material for a building's load bearing structure?'***. After completing the research in this thesis, it can be stated that there are three possible design strategies one can follow in the initial design phase of an office building, all focussing on different CE principles. The extent to which the selection of a specific design strategy influences the final material selection, can be partly investigated by comparing the results of the case study on ESA/ESTEC. After performing the MCA for both design strategy 2 and 3 for this project, the final outcome of the analysis is certainly different for both strategies. For design strategy 2, a bolted steel structure seems to be the most suitable solution, while for design strategy 3 the best result belongs to a timber supporting structure. This implies that designing according to a specific design strategy does indeed influence the final outcome regarding which building material is most suitable and might result in the lowest environmental impact.

To give an answer on how big this influence of a chosen design strategy is on the final material selection, is however more difficult. As can be seen in the comparison of the MCA results for both design strategy 2 and 3 for ESA/ESTEC, the difference between the final scores for steel and timber structures is quite small. It could be said that the MCA in this case can be used more for investigating which material is most likely not suitable for application in a specific design strategy, rather than selecting the best one. When the outcome of the MCA shows two or maybe more building materials with equally high results, further investigation is needed on which material results in the lowest environmental impact. This shows that the MCA can at least limit the number of materials that should be taken to a next design step and thereby help the designer in excluding materials that are most likely not fit for use. However, the proposed MCA approach needs to be applied on more case studies or projects from the past in order to verify these conclusions.

Chapter 11

Discussion of the results

Now the final conclusions are given, it's important to discuss the validity of the results and check if this research can be generalized and used in a broader field of research. In the section on the interpretation of the results, the actual MCA outcome is compared with some expected results and deviations from these expectations are explained. Finally, the limitations of this research are addressed, including an important simplification.

11.1 Validity of the data and research

Before being able to expand the knowledge from this research to a broader field of application, its validity needs to be checked and validated. The following sections focus on the validity of the data that functions as the input for the MCA.

11.1.1 ECI values for used building materials

As explained earlier, data from category 1 or 2 in the NMD is preferred, as this data was verified by external parties. However, almost all building materials used in this thesis where only publicly accessible for category 3. As the NMD was the only open database that could be used for all building materials, there was no other alternative resource for the ECI values. The biggest disadvantage of the data from the NMD is the lack of insight in which aspects are or are not included in the ECI values. For category 3 data, one can see the ECI value of a product per LCA module, however, no context is given about what processes are included for example in LCA module A.

Especially for timber building materials, this was a huge problem. When using timber that was produced under sustainable forest management, one could expect a negative ECI value in LCA module A1-3, due to the storage of CO2 in the wood. When the timber product would be burned at the end of its lifecycle, this would result in a positive ECI value in LCA module C3, as the captured CO2 is now again released into the atmosphere. In case the timber product isn't burned, but re-used in a new lifecycle, the ECI value in LCA module C3 would be zero. However, this would result in an imbalance of biogenic CO2, which is not allowed by EN 15804. Therefore, the weight of biogenic carbon's GWP is set to zero. This means that the positive effect of capturing CO2 in wood, is not included in the ECI values from the NMD. This would be fine in case a timber element is used for only one lifecycle, but when an element is re-used (as proposed in design strategy 3), this wouldn't be visible in the ECI value of the original product. It would then only be visible in the ECI value for the next lifecycle, as there the ECI value for LCA module A would be zero (no raw resources used).

The other possibility of including the capturing of CO2 in wood, is by placing a negative ECI value in LCA module D. It seems that the NMD has done this for CLT, however, it wasn't done for glulam and LVL. Due to the lack of explanation on which effects are included in every LCA module in the NMD, one can't be sure about the validity of these values. It would therefore be better to use ECI values from a better verified source or database, or to get a more detailed insight in the effects and processes that are included in each LCA module in the NMD.

As can be seen in Appendix D, the ECI values [euro/m3] of steel and aluminium in LCA module A are much higher than the ones for concrete and timber products. However, as the metal structures are significantly lighter than the other variants, the final ECI value for steel is the lowest one of all for both design strategy 2 and 3. It could be highly doubted if this is a realistic outcome. Bearing in mind that the ECI values for timber products are probably lower than stated by the NMD, it would be more logical that a timber structure would result in the lowest ECI value. Again, clear insight into the ECI values of the NMD is lacking here. However, when looking at the ECI value for LCA modules A, C and D combined, steel could indeed result in the lowest ECI value, as this material has a high negative value in module D. This is due to the fact that steel can be 100% recycled by melting it and making new steel members out of it. This can not be done with wood, resulting in less benefits in module D compared to steel. However, a foundation for the negative value in LCA module D for steel is missing, which makes it unclear what processes are included here (for example the energy needed for reheating and melting the steel).

11.1.2 Costs of used building materials

The costs for the used building materials are partly based on information from www.bouwkosten.bouwformatie.nl and partly on information from suppliers (Hekospanten for glulam and Metsä for LVL). The information provided by the wood suppliers clearly states that these costs are only for the material itself and exclude the costs associated with the connections and assembly of the structure. However, this type of explanation was not available for the data retrieved from www.bouwkosten.bouwformatie.nl. In the current results from the case study, timber structures seem to be the cheapest solution, however, from practice it's known that usually they are quite expensive. It could be questioned if the information from www.bouwkosten.bouwformatie.nl does include more aspects (such as assembly on site), resulting in higher costs for concrete and steel structures than for timber ones. In an ideal situation, all data regarding costs of a building material should come from the same source, in order to prevent this type of uncertainties.

11.1.3 Generalization of this research

Now that some uncertainties regarding the input data are addressed, it can be investigated whether the performed research can be generalized and used in a broader field of application. First of all, the methods that were used for the scoring system of all MCA criteria, are based on the same scoring systems used in research performed by Alba Concepts. Also, existing methods such as the factor method used in NEN-ISO 15686 were applied. These methods are not only applicable in the case of designing an office building, but are already more general, which implies that they could very well be used for the design of other structures.

As for the proposed design strategies, the generalization is a bit more complicated. The three design strategies and their timelines are specifically useful for office buildings, however, the same reasoning can be used for design strategies for other types of buildings. As long as one proposes a design strategy that focuses on specific CE principles and thereby optimizes for one or more of the design perspectives, the same MCA approach can be used.

In conclusion, it is very likely that the basic principles from this research, such like the development of design strategies and the selection of MCA criteria related to the optimizations per design strategy, can be used in the development of other types of buildings as well.

11.2 Interpretation of the results

11.2.1 Expected benefits of innovative building materials

Initially, it could be expected that some of the more innovative and less commonly used building materials, such as lightweight concrete and aluminium, would show clear benefits in comparison with traditional building materials. For lightweight concrete, the total self-weight of the supporting structure could be significantly lower, due its lower density. However, due to the lower Youngs modulus of lightweight concrete, the deflection in SLS of the beams becomes larger than for standard concrete. In order to still match the maximum deflection criterium, the cross sections of the beams can't get much smaller or even remain the same for both types of concrete. This means that designing for SLS becomes governing and the members are not fully optimized in ULS. Furthermore, it can be seen that the floors have the largest contribution to the total self-weight of the structure. In this research, only two concrete floor systems are considered and both of them are made of standard concrete mixtures, which excludes the possible benefits of lightweight concrete in terms of lower loads on the beams and columns. Combining these two factors, results in a very limited benefit for lightweight concrete structures. Besides this, it can also be expected that lightweight concrete mixtures are more expensive than standard ones, which makes it even less attractive to use this building material instead of standard concrete.

The same issues apply on an aluminium structure, when it's compared to a steel one. Aluminium's higher strength-to-weight ratio could result in a significantly lighter structure. However, its lower Youngs modulus causes deflections in SLS to become governing. Again, the aluminium member can not be fully optimized in ULS design, resulting in larger I- and H-sections than the ones for a steel structure. In the end, this results in a total self-weight of the supporting structure that is approximately the same as for a steel structure. Combining this with the significantly higher price of aluminium members, probably makes it a less attractive building variant than other materials.

Of course, the conclusions drawn in the sections above, only apply on the case study that was used for this research. It could very well be true that lightweight concrete and aluminium prove their potential benefits when applied in other projects, with different structural lay-outs and building sizes.

11.2.2 Expanding case study results for in-situ concrete to design strategy 1

The final MCA results for ESA/ESTEC design strategy 2 and 3 show that in both situations, in-situ cast concrete is not a very good option. Looking at the optimizations for design strategy 3, this is a very logical outcome. As in this design strategy the focus mainly lies on a high level of demountability, an in-situ concrete connection is not a desirable solution. Also, a concrete structure results in the heaviest load bearing elements, which limits their transportability. Therefore, it is quite logical that an in-situ concrete structure is not a good option when designing according to design strategy 3.

For design strategy 2, a structure's level of demountability and transportability is less important. Therefore, it could be expected that in-situ cast concrete would have a higher final MCA score in this design strategy. However, this design strategy aims for a type of connection that would enable future expansion of the building in order to increase its level of adaptability. In-situ cast connections don't score very high here, as it is very hard to connect additional future elements to the already existing structure. Therefore, the final MCA score of in-situ cast concrete structures is quite low, compared to other building materials.

The conclusions from the sections above might implicate that in-situ cast concrete is never a good solution, according to the proposed MCA. However, when looking at design strategy 1, where demountability, transportability and adaptability become irrelevant, in-situ concrete might become a more attractive building material. In this first design strategy, the focus mainly lies on the durability of the supporting structure and a limited amount of maintenance during its technical service life. Concrete shows a great potential here, as it is one of the most long-lasting building materials (as long as the correct environmental exposure conditions are selected and sufficient concrete cover is applied). Furthermore, when constructed properly, little to no maintenance is required over its technical service life. Combining this with the fact that in-situ cast concrete is relatively cheap (no additional costs for the prefabrication of elements), it might very well be one of the most suitable building materials when designing for design strategy 1.

11.2.3 Link between MCA results and further design steps

Import to emphasize when interpreting the MCA and its results from the case study, is the fact that this whole research is mainly focused on a building's initial design phase. This means that all ULS and SLS checks that where done in order to determine the structural element's dimensions, are only the initial checks. Of course, when the MCA results show one or two building materials that might be suitable for a project, the designer or engineer should perform more detailed checks for that specific building material. For concrete, this includes for example the dimensioning of stirrups in a beam to increase its shear capacity. In metal structures, the connections need a lot more checks and detailing in order to prevent typical failure mechanisms, such as failure of the bolts or the boltholes. Laminated wood requires additional checks in order to prevent separation of the lams. All in all, it's important to keep in mind that the results of the MCA as proposed in this research, are only an indication of which building material might result in the lowest environmental impact of the total supporting structure and is the most suitable material according to a specific design strategy. Also when two or more building materials result in approximately equal MCA scores, it might be a good solution to take both materials to the next design step in order to see if the more detailed checks give a clear difference in suitability of the material. Otherwise, the two materials can be compared based on other aspects, for example the transportation distance that can be expected for both materials, or the construction time that depends on the material.

11.3 Limitations of this research

As stated earlier, the basic principles that are applied in this research can be broadened to a larger field of application, if desired. However, this research also has certain limitations. This is mostly the result of the strict demarcation that was necessary for limiting the lengthiness of the report and the time that it took to perform the research. The following sections briefly elaborate on these limitations.

11.3.1 Limited number of criteria in MCA

In the current MCA approach, a total of nine criteria is included. Five of them are focused mainly on the material properties and the types of connections that are commonly used per building material. The other four criteria depend more on the design of the supporting structure. This design results in the total weight, price and ECI values of the load bearing elements. These nine criteria can give a good first estimation of which building material is most suitable for a project, but the list of criteria is still limited. Some important aspects are not included here, such as the costs that are associated with the assemblage of a structure in a specific building material, or the costs that can be expected for a type of connection. Also, the total building time is not included in the criteria. One can assume that a cast in-situ concrete structure takes longer to build than a prefabricated one, as all the formwork needs to be assembled on site and a certain waiting period is needed after the casting. When assembling a structure that was designed following design strategy 3, the total building time might also increase, as it usually takes more time to build a structure with a high level of demountability compared to one that is expected to last for a longer period of time without demounting it.

11.3.2 Limited number of building materials

As explained earlier, the building materials that are included in this research all needed to have enough information available to be included in the calculations and MCA. This includes strength characteristics needed for the ULS checks, costs indications of the material and ECI values (ideally split into the different values per LCA module). These requirements, together with the suggested building materials from Witteveen+Bos, resulted in the list of building materials that are included in this report. However, a lot more building materials show a great potential for application in load bearing structures (for example bamboo, plastics or other innovative types of concrete). Therefore, one of the limitations of this research is the fact that only a limited selection of building materials is included. On the other hand, one of the advantages of the used MCA approach, is the fact that future users can rather easily add new building materials to the list. As long as enough information of these building materials is available, one can incorporate them in the current MCA by scoring them with the same scoring systems used for the already included materials.

11.3.3 Use of standardized cross sections

As explained in chapter 6, all members are designed using standardized cross sections for each building material. For concrete this means practical dimensions, mostly increasing in steps of 50 mm. For metal members, standard I- and H-sections were used. Finally, for timber beams and columns commonly used cross sectional dimensions from the Quick Reference are selected. Designing the load bearing elements using standardized cross sections was done on purpose, as this is highly desired from a practical point of view. The disadvantage of these standardized cross sections, is the fact that not all cross sections can be equally optimized in the ULS and SLS design. Especially for concrete and timber members, this was a struggle. When one of the proposed cross sections resulted in a unity check that was just above 1,00, a standardized cross section that was one step smaller, often already resulted in a unity check below 0,80. When a standardized cross section results in slightly lowers unity check, meaning that the materials and cross section might be not used to its full potential, one can start to investigate whether it would be more beneficial to deviate from these standardized cross sections. Of course, this could result in higher costs, but at the same time it can result in savings with regards to the used amount of building material and a structure's self-weight. Especially for projects where a lot of the same elements are needed, the designer can considerate this possibility.

11.3.4 Simplification of wind bracings

Finally, in the 2D frameworks in Matrixframe that were used for designing the load bearing structures, a simplification needed to made regarding the wind bracings in the building. Normally, wind bracings limit the horizontal deformations resulting from wind loads on the façade elements. They can often be incorporated into the façade. However, in Matrixframe there is no special feature that can model these wind bracings. As a result of this, very large horizontal deformations occur when the horizontal wind load is applied. To limit these deformations, additional supports are introduced in the 2D models. These supports prevent horizontal deformations only and still enable the vertical displacements of the nodes. A schematization of a 2D frame is given in the figure below.

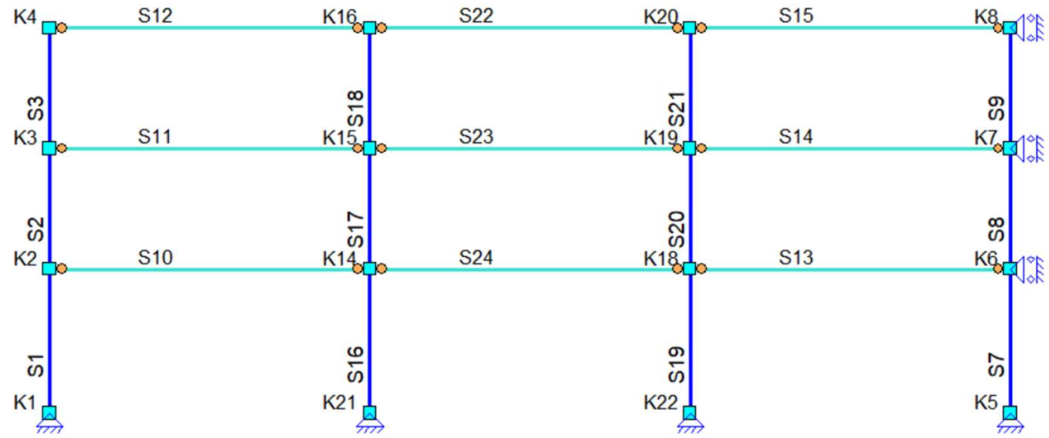


Figure 11.1 : Schematization of wind bracings in Matrixframe at nodes K6, K7 and K8

When making a more detailed design in next design phases, it's important to calculate the needed dimensions and locations of the wind bracings. Adding wind bracings if possible (for example when using different software) can help in eliminating the uncertainty regarding the wind bracings and the distribution of forces in other elements.

Chapter 12

Recommendations

The final part of this research includes making recommendations for future users of the MCA at Witteveen+Bos. Furthermore, some suggestions for further research in this field that could help in completing the proposed MCA are given.

12.1 Recommendations for Witteveen+Bos

As a result of the performed research, some recommendations for designers and future users of the MCA at Witteveen+Bos can be listed.

12.1.1 Verification of the MCA on past projects

To start with, it might be very useful to use the proposed MCA on projects that were done in the past. Especially projects where one or more principles of the CE played an important role in the design, can help in verifying whether the MCA focuses on the right topics. At the same time it can give insight in which aspects are important but still missing in the list of criteria. Also, applying the MCA on past project can help in understanding the choices that were made in order to increase a design's level of sustainability. Comparing the results from the MCA with the actual design of a past project can show which deliberate or undeliberate decisions were made during the design phase and whether they align with one of the three design strategies.

12.1.2 Use design strategies to actively work together with clients on sustainability

Most importantly, this research could help designers at Witteveen+Bos to actively work together with their clients on the topic of lowering a structure's environmental impact. Usually, clients ask for a sustainable building or design, without further specifications on how that could be achieved. As explained in this research, sustainability, or better said, the principles of the CE, consist of various aspects. In this research, these aspects are represented by the design perspectives as introduced by Tim Vonck. As some of these perspectives contradict, one design can never be optimized for all perspectives. This is something that needs to be discussed with the client, in order to activate them to think and discuss about which aspects they find most important in their structure. Following the three design strategies and the types of client that can potentially fit each strategy, the designer can help the client in selecting the right design strategy.

Another possibility is to ask the client to rank the nine design perspectives in order from most to least important. This can help the client in understanding that choices have to be made regarding which aspects to optimize in a design. After this, the designer can check whether the order of prioritization by the client, matches with one of the design strategies. This can all help in starting the dialogue between client and designer on which design strategy and corresponding timeline might be the best fit. After selecting the most suitable design strategy, the designer can perform the MCA and based on the results, propose one or a selection of building materials to the client that best fit the selected design strategy and might result in the lowest environmental impact of the structure.

12.2 Recommendations for future research

To conclude this research, the following sections give some recommendations for future research that might help in developing the proposed MCA.

12.2.1 Combining and adding new building materials and floor systems

First of all, it would be really interesting to look into combinations of different building materials. This allows one to combine beneficial properties of different materials into one supporting structure. For example, in his PhD report 'The Sustainable Office', Andy van den Dobbelsteen concluded that the combination of timber beams and columns and concrete TT-slabs shows a great potential for lowering an office building's environmental impact. When combining different building materials and floor systems is enabled in the MCA, it could be checked whether this conclusion still holds and if it depends on the selected design strategy. However, this would require more research on how this would affect the types of connections that can be used, as different building materials require different connections.

Besides combining different building materials, it is also advised to keep adding new materials to the MCA, in order to keep the analysis up to date and in accordance with the latest developments in the field of construction materials. As mentioned in the previous chapter, the list of building materials that is currently included in the MCA, is quite limited. However, due to the proposed MCA approach, future users can incorporate new materials, as long as enough information regarding strength, costs and ECI values is available.

Finally, it is also advised to include more types of flooring systems. For concrete, for example TT-slabs as mentioned above could be incorporated in the MCA, as well as composite floor systems where for example steel and concrete are combined. Optimizing the self-weight of a floor system can have a large influence on the total self-weight of the structure and thereby also on the needed amount of building material. Selecting and incorporating more efficient floor types can therefore result in higher MCA results and a lower environmental impact of a supporting structure. Note that here again sufficient information regarding the costs and ECI values needs to be available, in order to include their scores in the MCA.

12.2.2 ECI values and their sources

As explained earlier in the validity check of the used data, there are a lot of uncertainties regarding the ECI values as presented by the NMD. In order to get a better insight in which processes and aspects are or are not included in the ECI value per LCA module, it is advised to perform more detailed research into the ECI values from the NMD. This can be done for example by comparing the ECI values with the corresponding EPD's, as long as an EPD is available. Another possibility for limiting the uncertainties coming from the ECI values, is selecting a different database that can function as a source of more transparent ECI values. Preferably, all ECI values should be verified by an external and uninvolved third party that does not benefit from giving a higher or lower score to specific products. One of the biggest disadvantages of the data from the NMD, is the fact that the most reliable ECI values (the ones from category 1 or 2 that are verified by external parties) is often not publicly accessible. Unfortunately, not many databases such as the NMD are free to access, resulting in potentially high costs when wanting to use more reliable ECI values.

Bibliography

Alrawashdeh, A., & Eren, O. (2022). Mechanical and physical characterisation of steel fibre reinforced self-compacting concrete. Eastern Mediterranean University: Elsevier.

ASM Aerocpace Specification Metals. (n.d.). Aluminium 6061-T6. Retrieved from ASM Aerocpace Specification Metals: https://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6

Bak, R. L. (2021). Kantoren in cijfers 2021. Nieuwegein: NVM Business.

Borgström, E., & Fröbel, J. (2019). The CLT Handbook. Stockholm: Swedish Wood.

Bos, B., Geertjes, K., & Pennings, R. (2021). Landelijke Monitor Leegstand. CBS.

(n.d.).BOSCO VERTICALE. BOSCO VERTICALE. Pictorem.

Bouwen met Staal. (2013). Duurzame stalen vloersystemen. Zoetermeer: Bouwen met Staal.

Bouwen met Staal. (n.d.). Staalframebouw - Vloerenwijzer. Bouwen met Staal.

Brettschichtholz. (n.d.). Glued laminated timber - wood species. Retrieved from Brettschichtholz: https://www.glued-laminated-timber.com/glued-laminated-timber/wood-species/mn_42532

Caitlin. (2020, February 21). Building With Wood vs Steel. Retrieved from Vermont Timber Works: https://www.vermonttimberworks.com/blog/building-with-wood-vs-steel/

Canadian Wood Council. (n.d.). Laminated Veneer Lumber. Retrieved from Canadian Wood Council: https://cwc.ca/en/how-to-build-with-wood/wood-products/structural-composite/laminate-veneer-lumber

Cao, X.-Y., Xiong, C.-Z., Feng, D.-C., & Wu, G. (2021). Dynamic and Probabilistic Seismic Performance Assessment of Precast Prestressed Rcfs Incorporating Slab Inuence Through Three-Dimensional Spatial Model. Sipailou Campus: Southeast University: Research Square.

Carbon Equity. (2021, September 6). The Built Environment - An overview. Retrieved from Carbon Equity: https://carbonequity.com/2021/09/06/the-built-environment-an-overview/

CBS. (n.d.). CO2-equivalent. Retrieved from CBS: https://www.cbs.nl/nl-nl/nieuws/2020/19/uitstoot-broeikasgassen-3-procent-lager-in-2019/co2-equivalent

ClientEarth. (2020, December 22). What is a carbon sink? Retrieved from ClientEarth: https://www.clientearth.org/latest/latest-updates/stories/what-is-a-carbon-sink

Climate Policy Watcher. (2022, January 7). The Warming Effects of the Industrial Revolution. Retrieved from Climate Policy Watcher: https://www.climate-policy-watcher.org/global-temperatures/the-warming-effects-of-the-industrial-revolution.html

CO2 Human Emissions. (2017, December 13). Main sources of carbon dioxide emissions. Retrieved from CO2 Human Emissions: https://www.che-project.eu/news/main-sources-carbon-dioxide-emissions

Construction Field. (2011). Steel Frame Construction Process. Retrieved from Construction Field: https://constructionfield.org/steel-frame-construction-process/?amp=1

Dobbelsteen, A. v. (2004). The sustainable office - An exploration of the potential for factor 20 environmental improvement of office accomodation. Delft University of Technology.

Drost, R. (2021). Are you prepared for the Product Environmental Footprint? Retrieved from Ecochain: https://ecochain.com/knowledge/are-you-prepared-for-the-product-environmental-footprint/

Ecochain. (2021). Environmental Product Declaration (EPD) – Overzicht. Retrieved from Ecochain: https://ecochain.com/nl/knowledge-nl/environmental-product-declaration-epd-overzicht/

Ecochain. (2021). Levenscyclusanalyse (LCA) – Een Volledig Overzicht voor Beginners. Retrieved from Ecochain: https://ecochain.com/nl/knowledge/levenscyclusanalyse-life-cycle-assessment-lca-complete-beginners-guide/

Ecochain. (2021). Milieukostenindicator (MKI) – Overzicht. Opgehaald van Ecochain: https://ecochain.com/nl/knowledge-nl/milieukosten-indicator-mki/

Grand Canyon University. (2021, July 30). People, Planet, Profit: Looking at the Triple Bottom Line. Retrieved from GCU: https://www.gcu.edu/blog/business-management/people-planet-profit-looking-triple-bottom-line

Ingenieur Holzbau.de; Finnish Woodworking Industries. (2019). Laminated veneer lumber (LVL) bulletin. Wuppertal: Studiengemeinschaft Holzleimbau e.V.

Intergovernmental Panel on Climate Change (IPCC). (2021). Climate Change 2021 - The Physical Science Basis. Switzerland: IPCC.

IsoBouw. (n.d.). De 10R circulariteitsladder. Retrieved from IsoBouw: https://www.isobouw.nl/nl/wij-zijn-circulair/de-10r-circulariteitsladder/

Jonkers, H., & Ottelé, M. (2020). CIE4100 Materials and Ecological Engineering. Delft.

Lansink, A. (2014, June 5). Ladder van Lansink. Retrieved from Ad Lansink's Website: https://www.adlansink.nl/voorbeeld-pagina/

Lax, N. (2018, March 14). Recycling, Upcycling en Downcycling - Wat Zijn De Verschillen? Retrieved from Alles over Afval: https://allesoverafval.vanhappencontainers.nl/afval-scheiden/recycling-upcycling-en-downcycling-verschillen/

Mishra, G. (n.d.). What is Lightweight Concrete? - Types, Uses and Advantages. Retrieved from The Constructor: https://theconstructor.org/concrete/lightweight-concrete/1670/

Nationale Milieudatabase. (n.d.). Betonmortel GWW C3545. Retrieved from Milieudatabase: https://viewer.milieudatabase.nl/producten

Nationale Milieudatabase. (n.d.). Nationale Milieudatabase. Retrieved from Milieudatabase: https://viewer.milieudatabase.nl/

Naturally:Wood. (n.d.). Laminated veneer lumber (LVL). Retrieved from Naturally:Wood: https://www.naturallywood.com/products/laminated-veneer-lumber/

Navarro-Rubio, J., Pineda, P., & García-Martínez, A. (2018). Sustainability, prefabrication and building optimization under different durability and re-using scenarios: Potential of dry precast structural connections. Department of Building Construction, Universidad de Sevilla: Elsevier.

NEN-EN 15804. (2019). Sustainability of construction works. Brussels: European Committee for Standardization.

NEN-EN 1990. (2021). Eurocode: Basis of structural and geotechnical design. Brussels: European Committee for Standardization.

NEN-EN 1991-1-1. (2002). Eurocode 1: Actions on structures, Part 1-1: General actions. Brussels: European Committee for Standardization.

NEN-EN 1992-1-1. (2004). Eurocode 2: Design of concrete structures, Part 1-1: General rules and rules for buildings. Brussels: European Committee for Standardization.

NEN-EN-ISO 14025. (2010). Environmental labels and declarations. Brussels: European Committee for Standardization.

NEN-ISO 15686-8. (2008). Buildings and constructed assets, Part 8: Reference service life and service life estimation. Brussels: European Committee for Standardization.

Nodehi, M., Ozbakkaloglu, T., & Gholampour, A. (2022). A systematic review of bacteria-based self-healing concrete: Biomineralization, mechanical and durability properties . Texas State University: Elsevier.

Platform CB'23. (2019). Lexicon Circulair Bouwen. Platform CB'23 - Actieteam Framework.

Platform CB'23. (2020). Lexicon Circular Construction. Platform CB'23.

Posner, M., Ritchie, H., & Ortiz-Ospina, E. (2019, May 1). World Population Growth. Retrieved from Our World in Data: https://ourworldindata.org/world-population-growth

PredalCo. (n.d.). Predallen. Retrieved from Publitas: https://view.publitas.com/quoted/predalco-brochure-verschillende-types-predallen-en-ontwerpmogelijkheden-ed4ekd79p899/page/7

Ritchie, H. (2020, September 18). Sector by sector: where do global greenhouse gas emissions come from? Retrieved from Our World in Data: https://ourworldindata.org/ghg-emissions-by-sector

Ritchie, H., & Posner, M. (2019, November 1). Urbanization. Retrieved from Our World in Data: https://ourworldindata.org/urbanization#what-share-of-people-will-live-in-urban-areas-in-the-future

Sassi, P. (n.d.). Assessing Materials for Recycling. Retrieved from Greenspec: https://www.greenspec.co.uk/building-design/assessing-materials/

Specify Concrete. (2019, April 25). What Exactly Is Lightweight Concrete? Retrieved from Specify Concrete: https://www.specifyconcrete.org/blog/what-exactly-is-lightweight-concrete#:~:text=Lightweight%20concrete%20is%20a%20mixture,140%20to%20150%20lb%2Fft%C2%B3.

Sprecher, B., Verhagen, T. J., Sauer, M. L., Baars, M., Heintz, J., & Fishman, T. (2021). Material intensity database for the Dutch building stock - Towards Big Data in material stock analysis. Leiden: Journal of Industrial Ecology and Wiley Periodicals LLC on behalf of Yale University.

Steel Beam Calculator. (n.d.). Standard loads of materials. Retrieved from Steel Beam Calculator: https://www.steelbeamcalculator.co.uk/en-gb/standard-loads

Steven. (2021, November 15). Average Quantities of Reinforcement in Concrete. Retrieved from One Click LCA: https://oneclicklca.zendesk.com/hc/en-us/articles/360020943800-Average-Quantities-of-Reinforcement-in-Concrete

Suárez-Eiroa, B., Fernández, E., Méndez-Martínex, G., & Soto-Onate, D. (2019). Operational principles of circular economy for sustainable development: Linking theory and practice. University of Vigo: Elsevier.

The Engineering Toolbox. (2008). Aluminium Alloys - Mechanical Properties. Retrieved from The Engineering Toolbox: https://www.engineeringtoolbox.com/properties-aluminum-pipe-d_1340.html

The World Counts. (2022). Depletion of Natural Resources. Retrieved from The World Counts: https://www.theworldcounts.com/stories/depletion-of-natural-resources

United Nations. (1987). Report of the World Commission on Environment and Development: Our Common Future. United Nations.

United Nations Environment Programme. (2021). 2021 Global Status Report for Buildings and Construction. United Nations Environment Programme.

University of Wisconsin. (n.d.). The Triple Bottom Line. Retrieved from University of Wisconsin - Sustainable Management: https://sustain.wisconsin.edu/sustainability/triple-bottom-line/

Vliet, M. v., Grinsven, J. v., & Teunizen, J. (2021). Circular Buildings - Meetmethodiek losmaakbaarheid. -: Alba Concepts.

Vonck, T. (2019). An Eco-Effective Structure. Delft: Delft University of Technology.

Wagemans, L. (2014). Quick Reference. Delft University of Technology.

Wigo Group. (n.d.). The manufacturing process of CLT. Retrieved from Wigo: https://wigo.info/clt-timber

World Economic Forum. (2020, November 4). How has the world's urban population changed from 1950 to today? Retrieved from World Economic Forum: https://www.weforum.org/agenda/2020/11/global-continent-urban-population-urbanisation-percent/

World101. (n.d.). Enhanced greenhouse effect. World101.

PART IV

Appendices

Appendix A

Additional background information

As mentioned in the first chapter of this thesis, Appendix A contains relevant background knowledge that links the performed research to its core motivation. This appendix explains the bigger picture where this thesis needs to be placed in, in order to completely understand the importance and relevance of it. In the following sections, the most basic principles of climate change and resource depletion are briefly explained, followed by relevant emissions from the building and construction sector that contribute to these current crises. The transition from a linear economy towards a circular one and the importance of doing so is introduced using life cycle stages, which are nowadays at the core of assessing a structure's or product's environmental impact.

A.1 Climate change

Climate change; probably the two words that have been discussed the most in the past one or two decades. In The Netherlands there is a tradition of choosing a word of the year. The chosen word is often linked to the most discussed topic of that year and reflects on the major issues that were dealt with. If there had to be a similar contest for choosing such a word that typifies the last two decades, I would suggest those two words: climate change.

As climate change nowadays is one of the topics that is behind a lot of research, it is also the driving motivation for this thesis. For that reason, the only good beginning of the theoretical background that is needed for this research, is to explain the basic principles and direct effects of climate change.

It is good to state that there have always been greenhouse gases in the atmosphere due to natural processes. CO2 is emitted in many natural processes, such as volcanic activity, decomposition and respiration (CO2 Human Emissions, 2017). Nature has its own way of balancing this emitted amount of CO2 using carbon sinks, which is anything in nature that captures more CO2 than it emits. The most well-known examples of such sinks are forests, oceans and soils (ClientEarth, 2020). In history, or more specific, before the industrial revolution, these natural carbon sinks and sources made sure that the amount of greenhouse gases in the atmosphere was always balanced. This process is often referred to as the natural greenhouse effect.

The industrial revolution lead to the use of steam engines and soon CO2 emissions caused by human activities started to rise due to burning fossil fuels such as coal and oil (Climate Policy Watcher, 2022). The rising CO2 concentration distorts the natural balance and leads to more CO2 in the atmosphere than the natural sinks can absorb. This effect is called the enhanced greenhouse effect and is, unlike the natural greenhouse effect, entirely the result of human influence. As long as there is more CO2 emitted by natural processes and human activities than carbon sinks can absorb, this enhanced greenhouse effect will continue to happen, causing rising greenhouse gas concentrations in the atmosphere.

As stated previously, a certain concentration of greenhouse gases in the atmosphere is normal and necessary for a viable living environment. When solar radiation enters the atmosphere, most of this radiation is absorbed by the earth's surface and used for warming it. Some radiation is reflected by the surface back into the atmosphere. A part of that radiated heat leaves the atmosphere, but there is also a part that stays in the atmosphere, due to absorption by greenhouse gases. This energy is then re-emitted by the greenhouse gas molecules, so more greenhouse gas molecules in the atmosphere result in a rising temperature. This process is briefly explained in the figure below.

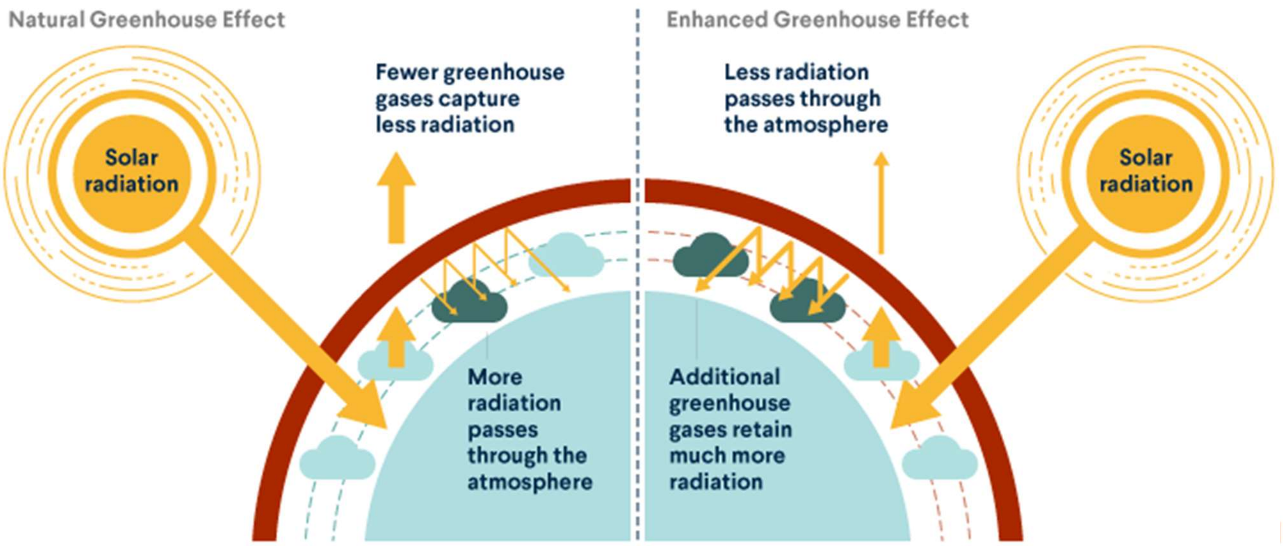


Figure A.1: Natural and enhanced greenhouse effect (World101)

Now the driving mechanism behind climate change is explained, it is time to talk about the consequences. Rising temperatures of the earth's surface and ocean will result in melting icecaps in the polar regions. Melted ice will enter the ocean and cause sea level rising. It is also expected that more often extreme temperatures and weather conditions will occur, such as long lasting droughts or more intense rainfall. Those direct effects on the world's climate also have a large impact on animal species as their living environment will change along with the changing climate. Various studies have been done and are going on about how the current climate crisis will develop and what possible future scenarios are. One message is very clear: to limit the damage climate change will cause, it is inevitable that the emission of greenhouse gases needs to be decreased.

A.2 Resource depletion

Next to the climate crisis as explained above, also the problem regarding the depletion of (natural) resources is highly important in the context of this research. Resource depletion holds that (natural) resources are being used faster than they can replenish themselves (The World Counts, 2022). Multiple aspects contribute to this problem, namely overpopulation, overconsumption, deforestation and the destruction of ecosystems that lead to a loss of biodiversity, erosion and the pollution and contamination of resources.

This research's main goal is to minimize the used amount of resources (building materials and energy that is needed in the production process of building materials and elements) for an office building's load bearing structure. Doing so, may result in lowering the contribution of the building and construction sector to the problem of resource depletion.

A.3 Emissions per sector

The latest IPCC report states very clearly:

> **''It is unequivocal that human influence has warmed the atmosphere, ocean and land.''**
> (Intergovernmental Panel on Climate Change (IPCC), 2021)

So, it is clear that human activities have caused rising greenhouse gas concentrations, but which sectors contribute most to this problem? The following figure shows a complete distribution of all emitted greenhouse gas emissions of the year 2016. The total amount of emitted greenhouse gases that year was 49.4 billion tonnes CO2-equivalent[1] (Ritchie, Sector by sector: where do global greenhouse gas emissions come from?, 2020).

[1] **While CO2 is seen as the most important greenhouse gas, there are various other types of gas that are part of the so called greenhouse gases, for example nitrous oxide (N2O), methane (CH4) and fluorinated gases (F-gases). Based on the Global Warming Potential (GWP), the influence of each gas on the total greenhouse effect is calculated and then converted to an equivalent amount of CO2, which leads to the unit CO2-equivalent (CBS, n.d.).**

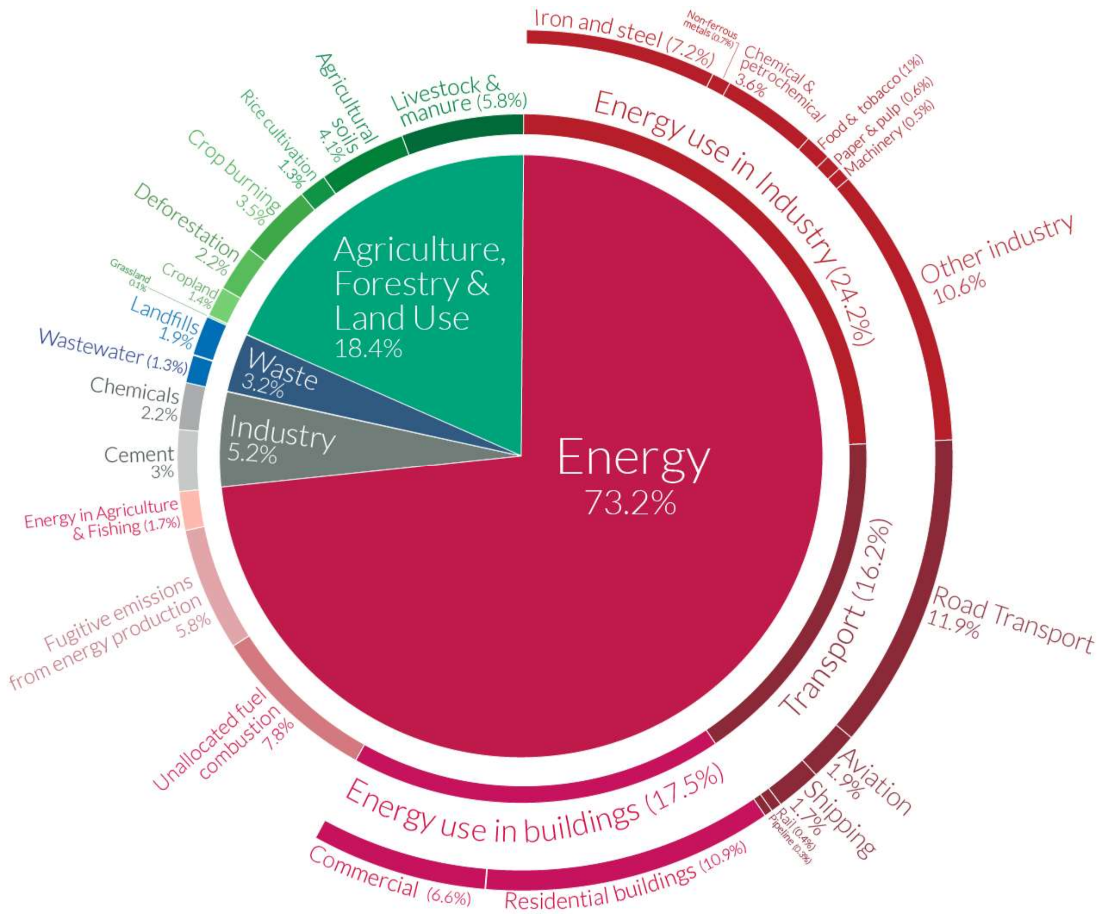


Figure A.2: Global greenhouse gas emissions by sector (Ritchie, Sector by sector: where do global greenhouse gas emissions come from?, 2020)

Looking specifically at the building sector, it can be seen that CO2 emissions in this sector can be divided in multiple categories from the figure above: the production of building materials such as cement, iron, steel and aluminium, the transportation of (raw) building materials and building elements and the use of machinery on the building site. The 2021 Global Status Report for Buildings and Construction states that this sector was responsible for 37% of the global energy-related CO2 emissions in 2020, which is equivalent to 11.7 gigatons CO2 (United Nations Environment Programme, 2021). The sub-category Buildings construction industry is devoted to energy-related CO2 emitted during the manufacturing of building materials and was responsible for 10% of the global energy-related CO2 emissions in 2020, which corresponds to 3.2 gigatons CO2.

In the same year, the buildings and construction sector accounted for 36% of the global energy consumption, which is the same as 149 EJ. The largest part of this energy was used in building operations and the other part, 6% of the total consumed energy, equivalent to 22 EJ, was used for the production of building materials.

In conclusion: 22 EJ was used for the production of building materials and 3.2 gigatons CO2 were emitted in the process of generating that amount of energy.

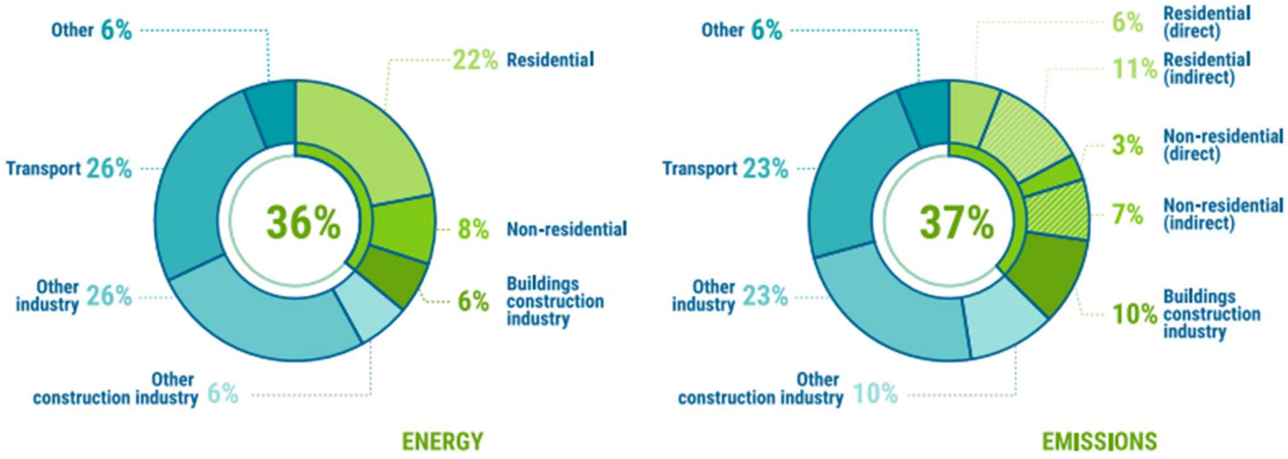


Figure A.3: Consumed energy and energy-related CO2 emissions for buildings and construction sector (United Nations Environment Programme, 2021)

A.4 Life cycle stages

In the 2021 Global Status Report for Buildings and Construction, the consumed energy and energy-related CO2 emissions are linked to the production process of building materials. However, there are more life cycle stages in a construction works life cycle. In building code NEN-EN 15804 on the sustainability of construction works, a so called Life Cycle Assessment (LCA) is used. This LCA looks at all the different life cycle stages of a construction work and defines various LCA modules based on those stages, as can be seen below.

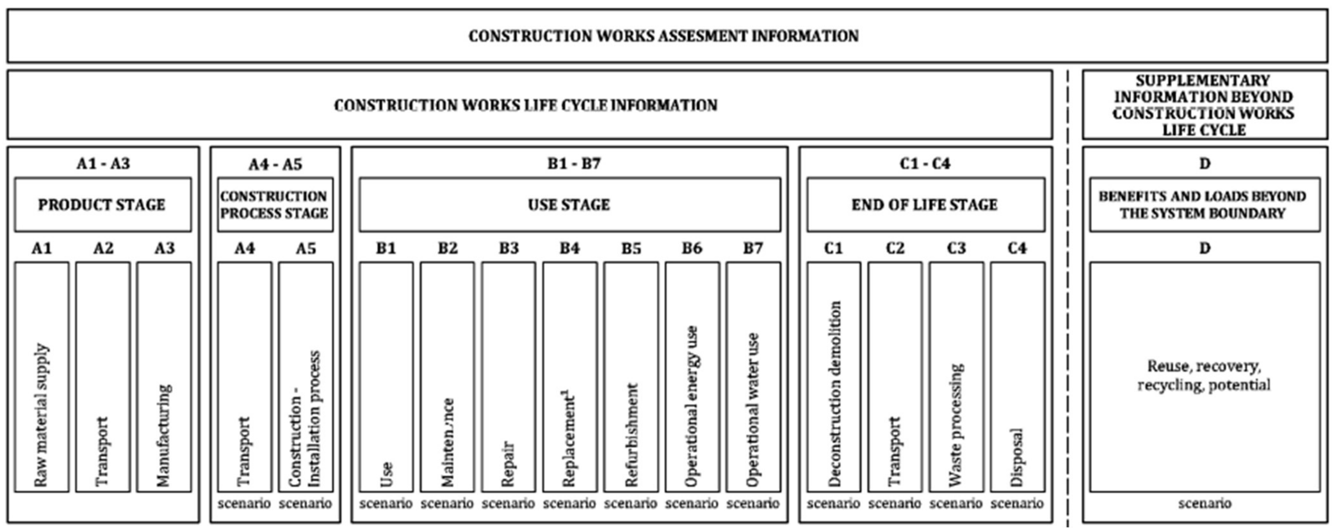


Figure A.4: Life cycle stages of a (half) product (NEN-EN 15804, 2019)

A traditional linear building process, often referred to as the linear economy, roughly consists of the following six phases (Jonkers & Ottelé, 2020).

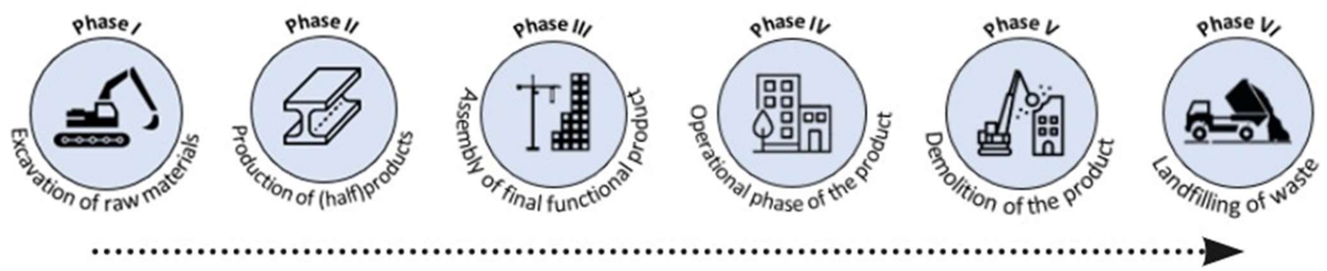


Figure A.5: Life cycle stages in LE

Apart from these phases, an additional 'phase' can be introduced, namely all transportation of materials, (half)products and waste.

The six phases as shown above can also be linked to the life cycle stages as given in the NEN-EN 15804:

- Phases 1, 2 and 3 correspond to LCA module A
- Phase 4 corresponds to LCA module B
- Phases 5 and 6 correspond to LCA module C

In order to limit the extraction of raw materials and in that way aim for a more sustainable process, the building industry is aiming to move from a linear to a circular economy. This holds recycling waste products after the demolition phase and possible re-use of parts of the demolished structure. By introducing this step, phase 1 and 6 can be removed from the life cycle stages and a connection is made directly between phase 5 and 2. This additional step transforms the LE towards a CE.

This step is also included in the LCA table as module D. This module comments on the potential for re-use of building elements, recycling of used materials and other beneficial aspects that are beyond the scope of the other LCA modules.

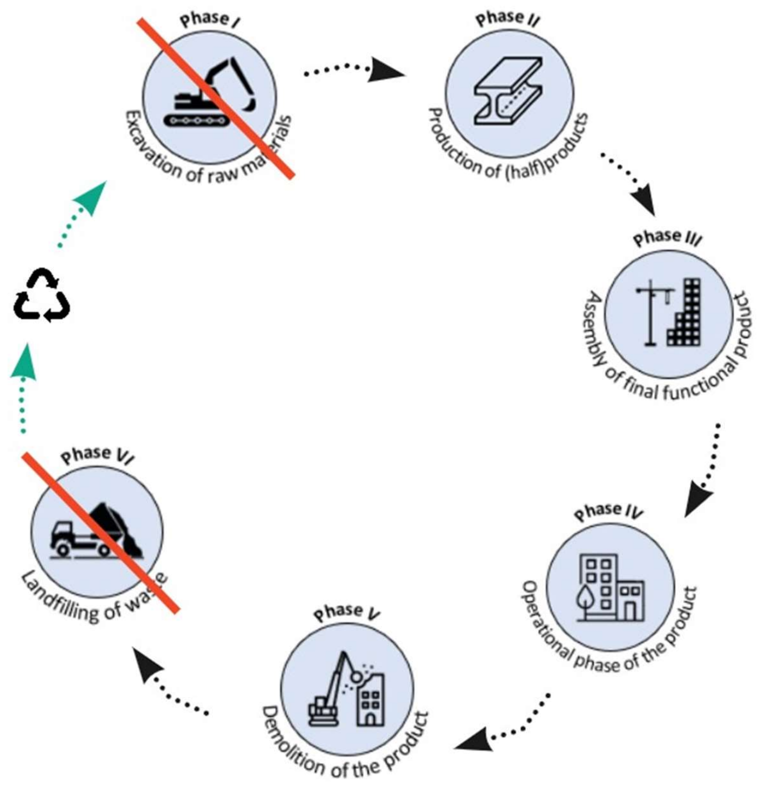


Figure A.6: Life cycle stages in CE

To finalize the different life cycle stages and matching LCA modules, it is important to mention three trajectories when looking at the LE model. For the production of waste, emissions and other by-products of a structure, it needs to be specified which stages of the full life cycle are included (Jonkers & Ottelé, 2020).

- **Cradle to gate**
  This trajectory focuses mainly on the production of a (half)product and starts with the excavation of raw materials and ends at the gate of the factory. Therefore it includes LCA modules A1-A3.
- **Cradle to grave**
  In this case the whole service life of a structure is considered, so it starts with the extraction of raw materials and ends with the demolition of the structure and the landfilling of waste. LCA modules A1-A5, B1-B7 and C1-C4 are included.
- **Cradle to cradle**
  This trajectory includes all steps of the cradle to grave-path and finally also considers the potential value of the structure when recycling or re-using parts of it. Therefore it includes LCA modules A1-A5, B1-B7, C1-C4 and D.

A.5 Lansink's Ladder

A few years before the presentation of the Brundtland report, a Dutch politician was already actively thinking about sustainability, although that specific term was not mentioned at the time. Around 1979, Ad Lansink linked the economic growth of The Netherlands to the use of new-resources. In order to grow, the addition of new materials is needed into the production process of goods. However, one day the world can run out of some of the raw materials, known as fossil fuels. When those materials are no longer available, the economic growth will come to an end. Of course, this needed to be prevented and Ad Lansink came up with the so called ''Lansink's Ladder''. This model consists of steps that start with landfilling of waste and move up to the complete prevention of waste production.

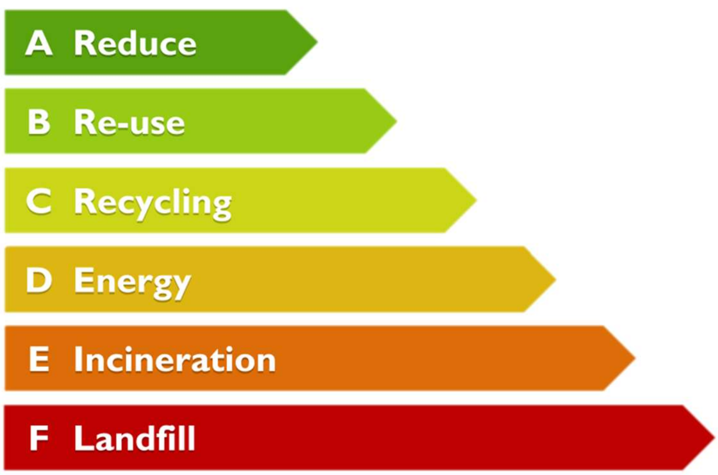


Figure A.7: Lansink's Ladder (Lansink, 2014)

The lowest level on the ladder is the landfilling of waste, which was the current practice at the time Ad Lansink developed this method. Instead of landfilling, another way of getting rid of waste is burning it, whit removing waste from the environment as only goal. Moving a step up, the burning of waste could also be done with the goal of generating energy that could be used for new purposes. These lowest three steps (D, E and F) all somehow belong more to a LE. Starting from step C, the ladder moves more towards a CE. First, the recycling of waste is discussed, which can result in either downcycling or upcycling, but in both cases waste materials are seen as possible materials that can again be added to the process. Step B focusses on the re-use of a complete (element of a) product, instead of demolishing it and recycling only the materials. The highest step on the ladder is the reduction and ultimately the prevention of waste produced in a production process.

A.6 Cramer's 10R model

Many years later, in 2011, Jacqueline Cramer founded the Utrecht Sustainability Institute. There, she developed the 10R model, which is nowadays also a very well-known model that builds a bridge between sustainability and policy. This model continuous on the work of Ad Lansink and organises methods that contribute to sustainable development into three categories. The first category focusses on the useful application of waste material, the second category is about increasing a product's lifespan and the last category encourages to improve the design of a product in such a way that the product itself becomes more sustainable (IsoBouw, n.d.). The following figure shows these categories and the steps belonging to each of them.

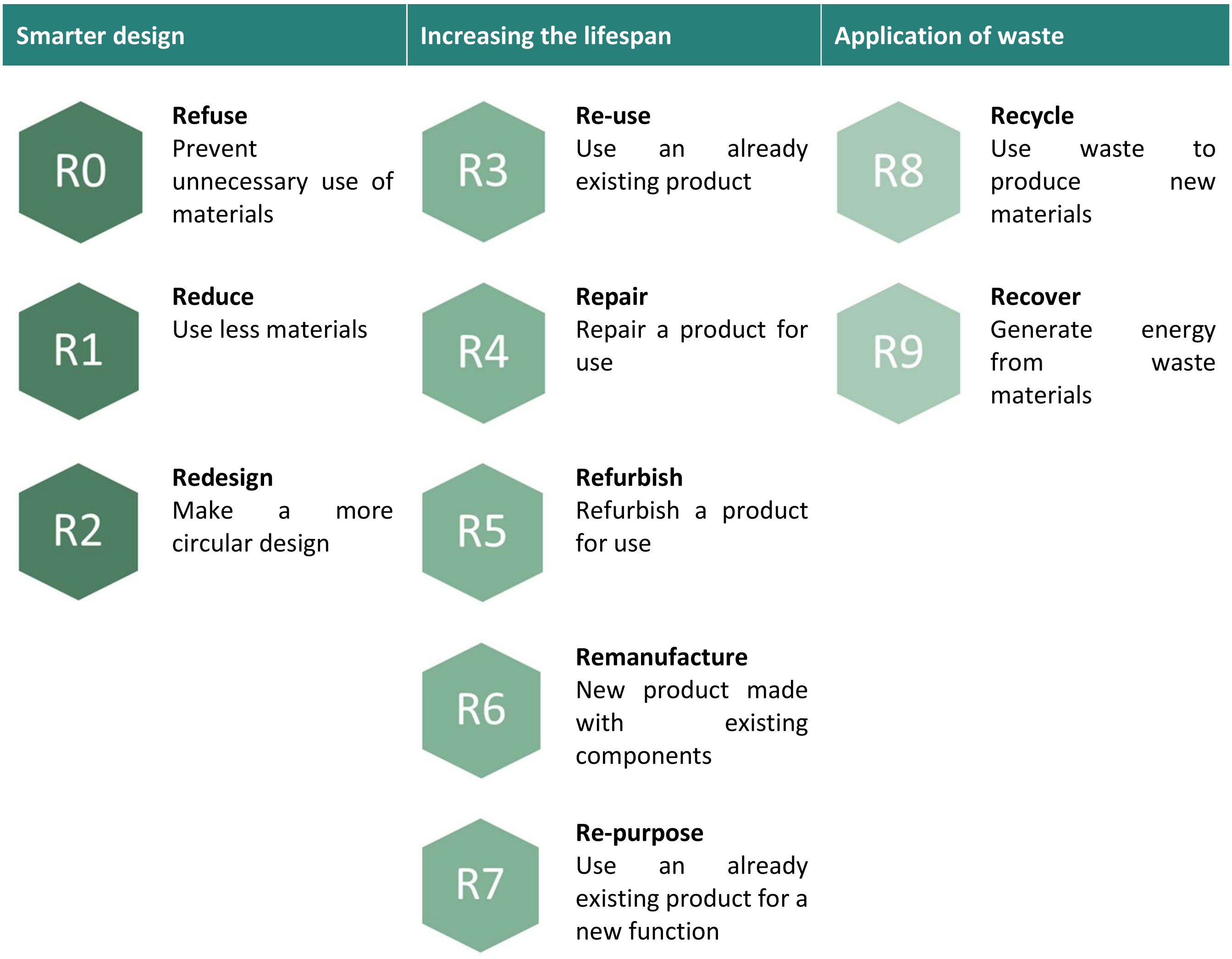


Figure A.8: 10R model

The steps in this model are numbered from R0 to R9, where R0 is the highest possible level in this theory, while R9 is the lowest. This latter category can be linked to category D in Lansink's Ladder. This immediately shows that the lowest categories from this ladder, namely category E and F, are not included in the 10R model. From this point of view, the 10R model can already be seen as a model that approaches a CE more than Lansink's Ladder. Steps R7 to R3 can be linked to category B of the ladder, as all steps aim for elongating the lifespan of an element or product. The highest category of the 10R model can be linked to the highest step on Lansink's Ladder, as steps R2 to R0 are all about reducing or preventing material use.

A.7 Methods for measuring the environmental impact

In addition to the theoretical framework as presented in the beginning of this report, the following ways of measuring and quantifying a product's environmental impact are explained in more detail below.

Life Cycle Assessment (LCA)

Afters specifying the considered life cycle stages as described in section A.4, the next step in a LCA is setting boundaries on which parts or aspects of a product or structure to take into account. Which parts are being considered and which are not? In this phase, it is also important to state which environmental impact categories are considered as most important in the LCA. Appendix B shows an overview and explanation of all the possible impact categories.

Now the functional unit and boundaries of the analysis are set, all different inputs and outputs can be listed for the considered life cycle stages. This can include resources, different forms of energy, water, possible emissions or waste as a result of a production process and used equipment and fuel. Already for simple products, this list can become quite extensive. Much information that is needed for performing a LCA is combined in databases. These databases are filled with quantitative information, mostly delivered by the producer or manufacturer, regarding processes, used resources and the final product that they deliver. The result of this phase is a Life Cycle Inventory (LCI).

When all information from the first two steps is structured, the following step is a Life Cycle Impact Assessment (LCIA), where the importance and weight of all impacts as defined earlier is determined. All elements from the LCI are linked to environmental impact categories and the final impacts can be calculated. The unit of those impacts depends on the environmental impact category, for example, global warming potential is expressed in CO2-equivalents, while the abiotic depletion potential is expressed in Sb-equivalents.

Environmental Product Declaration (EPD)

An Environmental Product Declaration (EPD) is a standardized document that contains information regarding possible impacts on the environment and health. The information in an EPD is a result of a LCA, but much more compact and therefore more often used in communication with other companies than a full LCA (Ecochain, 2021). In order to make sure that an EPD contains the same information, even when produced by different manufacturers, there are specific guidelines on how to make calculations for such a document, the so called Product Category Rules (PCR's). Regulations regarding the formulation of an EPD can be found in NEN-EN 15804 (NEN-EN 15804, 2019). Further information on how to formulate PCR’s is documented in NEN-EN-ISO 14025 and existing PCR’s on building materials can be found in corresponding Eurocodes (NEN-EN-ISO 14025, 2010).

Product Environmental Footprint (PEF)

A relatively new way of quantifying harmful effects on the environment, is by comparing Product Environmental Footprint (PEF) results of different goods or services. The European Union initiated this new method, in order to give people more reliable information regarding how environmental friendly a product or service is (Drost, 2021). PEF is still in the development phase, but since 2013 many different companies joined the pilot, in order to help this method gain information that is necessary for implementation.

Appendix B

Environmental impact categories

Impact Category	Indicator	Unit	Model
Climate change – total [a]	Global Warming Potential total (GWP-total)	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013
Climate change - fossil	Global Warming Potential fossil fuels (GWP-fossil)	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013
Climate change - biogenic	Global Warming Potential biogenic (GWP-biogenic)	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013
Climate change - land use and land use change[b]	Global Warming Potential land use and land use change (GWP-luluc)	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013
Ozone Depletion	Depletion potential of the stratospheric ozone layer (ODP)	kg CFC 11 eq.	Steady-state ODPs, WMO 2014
Acidification	Acidification potential, Accumulated Exceedance (AP)	mol H^+ eq.	Accumulated Exceedance, Seppälä et al. 2006, Posch et al., 2008
Eutrophication aquatic freshwater	Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-freshwater)	kg PO_4 eq.	EUTREND model, Struijs et al., 2009b, as implemented in ReCiPe
Eutrophication aquatic marine	Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-marine)	kg N eq.	EUTREND model, Struijs et al., 2009b, as implemented in ReCiPe
Eutrophication terrestrial	Eutrophication potential, Accumulated Exceedance (EP-terrestrial)	mol N eq.	Accumulated Exceedance, Seppälä et al. 2006, Posch et al.
Photochemical ozone formation	Formation potential of tropospheric ozone (POCP);	kg NMVOC eq.	LOTOS-EUROS ,Van Zelm et al., 2008, as applied in ReCiPe
Depletion of abiotic resources - minerals	Abiotic depletion potential for non-fossil	kg Sb eq.	CML 2002, Guinée et al., 2002, and van

Impact Category	Indicator	Unit	Model
and metals[c,d]	resources (ADP-minerals&metals)		Oers et al. 2002.
Depletion of abiotic resources - fossil fuels[c]	Abiotic depletion potential for fossil resources (ADP-fossil)	MJ, net calorific value	CML 2002, Guinée et al., 2002, and van Oers et al. 2002.
Water use	Water (user) deprivation potential, deprivation-weighted water consumption (WDP)	m^3 world eq. deprived	Available WAter REmaining (AWARE) Boulay et al., 2016

[a] The total global warming potential (GWP-total) is the sum (see C.2) of
— GWP-fossil
— GWP-biogenic
— GWP-luluc.

[b] It is permitted to omit GWP-luluc as separate information if its contribution is < 5 % of GWP-total over the declared modules excluding module D.

[c] The abiotic depletion potential is calculated and declared in two different indicators:
— ADP-minerals&metals include all non-renewable, abiotic material resources (i.e. excepting fossil resources);
— ADP-fossil includes all fossil resources and includes uranium.

[d] ultimate reserve model of the ADP-minerals&metals model.

(NEN-EN 15804, 2019)

Appendix C

Assessing materials for recycling

no	SUMMARY OF MATERIALS STUDIED description of materials to be reused/ reclaimed/ reprocessed	current recycling practice	index for suitability for recycling	ranking	index of benefits from recycling	ranking
1	clay brick wall with lime mortar, to be reclaimed and reused	minimal	0.86	6	0.60	14
2	clay brick wall with cement mortar, reprocessed for hard-core	minor	0.76	13	0.51	18
3	calcium silicate bricks cement mortar, reprocessed to hard-core	major	0.76	12	0.51	18
4	dense blocks with plaster internally, reprocessed in aggregate	minimal	0.71	16	0.50	19
5	aerated blocks with external render, reprocessed in aggregate	minimal	0.79	11	0.50	19
6	aerated blocks with plasterboard, reprocessed in aggregate	minimal	0.84	7	0.50	19
7	stone ashlar walling, stones to be reclaimed and reused	minimal	0.71	16	0.56	16
8	stone cladding to external wall, to be reclaimed and reused	minimal	0.88	4	0.56	16
9	stone ashlar walling, stones to be reprocessed as hard-core	minor	0.77	12	0.51	18
10	steel welded structure, sections to be reprocessed	major	0.67	19	0.63	11
11	steel bolted structure, sections to be reused	major	0.66	20	0.76	4
12	timber structure, timber sections reused	minor	0.76	13	0.66	9
13	timber structure, reprocessed to manufacture timber boards	minimal	0.69	18	0.49	20
14	pre-cast concrete elements, to be reused	minimal	0.80	10	0.60	14
15	concrete structure, to be reprocessed to form aggregate	major	0.72	15	0.47	22

16	timber windows reused as a whole element	minor	0.77	12	0.68	8
17	timber windows disassembled and reprocessed	minimal	0.65	21	0.58	15
18	aluminium windows disassembled and reprocessed	minimal	0.71	17	0.70	7
19	profiled metal cladding coated with plastisol reprocessed	major	0.86	6	0.70	7
20	untreated timber boarding reprocessed to form board material	minor	0.88	4	0.43	25
21	profiled PVC cladding to be reprocessed	minimal	0.69	18	0.74	5
22	clay roof tiles reused	major	0.90	3	0.53	17
23	fibre cement slating to be reprocessed to hard-core	minor	0.88	4	0.45	24
24	natural slating to be reused	major	0.90	3	0.53	17
25	lead sheet roofing removed and reprocessed	major	0.82	9	0.61	13
26	aluminium sheet roofing removed and reprocessed	major	0.92	1	0.65	10
27	copper sheet roofing removed and reprocessed	major	0.91	2	0.58	15
28	zinc sheet roofing removed and reprocessed	major	0.82	9	0.53	17
29	stainless steel sheet flashings removed and reprocessed	major	0.91	2	0.66	9
30	tern coated steel sheet roofing removed and reprocessed	major	0.82	9	0.65	10
31	epdm membrane roofing reused	minimal	0.82	9	0.83	3
32	pvc membrane roofing reused	minimal	0.69	18	0.73	6
33	asphalt roofing removed and reprocessed	minimal	0.60	23	0.70	7
34	blockwork partitions, blocks reprocessed to form hard-core	minor	0.76	13	0.47	22

35	plasterboard partitions dismantled and reused	minimal	0.83	8	0.62	12
36	plasterboard partitions dismantled and reprocessed	minimal	0.74	14	0.48	21
37	timber doors removed and reused	minor	0.83	8	0.62	12
38	timber doors removed and reprocessed	minimal	0.76	13	0.48	21
39	steel doors disassembled and reprocessed	minor	0.87	5	0.70	7
40	ceramic floor finish reprocessed	minimal	0.80	10	0.46	23
41	timber floor finish reused	major	0.87	5	0.62	12
42	vinyl floor finishes reused	minimal	0.88	4	0.93	1
43	foam glass reused	minimal	0.91	2	0.53	17
44	expanded polystyrene reused	minor	0.87	5	0.86	2
45	cellulose fibre reprocessed	minimal	0.63	22	0.33	26

(Sassi, n.d.)

Appendix D

Calculation of ECI values

Sources:

Concrete C35/45 - standard reinforcement

Component	Vol. %	Density [kg/m3]	Weight [kg]	Volume [m3]	unit ECI [€/m3]			unit ECI [€/kg]			total ECI [€]					Sources
					LCA A (1-3)	LCA C (1-4)	LCA D	LCA A (1-3)	LCA C (1-4)	LCA D	**LCA A (1-3)**	**LCA C (1-4)**	**LCA D**			
Concrete (C35/45)	98.50	2400.00	2364.00	0.9850	20.7177	2.5278	-1.2466				20.4069	2.4899	-1.2279	21.6689		*NMD: Betonmortel voor GWW C3545 CEM I + CEM III 5050% 2346 kgm3 compleet*
Reinforcement (B500)	1.50	7850.00	117.75	0.0150				0.1958	0.0005	-0.1097	23.0555	0.0640	-12.9172	10.2023		*NMD: Constructies in kg of m3, Wapeningsstaal*
total	100.00		2481.75	1.0000							**43.4624**	**2.5539**	**-14.1451**	**31.8712**	**euro/m3**	

Lightweight concrete C40/44 - standard reinforcement

Component	Vol. %	Density [kg/m3]	Weight [kg]	Volume [m3]	unit ECI [€/m3]			unit ECI [€/kg]			total ECI [€]					Sources
					LCA A (1-3)	LCA C (1-4)	LCA D	LCA A (1-3)	LCA C (1-4)	LCA D	**LCA A (1-3)**	**LCA C (1-4)**	**LCA D**			
LW concrete (C40/44)	-	-	-	-	-	-	-	-	-	-	20.4069	2.4899	-1.2279	21.6689		*Difference between LW conrete and NW concrete lies mostly in aggregates, cement content remains same, so assume same ECI values*
Reinforcement (B500)	1.50	7850.00	117.75	0.0150				0.1958	0.0005	-0.1097	23.0555	0.0640	-12.9172	10.2023		*NMD: Constructies in kg of m3, Wapeningsstaal*
total	1.50		117.75	0.0150							**43.4624**	**2.5539**	**-14.1451**	**31.8712**	**euro/m3**	

Self healing concrete C35/45 - standard reinforcement

Component	Vol. %	Density [kg/m3]	Weight [kg]	Volume [m3]	unit ECI [€/m3]			unit ECI [€/kg]			total ECI [€]					Sources
					LCA A (1-3)	LCA C (1-4)	LCA D	LCA A (1-3)	LCA C (1-4)	LCA D	**LCA A (1-3)**	**LCA C (1-4)**	**LCA D**			
Concrete (C35/45)	98.50	2400.00	2364.00	0.9850	20.7177	2.5278	-1.2466				20.4069	2.4899	-1.2279	21.6689		*NMD: Betonmortel voor GWW C3545 CEM I + CEM III 5050% 2346 kgm3 compleet*
Reinforcement (B500)	1.50	7850.00	117.75	0.0150				0.1958	0.0005	-0.1097	23.0555	0.0640	-12.9172	10.2023		*NMD: Constructies in kg of m3, Wapeningsstaal*
Self healing additives								0.0807	0.0332	-0.0003	0.4035	0.1660	-0.0015	0.5680		*NMD: Schuimisolatie van biopolymeren (BIO-EPS) - assuming 5 kg polymer per m3 concrete*
total	100.00		2481.75	1.0000							**43.8659**	**2.7199**	**-14.1466**	**32.4392**	**euro/m3**	

Concrete hollow-core slab

Component	Vol. %	Density [kg/m3]	Weight [kg]	Volume [m3]	unit ECI [€/m3]			unit ECI [€/kg]			total ECI [€]					Sources
					LCA A (1-3)	LCA C (1-4)	LCA D	LCA A (1-3)	LCA C (1-4)	LCA D	**(not specified per LCA module)**					
Dycore 320 mm	-	-	-	-	-	-	-	-	-	-		5.4924		**5.4924**	**euro/m2**	*NMD: Vrijdragende Vloeren, Dycore kanaalplaatvloer 320 mm*

Concrete composite slab

Component	Vol. %	Density [kg/m3]	Weight [kg]	Volume [m3]	unit ECI [€/m3]			unit ECI [€/kg]			total ECI [€]					Sources
					LCA A (1-3)	LCA C (1-4)	LCA D	LCA A (1-3)	LCA C (1-4)	LCA D	**(not specified per LCA module)**					
In-situ layer	-	-	-	-	-	-	-	-	-	-		3.8565				*NMD: Vrijdragende Vloeren, Betonhuis; druklaag breedplaatvloer; betonmortel C30/37,CEMIII; incl. wapening*
Predal	-	-	-	-	-	-	-	-	-	-		2.6065				*NMD: Vrijdragende Vloeren, Breedplaat, excl. druklaag, 60mm; prefab beton; AB-FAB*
total														**6.4630**	**euro/m2**	

Steel S355

Component	Vol. %	Density [kg/m3]	Weight [kg]	Volume [m3]	unit ECI [€/m3]			unit ECI [€/kg]			total ECI [€]					Sources
					LCA A (1-3)	LCA C (1-4)	LCA D	LCA A (1-3)	LCA C (1-4)	LCA D	**LCA A (1-3)**	**LCA C (1-4)**	**LCA D**			
Steel S355	100.00	7850.00	7850.00	1.0000				0.1161	0.0001	-0.0975	911.3850	0.7850	-765.3750	**146.7950**	**euro/m3**	*NMD: Damwand, staal (constructiestaal)*

Steel deck structure

Component	Vol. %	Density [kg/m3]	Weight [kg]	Volume [m3]	unit ECI [€/m3]			unit ECI [€/kg]			total ECI [€]					Sources
					LCA A (1-3)	LCA C (1-4)	LCA D	LCA A (1-3)	LCA C (1-4)	LCA D	**(not specified per LCA module)**					
Anhydrite layer	-	-	-	-	-	-	-	-	-	-		0.7086				*NMD: Anhydriet gietvloer, hechtend (NBVG)*
Wood-based material	-	-	-	-	-	-	-	-	-	-		0.3448				*NMD: Bekledingen systeemwanden niet dragend, Spaanplaat*
S355 C-section	-	-	-	-	-	-	-	-	-	-		1.6259				*NMD: Lateien, Staal; UNP, UNP300*
total														**2.6793**	**euro/m2**	

Aluminium 6061-T6

Component	Vol. %	Density [kg/m3]	Weight [kg]	Volume [m3]	unit ECI [€/m3]			unit ECI [€/kg]			total ECI [€]					Sources
					LCA A (1-3)	LCA C (1-4)	LCA D	LCA A (1-3)	LCA C (1-4)	LCA D	**LCA A (1-3)**	**LCA C (1-4)**	**LCA D**			
Aluminium 6061-T6	100.00	2700.00	2700.00	1.0000				0.9080	0.0011	-0.7704	2451.6000	2.9700	-2080.0800	**374.4900**	**euro/m3**	*NMD: Kolommen, onderdeel aluminium verkeersportaal, per kg constructiegewicht*

Aluminium deck structure

Component	Vol. %	Density [kg/m3]	Weight [kg]	Volume [m3]	unit ECI [€/m3]			unit ECI [€/kg]			total ECI [€]					Sources
					LCA A (1-3)	LCA C (1-4)	LCA D	LCA A (1-3)	LCA C (1-4)	LCA D	**(not specified per LCA module)**					
Anhydrite layer	-	-	-	-	-	-	-	-	-	-		0.7086				*NMD: Anhydriet gietvloer, hechtend (NBVG)*
Wood-based material	-	-	-	-	-	-	-	-	-	-		0.3448				*NMD: Bekledingen systeemwanden niet dragend, Spaanplaat*
6061-T6 C-section	-	-	-	-	-	-	-	-	-	-		4.3736				*Based on difference between aluminium and steel ECI values for LCA A (1-3)*
total														**5.4270**	**euro/m2**	

Glulam

Component	Vol. %	Density [kg/m3]	Weight [kg]	Volume [m3]	unit ECI [€/m3]			unit ECI [€/kg]			total ECI [€]					Sources
					LCA A (1-3)	LCA C (1-4)	LCA D	LCA A (1-3)	LCA C (1-4)	LCA D	**LCA A (1-3)**	**LCA C (1-4)**	**LCA D**			
Glulam GL32h	100.00	460.00	460.00	1.0000				0.0623	-0.0291	0	28.6580	0.0000	0.0000	**28.6580**	**euro/m3**	*NMD: Constructies in kg of m3, Hout gelamineerd europees naaldhout, duurzame bosbouw*
																** neglect negative unit ECI value in LCA module C (mistake from NMD)*

LVL

Component	Vol. %	Density [kg/m3]	Weight [kg]	Volume [m3]	unit ECI [€/m3]			unit ECI [€/kg]			total ECI [€]					

					LCA A (1-3)	LCA C (1-4)	LCA D	LCA A (1-3)	LCA C (1-4)	LCA D	**LCA A (1-3)**	**LCA C (1-4)**	**LCA D**				
LVL50P	100.00	600.00	600.00	1.0000				0.0623	-0.0291	0	37.3800	0.0000	0.0000	**37.3800**	**euro/m3**		*NMD: Constructies in kg of m3, Hout gelamineerd europees naaldhout, duurzame bosbouw*
																	** neglect negative unit ECI value in LCA module C (mistake from NMD)*
CLT																	
Component	Vol. %	Density [kg/m3]	Weight [kg]	Volume [m3]	unit ECI [€/m3]			unit ECI [€/kg]			**total ECI [€]**						
					LCA A (1-3)	LCA C (1-4)	LCA D	LCA A (1-3)	LCA C (1-4)	LCA D	**(not specified per LCA module)**						
CL28h	100.00	420.00	420.00	1.0000	31.2897	3.0141	-8.5936				31.2897	3.0141	-8.5936	**25.7102**	**euro/m3**		*NMD: Kruislings gelamineerde houten wand, 3 laags*
CLT panels																	
Component	Vol. %	Density [kg/m3]	Weight [kg]	Volume [m3]	unit ECI [€/m3]			unit ECI [€/kg]			**total ECI [€]**						
					LCA A (1-3)	LCA C (1-4)	LCA D	LCA A (1-3)	LCA C (1-4)	LCA D	**(not specified per LCA module)**						
CLT	-	-	-	-	-	-	-	-	-	-	5.3837			**5.3837**	**euro/m2**		*NMD: Kruislings gelamineerde houten vloer, 5 laags*

Appendix E

Calculation of costs per building material

Material	C35/45 - prefab	
b = 200 mm	181.48	euro/m
b = 230 mm	199.67	euro/m
b = 250 mm	215.52	euro/m
b = 300 mm	257.02	euro/m
b = 350 mm	298.51	euro/m

Material	Hollow-core slab		
h = 320 mm	**span up to 9.50 m**	64.41	euro/m2
	span up to 12.50 m	67.04	euro/m2

Material	Composite slab		
h = 320 mm	**span up to 10.00 m**	136.10	euro/m2

Material	C35/45 - in-situ	
b = 200 mm	95.78	euro/m
b = 300 mm	122.48	euro/m
b = 400 mm	169.10	euro/m
b = 500 mm	220.69	euro/m
b = 600 mm	279.35	euro/m

Material	LW C40/44 - prefab	*(assuming LW concrete about 30% more expensive than normal concrete)*
b = 200 mm	235.92	euro/m
b = 230 mm	259.57	euro/m
b = 250 mm	280.18	euro/m
b = 300 mm	334.12	euro/m
b = 350 mm	388.06	euro/m

Material	LW C40/44 - in-situ	*(assuming LW concrete about 30% more expensive than normal concrete)*
b = 200 mm	124.52	euro/m
b = 300 mm	159.22	euro/m
b = 400 mm	219.83	euro/m
b = 500 mm	286.90	euro/m
b = 600 mm	363.15	euro/m

for self-healing concrete: additional 40 euro/m3 on top of normal concrete prices

* sources:	www.bouwkosten.bouwinformatie.nl
	Cost Comparison of Lightweight Concrete

Material	S355		Material	6061-T6	*(assuming aluminium 3x more expensive than steel)*
IPE 80	8.99	euro/m	26.97	euro/m	
IPE 100	11.94	euro/m	35.82	euro/m	
IPE 120	15.18	euro/m	45.54	euro/m	
IPE 140	18.80	euro/m	56.40	euro/m	
IPE 160	22.77	euro/m	68.31	euro/m	
IPE 180	27.12	euro/m	81.36	euro/m	
IPE 200	32.31	euro/m	96.93	euro/m	
IPE 220	37.63	euro/m	112.89	euro/m	
IPE 240	44.74	euro/m	134.22	euro/m	
IPE 270	52.58	euro/m	157.74	euro/m	
IPE 300	61.55	euro/m	184.65	euro/m	
IPE 330	72.23	euro/m	216.69	euro/m	
IPE 360	83.87	euro/m	251.61	euro/m	
IPE 400	97.41	euro/m	292.23	euro/m	
IPE 450	118.66	euro/m	355.98	euro/m	
IPE 500	138.74	euro/m	416.22	euro/m	
IPE 550	167.42	euro/m	502.26	euro/m	
IPE 600	192.65	euro/m	577.95	euro/m	
HE 100 A	24.40	euro/m	73.20	euro/m	
HE 120 A	28.93	euro/m	86.79	euro/m	
HE 140 A	35.70	euro/m	107.10	euro/m	
HE 160 A	43.88	euro/m	131.64	euro/m	
HE 180 A	51.21	euro/m	153.63	euro/m	
HE 200 A	62.29	euro/m	186.87	euro/m	
HE 220 A	74.24	euro/m	222.72	euro/m	
HE 240 A	89.48	euro/m	268.44	euro/m	
HE 260 A	101.11	euro/m	303.33	euro/m	
HE 280 A	113.32	euro/m	339.96	euro/m	
HE 300 A	130.90	euro/m	392.70	euro/m	
HE 320 A	144.70	euro/m	434.10	euro/m	
HE 340 A	157.78	euro/m	473.34	euro/m	
HE 360 A	170.86	euro/m	512.58	euro/m	
HE 400 A	190.60	euro/m	571.80	euro/m	
HE 450 A	219.46	euro/m	658.38	euro/m	
HE 500 A	242.99	euro/m	728.97	euro/m	
HE 550 A	260.20	euro/m	780.60	euro/m	
HE 600 A	278.96	euro/m	836.88	euro/m	
HE 650 A	297.87	euro/m	893.61	euro/m	
HE 700 A	319.70	euro/m	959.10	euro/m	
HE 800 A	351.06	euro/m	1053.18	euro/m	
HE 900 A	395.04	euro/m	1185.12	euro/m	
HE 1000 A	426.24	euro/m	1278.72	euro/m	

Material	S355 floor system			
finishing layer	**Anhydrite (t = 35 mm)**	7.82	euro/m2	
plate material	**wood-based**	5.84	euro/m2	
C-section	**UNP 300**	66.9	euro/m	*(1 C-section per m width)*

Material	6061-T6 floor system			
finishing layer	**Anhydrite (t = 35 mm)**	7.82	euro/m2	
plate material	**wood-based**	5.84	euro/m2	
C-section	**UNP 300**	200.7	euro/m	*(1 C-section per m width)*

* sources:	www.bouwkosten.bouwinformatie.nl
	Fastmarkets - Steel vs Aluminium

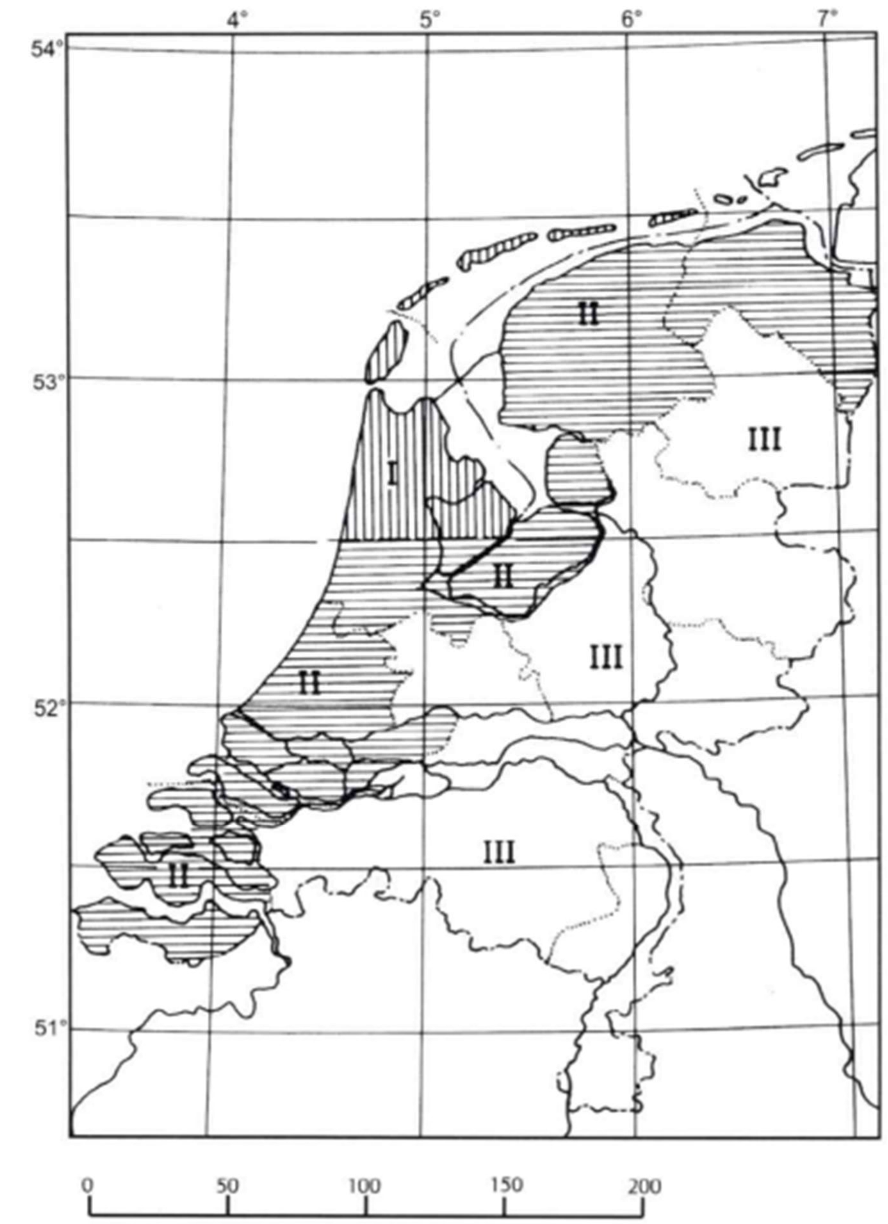
Material	Glulam				Material	CLT panels	
GL32h	1000.00	euro/m3			**CLT**	34.50	euro/m2
Material	LVL						
LVL50P	900.00	euro/m3					
Material	CLT						
CLT	700.00	euro/m3					
* sources:	Hekospanten						
	Metsä Group						

Appendix F

Peak velocity pressure for wind loads

z_e [m]		$q_p(z_e)$ [kN/m²]						
	Area I			Area II			Area III	
	Coastal	Rural	Urban	Coastal	Rural	Urban	Rural	Urban
1	0,93	0,71	0,69	0,78	0,60	0,58	0,49	0,48
2	1,11	0,71	0,69	0,93	0,60	0,58	0,49	0,48
3	1,22	0,71	0,69	1,02	0,60	0,58	0,49	0,48
4	1,30	0,71	0,69	1,09	0,60	0,58	0,49	0,48
5	1,37	0,78	0,69	1,14	0,66	0,58	0,54	0,48
6	1,42	0,84	0,69	1,19	0,71	0,58	0,58	0,48
7	1,47	0,89	0,69	1,23	0,75	0,58	0,62	0,48
8	1,51	0,94	0,73	1,26	0,79	0,62	0,65	0,51
9	1,55	0,98	0,77	1,29	0,82	0,65	0,68	0,53
10	1,58	1,02	0,81	1,32	0,85	0,68	0,70	0,56
15	1,71	1,16	0,96	1,43	0,98	0,80	0,80	0,66
20	1,80	1,27	1,07	1,51	1,07	0,90	0,88	0,74
25	1,88	1,36	1,16	1,57	1,14	0,97	0,94	0,80
30	1,94	1,43	1,23	1,63	1,20	1,03	0,99	0,85
35	2,00	1,50	1,30	1,67	1,25	1,09	1,03	0,89
40	2,04	1,55	1,35	1,71	1,30	1,13	1,07	0,93
45	2,09	1,60	1,40	1,75	1,34	1,17	1,11	0,97
50	2,12	1,65	1,45	1,78	1,38	1,21	1,14	1,00
55	2,16	1,69	1,49	1,81	1,42	1,25	1,17	1,03
60	2,19	1,73	1,53	1,83	1,45	1,28	1,19	1,05
65	2,22	1,76	1,57	1,86	1,48	1,31	1,22	1,08
70	2,25	1,80	1,60	1,88	1,50	1,34	1,24	1,10
75	2,27	1,83	1,63	1,90	1,53	1,37	1,26	1,13
80	2,30	1,86	1,66	1,92	1,55	1,39	1,28	1,15
85	2,32	1,88	1,69	1,94	1,58	1,42	1,30	1,17
90	2,34	1,91	1,72	1,96	1,60	1,44	1,32	1,18
95	2,36	1,93	1,74	1,98	1,62	1,46	1,33	1,20
100	2,38	1,96	1,77	1,99	1,64	1,48	1,35	1,22
110	2,42	2,00	1,81	2,03	1,68	1,52	1,38	1,25
120	2,45	2,04	1,85	2,05	1,71	1,55	1,41	1,28
130	2,48	2,08	1,89	2,08	1,74	1,59	1,44	1,31
140	2,51	2,12	1,93	2,10	1,77	1,62	1,46	1,33
150	2,54	2,15	1,96	2,13	1,80	1,65	1,48	1,35
160	2,56	2,18	2,00	2,15	1,83	1,67	1,50	1,38
170	2,59	2,21	2,03	2,17	1,85	1,70	1,52	1,40
180	2,61	2,24	2,06	2,19	1,88	1,72	1,54	1,42
190	2,63	2,27	2,08	2,20	1,90	1,75	1,56	1,44
200	2,65	2,29	2,11	2,22	1,92	1,77	1,58	1.46

(Wagemans, 2014)



(Wagemans, 2014)

Appendix G

Concrete strength classes

The following table from Eurocode 2 on concrete structures shows basic material characteristics for different concrete strength classes.

	Sterkteklassen voor beton														Vergelijking/Verklaring
f_{ck} (MPa)	12	16	20	25	30	35	40	45	50	55	60	70	80	90	
$f_{ck,cube}$ (MPa)	15	20	25	30	37	45	50	55	60	67	75	85	95	105	
f_{cm} (MPa)	20	24	28	33	38	43	48	53	58	63	68	78	88	98	$f_{cm} = f_{ck}+8$(MPa)
f_{ctm} (MPa)	1,6	1,9	2,2	2,6	2,9	3,2	3,5	3,8	4,1	4,2	4,4	4,6	4,8	5,0	$f_{ctm}=0,30\times f_{ck}^{(2/3)} \leq$C50/60 $f_{ctm}=2,12\cdot\ln(1+(f_{cm}/10))$ > C50/60
$f_{ctk,0,05}$ (MPa)	1,1	1,3	1,5	1,8	2,0	2,2	2,5	2,7	2,9	3,0	3,1	3,2	3,4	3,5	$f_{ctk;0,05} = 0,7\times f_{ctm}$ 5 % fractiel
$f_{ctk,0,95}$ (MPa)	2,0	2,5	2,9	3,3	3,8	4,2	4,6	4,9	5,3	5,5	5,7	6,0	6,3	6,6	$f_{ctk;0,95} = 1,3\times f_{ctm}$ 95 % fractiel
E_{cm} (GPa)	27	29	30	31	33	34	35	36	37	38	39	41	42	44	$E_{cm} = 22[(f_{cm})/10]^{0,3}$ (f_{cm} in MPa)
ε_{c1} (‰)	1,8	1,9	2,0	2,1	2,2	2,25	2,3	2,4	2,45	2,5	2,6	2,7	2,8	2,8	zie figuur 3.2 ε_{c1} ($^0/_{00}$) = 0,7 $f_{cm}^{0,31} \leq 2,8$
ε_{cu1} (‰)	3,5									3,2	3,0	2,8	2,8	2,8	zie figuur 3.2 voor $f_{ck} \geq 50$ MPa $\varepsilon_{cu1}(^0/_{00})=2,8+27[(98-f_{cm})/100]^4$
ε_{c2} (‰)	2,0									2,2	2,3	2,4	2, 5	2,6	zie figuur 3.3 voor $f_{ck} \geq 50$ MPa $\varepsilon_{c2}(^0/_{00})=2,0+0,085(f_{ck}-50)^{0,53}$
ε_{cu2} (‰)	3,5									3,1	2,9	2,7	2,6	2,6	zie figuur 3.3 voor $f_{ck} \geq 50$ MPa $\varepsilon_{cu2}(^0/_{00})=2,6+35[(90-f_{ck})/100]^4$
n	2,0									1,75	1,6	1,45	1,4	1,4	voor $f_{ck} \geq 50$ MPa $n=1,4+23,4[(90-f_{ck})/100]^4$
ε_{c3} (‰)	1,75									1,8	1,9	2,0	2,2	2,3	zie figuur 3.4 voor $f_{ck} \geq 50$ MPa $\varepsilon_{c3}(^0/_{00})=1,75+0,55[(f_{ck}-50)/40]$
ε_{cu3} (‰)	3,5									3,1	2,9	2,7	2,6	2,6	zie figuur 3.4 voor $f_{ck} \geq 50$ MPa $\varepsilon_{cu3}(^0/_{00})=2,6+35[(90-f_{ck})/100]^4$

(NEN-EN 1992-1-1, 2004)

The following table from Eurocode 2 on concrete structures shows basic material characteristics for different lightweight concrete strength classes, which can be derived from the characteristics of standard concrete.

Sterkteklassen voor lichtbeton														Analytische uitdrukking/uitleg
f_{lck} (MPa)	12	16	20	25	30	35	40	45	50	55	60	70	80	
$f_{lck,cube}$ (MPa)	13	18	22	28	33	38	44	50	55	60	66	77	88	
f_{lcm} (MPa)	17	22	28	33	38	43	48	53	58	63	68	78	88	Voor $f_{lck} \geq 20$ Mpa $f_{lcm} = f_{lck} + 8$ (MPa)
f_{lctm} (MPa)	$f_{lctm} = f_{ctm} \cdot \eta_1$													η_1=0,40+0,60ρ/2200
$f_{lctk,0,05}$ (MPa)	$f_{lctk,0,05} = f_{ctk,0,05} \cdot \eta_1$													5 % - fractiel
$f_{lctk,0,95}$ (MPa)	$f_{lctk,0,95} = f_{ctk,0,95} \cdot \eta_1$													95 % - fractiel
E_{lcm} (GPa)	$E_{lcm} = E_{cm} \cdot \eta_E$													$\eta_E = (\rho/2200)^2$
ε_{lc1} (‰)	$kf_{lcm}/(E_{cm} \cdot \eta_E)$ { k = 1,1 voor lichtbeton met zand; k = 1,0 voor beton met enkel lichte granulaten													zie figuur 3.2
ε_{lcu1}(‰)	ε_{lc1}													zie figuur 3.2
ε_{lc2} (‰)	2,0									2,2	2,3	2,4	2,5	zie figuur 3.3
ε_{lcu2} (‰)	3,5 η_1									3,1η_1	2,9η_1	2,7η_1	2,6η_1	zie figuur 3.3 $\lvert\varepsilon_{lcu2}\rvert \geq \lvert\varepsilon_{lc2}\rvert$
n	2,0									1,75	1,6	1,45	1,4	
ε_{lc3}(‰)	1,75									1,8	1,9	2,0	2,2	zie figuur 3.4
ε_{lcu3}(‰)	3,5 η_1									3,1η_1	2.9η_1	2.7η_1	2,6η_1	zie figuur 3.4 $\lvert\varepsilon_{lcu3}\rvert \geq \lvert\varepsilon_{lc3}\rvert$

(NEN-EN 1992-1-1, 2004)

Appendix H

Steel properties and profiles

The following table gives a quick overview of the material properties for different steel grades. In the context of this research, S355 will be considered.

material property			steel grade S235	S275	S355	S420	S460
density	ρ_k	[kg/ m³]	7850	7850	7850	7850	7850
Young's modulus	E_k	[N/mm²]	$210 \cdot 10^3$	$210 \cdot 10^3$	$210 \cdot 10^3$	$210 \cdot 10^3$	$210 \cdot 10^3$
design yield stress	$f_{y;d}$	[N/mm²]	235	275	355	420	460
design tensile strength	$f_{t;d}$	[N/mm²]	360	430	510	--	--
yield strain	$\varepsilon_{y;d}$	[‰]	1,12	1,31	1,69	--	--
shear modulus	G_k	[N/mm²]	$8{,}1 \cdot 10^4$	$8{,}1 \cdot 10^4$	$8{,}1 \cdot 10^4$	$8{,}1 \cdot 10^4$	$8{,}1 \cdot 10^4$
coefficient of thermal expansion	α	[K⁻¹]	$12 \cdot 10^{-6}$	$12 \cdot 10^{-6}$	$12 \cdot 10^{-6}$	$12 \cdot 10^{-6}$	$12 \cdot 10^{-6}$

(Wagemans, 2014)

The following table shows all relevant sections properties for I-sections, which are used for the design of load bearing beams in this research.

profile type	mass	dimensions				section properties						
	G	h	b	t_w	t_f	A_{tot} x 10^2	I_y x 10^4	I_z x 10^4	$W_{y,el}$ x 10^3	$W_{z,el}$ x 10^3	i_y	i_z
	[kg/m]	[mm]	[mm]	[mm]	[mm]	[mm²]	[mm⁴]	[mm⁴]	[mm³]	[mm³]	[mm]	[mm]
IPE 100A	6.9	98.0	55.0	3.60	4.70	8.78	141	13.1	28.8	4.77	40.1	12.2
IPE 100	8.1	100.0	55.0	4.10	5.70	10.3	171	15.9	34.2	5.79	40.7	12.4
IPE 120 A	8.7	117.6	64.0	3.80	5.10	11.0	257	22.4	43.8	7.00	48.3	14.2
IPE 120	10.4	120.0	64.0	4.40	6.30	13.2	318	27.7	53.0	8.65	49.0	14.5
IPE 140 A	10.5	137.4	73.0	3.80	5.60	13.4	435	36.4	63.3	9.98	57.0	16.5
IPE 140	12.9	140.0	73.0	4.70	6.90	16.4	541	44.9	77.3	12.3	57.4	16.5
IPE 140 R	14.4	142.0	72.0	5.30	7.80	18.4	611	48.8	86.1	13.5	57.7	16.3
IPE 160 A	12.7	157.0	82.0	4.00	5.90	16.2	689	54.4	87.8	13.3	65.3	18.3
IPE 160	15.8	160.0	82.0	5.00	7.40	20.1	869	68.3	109	16.7	65.8	18.4
IPE 160 R	17.7	162.0	81.0	5.60	8.50	22.6	989	75.7	122	18.7	66.2	18.3
IPE 180 A	15.4	177.0	91.0	4.30	6.50	19.6	1063	81.9	120	18.0	73.7	20.5
IPE 180	18.8	180.0	91.0	5.30	8.00	23.9	1317	101	146	22.2	74.2	20.5
IPE 180 O	21.3	182.0	92.0	6.00	9.00	27.1	1505	117	165	25.5	74.5	20.8
IPE 180 R	22.1	183.0	89.0	6.40	9.50	28.1	1554	112	170	25.2	74.4	20.0
IPE 200 A	18.4	197.0	100.0	4.50	7.00	23.5	1591	117	162	23.4	82.3	22.3
IPE 200	22.4	200.0	100.0	5.60	8.50	28.5	1943	142	194	28.5	82.6	22.4
IPE 200 O	25.1	202.0	102.0	6.20	9.50	32.0	2211	169	219	33.1	83.2	23.0
IPE 200 R	26.6	204.0	98.0	6.60	10.5	33.9	2363	166	232	33.8	83.5	22.1
IPE 220 A	22.2	217.0	110.0	5.00	7.70	28.3	2317	171	214	31.2	90.5	24.6
IPE 220	26.2	220.0	110.0	5.90	9.20	33.4	2772	205	252	37.3	91.1	24.8
IPE 220 O	29.4	222.0	112.0	6.60	10.2	37.4	3134	240	282	42.8	91.6	25.3
IPE 220 R	31.6	225.0	108.0	6.70	11.8	40.2	3474	249	309	46.1	92.9	24.9
IPE 240 A	26.2	237.0	120.0	5.20	8.30	33.3	3290	240	278	40.0	99.4	26.8
IPE 240	30.7	240.0	120.0	6.20	9.80	39.1	3892	284	324	47.3	99.7	26.9
IPE 240 O	34.3	242.0	122.0	7.00	10.8	43.7	4369	329	361	53.9	100.0	27.4
IPE 240 R	37.3	245.0	118.0	7.50	12.3	47.5	4823	339	394	57.4	101.0	26.7
IPE 270 A	30.7	267.0	135.0	5.50	8.70	39.1	4917	358	368	53.0	112.0	30.2
IPE 270	36.1	270.0	135.0	6.60	10.2	45.9	5790	420	429	62.2	112.0	30.2
IPE 270 O	42.3	274.0	136.0	7.50	12.2	53.8	6947	513	507	75.5	114.0	30.9
IPE 270 R	44.0	276.0	133.0	7.70	13.1	56.0	7312	516	530	77.6	114.0	30.3
IPE 300 A	36.5	297.0	150.0	6.10	9.20	46.5	7173	519	483	69.2	124.0	33.4
IPE 300	42.2	300.0	150.0	7.10	10.7	53.8	8356	604	557	80.5	125.0	33.5
IPE 300O	49.3	304.0	152.0	8.00	12.7	62.8	9994	746	658	98.1	126.0	34.5
IPE 300 R	51.7	306.0	147.0	8.50	13.7	65.9	10500	728	686	99.0	126.0	33.2

profile type	mass	dimensions				section properties						
	G	h	b	t_w	t_f	A_{tot} $\times 10^2$	I_y $\times 10^4$	I_z $\times 10^4$	$W_{y;el}$ $\times 10^3$	$W_{z;el}$ $\times 10^3$	i_y	i_z
	[kg/m]	[mm]	[mm]	[mm]	[mm]	[mm²]	[mm⁴]	[mm⁴]	[mm³]	[mm³]	[mm]	[mm]
IPE 330 A	43.0	327.0	160.0	6.50	10.0	54.7	10230	685	626	85.6	137.0	35.4
IPE 330	49.1	330.0	160.0	7.50	11.5	62.6	11770	788	713	98.5	137.0	35.5
IPE 330 O	57.0	334.0	162.0	8.50	13.5	72.6	13910	960	833	119	138.0	36.4
IPE 330 R	60.3	336.0	158.0	9.20	14.5	76.8	14690	958	874	121	138.0	35.3
IPE 360 A	50.2	357.6	170.0	6.60	11.5	64.0	14520	944	812	111	151.0	38.4
IPE 360	57.1	360.0	170.0	8.00	12.7	72.7	16270	1043	904	123	150.0	37.9
IPE 360 O	66.0	364.0	172.0	9.20	14.7	84.1	19050	1251	1047	145	150.0	38.6
IPE 360 R	70.3	366.0	168.0	9.90	16.0	89.6	20290	1270	1109	151	150.0	37.6
IPE 400 A	57.4	397.0	180.0	7.00	12.0	73.1	20290	1171	1022	130	167.0	40.0
IPE 400	66.3	400.0	180.0	8.60	13.5	84.5	23130	1318	1156	146	165.0	39.5
IPE 400 O	75.7	404.0	182.0	9.70	15.5	96.4	26750	1564	1324	172	167.0	40.3
IPE 400 R	81.5	407.0	178.0	10.6	17.0	104	28860	1606	1418	180	167.0	39.3
IPE 400 V	84.0	408.0	182.0	10.6	17.5	107	30140	1766	1477	194	168.0	40.6
IPE 450 A	67.2	447.0	190.0	7.60	13.1	85.5	29760	1502	1331	158	187.0	41.9
IPE 450	77.6	450.0	190.0	9.40	14.6	98.8	33740	1676	1500	176	185.0	41.2
IPE 450 O	92.4	456.0	192.0	11.0	17.6	118	40920	2085	1795	217	186.0	42.1
IPE 450 R	95.2	458.0	188.0	11.3	18.6	121	42400	2070	1851	220	187.0	41.3
IPE 450 V	103.6	460.0	194.0	12.4	19.6	132	46200	2397	2009	247	187.0	42.6
IPE 500 A	79.4	497.0	200.0	8.40	14.5	101	42930	1939	1728	194	206.0	43.8
IPE 500	90.7	500.0	200.0	10.2	16.0	116	48200	2142	1928	214	204.0	43.1
IPE 500 O	107.3	506.0	202.0	12.0	19.0	137	57780	2622	2284	260	206.0	43.8
IPE 500 R	111.4	508.0	198.0	12.6	20.0	142	59930	2600	2360	263	205.0	42.8
IPE 500 V	128.8	514.0	204.0	14.2	23.0	164	70720	3271	2752	321	208.0	44.7
IPE 550 A	92.1	547.0	210.0	9.00	15.7	117	59980	2432	2193	232	226.0	45.5
IPE 550	105.5	550.0	210.0	11.1	17.2	134	67120	2668	2441	254	223.0	44.5
IPE 550 O	122.5	556.0	212.0	12.7	20.2	156	79160	3224	2847	304	225.0	45.5
IPE 550 R	133.7	560.0	210.0	14.0	22.2	170	86600	3447	3093	328	225.0	45.0
IPE 550 V	158.6	566.0	216.0	17.1	25.2	202	102300	4265	3616	395	225.0	46.0
IPE 600 A	107.6	597.0	220.0	9.80	17.5	137	82920	3116	2778	283	246.0	47.7
IPE 600	122.4	600.0	220.0	12.0	19.0	156	92080	3387	3069	308	243.0	46.6
IPE 600 O	154.5	610.0	224.0	15.0	24.0	197	118300	4521	3879	404	245.0	47.9
IPE 600 R	144.4	608.0	218.0	14.0	23.0	184	110300	3993	3629	366	245.0	46.6
IPE 600 V	183.5	618.0	228.0	18.0	28.0	234	141600	5570	4582	489	246.0	48.8
IPE 750 x 137	137.0	753.0	263.0	11.5	17.0	175	159900	5166	4246	393	303.0	54.4
IPE 750 x 147	147.2	753.0	265.0	13.2	17.0	187	166100	5289	4411	399	298.0	53.1
IPE 750 x 161	160.5	758.0	266.0	13.8	19.3	204	186100	6073	4909	457	302.0	54.5
IPE 750 x 174	173.7	762.0	267.0	14.4	21.6	221	205800	6873	5402	515	305.0	55.7
IPE 750 x 185	185.0	766.0	267.0	14.9	23.6	236	223000	7510	5821	563	308.0	56.5

(Wagemans, 2014)

The following table shows all relevant sections properties for H-sections, which are used for the design of load bearing columns in this research.

profile type	mass	dimensions						section properties				
	G [kg/m]	h [mm]	b [mm]	t_w [mm]	t_f [mm]	A_{tot} x 10^2 [mm^2]	I_y x 10^4 [mm^4]	I_z x 10^4 [mm^4]	$W_{y;el}$ x 10^3 [mm^3]	$W_{z;el}$ x 10^3 [mm^3]	i_y [mm]	i_z [mm]
HE 100 AA	12.2	91.0	100.0	4.20	5.50	15.6	237	92.1	52.0	18.4	38.9	24.3
HE 100 A	16.7	96.0	100.0	5.00	8.00	21.2	349	134	72.8	26.8	40.6	25.1
HE 100 B	20.4	100.0	100.0	6.00	10.0	26.0	450	167	89.9	33.5	41.6	25.3
HE 120 AA	14.6	109.0	120.0	4.20	5.50	18.6	413	159	75.8	26.5	47.2	29.3
HE 120 A	19.9	114.0	120.0	5.00	8.00	25.3	606	231	106	38.5	48.9	30.2
HE 120 B	26.7	120.0	120.0	6.50	11.0	34.0	864	318	144	52.9	50.4	30.6
HE 140 AA	18.1	128.0	140.0	4.30	6.00	23.0	719	275	112	39.3	55.9	34.5
HE 140 A	24.7	133.0	140.0	5.50	8.50	31.4	1033	389	155	55.6	57.3	35.2
HE 140 B	33.7	140.0	140.0	7.00	12.0	43.0	1509	550	216	78.5	59.3	35.8
HE 160 AA	23.8	148.0	160.0	4.50	7.00	30.4	1283	479	173	59.8	65.0	39.7
HE 160 A	30.4	152.0	160.0	6.00	9.00	38.8	1673	616	220	76.9	65.7	39.8
HE 160 B	42.6	160.0	160.0	8.00	13.0	54.3	2492	889	312	111	67.8	40.5
HE 160 M	76.2	180.0	166.0	14.0	23.0	97.1	5098	1759	566	212	72.5	42.6
HE 180 AA	28.7	167.0	180.0	5.00	7.50	36.5	1967	730	236	81.1	73.4	44.7
HE 180 A	35.5	171.0	180.0	6.00	9.50	45.3	2510	925	294	103	74.5	45.2
HE 180 B	51.2	180.0	180.0	8.50	14.0	65.3	3831	1363	426	151	76.6	45.7
HE 180 M	88.9	200.0	186.0	14.5	24.0	113	7483	2580	748	277	81.3	47.7
HE 200 AA	34.6	186.0	200.0	5.50	8.00	44.1	2944	1068	317	107	81.7	49.2
HE 200 A	42.3	190.0	200.0	6.50	10.0	53.8	3692	1336	389	134	82.8	49.8
HE 200 B	61.3	200.0	200.0	9.00	15.0	78.1	5696	2003	570	200	85.4	50.7
HE 200 M	103.1	220.0	206.0	15.0	25.0	131	10640	3651	967	354	90.0	52.7
HE 220 AA	40.4	205.0	220.0	6.00	8.50	51.5	4170	1510	407	137	90.0	54.2
HE 220 A	50.5	210.0	220.0	7.00	11.0	64.3	5410	1955	515	178	91.7	55.1
HE 220 B	71.5	220.0	220.0	9.50	16.0	91.0	8091	2843	736	258	94.3	55.9
HE 220 M	117.3	240.0	226.0	15.5	26.0	149	14600	5012	1217	444	98.9	57.9
HE 240 AA	47.4	224.0	240.0	6.50	9.00	60.4	5835	2077	521	173	98.3	58.7
HE 240 A	60.3	230.0	240.0	7.50	12.0	76.8	7763	2769	675	231	101.0	60.0
HE 240 B	83.2	240.0	240.0	10.0	17.0	106	11260	3923	938	327	103.0	60.8
HE 240 M	156.7	270.0	248.0	18.0	32.0	200	24290	8153	1799	657	110.0	63.9
HE 260 AA	54.1	244.0	260.0	6.50	9.50	69.0	7981	2788	654	214	108.0	63.6
HE 260 A	68.2	250.0	260.0	7.50	12.5	86.8	10450	3668	836	282	110.0	65.0
HE 260 B	93.0	260.0	260.0	10.0	17.5	118	14920	5135	1148	395	112.0	65.8
HE 260 M	172.4	290.0	268.0	18.0	32.5	220	31310	10450	2159	780	119.0	69.0
HE 280 AA	61.2	264.0	280.0	7.00	10.0	78.0	10560	3664	800	262	116.0	68.5
HE 280 A	76.4	270.0	280.0	8.00	13.0	97.3	13670	4763	1013	340	119.0	70.0
HE 280 B	103.1	280.0	280.0	10.5	18.0	131	19270	6595	1376	471	121.0	70.9
HE 280 M	188.5	310.0	288.0	18.5	33.0	240	39550	13160	2551	914	128.0	74.0

profile type	mass	dimensions				section properties						
	G	h	b	t_w	t_f	A_{tot} x 10^2	I_y x 10^4	I_z x 10^4	$W_{y;el}$ x 10^3	$W_{z;el}$ x 10^3	i_y	i_z
	[kg/m]	[mm]	[mm]	[mm]	[mm]	[mm^2]	[mm^4]	[mm^4]	[mm^3]	[mm^3]	[mm]	[mm]
HE 300 AA	69.8	283.0	300.0	7.50	10.5	88.9	13800	4734	976	316	125.0	73.0
HE 300 A	88.3	290.0	300.0	8.50	14.0	113	18260	6310	1260	421	127.0	74.9
HE 300 B	117.0	300.0	300.0	11.0	19.0	149	25170	8563	1678	571	130.0	75.8
HE 300 C	176.7	320.0	305.0	16.0	29.0	225	40950	13740	2559	901	135.0	78.1
HE 300 M	237.9	340.0	310.0	21.0	39.0	303	59200	19400	3482	1252	140.0	80.0
HE 320 AA	74.2	301.0	300.0	8.00	11.0	94.6	16450	4959	1093	331	132.0	72.4
HE 320 A	97.6	310.0	300.0	9.00	15.5	124	22930	6985	1479	466	136.0	74.9
HE 320 B	126.7	320.0	300.0	11.5	20.5	161	30820	9239	1926	616	138.0	75.7
HE 320 M	245.0	359.0	309.0	21.0	40.0	312	68130	19710	3796	1276	148.0	79.5
HE 340 AA	78.9	320.0	300.0	8.50	11.5	101	19550	5185	1222	346	139.0	71.8
HE 340 A	104.8	330.0	300.0	9.50	16.5	133	27690	7436	1678	496	144.0	74.6
HE 340 B	134.2	340.0	300.0	12.0	21.5	171	36660	9690	2156	646	146.0	75.3
HE 340 M	247.9	377.0	309.0	21.0	40.0	316	76370	19710	4052	1276	156.0	79.0
HE 360 AA	83.7	339.0	300.0	9.00	12.0	107	23040	5410	1359	361	147.0	71.2
HE 360 A	112.1	350.0	300.0	10.0	17.5	143	33090	7887	1891	526	152.0	74.3
HE 360 B	141.8	360.0	300.0	12.5	22.5	181	43190	10140	2400	676	155.0	74.9
HE 360 M	250.3	395.0	308.0	21.0	40.0	319	84870	19520	4297	1268	163.0	78.3
HE 400 AA	92.4	378.0	300.0	9.50	13.0	118	31250	5861	1654	391	163.0	70.6
HE 400 x 107	107.2	384.0	297.0	10.0	16.0	136	37640	6998	1960	471	166.0	71.6
HE 400 A	124.8	390.0	300.0	11.0	19.0	159	45070	8564	2311	571	168.0	73.4
HE 400 B	155.3	400.0	300.0	13.5	24.0	198	57680	10820	2884	721	171.0	74.0
HE 400 M	255.7	432.0	307.0	21.0	40.0	326	104100	19340	4820	1260	179.0	77.0
HE450 AA	99.7	425.0	300.0	10.0	13.5	127	41890	6088	1971	406	182.0	69.2
HE 450 x 124	123.9	435.0	300.0	10.2	18.5	158	55860	8338	2568	556	188.0	72.7
HE 450 A	139.8	440.0	300.0	11.5	21.0	178	63720	9465	2896	631	189.0	72.9
HE 450 B	171.1	450.0	300.0	14.0	26.0	218	79890	11720	3551	781	191.0	73.3
HE 450 M	263.3	478.0	307.0	21.0	40.0	335	131500	19340	5501	1260	198.0	75.9
HE 500 AA	107.4	472.0	300.0	10.5	14.0	137	54640	6314	2315	421	200.0	67.9
HE 500 A	155.1	490.0	300.0	12.0	23.0	198	86970	10370	3550	691	210.0	72.4
HE 500 B	187.3	500.0	300.0	14.5	28.0	239	107200	12620	4287	842	212.0	72.7
HE 500 M	270.3	524.0	306.0	21.0	40.0	344	161900	19150	6180	1252	217.0	74.6
HE 550 AA	120.0	522.0	300.0	11.5	15.0	153	72870	6767	2792	451	218.0	66.5
HE 550 A	166.2	540.0	300.0	12.5	24.0	212	111900	10820	4146	721	230.0	71.5
HE 550 B	199.4	550.0	300.0	15.0	29.0	254	136700	13080	4971	872	232.0	71.7
HE 550 M	278.2	572.0	306.0	21.0	40.0	354	198000	19160	6923	1252	236.0	73.5
HE 600 AA	128.8	571.0	300.0	12.0	15.5	164	91870	6993	3218	466	237.0	65.3
HE 600 x 137	137.4	575.0	300.0	11.8	17.5	175	101500	7893	3529	526	241.0	67.2
HE 600 x 151	151.2	582.0	300.0	11.6	20.6	193	117100	9287	4024	619	247.0	69.4
HE 600 x 175	175.2	588.0	300.0	13.6	23.9	223	136400	10780	4639	719	247.0	69.5
HE 600 A	177.8	590.0	300.0	13.0	25.0	226	141200	11270	4787	751	250.0	70.5
HE 600 B	211.9	600.0	300.0	15.5	30.0	270	171000	13530	5701	902	252.0	70.8
HE 600 M	285.5	620.0	305.0	21.0	40.0	364	237400	18980	7660	1244	256.0	72.2

profile type	mass	dimensions				section properties						
	G	h	b	t_w	t_f	A_{tot} x 10^2	I_y x 10^4	I_z x 10^4	$W_{y;el}$ x 10^3	$W_{z;el}$ x 10^3	i_y	i_z
	[kg/m]	[mm]	[mm]	[mm]	[mm]	[mm^2]	[mm^4]	[mm^4]	[mm^3]	[mm^3]	[mm]	[mm]
HE 650 AA	138.0	620.0	300.0	12.5	16.0	176	113900	7221	3676	481	255.0	64.1
HE 650 A	189.7	640.0	300.0	13.5	26.0	242	175200	11720	5474	782	269.0	69.7
HE 650 B	224.8	650.0	300.0	16.0	31.0	286	210600	13980	6480	932	271.0	69.9
HE 650 M	293.4	668.0	305.0	21.0	40.0	374	281700	18980	8433	1245	275.0	71.3
HE 700 AA	149.9	670.0	300.0	13.0	17.0	191	142700	7673	4260	512	273.0	63.4
HE 700 x 166	166.2	678.0	300.0	12.5	21.0	212	168900	9471	4982	631	282.0	66.9
HE 700 A	204.5	690.0	300.0	14.5	27.0	260	215300	12180	6241	812	288.0	68.4
HE 700 B	240.5	700.0	300.0	17.0	32.0	306	256900	14440	7340	963	290.0	68.7
HE 700 M	300.7	716.0	304.0	21.0	40.0	383	329300	18800	9198	1237	293.0	70.1
HE 800 AA	171.5	770.0	300.0	14.0	18.0	218	208900	8134	5426	542	309.0	61.0
HE 800 A	224.4	790.0	300.0	15.0	28.0	286	303400	12640	7682	843	326.0	66.5
HE 800 B	262.3	800.0	300.0	17.5	33.0	334	359100	14900	8977	994	328.0	66.8
HE 800 M	317.3	814.0	303.0	21.0	40.0	404	442600	18630	10870	1230	331.0	67.9
HE 900 AA	198.0	870.0	300.0	15.0	20.0	252	301100	9041	6923	603	346.0	59.9
HE 900 A	251.6	890.0	300.0	16.0	30.0	321	422100	13550	9485	903	363.0	65.0
HE 900 B	291.5	900.0	300.0	18.5	35.0	371	494100	15820	10980	1054	365.0	65.3
HE 900 M	332.5	910.0	302.0	21.0	40.0	424	570400	18450	12540	1222	367.0	66.0
HE 1000 A	221.5	970.0	300.0	16.0	21.0	282	406500	9501	8380	633	380.0	58.0
HE 1000 A	272.3	990.0	300.0	16.5	31.0	347	553800	14000	11190	934	400.0	63.5
HE 1000 B	314.0	1000.0	300.0	19.0	36.0	400	644700	16280	12890	1085	401.0	63.8
HE 1000 M	348.7	1008.0	302.0	21.0	40.0	444	722300	18460	14330	1222	403.0	64.5

(Wagemans, 2014)

Appendix I

Timber properties and profiles

H.1 Glulam

The table below shows an overview of the material properties for different strength classes of glulam.

material property			Strength class GL24h	GL28h	GL32h
Bending	$f_{m,k}$	[N/mm²]	24	28	32
Tension //	$f_{t,0,k}$	[N/mm²]	16,5	19,5	22,5
Tension ⊥	$f_{t,90,k}$	[N/mm²]	0,4	0,45	0,5
Compression //	$f_{c,0,k}$	[N/mm²]	24	26,5	29
Compression ⊥	$f_{c,90,k}$	[N/mm²]	2,7	3,0	3,3
Shear	$f_{v,k}$	[N/mm²]	2,7	3,2	3,8
Mean MOE* //	$E_{0,mean}$	[N/mm²]	11600	12600	13700
5% MOE //	$E_{0,05}$	[N/mm²]	9400	10200	11100
Mean MOE ⊥	$E_{90,mean}$	[N/mm²]	390	420	460
Mean shear modulus	G_{mean}	[N/mm²]	720	780	850
Density	ρ_k	[kg/m³]	380	410	430
Mean density	ρ_{mean}	[kg/m³]	420	450	470

(Wagemans, 2014)

The following table gives an overview of the possible cross sections of glulam beams and columns.

	width 55 mm			width 85 mm			width 110 mm		
h	A 10^3 [mm^2]	W_y 10^6 [mm^3]	I_y 10^6 [mm^4]	A 10^3 [mm^2]	W_y 10^6 [mm^3]	I_y 10^6 [mm^4]	A 10^3 [mm^2]	W_y 10^6 [mm^3]	I_y 10^6 [mm^4]
200	11,0	0,36	36,6	17,0	0,56	56,6	22,0	0,73	73,3
250	13,7	0,57	71,6	21,2	0,88	110,6	27,5	1,14	143,2
300	16,5	0,82	123,7	25,5	1,27	191,2	33,0	1,65	247,5
350	19,2	1,12	196,5	29,7	1,73	303,6	38,5	2,24	393,0
400	22,0	1,46	293,3	34,0	2,26	453,3	44,0	2,93	586,6
450	24,7	1,85	417,6	38,2	2,86	645,4	49,5	3,71	835,3
500	27,5	2,29	572,9	42,5	3,54	885,4	55,0	4,58	1145,8
550	30,2	2,77	762,5	46,7	4,28	1178,4	60,5	5,54	1525,1
600				51,0	5,10	1530,0	66,0	6,60	1980,0
650				55,2	5,98	1945,2	71,5	7,74	2517,3
700				59,5	6,94	2429,5	77,0	8,98	3144,1
750				63,7	7,96	2988,2	82,5	10,31	3867,1
800				68,0	9,06	3626,6	88,0	11,73	4693,3
850				72,2	10,23	4350,0	93,5	13,24	5629,4
900							99,0	14,85	6682,5
950							104,5	16,54	7859,2
1000							110,0	18,33	9166,6
1050							115,5	20,21	10611,5
1100							121,0	22,18	12200,8
1150									

	width 135 mm			width 160 mm			width 185 mm			width 205 mm		
h	A 10^3 [mm^2]	W_y 10^6 [mm^3]	I_y 10^6 [mm^4]	A 10^3 [mm^2]	W_y 10^6 [mm^3]	I_y 10^6 [mm^4]	A 10^3 [mm^2]	W_y 10^6 [mm^3]	I_y 10^6 [mm^4]	A 10^3 [mm^2]	W_y 10^6 [mm^3]	I_y 10^6 [mm^4]
200	27,0	0,90	90,0	32,0	1,06	106,6	37,0	1,23	123,3	41,0	1,36	136,6
250	33,7	1,40	175,7	40,0	1,66	208,3	46,2	1,92	240,8	51,2	2,13	266,9
300	40,5	2,02	303,7	48,0	2,40	360,0	55,5	2,77	416,2	61,5	3,07	461,2
350	47,2	2,75	482,3	56.0	3,26	571,6	64,7	3,77	660,9	71,7	4,18	732,4
400	54,0	3,60	720,0	64,0	4,26	853,3	74,0	4,93	986,6	82,0	5,46	1093,3
450	60,7	4,55	1025,1	72,0	5,40	1215,0	83,2	6,24	1404,8	92,2	6,91	1556,7
500	67,5	5,62	1406,2	80,0	6,66	1666,6	92,5	7,70	1927,0	102,5	8,54	2135,4
550	74,2	6,80	1871,7	88,0	8,06	2218,3	101,7	9,32	2564,9	112,7	10,33	2842,2
600	81,0	8,10	2430,0	96,0	9,60	2880,0	111,0	11,10	3330,0	123,0	12,30	3690,0
650	87,7	9,50	3089,5	104,0	11,26	3661,6	120,2	13,02	4233,8	133,2	14,43	4691,5
700	94,5	11,02	3858,7	112,0	13,06	4573,3	129,5	15,10	5287,9	143,5	16,74	5859,5
750	101,2	12,65	4746,0	120,0	15,00	5625,0	138,7	17,34	6503,9	153,7	19,21	7207,0
800	108,0	14,40	5760,0	128,0	17,06	6826,6	148,0	19,73	7893,3	164,0	21,86	8746,6
850	114,7	16,25	6908,9	136,0	19,26	8188,3	157,2	22,27	9467,7	174,2	24,68	10491,3
900	121,5	18,22	8201,2	144,0	21,60	9720,0	166,5	24,97	11238,7	184,5	27,67	12453,7
950	128,2	20,30	9645,4	152,0	24,06	11431,6	175,7	27,82	13217,8	194,7	30,83	14646,8
1000	135,0	22,50	11250,0	160,0	26,66	13333,3	185,0	30,83	15416,6	205,0	34,16	17083,3
1050	141,7	24,80	13023,2	168,0	29,40	15435,0	194,2	33,99	17846,7	215,2	37,66	19776,0
1100	148,5	27,22	14973,7	176,0	32,26	17746,6	203,5	37,30	20519,5	225,5	41,34	22737,9
1150	155,2	29,75	17109,8	184,0	35,26	20278,3	212,7	40,77	23446,8	235,7	45,18	25981,6
1200	162,0	32,40	19440,0	192,0	38,40	23040,0	222,0	44,40	26640,0	246,0	49,20	29520,0
1250	168,7	35,15	21972,6	200,0	41,66	26041,6	231,2	48,17	30110,6	256,2	53,38	33365,8
1300	175,5	38,02	24716,2	208,0	45,06	29293,3	240,5	52,10	33870,4	266,5	57,74	37532,0
1350	182,2	41,00	27679,2	216,0	48,60	32805,0	249,7	56,19	37930,7	276,7	62,26	42031,4
1400				224,0	52,26	36586,6	259,0	60,43	42303,3	287,0	66,96	46876,6
1450				232,0	56,06	40648,3	268,2	64,82	46999,6	297,2	71,83	52080,6
1500				240,0	60,00	45000,0	277,5	69,37	52031,2	307,5	76,87	57656,2
1550				248,0	64,06	49651,6	286,7	74,07	57409,7	317,7	82,08	63616,1
1600				256,0	68,26	54613,3	296,0	78,93	63146,6	328,0	87,46	69973,3
1650							305,2	83,94	69253,5	338,2	93,01	76740,4
1700							314,5	89,10	75742,0	348,5	98,74	83930,4
1750							323,7	94,42	82623,6	358,7	104,63	91555,9
1800							333,0	99,90	89910,0	369,0	110,70	99630,0

(Wagemans, 2014)

H.2 LVL

The table below gives an overview of various LVL strength classes and their material properties.

	Property [a]	Symbol	Unit	Strength class LVL 32 P	LVL 35 P	LVL 48 P	LVL 50 P	LVL 80 P
Bending strength	Edgewise, parallel to grain (depth 300 mm)	$f_{m,0,edge,k}$	N/mm²	27	30	44	46	75
	Flatwise, parallel to grain	$f_{m,0,flat,k}$	N/mm²	32	35	48	50	80
	Size effect parameter	s	–	0,15	0,15	0,15	0,15	0,15
Tension strength	Parallel to grain (length 3 000 mm)	$f_{t,0,k}$	N/mm²	22	22	35	36	60
	Perpendicular to grain, edgewise	$f_{t,90,edge,k}$	N/mm²	0,5	0,5	0,8	0,9	1,5
Compression strength	Parallel to grain for service class 1	$f_{c,0,k}$	N/mm²	26	30	35	42	69
	Parallel to grain for service class 2 [b]	$f_{c,0,k}$	N/mm²	21	25	29	35	57
	Perpendicular to grain, edgewise	$f_{c,90,edge,k}$	N/mm²	4	6	6	8,5	14
	Perpendicular to grain, flatwise (except pine)	$f_{c,90,flat,k}$	N/mm²	0,8	2,2	2,2	3,5	12
	Perpendicular to grain, flatwise, pine	$f_{c,90,flat,k,pine}$	N/mm²	MDV [c]	3,3	3,3	3,5	– [d]
Shear strength	Edgewise parallel to grain	$f_{v,0,edge,k}$	N/mm²	3,2	3,2	4,2	4,8	8
	Flatwise, parallel to grain	$f_{v,0,flat,k}$	N/mm²	2,0	2,3	2,3	3,2	8
Modulus of elasticity	Parallel to grain	$E_{0,mean}$ [e]	N/mm²	9 600	12 000	13 800	15 200	16 800
	Parallel to grain	$E_{0,k}$ [f]	N/mm²	8 000	10 000	11 600	12 600	14 900
	Perpendicular to grain, edgewise	$E_{c,90,edge,mean}$ [g]	N/mm²	MDV [c]	MDV [c]	430	430	470
	Perpendicular to grain, edgewise	$E_{c,90,edge,k}$ [h]	N/mm²	MDV [c]	MDV [c]	350	350	400
Shear modulus	Edgewise, parallel to grain	$G_{0,edge,mean}$	N/mm²	500 [i]	500 [i]	600	650	760
	Edgewise, parallel to grain	$G_{0,edge,k}$	N/mm²	300 [i]	350 [i]	400	450	630
	Flatwise, parallel to grain	$G_{0,flat,mean}$	N/mm²	320 [i]	380 [i]	380	600	850
	Flatwise, parallel to grain	$G_{0,flat,k}$	N/mm²	240 [i]	270 [i]	270	400	760
Density		ρ_{mean}	kg/m³	440	510	510	580	800
		ρ_k	kg/m³	410	480	480	550	730

(Ingenieur Holzbau.de; Finnish Woodworking Industries, 2019)

As stated in the section on LVL timber products, the available sizes for LVL are limited compared to glulam. The maximum width is limited to 160 mm, the maximum height is limited to 600 mm.

The following table shows an overview of the strength characteristics for CL28h. The same cross sectional properties are used as for glulam.

Base material T14; CV[$f_{t,0,\ell}$] =		25 ± 5 %	35 ± 5 %
Property [–]	**Symbol [–]**	**CL 24h**	**CL 28h**
Bending strength	$f_{m,CLT,k}$ [N/mm²]	24.0	28.0
Tensile strength perpendicular to grain	$f_{t,90,CLT,k}$ [N/mm²]	0.5	
Compression strength perpendicular to grain	$f_{c,90,CLT,k}$ [N/mm²]	3.0	
Shear strength	$f_{v,CLT,k}$ [N/mm²]	3.5	
Rolling shear strength	$f_{r,CLT,k}$ [N/mm²] $f_{r,lay,k}$ [N/mm²]	1.40, for $w_\ell / t_\ell \geq 4$ 0.80, for $w_\ell / t_\ell < 4$	
Modulus of elasticity parallel to grain	$E_{0,CLT,mean}$ [N/mm²] $E_{0,lay,mean}$ [N/mm²]	11,600	
Modulus of elasticity perpendicular to grain	$E_{90,CLT,mean}$ [N/mm²] $E_{90,lay,mean}$ [N/mm²]	300	
Modulus of elasticity in compression perp. to grain	$E_{c,90,CLT,mean}$ [N/mm²]	450	
Shear modulus	$G_{0,lay,mean}$ [N/mm²]	650	
Rolling shear modulus	$G_{r,lay,mean}$ [N/mm²]	100, for $w_\ell / t_\ell \geq 4$ 65, for $w_\ell / t_\ell < 4$	
Elastic & shear properties' 5 %-quantiles	$E_{CLT,05}$ [N/mm²] $E_{lay,05}$ [N/mm²] $G_{CLT,05}$ [N/mm²] $G_{lay,05}$ [N/mm²]	$E_{05} = 5/6\ E_{mean}$ $G_{05} = 5/6\ G_{mean}$	

Base material T14; CV[$f_{t,0,\ell}$] =		25 ± 5 %	35 ± 5 %
Property [–]	**Symbol [–]**	**CL 24h**	**CL 28h**
Tensile strength parallel to grain	$f_{t,0,CLT,net,k}$ [N/mm²]	16.0	18.0
Compression strength parallel to grain	$f_{c,0,CLT,net,k}$ [N/mm²]	24.0	28.0
Shear strength in-plane (shear & torsion)	$f_{v,net,k,ref}$ [N/mm²] $f_{v,gross,k}$ [N/mm²] $f_{T,node,k}$ [N/mm²]	5.5 3.5 2.5	
Shear modulus in-plane	$G_{CLT,mean}$ [N/mm²]	450 [a)] 650 [b)]	
Shear properties' 5 %-quantiles	$G_{CLT,05}$ [N/mm²]	$G_{05} = 5/6\ G_{mean}$	

[a)] simplified value for CLT without narrow face bonding or with cracks or checks; more detailed approach provided by [31]

[b)] CLT with narrow face bonding; edge bonding has to be secured over the entire lifetime

(Falk, Dietsch, & Schmid, 2016)

Appendix J

Formulas used for wind loads

Building parameters and wind forces for ESA/ESTEC - design strategy 2

h	12	m	loaction:		Noordwijk
d	30.6	m	windregion:		II, coastal
b	37.8	m	qp [kN/m2]:		1.36
e	24	m			

linear interpolation for h 10-15 m

h	qp(h)		lin. int h	0.022
10	1.32			
11	1.34			
12	1.36			
13	1.39			
14	1.41			
15	1.43			

wind loading on facade

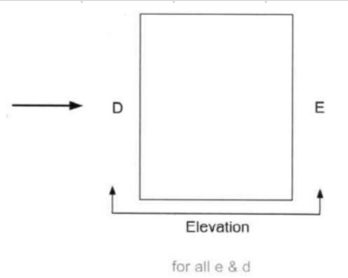
values for cf

h/d	A	B	C	D	E
≥5	-1.2	-0.8	-0.5	0.8	-0.7
1	-1.2	-0.8	-0.5	0.8	-0.5
≤0.25	-1.2	-0.8	-0.5	0.7	-0.3

h/d	0.392157

Linear interpolation for h/d 0.25-1

h/d	cf zone D	cf zone E			
0.25	0.70	-0.30		lin. int D	0.006667
0.30	0.71	-0.31		lin. int E	-0.01333
0.35	0.71	-0.33			
0.40	0.72	-0.34			
0.45	0.73	-0.35			
0.50	0.73	-0.37			
0.55	0.74	-0.38			
0.60	0.75	-0.39			
0.65	0.75	-0.41			
0.70	0.76	-0.42			
0.75	0.77	-0.43			
0.80	0.77	-0.45			
0.85	0.78	-0.46			
0.90	0.79	-0.47			
0.95	0.79	-0.49			
1.00	0.80	-0.50			



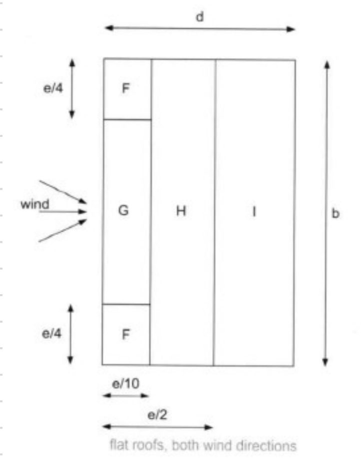
cscd	1.00		
cf_D	0.72		
cf_E	-0.34		
qp	1.36	kN/m2	
b_ref	7.00	m	*distance between load bearing columns*
Fwind_D	6.9	kN/m	
Fwind_E	-3.2	kN/m	

wind loading on flat roof

values for cf

F	G	H	I
-1.8	-1.2	-0.7	-0.2

height F	6	m
width F	2.4	m
height G	25.8	m
width G	2.4	m
width H	9.6	m
width I	18.6	m



cscd	1.00		
cf_F	-1.80		
cf_G	-1.20		
cf_H	-0.70		
cf_I	-0.20		
qp	1.36	kN/m2	
b_ref	7.00	m	*distance between load bearing columns*
Fwind_F	-17.2	kN/m	
Fwind_G	-11.5	kN/m	
Fwind_H	-6.7	kN/m	
Fwind_I	-1.9	kN/m	

Building parameters and wind forces for ESA/ESTEC - design strategy 3

h	12	m	loaction:		Noordwijk
d	30.6	m	windregion:		II, coastal
b	37.8	m	qp [kN/m2]:		1.36
e	24	m			

linear interpolation for h 10-15 m

h	qp(h)		lin. int h	0.022
10	1.32			
11	1.34			
12	1.36			
13	1.39			
14	1.41			
15	1.43			

wind loading on facade

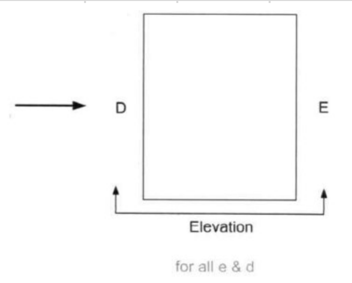
values for cf

h/d	A	B	C	D	E
≥5	-1.2	-0.8	-0.5	0.8	-0.7
1	-1.2	-0.8	-0.5	0.8	-0.5
≤0.25	-1.2	-0.8	-0.5	0.7	-0.3

h/d 0.392157

Linear interpolation for h/d 0.25-1

h/d	cf zone D	cf zone E		lin. int D	0.006667
0.25	0.70	-0.30		lin. int E	-0.01333
0.30	0.71	-0.31			
0.35	0.71	-0.33			
0.40	0.72	-0.34			
0.45	0.73	-0.35			
0.50	0.73	-0.37			
0.55	0.74	-0.38			
0.60	0.75	-0.39			
0.65	0.75	-0.41			
0.70	0.76	-0.42			
0.75	0.77	-0.43			
0.80	0.77	-0.45			
0.85	0.78	-0.46			
0.90	0.79	-0.47			
0.95	0.79	-0.49			
1.00	0.80	-0.50			



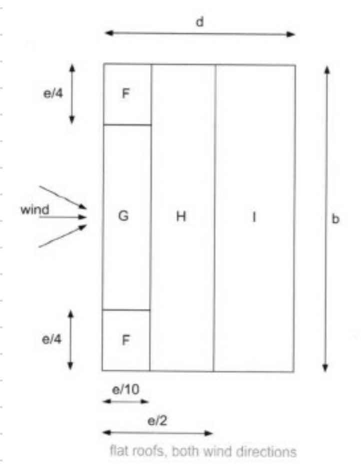
cscd	1.00		
cf_D	0.72		
cf_E	-0.34		
qp	1.36	kN/m2	
b_ref	5.00	m	*distance between load bearing columns*
Fwind_D	4.9	kN/m	
Fwind_E	-2.3	kN/m	

wind loading on flat roof

values for cf

F	G	H	I
-1.8	-1.2	-0.7	-0.2

height F	6	m
width F	2.4	m
height G	25.8	m
width G	2.4	m
width H	9.6	m
width I	18.6	m



cscd	1.00		
cf_F	-1.80		
cf_G	-1.20		
cf_H	-0.70		
cf_I	-0.20		
qp	1.36	kN/m2	
b_ref	5.00	m	*distance between load bearing columns*
Fwind_F	-12.3	kN/m	
Fwind_G	-8.2	kN/m	
Fwind_H	-4.8	kN/m	
Fwind_I	-1.4	kN/m	

Appendix K

Formulas used for ULS checks

ULS - Concrete beam - standard reinforcement					
cross section	b		mm		
	h		mm		
	A	b*h	mm2		
	W	(1/6)*b*h^2	mm3		
	I	(1/12)*b*h^3	mm4		
reinforcement	gamma_s	1.15			
	f_tk		N/mm2		
	f_yd	f_tk/gamma_s	N/mm2		
	diameter		mm	spacing	(b-2*c-n*bars)/(bars-1)
	bars			min. spacing	max(c ; 37mm ; 20 mm)
	As	pi * (1/2 d) ^2 * n	mm2		
	Ac	A - As	mm2		
	rho	min(As/(b*d) ; 0.02)			
	c	20	mm		
	stirrups	8	mm		
	d	h-c-stirrups-(1/2)*bars	mm		
beam span	l		mm		
E modulus	E		N/mm2		
strenght	gamma_c	1.5			
	f_ck		N/mm2		
	f_cd	f_ck/gamma_c	N/mm2		
	f_ctk		N/mm2		
	f_ctd	f_ctk/gamma_c	N/mm2		
forces	Mmax		kNm	*1000^2	Nmm
MatrixFrame	Nmax		kN	*1000	N
	Vmax		kN	*1000	N
check (moment)	Ns	As*f_yd	N		
	Nc	Ns-Nmax	N		
	alpha	0.75			
	beta	0.39			
	x_u	Nc/(alpha*b*f_cd)	mm		
	Mrd	Ns*d-Nmax*(1/2)*h-Nc*beta*x_u	Nmm	UC_moment	Mmax/Mrd
check (shear)	k	min(1+wortel(200/d) ; 2)			
	sigma_cp	Nmax/Ac	N/mm2	*should be smaller than 6 N/mm2*	
	Crd_c	0.12			
	k1	0.15			
	Vrd_c	(Crd_c*k*(100*rho*f_ck)^(1/3)+k1*sigma_cp)*b*d	N		
	v_min	0.035*k^(3/2)*wortel(f_ck)	N/mm2		
	Vrd_c_min	(v_min+k1*sigma_cp)*b*d	N		
	Vrd_c_final	max(Vrd_c ; Vrd_c_min)	N	UC_shear	Vmax/Vrd_c_final
				stirrups are necessary when UC_shear > 1	

ULS - Concrete column - standard reinforcement - maximum M

cross section	b		mm			
	h		mm			
	A	b*h	mm2			
	W	(1/6)*b*h^2	mm3			
	I	(1/12)*b*h^3	mm4			
column height	l		mm			
	l_cr	l*0.7	mm			
E modulus	E		N/mm2			
strenght	gamma_c	1.5				
	f_ck		N/mm2			
	f_cd	f_ck/gamma_c	N/mm2			
	f_ctk		N/mm2			
	f_ctd	f_ctk/gamma_c	N/mm2			
forces	Mmax		kNm	*1000^2	Nmm	
MatrixFrame	Nmax		kN	*1000	N	
	Vmax		kN	*1000	N	
check (stress)	sigma_c1	N/A-M/W	N/mm2	compression	UC_sigma_c1	sigma_c1/f_cd
	sigma_c2	N/A+M/W	N/mm2	compression	UC_sigma_c2	sigma_c2/f_cd
check (buckling)	F_R_buck	(pi^2*EI)/l_cr^2	N		UC_buck	Nmax/F_R_buck
check (shear)	k	min(1+wortel(200/d) ; 2)				
	Vrd_c_min	0.035*k^(3/2)*wortel(f_ck)*b*h	N		UC_shear	Vmax/Vrd_c_min

ULS - Concrete column - standard reinforcement - maximum N

forces	Mmax		kNm	*1000^2	Nmm	
MatrixFrame	Nmax		kN	*1000	N	
check (stress)	sigma_c1	N/A-M/W	N/mm2	compression	UC_sigma_c1	sigma_c1/f_cd
	sigma_c2	N/A+M/W	N/mm2	compression	UC_sigma_c2	sigma_c2/f_cd
check (buckling)	F_R_buck	(pi^2*EI)/l_cr^2	N		UC_buck	Nmax/F_R_buck

ULS - Metal beam						
cross section	profile					
	h		mm			
	b		mm			
	t_web		mm			
	t_flange		mm			
	A_web	(h-(2*t_flange))*t_web	mm2			
	A_total		mm2			
	I_y		mm4			
	I_z		mm4			
	W_y		mm3			
	W_z		mm3			
	i_y		mm			
	i_z		mm			
beam span	l		mm			
E modulus	E		N/mm2			
strength	gamma_m0	1				
	gamma_m1	1				
	f_yd		N/mm2			
	f_td		N/mm2			
forces	Mmax		kNm	*1000^2	Nmm	
MatrixFrame	Nmax		kN	*1000	N	
	Vmax		kN	*1000	N	
check (moment)	M_el,rd	(W_y*f_yd)/gamma_m0	Nmm		UC_moment	Mmax/M_el,rd
check (shear)	V_pl,rd	(A_web*(f_yd/wortel(3))/gamma_m0	N		UC_shear	Vmax/V_pl,rd
check (axial)	N_pl,rd	(A_total*f_yd)/gamma_m0	N		UC_axial	Nmax/N_pl,rd
check (combi)	M + N	UC_moment+UC_axial<1			UC_combi	UC_moment+UC_axial

ULS - Metal column						
cross section	profile					
	h		mm			
	b		mm			
	t_web		mm			
	t_flange		mm			
	A_web	(h-(2*t_flange))*t_web	mm2			
	A_total		mm2			
	I_y		mm4			
	I_z		mm4			
	W_y		mm3			
	W_z		mm3			
	i_y		mm			
	i_z		mm			
column height	l		mm			
	l_cr	l*0.7	mm			
E modulus	E		N/mm2			
strength	gamma_m0	1				
	gamma_m1	1				
	f_yd		N/mm2			
	f_td		N/mm2			
forces	Mmax		kNm	*1000^2	Nmm	
MatrixFrame	Nmax		kN	*1000	N	
	Vmax		kN	*1000	N	
check (moment)	M_el,rd	(W_y*f_yd)/gamma_m0	Nmm		UC_moment	Mmax/M_el,rd
check (shear)	V_pl,rd	(A_web*(f_yd/wortel(3))/gamma_m0	N		UC_shear	Vmax/V_pl,rd
check (axial)	N_pl,rd	(A_total*f_yd)/gamma_m0	N		UC_axial	Nmax/N_pl,rd
check (combi)	M + N	UC_moment+UC_axial<1			UC_combi	UC_moment+UC_axial
check (buckling)	weak axis	z-axis				
around weak axis	lambda_1	76				
	lambda	l_cr/(i_z*lambda_1)	(slenderness)			
	h/b ratio	h/b				
	if h/b < 1.2	*buckling curve c*	alpha_c	0.49		
	if h/b > 1.2	*buckling curve b*	alpha_b	0.34		
	phi	0.5*(1+alpha*(lambda-0.2)+lambda^2)				
	chi	1/(phi+wortel(phi^2-lambda^2)				
	F_R_buck	chi*((A_total*f_yd)/gamma_m1)	N		UC_buckling	Nmax/F_R_buck

ULS - Timber beam						
cross section	b		mm			
	h		mm			
	A	b*h	mm2			
	W	(1/6)*b*h^2	mm3			
	I	(1/12)*b*h^3	mm4			
beam span	l		mm			
E modulus	E_0,mean		N/mm2			
	E_90,mean		N/mm2			
strength	gamma_m	1.25				
	k_mod	0.80				
	f_m,k		N/mm2			
	f_t,0,k		N/mm2			
	f_c,0,k		N/mm2			
	f_v,k		N/mm2			
forces	Mmax		kNm	*1000^2	Nmm	
MatrixFrame	Nmax		kN	*1000	N	
	Vmax		kN	*1000	N	
check (stress)	sigma_1	-(N/A)-(M/W)	N/mm2		UC_sigma_1	sigma_1/f_d,m,k
	sigma_2	-(N/A)+(M/W)	N/mm2		UC_sigma_2	sigma_2/f_d,m,k
	f_d,m,k	(f_m,k*k_mod)/gamma_m				
check (shear)	k_cr	0.67	*for laminated timber*			
	b_ef	k_cr*b	mm			
	Vrd	((f_v,k*k_mod)/gamma_m)*b_ef*h	N		UC_shear	Vmax/Vrd
check (axial)	Nrd	((f_c,0,k*k_mod)/gamma_m)*A	N		UC_axial	Nmax/Nrd

ULS - Timber beam						
cross section	b		mm			
	h		mm			
	A	b*h	mm2			
	W	(1/6)*b*h^2	mm3			
	I	(1/12)*b*h^3	mm4			
beam span	l		mm			
E modulus	E_0,mean		N/mm2			
	E_90,mean		N/mm2			
strength	gamma_m	1.25				
	k_mod	0.80				
	f_m,k		N/mm2			
	f_t,0,k		N/mm2			
	f_c,0,k		N/mm2			
	f_v,k		N/mm2			
forces	Mmax		kNm	*1000^2	Nmm	
MatrixFrame	Nmax		kN	*1000	N	
	Vmax		kN	*1000	N	
check (stress)	sigma_1	-(N/A)-(M/W)	N/mm2		UC_sigma_1	sigma_1/f_d,m,k
	sigma_2	-(N/A)+(M/W)	N/mm2		UC_sigma_2	sigma_2/f_d,m,k
	f_d,m,k	(f_m,k*k_mod)/gamma_m				
check (shear)	k_cr	0.67	*for laminated timber*			
	b_ef	k_cr*b	mm			
	Vrd	((f_v,k*k_mod)/gamma_m)*b_ef*h	N		UC_shear	Vmax/Vrd
check (axial)	Nrd	((f_c,0,k*k_mod)/gamma_m)*A	N		UC_axial	Nmax/Nrd
check (buckling)	F_R_buck	(pi^2*EI)/l_cr^2	N		UC_buck	Nmax/F_R_buck

Appendix L

Design ESA/ESTEC – design strategy 2

ULS - Concrete beam C35/45 (prefab) - standard reinforcement						
cross section	b	450	mm			
	h	650	mm			
	A	292500	mm2			
	W	31687500	mm3	W = 1/6 bh^2		
	I	10298437500	mm4	I = 1/12 bh^3		
reinforcement	gamma_s	1.15				
	f_tk	500	N/mm2			
	f_yd	435	N/mm2			
	diameter	32	mm	spacing	38.8	mm
	bars	6		min. spacing	37	mm
	As	4825	mm2			
	Ac	287675	mm2			
	rho	0.02				
	c	32	mm			
	stirrups	8	mm			
	d	594	mm			
beam span	l	10000	mm			
E modulus	E	34000	N/mm2			
strenght	gamma_c	1.50				
	f_ck	45.00	N/mm2			
	f_cd	30.00	N/mm2	f_cd = f_ck / gamma_c		
	f_ctk	2.20	N/mm2			
	f_ctd	1.47	N/mm2	f_ctd = f_ctk / gamma_c		
forces	Mmax	975.94	kNm	975940000	Nmm	
MatrixFrame	Nmax	29.13	kN	29130	N	
	Vmax	390.37	kN	390370	N	
check (moment)	Ns	2098037.53	N			
	Nc	2068907.53	N			
	alpha	0.75				
	beta	0.39				
	x_u	204.34	mm			
	Mrd	1072362934.84	Nmm	UC_moment	0.91	
check (shear)	k	1.58				
	sigma_cp	0.10	N/mm2	*should be smaller than 6 N/mm2*		
	Crd_c	0.12				
	k1	0.15				
	Vrd_c	223589.75	N			
	v_min	0.47	N/mm2			
	Vrd_c_min	128731.08	N			
	Vrd_c_final	223589.75	N	UC_shear	1.75	
				stirrups are necessary		

SLS - Concrete beam C35/45 (prefab) - standard reinforcement						
w_max	40	mm				
max deflection (SLS)	25.20	mm			UC_deflection	0.63

ULS - Concrete column C35/45 (prefab) - standard reinforcement - maximum M						
cross section	b	300	mm			
	h	300	mm			
	A	90000	mm2			
	W	4500000	mm3	W = 1/6 bh^2		
	I	675000000	mm4	I = 1/12 bh^3		
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E	34000	N/mm2			
strenght	gamma_c	1.50				
	f_ck	45.00	N/mm2			
	f_cd	30.00	N/mm2	f_cd = f_ck / gamma_c		
	f_ctk	2.20	N/mm2			
	f_ctd	1.47	N/mm2	f_ctd = f_ctk / gamma_c		
forces	Mmax	-11.53	kNm	-11530000	Nmm	
MatrixFrame	Nmax	907.88	kN	907880	N	
	Vmax	16.54	kN	16540	N	
check (stress)	sigma_c1	-7.525333333	N/mm2	compression	UC_sigma_c1	0.25
	sigma_c2	-12.64977778	N/mm2	compression	UC_sigma_c2	0.42
check (buckling)	F_R_buck	22827656.44	N		UC_buck	0.04
check (shear)	k	1.816496581				
	Vrd_c_min	51733.12	N		UC_shear	0.32

ULS - Concrete column C35/45 (prefab) - standard reinforcement - maximum N						
forces	Mmax	0.00	kNm	0	Nmm	
MatrixFrame	Nmax	1807.65	kN	1807650	N	
check (stress)	sigma_c1	-20.085	N/mm2	compression	UC_sigma_c1	0.67
	sigma_c2	-20.085	N/mm2	compression	UC_sigma_c2	0.67
check (buckling)	F_R_buck	22827656.44	N		UC_buck	0.08

ULS - Lightweight concrete beam C40/44 (prefab) - standard reinforcement						
cross section	b	400	mm			
	h	750	mm			
	A	300000	mm2			
	W	37500000	mm3	W = 1/6 bh^2		
	I	14062500000	mm4	I = 1/12 bh^3		
reinforcement	gamma_s	1.15				
	f_tk	500	N/mm2			
	f_yd	435	N/mm2			
	diameter	32	mm	spacing	44	mm
	bars	5		min. spacing	37	mm
	As	4021	mm2			
	Ac	295979	mm2			
	rho	0.01				
	c	32	mm			
	stirrups	8	mm			
	d	694	mm			
beam span	l	10000	mm			
E modulus	E	18000	N/mm2			
strenght	gamma_c	1.50				
	f_ck	44.00	N/mm2			
	f_cd	29.33	N/mm2	f_cd = f_ck / gamma_c		
	f_ctk	1.84	N/mm2			
	f_ctd	1.23	N/mm2	f_ctd = f_ctk / gamma_c		
forces	Mmax	909.6	kNm	909600000	Nmm	
MatrixFrame	Nmax	29.18	kN	29180	N	
	Vmax	363.84	kN	363840	N	
check (moment)	Ns	1748364.61	N			
	Nc	1719184.61	N			
	alpha	0.75				
	beta	0.39				
	x_u	195.36	mm			
	Mrd	1071809090.46	Nmm	UC_moment	0.85	
check (shear)	k	1.54				
	sigma_cp	0.10	N/mm2	*should be smaller than 6 N/mm2*		
	Crd_c	0.12				
	k1	0.15				
	Vrd_c	208603.82	N			
	v_min	0.44	N/mm2			
	Vrd_c_min	126892.04	N			
	Vrd_c_final	208603.82	N	UC_shear	1.74	
				stirrups are necessary		

SLS - Lightweight concrete beam C40/44 (prefab) - standard reinforcement						
w_max	40	mm				
max deflection (SLS)	36.60	mm			UC_deflection	0.92

ULS - Lightweight concrete column C40/44 (prefab) - standard reinforcement - maximum M						
cross section	b	250	mm			
	h	250	mm			
	A	62500	mm2			
	W	2604167	mm3	W = 1/6 bh^2		
	I	325520833	mm4	I = 1/12 bh^3		
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E	18000	N/mm2			
strenght	gamma_c	1.50				
	f_ck	44.00	N/mm2			
	f_cd	29.33	N/mm2	f_cd = f_ck / gamma_c		
	f_ctk	1.84	N/mm2			
	f_ctd	1.23	N/mm2	f_ctd = f_ctk / gamma_c		
forces	Mmax	-11.63	kNm	-11630000	Nmm	
MatrixFrame	Nmax	813.44	kN	813440	N	
	Vmax	16.56	kN	16560	N	
check (stress)	sigma_c1	-8.54912	N/mm2	compression	UC_sigma_c1	0.29
	sigma_c2	-17.48096	N/mm2	compression	UC_sigma_c2	0.60
check (buckling)	F_R_buck	5828139.41	N		UC_buck	0.14
check (shear)	k	1.89442719				
	Vrd_c_min	37834.79	N		UC_shear	0.44

ULS - Lightweight concrete column C40/44 (prefab) - standard reinforcement - maximum N						
forces	Mmax	0.00	kNm	0	Nmm	
MatrixFrame	Nmax	1621.46	kN	1621460	N	
check (stress)	sigma_c1	-25.94336	N/mm2	compression	UC_sigma_c1	0.88
	sigma_c2	-25.94336	N/mm2	compression	UC_sigma_c2	0.88
check (buckling)	F_R_buck	5828139.41	N		UC_buck	0.28

ULS - Concrete beam C35/45 (in-situ) - standard reinforcement						
cross section	b	600	mm			
	h	700	mm			
	A	420000	mm2			
	W	49000000	mm3	W = 1/6 bh^2		
	I	17150000000	mm4	I = 1/12 bh^3		
reinforcement	gamma_s	1.15				
	f_tk	500	N/mm2			
	f_yd	435	N/mm2			
	diameter	32	mm	spacing	40	mm
	bars	8		min. spacing	37	mm
	As	6434	mm2			
	Ac	413566	mm2			
	rho	0.02				
	c	32	mm			
	stirrups	8	mm			
	d	644	mm			
beam span	l	10000	mm			
E modulus	E	34000	N/mm2			
strenght	gamma_c	1.50				
	f_ck	45.00	N/mm2			
	f_cd	30.00	N/mm2	f_cd = f_ck / gamma_c		
	f_ctk	2.20	N/mm2			
	f_ctd	1.47	N/mm2	f_ctd = f_ctk / gamma_c		
forces	Mmax	1391.25	kNm	1391250000	Nmm	
MatrixFrame	Nmax	29.16	kN	29160	N	
	Vmax	556.50	kN	556500	N	
check (moment)	Ns	2797383.37	N			
	Nc	2768223.37	N			
	alpha	0.75				
	beta	0.39				
	x_u	205.05	mm			
	Mrd	1570562288.63	Nmm	UC_moment	0.89	
check (shear)	k	1.56				
	sigma_cp	0.07	N/mm2	*should be smaller than 6 N/mm2*		
	Crd_c	0.12				
	k1	0.15				
	Vrd_c	308504.20	N			
	v_min	0.46	N/mm2			
	Vrd_c_min	180390.10	N			
	Vrd_c_final	308504.20	N	UC_shear	1.80	
				stirrups are necessary		

SLS - Concrete beam C35/45 (in-situ) - standard reinforcement						
w_max	40	mm				
max deflection (SLS)	23.80	mm			UC_deflection	0.60

ULS - Doncrete column C35/45 (in-situ) - standard reinforcement - maximum M

cross section	b	300	mm			
	h	300	mm			
	A	90000	mm2			
	W	4500000	mm3	W = 1/6 bh^2		
	I	675000000	mm4	I = 1/12 bh^3		
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E	34000	N/mm2			
strenght	gamma_c	1.50				
	f_ck	45.00	N/mm2			
	f_cd	30.00	N/mm2	f_cd = f_ck / gamma_c		
	f_ctk	2.20	N/mm2			
	f_ctd	1.47	N/mm2	f_ctd = f_ctk / gamma_c		
forces	Mmax	-11.59	kNm	-11590000	Nmm	
MatrixFrame	Nmax	1259.25	kN	1259250	N	
	Vmax	16.55	kN	16550	N	
check (stress)	sigma_c1	-11.41611111	N/mm2	compression	UC_sigma_c1	0.38
	sigma_c2	-16.56722222	N/mm2	compression	UC_sigma_c2	0.55
check (buckling)	F_R_buck	22827656.44	N		UC_buck	0.06
check (shear)	k	1.816496581				
	Vrd_c_min	51733.12	N		UC_shear	0.32

ULS - Concrete column C35/45 (in-situ) - standard reinforcement - maximum N

forces	Mmax	0.00	kNm	0	Nmm	
MatrixFrame	Nmax	2510.40	kN	2510400	N	
check (stress)	sigma_c1	-27.89333333	N/mm2	compression	UC_sigma_c1	0.93
	sigma_c2	-27.89333333	N/mm2	compression	UC_sigma_c2	0.93
check (buckling)	F_R_buck	22827656.44	N		UC_buck	0.11

ULS - Lightweight concrete beam C40/44 (in-situ) - standard reinforcement						
cross section	b	550	mm			
	h	750	mm			
	A	412500	mm2			
	W	51562500	mm3	W = 1/6 bh^2		
	I	19335937500	mm4	I = 1/12 bh^3		
reinforcement	gamma_s	1.15				
	f_tk	500	N/mm2			
	f_yd	435	N/mm2			
	diameter	32	mm	spacing	43.6666667	mm
	bars	7		min. spacing	37	mm
	As	5630	mm2			
	Ac	406870	mm2			
	rho	0.01				
	c	32	mm			
	stirrups	8	mm			
	d	694	mm			
beam span	l	10000	mm			
E modulus	E	18000	N/mm2			
strenght	gamma_c	1.50				
	f_ck	44.00	N/mm2			
	f_cd	29.33	N/mm2	f_cd = f_ck / gamma_c		
	f_ctk	1.84	N/mm2			
	f_ctd	1.23	N/mm2	f_ctd = f_ctk / gamma_c		
forces	Mmax	1293.36	kNm	1293360000	Nmm	
MatrixFrame	Nmax	29.16	kN	29160	N	
	Vmax	517.34	kN	517340	N	
check (moment)	Ns	2447710.45	N			
	Nc	2418550.45	N			
	alpha	0.75				
	beta	0.39				
	x_u	199.88	mm			
	Mrd	1499779248.16	Nmm	UC_moment	0.86	
check (shear)	k	1.54				
	sigma_cp	0.07	N/mm2	*should be smaller than 6 N/mm2*		
	Crd_c	0.12				
	k1	0.15				
	Vrd_c	286982.93	N			
	v_min	0.44	N/mm2			
	Vrd_c_min	172935.30	N			
	Vrd_c_final	286982.93	N	UC_shear	1.80	
				stirrups are necessary		

SLS - Lightweight concrete beam C40/44 (in-situ) - standard reinforcement

w_max	40	mm				
max deflection (SLS)	38.30	mm			UC_deflection	0.96

ULS - Lightweight concrete column C40/44 (in-situ) - standard reinforcement - maximum M						
cross section	b	300	mm			
	h	300	mm			
	A	90000	mm2			
	W	4500000	mm3	W = 1/6 bh^2		
	I	675000000	mm4	I = 1/12 bh^3		
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E	18000	N/mm2			
strenght	gamma_c	1.50				
	f_ck	44.00	N/mm2			
	f_cd	29.33	N/mm2	f_cd = f_ck / gamma_c		
	f_ctk	1.84	N/mm2			
	f_ctd	1.23	N/mm2	f_ctd = f_ctk / gamma_c		
forces	Mmax	-11.59	kNm	-11590000	Nmm	
MatrixFrame	Nmax	1129.33	kN	1129330	N	
	Vmax	16.55	kN	16550	N	
check (stress)	sigma_c1	-9.972555556	N/mm2	compression	UC_sigma_c1	0.34
	sigma_c2	-15.12366667	N/mm2	compression	UC_sigma_c2	0.52
check (buckling)	F_R_buck	12085229.88	N		UC_buck	0.09
check (shear)	k	1.816496581				
	Vrd_c_min	51155.08	N		UC_shear	0.32

ULS - Lightweight concrete column C40/44 (in-situ) - standard reinforcement - maximum N						
forces	Mmax	0.00	kNm	0	Nmm	
MatrixFrame	Nmax	2255.55	kN	2255550	N	
check (stress)	sigma_c1	-25.06166667	N/mm2	compression	UC_sigma_c1	0.85
	sigma_c2	-25.06166667	N/mm2	compression	UC_sigma_c2	0.85
check (buckling)	F_R_buck	12085229.88	N		UC_buck	0.19

ULS - Steel beam S355						
cross section	profile	IPE 550				
	h	550	mm			
	b	210	mm			
	t_web	11.10	mm			
	t_flange	17.20	mm			
	A_web	5723	mm2			
	A_total	13400	mm2			
	I_y	671200000	mm4			
	I_z	26680000	mm4			
	W_y	2441000	mm3			
	W_z	254000	mm3			
	i_y	223.00	mm			
	i_z	44.50	mm			
beam span	l	10000	mm			
E modulus	E	210000	N/mm2			
strength	gamma_m0	1				
	gamma_m1	1				
	f_yd	355	N/mm2			
	f_td	510	N/mm2			
forces	Mmax	577.58	kNm	577580000	Nmm	
MatrixFrame	Nmax	29.12	kN	29120	N	
	Vmax	231.03	kN	231030	N	
check (moment)	M_el,rd	866555000.00	Nmm		UC_moment	0.67
check (shear)	V_pl,rd	1173015.13	N		UC_shear	0.20
check (axial)	N_pl,rd	4757000.00	N		UC_axial	0.01
check (combi)	M + N				UC_combi	0.67
check (combi)	M + V					
	VEd	231030.00	N			
	0.5 * V_pl,rd	586507.56	N			
	*if VEd < 0.5 * V_pl,rd, combination of bending and shear may be neglected*					
SLS - Steel beam S355						
w_max	40	mm				
max deflection (SLS)	35.30	mm			UC_deflection	0.88

ULS - Steel column S355						
cross section	profile	HE 200 A				
	h	190	mm			
	b	200	mm			
	t_web	6.50	mm			
	t_flange	10.00	mm			
	A_web	1105	mm2			
	A_total	5380	mm2			
	I_y	36920000	mm4			
	I_z	13360000	mm4			
	W_y	389000	mm3			
	W_z	134000	mm3			
	i_y	82.80	mm			
	i_z	49.80	mm			
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E	210000	N/mm2			
strength	gamma_m0	1				
	gamma_m1	1				
	f_yd	355	N/mm2			
	f_td	510	N/mm2			
forces	Mmax	-11.50	kNm	-11500000	Nmm	
MatrixFrame	Nmax	1068.87	kN	1068870	N	
	Vmax	16.53	kN	16530	N	
check (moment)	M_el,rd	138095000.00	Nmm		UC_moment	0.08
check (shear)	V_pl,rd	226480.08	N		UC_shear	0.07
check (axial)	N_pl,rd	1909900.00	N		UC_axial	0.56
check (combi)	M + N				UC_combi	0.64
check (buckling)	weak axis	z-axis				
around weak axis	lambda_1	76				
	lambda	0.83	(slenderness)			
	h/b ratio	0.95				
	if h/b < 1.2	*buckling curve c*	alpha_c	0.49		
	if h/b > 1.2	*buckling curve b*	alpha_b	0.34		
	phi	1.00				
	chi	0.64				
	F_R_buck	1225975.16	N		UC_buckling	0.87

ULS - Aluminium beam 6061-T6						
cross section	profile	IPE 750x185				
	h	766	mm			
	b	267	mm			
	t_web	14.90	mm			
	t_flange	23.60	mm			
	A_web	3275	mm2			
	A_total	23600	mm2			
	I_y	2230000000	mm4			
	I_z	75100000	mm4			
	W_y	5821000	mm3			
	W_z	563000	mm3			
	i_y	308.00	mm			
	i_z	56.50	mm			
beam span	l	10000	mm			
E modulus	E	69000	N/mm2			
strength	gamma_m0	1				
	gamma_m1	1				
	f_yd	276	N/mm2			
	f_td	310	N/mm2			
forces	Mmax	539.81	kNm	539810000	Nmm	
MatrixFrame	Nmax	29.13	kN	29130	N	
	Vmax	215.92	kN	215920	N	
check (moment)	M_el,rd	1606596000.00	Nmm		UC_moment	0.34
check (shear)	V_pl,rd	521870.10	N		UC_shear	0.41
check (axial)	N_pl,rd	6513600.00	N		UC_axial	0.00
check (combi)	M + N				UC_combi	0.34
check (combi)	M + V					
	VEd	215920.00	N			
	0.5 * V_pl,rd	260935.05	N			
	if VEd < 0.5 * V_pl,rd, combination of bending and shear may be neglected					

SLS - Aluminium beam 6061-T6						
w_max	40	mm				
max deflection (SLS)	36.70	mm			UC_deflection	0.92

ULS - Aluminium column 6061-T6						
cross section	profile	HE 220 A				
	h	210	mm			
	b	220	mm			
	t_web	7.00	mm			
	t_flange	11.00	mm			
	A_web	1316	mm2			
	A_total	6430	mm2			
	I_y	54100000	mm4			
	I_z	19550000	mm4			
	W_y	515000	mm3			
	W_z	178000	mm3			
	i_y	91.70	mm			
	i_z	55.10	mm			
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E	69000	N/mm2			
strength	gamma_m0	1				
	gamma_m1	1				
	f_yd	276	N/mm2			
	f_td	310	N/mm2			
forces	Mmax	-11.54	kNm	-11540000	Nmm	
MatrixFrame	Nmax	999.84	kN	999840	N	
	Vmax	16.54	kN	16540	N	
check (moment)	M_el,rd	142140000.00	Nmm		UC_moment	0.08
check (shear)	V_pl,rd	209702.86	N		UC_shear	0.08
check (axial)	N_pl,rd	1774680.00	N		UC_axial	0.56
check (combi)	M + N				UC_combi	0.64
check (buckling)	weak axis	z-axis				
around weak axis	lambda_1	76				
	lambda	0.75	(slenderness)			
	h/b ratio	0.954545455				
	if h/b < 1.2	*buckling curve c*	alpha_c	0.49		
	if h/b > 1.2	*buckling curve b*	alpha_b	0.34		
	phi	0.92				
	chi	0.69				
	F_R_buck	1228336.18	N		UC_buckling	0.81

ULS - Timber beam GL32h						
cross section	b	205	mm			
	h	850	mm			
	A	174250	mm2			
	W	24685417	mm3			
	I	10491302083	mm4			
beam span	l	10000	mm			
E modulus	E_0,mean	13700	N/mm2			
	E_90,mean	460	N/mm2			
strength	gamma_m	1.25				
	k_mod	0.80				
	f_m,k	32.00	N/mm2			
	f_t,0,k	22.50	N/mm2			
	f_c,0,k	29.00	N/mm2			
	f_v,k	3.80	N/mm2			
forces	Mmax	467.73	kNm	467730000	Nmm	
MatrixFrame	Nmax	29.05	kN	29050	N	
	Vmax	187.09	kN	187090	N	
check (stress)	sigma_1	-19.11	N/mm2		UC_sigma_1	0.93
	sigma_2	18.78	N/mm2		UC_sigma_2	0.92
	f_d,m,k	20.48	N/mm2			
check (shear)	k_cr	0.67	*for laminated timber*			
	b_ef	137.35	mm			
	Vrd	283929.92	N		UC_shear	0.66
check (axial)	Nrd	3234080.00	N		UC_axial	0.01

SLS - Timber beam GL32h						
w_max	40	mm				
max deflection (SLS)	29.10	mm			UC_deflection	0.73

ULS - Timber column GL32h						
cross section	b	135	mm			
	h	400	mm			
	A	54000	mm2			
	W	3600000	mm3			
	I	720000000	mm4			
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E_0,mean	13700	N/mm2			
	E_90,mean	460	N/mm2			
strength	gamma_m	1.25				
	k_mod	0.80				
	f_m,k	32.00	N/mm2			
	f_t,0,k	22.50	N/mm2			
	f_c,0,k	29.00	N/mm2			
	f_v,k	3.80	N/mm2			
forces	Mmax	-11.39	kNm	-11390000	Nmm	
MatrixFrame	N (at Mmax)	443.61	kN	443610	N	
	Nmax	886.41	kN	886410	N	
	Vmax	16.50	kN	16500	N	
check (stress)	sigma_1	-5.05	N/mm2		UC_sigma_1	0.25
	sigma_2	-11.38	N/mm2		UC_sigma_2	0.56
	f_d,m,k	20.48				
check (shear)	k_cr	0.67	*for laminated timber*			
	b_ef	90.45	mm			
	Vrd	87989.76	N		UC_shear	0.19
check (axial)	Nrd	1002240.00	N		UC_axial	0.88
check (buckling)	F_R_buck	9811416.26	N		UC_buck	0.09

ULS - Timber beam LVL50P

cross section	b	205	mm			
	h	750	mm			
	A	153750	mm2			
	W	19218750	mm3			
	I	7207031250	mm4			
beam span	l	10000	mm			
E modulus	E_0,mean	15200	N/mm2			
	E_90,mean	430	N/mm2			
strength	gamma_m	1.25				
	k_mod	0.80				
	f_m,k	50.00	N/mm2			
	f_t,0,k	36.00	N/mm2			
	f_c,0,k	35.00	N/mm2			
	f_v,k	3.20	N/mm2			
forces	Mmax	470.58	kNm	470580000	Nmm	
MatrixFrame	Nmax	29.10	kN	29100	N	
	Vmax	188.23	kN	188230	N	
check (stress)	sigma_1	-24.67	N/mm2		UC_sigma_1	0.77
	sigma_2	24.30	N/mm2		UC_sigma_2	0.76
	f_d,m,k	32.00	N/mm2			
check (shear)	k_cr	0.67	*for laminated timber*			
	b_ef	137.35	mm			
	Vrd	210969.60	N		UC_shear	0.89
check (axial)	Nrd	3444000.00	N		UC_axial	0.01

SLS - Timber beam LVL50P

w_max	40	mm				
max deflection (SLS)	36.90	mm			UC_deflection	0.92

ULS - Timber column LVL50P						
cross section	b	135	mm			
	h	350	mm			
	A	47250	mm2			
	W	2756250	mm3			
	I	482343750	mm4			
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E_0,mean	15200	N/mm2			
	E_90,mean	430	N/mm2			
strength	gamma_m	1.25				
	k_mod	0.80				
	f_m,k	50.00	N/mm2			
	f_t,0,k	36.00	N/mm2			
	f_c,0,k	35.00	N/mm2			
	f_v,k	3.20	N/mm2			
forces	Mmax	-11.47	kNm	-11470000	Nmm	
MatrixFrame	N (at Mmax)	447.55	kN	447550	N	
	Nmax	894.09	kN	894090	N	
	Vmax	16.52	kN	16520	N	
check (stress)	sigma_1	-5.31	N/mm2		UC_sigma_1	0.17
	sigma_2	-13.63	N/mm2		UC_sigma_2	0.43
	f_d,m,k	32				
check (shear)	k_cr	0.67	*for laminated timber*			
	b_ef	90.45	mm			
	Vrd	64834.56	N		UC_shear	0.25
check (axial)	Nrd	1058400.00	N		UC_axial	0.84
check (buckling)	F_R_buck	7292541.03	N		UC_buck	0.12

ULS - Timber beam CL28h						
cross section	b	205	mm			
	h	900	mm			
	A	184500	mm2			
	W	27675000	mm3			
	I	12453750000	mm4			
beam span	l	10000	mm			
E modulus	E_0,mean	11600	N/mm2			
	E_90,mean	300	N/mm2			
strength	gamma_m	1.25				
	k_mod	0.80				
	f_m,k	28.00	N/mm2			
	f_t,0,k	18.00	N/mm2			
	f_c,0,k	28.00	N/mm2			
	f_v,k	3.50	N/mm2			
forces	Mmax	468.15	kNm	468150000	Nmm	
MatrixFrame	Nmax	29.12	kN	29120	N	
	Vmax	187.26	kN	187260	N	
check (stress)	sigma_1	-17.07	N/mm2		UC_sigma_1	0.95
	sigma_2	16.76	N/mm2		UC_sigma_2	0.94
	f_d,m,k	17.92	N/mm2			
check (shear)	k_cr	0.67	*for laminated timber*			
	b_ef	137.35	mm			
	Vrd	276897.60	N		UC_shear	0.68
check (axial)	Nrd	3306240.00	N		UC_axial	0.01

SLS - Timber beam CL28h						
w_max	40	mm				
max deflection (SLS)	29.80	mm			UC_deflection	0.75

ULS - Timber column CL28h						
cross section	b	160	mm			
	h	350	mm			
	A	56000	mm2			
	W	3266667	mm3			
	I	571666667	mm4			
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E_0,mean	11600	N/mm2			
	E_90,mean	300	N/mm2			
strength	gamma_m	1.25				
	k_mod	0.80				
	f_m,k	28.00	N/mm2			
	f_t,0,k	18.00	N/mm2			
	f_c,0,k	28.00	N/mm2			
	f_v,k	3.50	N/mm2			
forces	Mmax	-11.47	kNm	-11470000	Nmm	
MatrixFrame	N (at Mmax)	444.16	kN	444160	N	
	Nmax	887.49	kN	887490	N	
	Vmax	16.52	kN	16520	N	
check (stress)	sigma_1	-4.42	N/mm2		UC_sigma_1	0.25
	sigma_2	-11.44	N/mm2		UC_sigma_2	0.64
	f_d,m,k	17.92				
check (shear)	k_cr	0.67	*for laminated timber*			
	b_ef	107.20	mm			
	Vrd	84044.8	N		UC_shear	0.20
check (axial)	Nrd	1003520.00	N		UC_axial	0.88
check (buckling)	F_R_buck	6595982.53	N		UC_buck	0.13

Appendix M

Design ESA/ESTEC – design strategy 3

ULS - Concrete beam C35/45 (prefab) - standard reinforcement						
cross section	b	300	mm			
	h	400	mm			
	A	120000	mm2			
	W	8000000	mm3	W = 1/6 bh^2		
	I	1600000000	mm4	I = 1/12 bh^3		
reinforcement	gamma_s	1.15				
	f_tk	500	N/mm2			
	f_yd	435	N/mm2			
	diameter	25	mm	spacing	50	mm
	bars	4		min. spacing	37	mm
	As	1963	mm2			
	Ac	118037	mm2			
	rho	0.02				
	c	25	mm			
	stirrups	8	mm			
	d	355	mm			
beam span	l	5000	mm			
E modulus	E	34000	N/mm2			
strenght	gamma_c	1.50				
	f_ck	45.00	N/mm2			
	f_cd	30.00	N/mm2	f_cd = f_ck / gamma_c		
	f_ctk	2.20	N/mm2			
	f_ctd	1.47	N/mm2	f_ctd = f_ctk / gamma_c		
forces	Mmax	212.81	kNm	212810000	Nmm	
MatrixFrame	Nmax	20.72	kN	20720	N	
	Vmax	170.25	kN	170250	N	
check (moment)	Ns	853693.66	N			
	Nc	832973.66	N			
	alpha	0.75				
	beta	0.39				
	x_u	123.40	mm			
	Mrd	258515785.54	Nmm	UC_moment	0.82	
check (shear)	k	1.75				
	sigma_cp	0.18	N/mm2	*should be smaller than 6 N/mm2*		
	Crd_c	0.12				
	k1	0.15				
	Vrd_c	100314.64	N			
	v_min	0.54	N/mm2			
	Vrd_c_min	60661.04	N			
	Vrd_c_final	100314.64	N	UC_shear	1.70	
				stirrups are necessary		

SLS - Concrete beam C35/45 (prefab) - standard reinforcement						
w_max	20	mm				
max deflection (SLS)	10.30	mm			UC_deflection	0.52

ULS - Concrete column C35/45 (prefab) - standard reinforcement - maximum M						
cross section	b	200	mm			
	h	200	mm			
	A	40000	mm2			
	W	1333333	mm3	W = 1/6 bh^2		
	I	133333333	mm4	I = 1/12 bh^3		
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E	34000	N/mm2			
strenght	gamma_c	1.50				
	f_ck	45.00	N/mm2			
	f_cd	30.00	N/mm2	f_cd = f_ck / gamma_c		
	f_ctk	2.20	N/mm2			
	f_ctd	1.47	N/mm2	f_ctd = f_ctk / gamma_c		
forces	Mmax	-8.26	kNm	-8260000	Nmm	
MatrixFrame	Nmax	381.00	kN	381000	N	
	Vmax	11.76	kN	11760	N	
check (stress)	sigma_c1	-3.33	N/mm2	compression	UC_sigma_c1	0.11
	sigma_c2	-15.72	N/mm2	compression	UC_sigma_c2	0.52
check (buckling)	F_R_buck	4509166.70	N		UC_buck	0.08
check (shear)	k	2				
	Vrd_c_min	26563.13	N		UC_shear	0.44

ULS - Concrete column C35/45 (prefab) - standard reinforcement - maximum N						
forces	Mmax	0.00	kNm	0	Nmm	
MatrixFrame	Nmax	758.40	kN	758400	N	
check (stress)	sigma_c1	-18.96	N/mm2	compression	UC_sigma_c1	0.63
	sigma_c2	-18.96	N/mm2	compression	UC_sigma_c2	0.63
check (buckling)	F_R_buck	4509166.70	N		UC_buck	0.17

ULS - Lightweight concrete beam C40/44 (prefab) - standard reinforcement						
cross section	b	300	mm			
	h	400	mm			
	A	120000	mm2			
	W	8000000	mm3	W = 1/6 bh^2		
	I	1600000000	mm4	I = 1/12 bh^3		
reinforcement	gamma_s	1.15				
	f_tk	500	N/mm2			
	f_yd	435	N/mm2			
	diameter	25	mm	spacing	50	mm
	bars	4		min. spacing	37	mm
	As	1963	mm2			
	Ac	118037	mm2			
	rho	0.02				
	c	25	mm			
	stirrups	8	mm			
	d	355	mm			
beam span	l	5000	mm			
E modulus	E	18000	N/mm2			
strenght	gamma_c	1.50				
	f_ck	44.00	N/mm2			
	f_cd	29.33	N/mm2	f_cd = f_ck / gamma_c		
	f_ctk	1.84	N/mm2			
	f_ctd	1.23	N/mm2	f_ctd = f_ctk / gamma_c		
forces	Mmax	201.56	kNm	201560000	Nmm	
MatrixFrame	Nmax	20.72	kN	20720	N	
	Vmax	161.25	kN	161250	N	
check (moment)	Ns	853693.66	N			
	Nc	832973.66	N			
	alpha	0.75				
	beta	0.39				
	x_u	126.21	mm			
	Mrd	257607271.55	Nmm	UC_moment	0.78	
check (shear)	k	1.75				
	sigma_cp	0.18	N/mm2	*should be smaller than 6 N/mm2*		
	Crd_c	0.12				
	k1	0.15				
	Vrd_c	99586.90	N			
	v_min	0.54	N/mm2			
	Vrd_c_min	60014.53	N			
	Vrd_c_final	99586.90	N	UC_shear	1.62	
				stirrups are necessary		

SLS - Lightweight concrete beam C40/44 (prefab) - standard reinforcement

w_max	20	mm				
max deflection (SLS)	18.00	mm			UC_deflection	0.90

ULS - Lightweight concrete column C40/44 (prefab) - standard reinforcement - maximum M						
cross section	b	200	mm			
	h	200	mm			
	A	40000	mm2			
	W	1333333	mm3	W = 1/6 bh^2		
	I	133333333	mm4	I = 1/12 bh^3		
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E	18000	N/mm2			
strenght	gamma_c	1.50				
	f_ck	44.00	N/mm2			
	f_cd	29.33	N/mm2	f_cd = f_ck / gamma_c		
	f_ctk	1.84	N/mm2			
	f_ctd	1.23	N/mm2	f_ctd = f_ctk / gamma_c		
forces	Mmax	-8.26	kNm	-8260000	Nmm	
MatrixFrame	Nmax	345.00	kN	345000	N	
	Vmax	11.76	kN	11760	N	
check (stress)	sigma_c1	-2.43	N/mm2	compression	UC_sigma_c1	0.08
	sigma_c2	-14.82	N/mm2	compression	UC_sigma_c2	0.51
check (buckling)	F_R_buck	2387205.90	N		UC_buck	0.14
check (shear)	k	2				
	Vrd_c_min	26266.33	N		UC_shear	0.45

ULS - Lightweight concrete column C40/44 (prefab) - standard reinforcement - maximum N						
forces	Mmax	0.00	kNm	0	Nmm	
MatrixFrame	Nmax	690.00	kN	690000	N	
check (stress)	sigma_c1	-17.25	N/mm2	compression	UC_sigma_c1	0.59
	sigma_c2	-17.25	N/mm2	compression	UC_sigma_c2	0.59
check (buckling)	F_R_buck	2387205.90	N		UC_buck	0.29

ULS - Concrete beam C35/45 (in-situ) - standard reinforcement

cross section	b	350	mm			
	h	400	mm			
	A	140000	mm2			
	W	9333333	mm3	W = 1/6 bh^2		
	I	1866666667	mm4	I = 1/12 bh^3		
reinforcement	gamma_s	1.15				
	f_tk	500	N/mm2			
	f_yd	435	N/mm2			
	diameter	25	mm	spacing	43.75	mm
	bars	5		min. spacing	37	mm
	As	2454	mm2			
	Ac	137546	mm2			
	rho	0.02				
	c	25	mm			
	stirrups	8	mm			
	d	355	mm			
beam span	l	5000	mm			
E modulus	E	34000	N/mm2			
strenght	gamma_c	1.50				
	f_ck	45.00	N/mm2			
	f_cd	30.00	N/mm2	f_cd = f_ck / gamma_c		
	f_ctk	2.20	N/mm2			
	f_ctd	1.47	N/mm2	f_ctd = f_ctk / gamma_c		
forces	Mmax	280.31	kNm	280310000	Nmm	
MatrixFrame	Nmax	20.72	kN	20720	N	
	Vmax	224.25	kN	224250	N	
check (moment)	Ns	1067117.07	N			
	Nc	1046397.07	N			
	alpha	0.75				
	beta	0.39				
	x_u	132.88	mm			
	Mrd	320077552.97	Nmm	UC_moment	0.88	
check (shear)	k	1.75				
	sigma_cp	0.15	N/mm2	*should be smaller than 6 N/mm2*		
	Crd_c	0.12				
	k1	0.15				
	Vrd_c	119217.05	N			
	v_min	0.54	N/mm2			
	Vrd_c_min	70307.83	N			
	Vrd_c_final	119217.05	N	UC_shear	1.88	
				stirrups are necessary		

SLS - Concrete beam C35/45 (in-situ) - standard reinforcement						
w_max	20	mm				
max deflection (SLS)	12.40	mm			UC_deflection	0.62

ULS - Doncrete column C35/45 (in-situ) - standard reinforcement - maximum M						
cross section	b	200	mm			
	h	200	mm			
	A	40000	mm2			
	W	1333333	mm3	W = 1/6 bh^2		
	I	133333333	mm4	I = 1/12 bh^3		
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E	34000	N/mm2			
strenght	gamma_c	1.50				
	f_ck	45.00	N/mm2			
	f_cd	30.00	N/mm2	f_cd = f_ck / gamma_c		
	f_ctk	2.20	N/mm2			
	f_ctd	1.47	N/mm2	f_ctd = f_ctk / gamma_c		
forces	Mmax	-8.27	kNm	-8270000	Nmm	
MatrixFrame	Nmax	490.50	kN	490500	N	
	Vmax	11.76	kN	11760	N	
check (stress)	sigma_c1	-6.06	N/mm2	compression	UC_sigma_c1	0.20
	sigma_c2	-18.465	N/mm2	compression	UC_sigma_c2	0.62
check (buckling)	F_R_buck	4509166.70	N		UC_buck	0.11
check (shear)	k	2				
	Vrd_c_min	26563.13	N		UC_shear	0.44

ULS - Concrete column C35/45 (in-situ) - standard reinforcement - maximum N						
forces	Mmax	0.00	kNm	0	Nmm	
MatrixFrame	Nmax	977.40	kN	977400	N	
check (stress)	sigma_c1	-24.435	N/mm2	compression	UC_sigma_c1	0.81
	sigma_c2	-24.435	N/mm2	compression	UC_sigma_c2	0.81
check (buckling)	F_R_buck	4509166.70	N		UC_buck	0.22

ULS - Lightweight concrete beam C40/44 (in-situ) - standard reinforcement						
cross section	b	300	mm			
	h	450	mm			
	A	135000	mm2			
	W	10125000	mm3	W = 1/6 bh^2		
	I	2278125000	mm4	I = 1/12 bh^3		
reinforcement	gamma_s	1.15				
	f_tk	500	N/mm2			
	f_yd	435	N/mm2			
	diameter	25	mm	spacing	50	mm
	bars	4		min. spacing	37	mm
	As	1963	mm2			
	Ac	133037	mm2			
	rho	0.02				
	c	25	mm			
	stirrups	8	mm			
	d	405	mm			
beam span	l	5000	mm			
E modulus	E	18000	N/mm2			
strenght	gamma_c	1.50				
	f_ck	44.00	N/mm2			
	f_cd	29.33	N/mm2	f_cd = f_ck / gamma_c		
	f_ctk	1.84	N/mm2			
	f_ctd	1.23	N/mm2	f_ctd = f_ctk / gamma_c		
forces	Mmax	267.19	kNm	267190000	Nmm	
MatrixFrame	Nmax	20.72	kN	20720	N	
	Vmax	213.75	kN	213750	N	
check (moment)	Ns	853693.66	N			
	Nc	832973.66	N			
	alpha	0.75				
	beta	0.39				
	x_u	126.21	mm			
	Mrd	299773954.34	Nmm	UC_moment	0.89	
check (shear)	k	1.70				
	sigma_cp	0.16	N/mm2	*should be smaller than 6 N/mm2*		
	Crd_c	0.12				
	k1	0.15				
	Vrd_c	105626.68	N			
	v_min	0.52	N/mm2			
	Vrd_c_min	65455.74	N			
	Vrd_c_final	105626.68	N	UC_shear	2.02	
				stirrups are necessary		

SLS - Lightweight concrete beam C40/44 (in-situ) - standard reinforcement

w_max	20	mm				
max deflection (SLS)	19.00	mm			UC_deflection	0.95

ULS - Lightweight concrete column C40/44 (in-situ) - standard reinforcement - maximum M						
cross section	b	200	mm			
	h	200	mm			
	A	40000	mm2			
	W	1333333	mm3	W = 1/6 bh^2		
	I	133333333	mm4	I = 1/12 bh^3		
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E	18000	N/mm2			
strenght	gamma_c	1.50				
	f_ck	44.00	N/mm2			
	f_cd	29.33	N/mm2	f_cd = f_ck / gamma_c		
	f_ctk	1.84	N/mm2			
	f_ctd	1.23	N/mm2	f_ctd = f_ctk / gamma_c		
forces	Mmax	-8.27	kNm	-8270000	Nmm	
MatrixFrame	Nmax	450.00	kN	450000	N	
	Vmax	11.76	kN	11760	N	
check (stress)	sigma_c1	-5.0475	N/mm2	compression	UC_sigma_c1	0.17
	sigma_c2	-17.4525	N/mm2	compression	UC_sigma_c2	0.59
check (buckling)	F_R_buck	2387205.90	N		UC_buck	0.19
check (shear)	k	2				
	Vrd_c_min	26266.33	N		UC_shear	0.45

ULS - Lightweight concrete column C40/44 (in-situ) - standard reinforcement - maximum N						
forces	Mmax	0.00	kNm	0	Nmm	
MatrixFrame	Nmax	900.00	kN	900000	N	
check (stress)	sigma_c1	-22.5	N/mm2	compression	UC_sigma_c1	0.77
	sigma_c2	-22.5	N/mm2	compression	UC_sigma_c2	0.77
check (buckling)	F_R_buck	2387205.90	N		UC_buck	0.38

ULS - Steel beam S355						
cross section	profile	IPE 300				
	h	300	mm			
	b	150	mm			
	t_web	7.10	mm			
	t_flange	10.70	mm			
	A_web	1978	mm2			
	A_total	5380	mm2			
	I_y	83560000	mm4			
	I_z	6040000	mm4			
	W_y	557000	mm3			
	W_z	80500	mm3			
	i_y	125.00	mm			
	i_z	33.50	mm			
beam span	l	5000	mm			
E modulus	E	210000	N/mm2			
strength	gamma_m0	1				
	gamma_m1	1				
	f_yd	355	N/mm2			
	f_td	510	N/mm2			
forces	Mmax	148.77	kNm	148770000	Nmm	
MatrixFrame	Nmax	20.67	kN	20670	N	
	Vmax	119.02	kN	119020	N	
check (moment)	M_el,rd	197735000.00	Nmm		UC_moment	0.75
check (shear)	V_pl,rd	405421.88	N		UC_shear	0.29
check (axial)	N_pl,rd	1909900.00	N		UC_axial	0.01
check (combi)	M + N				UC_combi	0.76
check (combi)	M + V					
	VEd	119020.00	N			
	0.5 * V_pl,rd	202710.94	N			
	*if VEd < 0.5 * V_pl,rd, combination of bending and shear may be neglected*					

SLS - Steel beam S355						
w_max	20	mm				
max deflection (SLS)	18.50	mm			UC_deflection	0.93

ULS - Steel column S355						
cross section	profile	HE 160 A				
	h	152	mm			
	b	160	mm			
	t_web	6.00	mm			
	t_flange	9.00	mm			
	A_web	804	mm2			
	A_total	3880	mm2			
	I_y	16730000	mm4			
	I_z	6160000	mm4			
	W_y	220000	mm3			
	W_z	76900	mm3			
	i_y	65.70	mm			
	i_z	39.80	mm			
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E	210000	N/mm2			
strength	gamma_m0	1				
	gamma_m1	1				
	f_yd	355	N/mm2			
	f_td	510	N/mm2			
forces	Mmax	-8.15	kNm	-8150000	Nmm	
MatrixFrame	Nmax	527.99	kN	527990	N	
	Vmax	11.73	kN	11730	N	
check (moment)	M_el,rd	78100000.00	Nmm		UC_moment	0.10
check (shear)	V_pl,rd	164787.31	N		UC_shear	0.07
check (axial)	N_pl,rd	1377400.00	N		UC_axial	0.38
check (combi)	M + N				UC_combi	0.49
check (buckling)	weak axis	z-axis				
around weak axis	lambda_1	76				
	lambda	1.04	(slenderness)			
	h/b ratio	0.95				
	if h/b < 1.2	*buckling curve c*	alpha_c	0.49		
	if h/b > 1.2	*buckling curve b*	alpha_b	0.34		
	phi	1.25				
	chi	0.52				
	F_R_buck	711154.84	N		UC_buckling	0.74

ULS - Aluminium beam 6061-T6

cross section	profile	IPE 450				
	h	450	mm			
	b	190	mm			
	t_web	9.40	mm			
	t_flange	14.60	mm			
	A_web	1512	mm2			
	A_total	9880	mm2			
	I_y	337400000	mm4			
	I_z	16760000	mm4			
	W_y	1500000	mm3			
	W_z	167000	mm3			
	i_y	185.00	mm			
	i_z	41.20	mm			
beam span	l	5000	mm			
E modulus	E	69000	N/mm2			
strength	gamma_m0	1				
	gamma_m1	1				
	f_yd	276	N/mm2			
	f_td	310	N/mm2			
forces	Mmax	142.56	kNm	142560000	Nmm	
MatrixFrame	Nmax	20.66	kN	20660	N	
	Vmax	114.05	kN	114050	N	
check (moment)	M_el,rd	414000000.00	Nmm		UC_moment	0.34
check (shear)	V_pl,rd	240858.71	N		UC_shear	0.47
check (axial)	N_pl,rd	2726880.00	N		UC_axial	0.01
check (combi)	M + N				UC_combi	0.35
check (combi)	M + V					
	VEd	114050.00	N			
	0.5 * V_pl,rd	120429.35	N			
	if VEd < 0.5 * V_pl,rd, combination of bending and shear may be neglected					

SLS - Aluminium beam 6061-T6

w_max	20	mm				
max deflection (SLS)	18.50	mm			UC_deflection	0.93

ULS - Aluminium column 6061-T6						
cross section	profile	HE 180 A				
	h	171	mm			
	b	180	mm			
	t_web	6.00	mm			
	t_flange	9.50	mm			
	A_web	912	mm2			
	A_total	4530	mm2			
	I_y	25100000	mm4			
	I_z	9250000	mm4			
	W_y	294000	mm3			
	W_z	103000	mm3			
	i_y	74.50	mm			
	i_z	45.20	mm			
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E	69000	N/mm2			
strength	gamma_m0	1				
	gamma_m1	1				
	f_yd	276	N/mm2			
	f_td	310	N/mm2			
forces	Mmax	-8.18	kNm	-8180000	Nmm	
MatrixFrame	Nmax	504.56	kN	504560	N	
	Vmax	11.74	kN	11740	N	
check (moment)	M_el,rd	81144000.00	Nmm		UC_moment	0.10
check (shear)	V_pl,rd	145325.99	N		UC_shear	0.08
check (axial)	N_pl,rd	1250280.00	N		UC_axial	0.40
check (combi)	M + N				UC_combi	0.50
check (buckling)	weak axis	z-axis				
around weak axis	lambda_1	76				
	lambda	0.92	(slenderness)			
	h/b ratio	0.95				
	if h/b < 1.2	*buckling curve c*	alpha_c	0.49		
	if h/b > 1.2	*buckling curve b*	alpha_b	0.34		
	phi	1.10				
	chi	0.59				
	F_R_buck	736957.98	N		UC_buckling	0.68

ULS - Timber beam GL32h						
cross section	b	185	mm			
	h	500	mm			
	A	92500	mm2			
	W	7708333	mm3			
	I	1927083333	mm4			
beam span	l	5000	mm			
E modulus	E_0,mean	13700	N/mm2			
	E_90,mean	460	N/mm2			
strength	gamma_m	1.25				
	k_mod	0.80				
	f_m,k	32.00	N/mm2			
	f_t,0,k	22.50	N/mm2			
	f_c,0,k	29.00	N/mm2			
	f_v,k	3.80	N/mm2			
forces	Mmax	129.89	kNm	129890000	Nmm	
MatrixFrame	Nmax	20.71	kN	20710	N	
	Vmax	103.92	kN	103920	N	
check (stress)	sigma_1	-17.07	N/mm2		UC_sigma_1	0.83
	sigma_2	16.63	N/mm2		UC_sigma_2	0.81
	f_d,m,k	20.48	N/mm2			
check (shear)	k_cr	0.67	*for laminated timber*			
	b_ef	123.95	mm			
	Vrd	150723.20	N		UC_shear	0.69
check (axial)	Nrd	1716800.00	N		UC_axial	0.01

SLS - Timber beam GL32h						
w_max	20	mm				
max deflection (SLS)	14.40	mm			UC_deflection	0.72

ULS - Timber column GL32h						
cross section	b	110	mm			
	h	250	mm			
	A	27500	mm2			
	W	1145833	mm3			
	I	143229167	mm4			
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E_0,mean	13700	N/mm2			
	E_90,mean	460	N/mm2			
strength	gamma_m	1.25				
	k_mod	0.80				
	f_m,k	32.00	N/mm2			
	f_t,0,k	22.50	N/mm2			
	f_c,0,k	29.00	N/mm2			
	f_v,k	3.80	N/mm2			
forces	Mmax	-8.23	kNm	-8230000	Nmm	
MatrixFrame	N (at Mmax)	232.54	kN	232540	N	
	Nmax	464.66	kN	464660	N	
	Vmax	11.75	kN	11750	N	
check (stress)	sigma_1	-1.27	N/mm2		UC_sigma_1	0.06
	sigma_2	-15.64	N/mm2		UC_sigma_2	0.76
	f_d,m,k	20.48				
check (shear)	k_cr	0.67	*for laminated timber*			
	b_ef	73.70	mm			
	Vrd	44809.6	N		UC_shear	0.26
check (axial)	Nrd	510400.00	N		UC_axial	0.91
check (buckling)	F_R_buck	1951779.13	N		UC_buck	0.24

ULS - Timber beam LVL50P						
cross section	b	160	mm			
	h	550	mm			
	A	88000	mm2			
	W	8066667	mm3			
	I	2218333333	mm4			
beam span	l	5000	mm			
E modulus	E_0,mean	15200	N/mm2			
	E_90,mean	430	N/mm2			
strength	gamma_m	1.25				
	k_mod	0.80				
	f_m,k	50.00	N/mm2			
	f_t,0,k	36.00	N/mm2			
	f_c,0,k	35.00	N/mm2			
	f_v,k	3.20	N/mm2			
forces	Mmax	130.42	kNm	130420000	Nmm	
MatrixFrame	Nmax	20.69	kN	20690	N	
	Vmax	104.33	kN	104330	N	
check (stress)	sigma_1	-16.40	N/mm2		UC_sigma_1	0.51
	sigma_2	15.93	N/mm2		UC_sigma_2	0.50
	f_d,m,k	32.00	N/mm2			
check (shear)	k_cr	0.67	*for laminated timber*			
	b_ef	107.20	mm			
	Vrd	120750.08	N		UC_shear	0.86
check (axial)	Nrd	1971200.00	N		UC_axial	0.01

SLS - Timber beam LVL50P						
w_max	20	mm				
max deflection (SLS)	12.40	mm			UC_deflection	0.62

ULS - Timber column LVL50P						
cross section	b	85	mm			
	h	300	mm			
	A	25500	mm2			
	W	1275000	mm3			
	I	191250000	mm4			
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E_0,mean	15200	N/mm2			
	E_90,mean	430	N/mm2			
strength	gamma_m	1.25				
	k_mod	0.80				
	f_m,k	50.00	N/mm2			
	f_t,0,k	36.00	N/mm2			
	f_c,0,k	35.00	N/mm2			
	f_v,k	3.20	N/mm2			
forces	Mmax	-8.20	kNm	-8200000	Nmm	
MatrixFrame	N (at Mmax)	232.75	kN	232750	N	
	Nmax	465.50	kN	465500	N	
	Vmax	11.74	kN	11740	N	
check (stress)	sigma_1	-2.70	N/mm2		UC_sigma_1	0.08
	sigma_2	-15.56	N/mm2		UC_sigma_2	0.49
	f_d,m,k	32				
check (shear)	k_cr	0.67	*for laminated timber*			
	b_ef	56.95	mm			
	Vrd	34990.08	N		UC_shear	0.34
check (axial)	Nrd	571200.00	N		UC_axial	0.81
check (buckling)	F_R_buck	2891503.15	N		UC_buck	0.16

ULS - Timber beam CL28h

cross section	b	160	mm			
	h	550	mm			
	A	88000	mm2			
	W	8066667	mm3			
	I	2218333333	mm4			
beam span	l	5000	mm			
E modulus	E_0,mean	11600	N/mm2			
	E_90,mean	300	N/mm2			
strength	gamma_m	1.25				
	k_mod	0.80				
	f_m,k	28.00	N/mm2			
	f_t,0,k	18.00	N/mm2			
	f_c,0,k	28.00	N/mm2			
	f_v,k	3.50	N/mm2			
forces	Mmax	129.80	kNm	129800000	Nmm	
MatrixFrame	Nmax	20.69	kN	20690	N	
	Vmax	103.84	kN	103840	N	
check (stress)	sigma_1	-16.33	N/mm2		UC_sigma_1	0.91
	sigma_2	15.86	N/mm2		UC_sigma_2	0.88
	f_d,m,k	17.92	N/mm2			
check (shear)	k_cr	0.67	*for laminated timber*			
	b_ef	107.20	mm			
	Vrd	132070.40	N		UC_shear	0.79
check (axial)	Nrd	1576960.00	N		UC_axial	0.01

SLS - Timber beam CL28h

w_max	20	mm				
max deflection (SLS)	15.10	mm			UC_deflection	0.76

ULS - Timber column CL28h						
cross section	b	85	mm			
	h	350	mm			
	A	29750	mm2			
	W	1735417	mm3			
	I	303697917	mm4			
column height	l	4500	mm			
	l_cr	3150	mm	l_cr = l * 0.7		
E modulus	E_0,mean	11600	N/mm2			
	E_90,mean	300	N/mm2			
strength	gamma_m	1.25				
	k_mod	0.80				
	f_m,k	28.00	N/mm2			
	f_t,0,k	18.00	N/mm2			
	f_c,0,k	28.00	N/mm2			
	f_v,k	3.50	N/mm2			
forces	Mmax	-8.13	kNm	-8130000	Nmm	
MatrixFrame	N (at Mmax)	231.27	kN	231270	N	
	Nmax	462.53	kN	462530	N	
	Vmax	11.74	kN	11740	N	
check (stress)	sigma_1	-3.09	N/mm2		UC_sigma_1	0.17
	sigma_2	-12.46	N/mm2		UC_sigma_2	0.70
	f_d,m,k	17.92				
check (shear)	k_cr	0.67	*for laminated timber*			
	b_ef	56.95	mm			
	Vrd	44648.8	N		UC_shear	0.26
check (axial)	Nrd	533120.00	N		UC_axial	0.87
check (buckling)	F_R_buck	3504115.72	N		UC_buck	0.13

Appendix N

Overview MCA scores

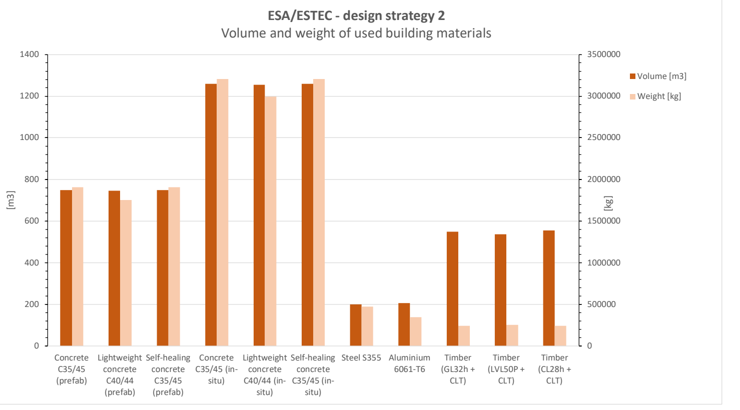
ESA/ESTEC - design strategy 2										*width [m]*	*length [m]*	*height [m]*	*number of floors*								
										30.00	35.00	12.00	3								
1	Concrete C35/45 (prefab) - standard reinforcement																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	hollow-core slab		4.50	0.32	1.20	7.00	1.51	3853.21	25	5	125	375	567	1444954	64.41	202891.50	*(no information, assume*		5.4924	17301.06
																		same as for LCA A+C+D)			
				self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	450x650		25.00	0.65	0.45	10.00	2.93	7454.13	3	6	18	54	158	402523	381.49	206004.60	43.4624	6864.89	31.8712	5034.06
				self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	300x300		25.00	0.30	0.30	4.50	0.41	1032.11	4	6	24	24	10	24771	257.02	27758.16	43.4624	422.45	31.8712	309.79
		300x300		25.00	0.30	0.30	3.25	0.29	745.41	4	6	24	48	14	35780	257.02	40095.12	43.4624	610.21	31.8712	447.47
	total													**749**	**1908028**		**476749.38**		**25198.61**		**23092.38**
														m3	kg		euro		euro		euro
2	Lightweight concrete C40/44 (prefab) - standard reinforcement																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	hollow-core slab		4.50	0.32	1.20	7.00	1.51	3853.21	25	5	125	375	567	1444954	64.41	202891.50	*(no information, assume*		5.4924	17301.06
																		same as for LCA A+C+D)			
				self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	400x750		17.00	0.75	0.40	10.00	3.00	5198.78	3	6	18	54	162	280734	442.00	238680.00	43.4624	7040.91	31.8712	5163.13
				self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	250x250		17.00	0.25	0.25	4.50	0.28	487.39	4	6	24	24	7	11697	280.18	30259.44	43.4624	293.37	31.8712	215.13
		250x250		17.00	0.25	0.25	3.25	0.20	352.00	4	6	24	48	10	16896	280.18	43708.08	43.4624	423.76	31.8712	310.74
	total													**746**	**1754281**		**515539.02**		**25059.10**		**22990.07**
														m3	kg		euro		euro		euro
3	Self-healing concrete C35/45 (prefab) - standard reinforcement																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	hollow-core slab		4.50	0.32	1.20	7.00	1.51	3853.21	25	5	125	375	567	1444954	64.41	202891.50	*(no information, assume*		5.4924	17301.06
																		same as for LCA A+C+D)			
				self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	450x650		25.00	0.65	0.45	10.00	2.93	7454.13	3	6	18	54	158	402523	381.49	212322.60	43.8659	6928.62	32.4392	5123.77
				self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	300x300		25.00	0.30	0.30	4.50	0.41	1032.11	4	6	24	24	10	24771	257.02	28146.96	43.8659	426.38	31.8712	309.79
		300x300		25.00	0.30	0.30	3.25	0.29	745.41	4	6	24	48	14	35780	257.02	40656.72	43.8659	615.88	31.8712	447.47
	total													**749**	**1908028**		**484017.78**		**25271.93**		**23182.09**
														m3	kg		euro		euro		euro
4	Concrete C35/45 (in-situ) - standard reinforcement																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	composite slab		8.00	0.32	3.00	7.00	6.72	17125.38	10	5	50	150	1008	2568807	136.10	428715.00	*(no information, assume*		6.4630	20358.45
																		same as for LCA A+C+D)			
				self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	600x700		25.00	0.70	0.60	10.00	4.20	10703.36	3	6	18	54	227	577982	279.35	150849.00	43.4624	9857.27	31.8712	7228.39
				self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	300x300		25.00	0.30	0.30	4.50	0.41	1032.11	4	6	24	24	10	24771	122.48	13227.84	43.4624	422.45	31.8712	309.79
		300x300		25.00	0.30	0.30	3.25	0.29	745.41	4	6	24	48	14	35780	122.48	19106.88	43.4624	610.21	31.8712	447.47
	total													**1259**	**3207339**		**611898.72**		**31248.39**		**28344.10**
														m3	kg		euro		euro		euro
5	Lightweight concrete C40/44 (in-situ) - standard reinforcement																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	composite slab		8.00	0.32	3.00	7.00	6.72	17125.38	10	5	50	150	1008	2568807	136.10	428715.00	*(no information, assume*		6.4630	20358.45
																		same as for LCA A+C+D)			
				self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	550X750		17.00	0.75	0.55	10.00	4.13	7148.32	3	6	18	54	223	386009	325.03	175516.20	43.4624	9681.25	31.8712	7099.31
				self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	300x300		17.00	0.30	0.30	4.50	0.41	701.83	4	6	24	24	10	16844	159.22	17195.76	43.4624	422.45	31.8712	309.79

		300x300		17.00	0.30	0.30	3.25	0.29	506.88	4	6	24	48	14	24330	159.22	24838.32	43.4624	610.21	31.8712	447.47
	total													**1255**	**2995991**		**646265.28**		**31072.37**		**28215.01951**
														m3	kg		euro		euro		euro
6	Self-healing concrete C35/45 (in-situ) - standard reinforcement																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	composite slab		8.00	0.32	3.00	7.00	6.72	17125.38	10	5	50	150	1008	2568807	136.10	428715.00	*(no information, assume*		6.4630	20358.45
																		same as for LCA A+C+D)			
				self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	600X700		25.00	0.70	0.60	10.00	4.20	10703.36	3	6	18	54	227	577982	279.35	159921.00	43.8659	9948.79	32.4392	7357.21
				self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	300x300		25.00	0.30	0.30	4.50	0.41	1032.11	4	6	24	24	10	24771	122.48	13616.64	43.8659	426.38	31.8712	309.79
		300x300		25.00	0.30	0.30	3.25	0.29	745.41	4	6	24	48	14	35780	122.48	19668.48	43.8659	615.88	31.8712	447.47
	total													**1259**	**3207339**		**621921.12**		**31349.49**		**28472.92027**
														m3	kg		euro		euro		euro
7	Steel S355																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	steel deck:																*(no information, assume*		2.6793	8439.80
		finishing layer		0.70	0.035	30.00	7.00	7.35	14984.71	1	5	5	15	110	224771	7.82	24633.00	*same as for LCA A+C+D)*			
		plate material		0.10	0.020	30.00	7.00	4.20	2140.67	1	5	5	15	63	32110	5.84	18396.00				
				self-weight [kN/m3]	area [m2]		span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**				
		steel C-sections		78.500	0.00588		7.00	0.04	329.36	30	5	150	450	19	148214	66.90	210735				
				self-weight [kN/m3]	area [m2]		span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	IPE 550		78.50	0.01340		10.00	0.13	1072.27	3	6	18	54	7.24	57903	167.42	90406.80	911.3850	6594.78	146.7950	1062.21
				self-weight [kN/m3]	area [m2]		length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	HE 200 A		78.50	0.00538		4.50	0.02	193.73	4	6	24	24	0.58	4650	74.24	8017.92	911.3850	529.55	146.7950	85.29
		HE 200 A		78.50	0.00538		3.25	0.02	139.92	4	6	24	48	0.84	6716	74.24	11581.44	911.3850	764.91	146.7950	123.20
	total													**200**	**474363**		**363770.16**		**16329.04**		**9710.50**
														m3	kg		euro		euro		euro
8	Aluminium 6061-T6																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	aluminium deck:																*(no information, assume*		5.427	17095.05
		finishing layer		0.70	0.035	30.00	7.00	7.35	14984.71	1	5	5	15	110	224771	7.82	24633.00	*same as for LCA A+C+D)*			
		plate material		0.10	0.020	30.00	7.00	4.20	2140.67	1	5	5	15	63	32110	5.84	18396.00				
				self-weight [kN/m3]	area [m2]		span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**				
		aluminium C-sections		27.000	0.00588		7.00	0.04	113.28	30	5	150	450	19	50978	200.70	632205.00				
				self-weight [kN/m3]	area [m2]		span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	IPE 750x185		27.00	0.02360		10.00	0.24	649.54	3	6	18	54	12.74	35075	805.02	434710.80	2451.6000	31243.19	374.4900	4772.50
				self-weight [kN/m3]	area [m2]		length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	HE 220 A		27.00	0.00643		4.50	0.03	79.64	4	6	24	24	0.69	1911	222.72	24053.76	2451.6000	1702.49	374.4900	260.06
		HE 220 A		27.00	0.00643		3.25	0.02	57.52	4	6	24	48	1.00	2761	222.72	34744.32	2451.6000	2459.15	374.4900	375.64
	total													**206**	**347606**		**1168742.88**		**52499.88**		**22503.25**
														m3	kg		euro		euro		euro
9	Timber (GL32h + CLT)																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	CLT panels		0.60	0.14	3.00	7.00	2.94	1284.40	10	5	50	150	441	192661	34.50	108675.00	*(no information, assume*		5.3837	16958.66
																		same as for LCA A+C+D)			
				self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m3]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	205x850		4.60	0.85	0.205	10.00	1.74	817.07	3	6	18	54	94	44122	1000.00	94095.00	28.6580	2696.57	28.6580	2696.57
				self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m3]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	135x400		4.60	0.40	0.135	4.50	0.24	113.94	4	6	24	24	6	2735	1000.00	5832.00	28.6580	167.13	28.6580	167.13
		135x400		4.60	0.40	0.135	3.25	0.18	82.29	4	6	24	48	8	3950	1000.00	8424.00	28.6580	241.41	28.6580	241.41
	total													**549**	**243467**		**217026.00**		**20063.78**		**20063.78**
														m3	kg		euro		euro		euro

10	Timber (LVL50P + CLT)																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	CLT panels		0.60	0.14	3.00	7.00	2.94	1284.40	10	5	50	150	441	192661	34.50	108675.00	*(no information, assume same as for LCA A+C+D)*		5.3837	16958.66
				self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m3]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	205x750		6.00	0.75	0.205	10.00	1.54	940.37	3	6	18	54	83	50780	900.00	74722.50	37.3800	3103.47	37.3800	3103.47
				self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m3]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	135x350		6.00	0.35	0.135	4.50	0.21	130.05	4	6	24	24	5	3121	900.00	4592.70	37.3800	190.75	37.3800	190.75
		135x350		6.00	0.35	0.135	3.25	0.15	93.92	4	6	24	48	7	4508	900.00	6633.90	37.3800	275.53	37.3800	275.53
	total													**536**	**251070**		**194624.10**		**20528.41**		**20528.41**
														m3	kg		euro		euro		euro
11	Timber (CL28h + CLT)																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	CLT panels		0.60	0.14	3.00	7.00	2.94	1284.40	10	5	50	150	441	192661	34.50	108675.00	*(no information, assume same as for LCA A+C+D)*		5.3837	16958.66
				self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m3]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	205x900		4.12	0.90	0.205	10.00	1.85	774.86	3	6	18	54	100	41843	700.00	69741.00	31.2897	3117.39	25.7102	2561.51
				self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m3]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	160x350		4.12	0.35	0.16	4.50	0.25	105.83	4	6	24	24	6	2540	700.00	4233.60	31.2897	189.24	25.7102	155.50
		160x350		4.12	0.35	0.16	3.25	0.18	76.44	4	6	24	48	9	3669	700.00	6115.20	31.2897	273.35	25.7102	224.60
	total													**555**	**240712**		**188764.80**		**20538.63**		**19900.26**
														m3	kg		euro		euro		euro

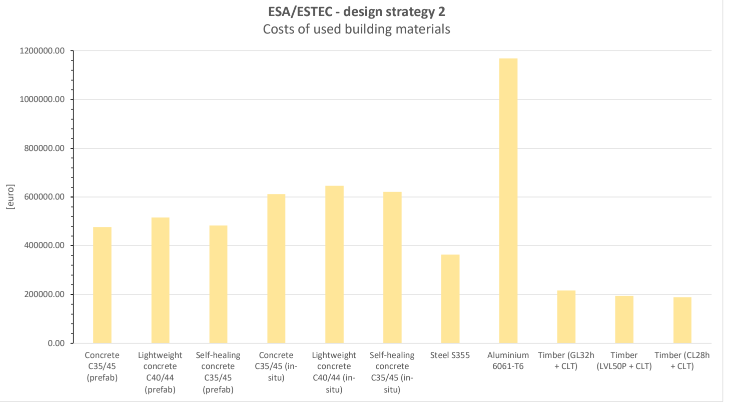
	Volume [m3]	bl	bl	Weight [kg]		
Concrete C35/45 (prefab)	749			1908028	793 %	**0.30**
Lightweight concrete C40/44 (prefab)	746			1754281	729 %	**0.30**
Self-healing concrete C35/45 (prefab)	749			1908028	793 %	**0.30**
Concrete C35/45 (in-situ)	1259			3207339	1332 %	**0.10**
Lightweight concrete C40/44 (in-situ)	1255			2995991	1245 %	**0.10**
Self-healing concrete C35/45 (in-situ)	1259			3207339	1332 %	**0.10**
Steel S355	200			474363	197 %	**0.70**
Aluminium 6061-T6	206			347606	144 %	**0.80**
Timber (GL32h + CLT)	549			243467	101 %	**0.90**
Timber (LVL50P + CLT)	536			251070	104 %	**0.90**
Timber (CL28h + CLT)	555			240712	100 %	**1.00**

Percentage	Score
100 %	1.00
100-125 %	0.90
125-150 %	0.80
150-200 %	0.70
200-300 %	0.60
300-400 %	0.50
400-600 %	0.40
600-800 %	0.30
800-1000 %	0.20
>1000 %	0.10



	Costs [€]		
Concrete C35/45 (prefab)	476749.38	253 %	**0.40**
Lightweight concrete C40/44 (prefab)	515539.02	273 %	**0.40**
Self-healing concrete C35/45 (prefab)	484017.78	256 %	**0.40**
Concrete C35/45 (in-situ)	611898.72	324 %	**0.30**
Lightweight concrete C40/44 (in-situ)	646265.28	342 %	**0.30**
Self-healing concrete C35/45 (in-situ)	621921.12	329 %	**0.30**
Steel S355	363770.16	193 %	**0.60**
Aluminium 6061-T6	1168742.88	619 %	**0.10**
Timber (GL32h + CLT)	217026.00	115 %	**0.80**
Timber (LVL50P + CLT)	194624.10	103 %	**0.90**
Timber (CL28h + CLT)	188764.80	100 %	**1.00**

Percentage	Score
100 %	1.00
100-110 %	0.90
110-125 %	0.80
125-150 %	0.70
150-200 %	0.60
200-250 %	0.50
250-300 %	0.40
300-400 %	0.30
400-500 %	0.20
>500 %	0.10

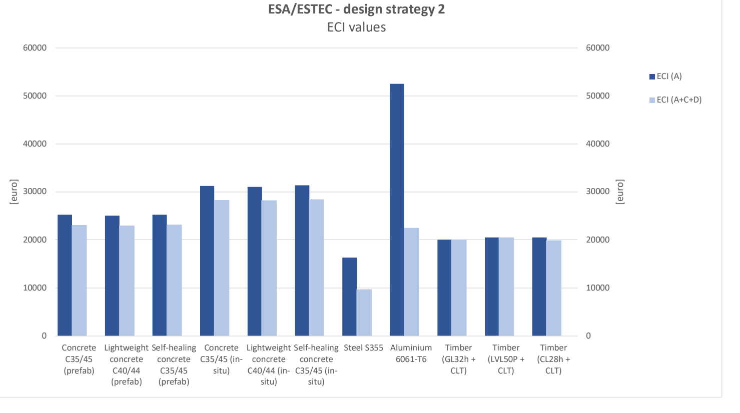


	ECI (A)	bl	bl	ECI (A+C+D)	**ECI (A)**	
Concrete C35/45 (prefab)	25199			23092	154 %	**0.60**
Lightweight concrete C40/44 (prefab)	25059			22990	153 %	**0.60**
Self-healing concrete C35/45 (prefab)	25272			23182	155 %	**0.60**
Concrete C35/45 (in-situ)	31248			28344	191 %	**0.60**
Lightweight concrete C40/44 (in-situ)	31072			28215	190 %	**0.60**
Self-healing concrete C35/45 (in-situ)	31349			28473	192 %	**0.60**
Steel S355	16329			9710	100 %	**1.00**
Aluminium 6061-T6	52500			22503	322 %	**0.30**
Timber (GL32h + CLT)	20064			20064	123 %	**0.80**
Timber (LVL50P + CLT)	20528			20528	126 %	**0.70**
Timber (CL28h + CLT)	20539			19900	126 %	**0.70**

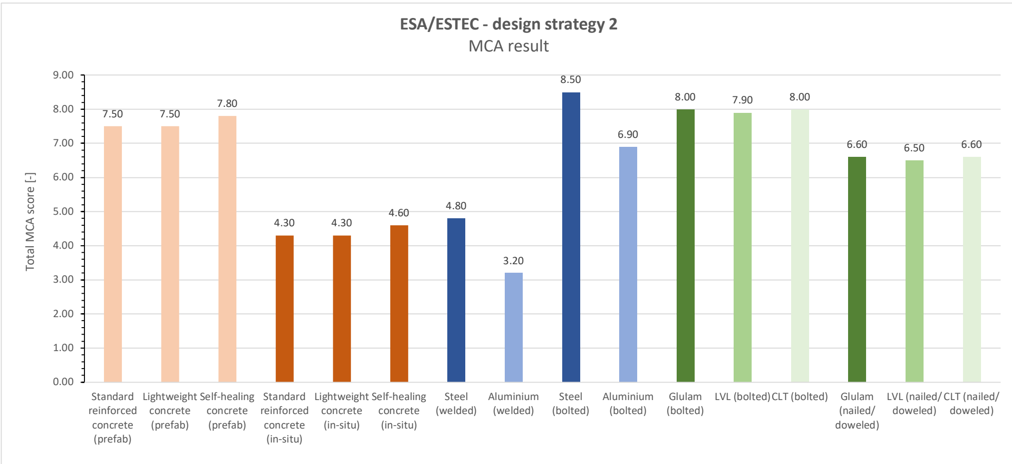
Percentage	Score
100 %	1.00
100-110 %	0.90
110-125 %	0.80
125-150 %	0.70
150-200 %	0.60
200-250 %	0.50
250-300 %	0.40
300-400 %	0.30
400-500 %	0.20
>500 %	0.10

ECI (A+C+D)	
238 %	**0.50**
237 %	**0.50**
239 %	**0.50**
292 %	**0.40**
291 %	**0.40**
293 %	**0.40**
100 %	**1.00**
232 %	**0.50**
207 %	**0.50**
211 %	**0.50**
205 %	**0.50**

Percentage	Score
100 %	1.00
100-110 %	0.90
110-125 %	0.80
125-150 %	0.70
150-200 %	0.60
200-250 %	0.50
250-300 %	0.40
300-400 %	0.30
400-500 %	0.20
>500 %	0.10



		Concrete						Metal				Timber					
		Prefab			In-situ			Welded connections		Bolted connections		Bolted connections			Nailed/ doweled connections		
		Standard reinforced concrete (prefab)	Lightweight concrete (prefab)	Self-healing concrete (prefab)	Standard reinforced concrete (in-situ)	Lightweight concrete (in-situ)	Self-healing concrete (in-situ)	Steel (welded)	Aluminium (welded)	Steel (bolted)	Aluminium (bolted)	Glulam (bolted)	LVL (bolted)	CLT (bolted)	Glulam (nailed/ doweled)	LVL (nailed/ doweled)	CLT (nailed/ doweled)
Lifespan of a building material		**0.90**	**0.90**	**1.00**	**0.80**	**0.80**	**0.90**	**0.60**	**0.70**	**0.90**	**1.00**	**0.80**	**0.80**	**0.80**	**0.60**	**0.60**	**0.60**
Estimated service life [ESL, years]		55	55	61	50	50	54	41	45	54	60	50	50	50	41	41	41
Reference service life [RSL, years]		50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
A.1 Inherent performance level		1	1	1	1	1	1	1	1	1	1	0.9	0.9	0.9	0.9	0.9	0.9
A.2 Inherent performance level		1	1	1.1	1	1	1.1	1	1.1	1	1.1	1	1	1	1	1	1
B. Design level		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
C. Work execution level		1.1	1.1	1.1	0.9	0.9	0.9	0.9	0.9	1.1	1.1	1	1	1	0.9	0.9	0.9
D. Indoor Environment		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
E. Outdoor Environment		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
F. Usage conditions		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
G. Maintenance level		1	1	1	1	1	1	1	1	1.1	1.1	1.1	1.1	1.1	1	1	1
H. Fire resistance		1	1	1	1.1	1.1	1.1	0.9	0.9	0.9	0.9	1	1	1	1	1	1
Building material's potential for recycling [I_recycling]		**0.595**	**0.595**	**0.595**	**0.595**	**0.595**	**0.595**	**0.650**	**0.705**	**0.650**	**0.705**	**0.590**	**0.590**	**0.590**	**0.590**	**0.590**	**0.590**
Index for benefits from recycling [BR]		0.47	0.47	0.47	0.47	0.47	0.47	0.63	0.70	0.63	0.70	0.49	0.49	0.49	0.49	0.49	0.49
Index for suitability for recycling [SR]		0.72	0.72	0.72	0.72	0.72	0.72	0.67	0.71	0.67	0.71	0.69	0.69	0.69	0.69	0.69	0.69
Type of connection [TC]		**0.80**	**0.80**	**0.80**	**0.10**	**0.10**	**0.10**	**0.10**	**0.10**	**0.80**	**0.80**	**0.80**	**0.80**	**0.80**	**0.60**	**0.60**	**0.60**
Accessibility of connection [AC]		**0.80**	**0.80**	**0.80**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.80**	**0.80**	**0.80**	**0.80**	**0.80**	**0.60**	**0.60**	**0.60**
Removability-index of a connection [I_connection_removability]		**0.80**	**0.80**	**0.80**	**0.16**	**0.16**	**0.16**	**0.16**	**0.16**	**0.80**	**0.80**	**0.80**	**0.80**	**0.80**	**0.60**	**0.60**	**0.60**
Total weight of used building material		**0.30**	**0.30**	**0.30**	**0.10**	**0.10**	**0.10**	**0.70**	**0.80**	**0.70**	**0.80**	**0.90**	**0.90**	**1.00**	**0.90**	**0.90**	**1.00**
Total price of used building material		**0.40**	**0.40**	**0.40**	**0.30**	**0.30**	**0.30**	**0.60**	**0.10**	**0.60**	**0.10**	**0.80**	**0.90**	**1.00**	**0.80**	**0.90**	**1.00**
ECI value for production process (LCA module A1-A3)		**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**1.00**	**0.30**	**1.00**	**0.30**	**0.80**	**0.70**	**0.70**	**0.80**	**0.70**	**0.70**
ECI value at end-of-life stage (LCA module A1-3 + C + D)		**0.50**	**0.50**	**0.50**	**0.40**	**0.40**	**0.40**	**1.00**	**0.50**	**1.00**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**
MCA criteria * weights for design strategy 2	weights																
Lifespan of a building material	**3**	2.70	2.70	3.00	2.40	2.40	2.70	1.80	2.10	2.70	3.00	2.40	2.40	2.40	1.80	1.80	1.8
Building material's potential for recycling [I_recycling]	**0**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Type of connection [TC]	**4**	3.20	3.20	3.20	0.40	0.40	0.40	0.40	0.40	3.20	3.20	3.20	3.20	3.20	2.40	2.40	2.4
Accessibility of connection [AC]	**0**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Removability-index of a connection [I_connection_removability]	**0**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Total weight of used building material	**0**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Total price of used building material	**1**	0.40	0.40	0.40	0.30	0.30	0.30	0.60	0.10	0.60	0.10	0.80	0.90	1.00	0.80	0.90	1
ECI value for production process (LCA module A1-A3)	**2**	1.20	1.20	1.20	1.20	1.20	1.20	2.00	0.60	2.00	0.60	1.60	1.40	1.40	1.60	1.40	1.4
ECI value at end-of-life stage (LCA module A1-3 + C + D)	**0**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Total MCA score	**10**	**7.50**	**7.50**	**7.80**	**4.30**	**4.30**	**4.60**	**4.80**	**3.20**	**8.50**	**6.90**	**8.00**	**7.90**	**8.00**	**6.60**	**6.50**	**6.60**



ESA/ESTEC - design strategy 3										*width [m]*	*length [m]*	*height [m]*	*number of floors*								
										30.00	35.00	12.00	3								
1	Concrete C35/45 (prefab) - standard reinforcement																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	hollow-core slab		4.50	0.32	1.20	5.00	1.08	2752.29	25	7	175	525	567	1444954	64.41	202891.50	*(no information, assume*		5.4924	17301.06
																		same as for LCA A+C+D)			
				self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	300x400		25.00	0.40	0.30	5.00	0.60	1529.05	6	8	48	144	86	220183	257.02	185054.40	43.4624	3755.15	31.8712	2753.67
				self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	200x200		25.00	0.20	0.20	4.50	0.18	458.72	7	8	56	56	10	25688	181.48	45732.96	43.4624	438.10	31.8712	321.26
		200x200		25.00	0.20	0.20	3.25	0.13	331.29	7	8	56	112	15	37105	181.48	66058.72	43.4624	632.81	31.8712	464.04
	total													**678**	**1727931**		**499737.58**		**22127.12**		**20840.04**
														m3	kg		euro		euro		euro
2	Lightweight concrete C40/44 (prefab) - standard reinforcement																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	hollow-core slab		4.50	0.32	1.20	5.00	1.08	2752.29	25	7	175	525	567	1444954	64.41	202891.50	*(no information, assume*		5.4924	17301.06
																		same as for LCA A+C+D)			
				self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	300x400		17.00	0.40	0.30	5.00	0.60	1039.76	6	8	48	144	86	149725	334.12	240566.40	43.4624	3755.15	31.8712	2753.67
				self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	200x200		17.00	0.20	0.20	4.50	0.18	311.93	7	8	56	56	10	17468	235.92	59451.84	43.4624	438.10	31.8712	321.26
		200x200		17.00	0.20	0.20	3.25	0.13	225.28	7	8	56	112	15	25231	235.92	85874.88	43.4624	632.81	31.8712	464.04
	total													**678**	**1637378**		**588784.62**		**22127.12**		**20840.04**
														m3	kg		euro		euro		euro
3	Self-healing concrete C35/45 (prefab) - standard reinforcement																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	hollow-core slab		4.50	0.32	1.20	5.00	1.08	2752.29	25	7	175	525	567	1444954	64.41	202891.50	*(no information, assume*		5.4924	17301.06
																		same as for LCA A+C+D)			
				self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	300x400		25.00	0.40	0.30	5.00	0.60	1529.05	6	8	48	144	86	220183	257.02	188510.40	43.8659	3790.01	32.4392	2802.75
				self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	200x200		25.00	0.20	0.20	4.50	0.18	458.72	7	8	56	56	10	25688	181.48	46136.16	43.8659	442.17	31.8712	321.26
		200x200		25.00	0.20	0.20	3.25	0.13	331.29	7	8	56	112	15	37105	181.48	66641.12	43.8659	638.69	31.8712	464.04
	total													**678**	**1727931**		**504179.18**		**22171.93**		**20889.11**
														m3	kg		euro		euro		euro
4	Concrete C35/45 (in-situ) - standard reinforcement																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	composite slab		8.00	0.32	3.00	5.00	4.80	12232.42	10	7	70	210	1008	2568807	136.10	428715.00	*(no information, assume*		6.4630	20358.45
																		same as for LCA A+C+D)			
				self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	350x400		25.00	0.40	0.35	5.00	0.70	1783.89	6	8	48	144	101	256881	145.79	104968.80	43.4624	4381.01	31.8712	3212.62
				self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	200x200		25.00	0.20	0.20	4.50	0.18	458.72	7	8	56	56	10	25688	95.78	24136.56	43.4624	438.10	31.8712	321.26
		200x200		25.00	0.20	0.20	3.25	0.13	331.29	7	8	56	112	15	37105	95.78	34863.92	43.4624	632.81	31.8712	464.04
	total													**1133**	**2888481**		**592684.28**		**25810.37**		**24356.37**
														m3	kg		euro		euro		euro
5	Lightweight concrete C40/44 (in-situ) - standard reinforcement																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	composite slab		8.00	0.32	3.00	5.00	4.80	12232.42	10	7	70	210	1008	2568807	136.10	428715.00	*(no information, assume*		6.4630	20358.45
																		same as for LCA A+C+D)			
				self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	350x400		17.00	0.40	0.35	5.00	0.70	1213.05	6	8	48	144	101	174679	189.53	136461.60	43.4624	4381.01	31.8712	3212.62
				self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	200x200		17.00	0.20	0.20	4.50	0.18	311.93	7	8	56	56	10	17468	124.52	31379.04	43.4624	438.10	31.8712	321.26

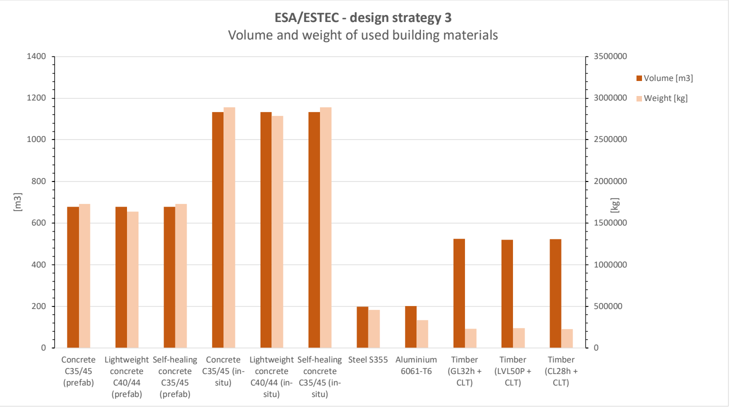
		200x200		17.00	0.20	0.20	3.25	0.13	225.28	7	8	56	112	15	25231	124.52	45325.28	43.4624	632.81	31.8712	464.04
	total													**1133**	**2786186**		**641880.92**		**25810.37**		**24356.37**
														m3	kg		euro		euro		euro
6	Self-healing concrete C35/45 (in-situ) - standard reinforcement																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	composite slab		8.00	0.32	3.00	5.00	4.80	12232.42	10	7	70	210	1008	2568807	136.10	428715.00	*(no information, assume same as for LCA A+C+D)*		6.4630	20358.45
				self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	350x400		25.00	0.40	0.35	5.00	0.70	1783.89	6	8	48	144	101	256881	145.79	109000.80	43.8659	4421.68	32.4392	3269.87
				self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	200x200		25.00	0.20	0.20	4.50	0.18	458.72	7	8	56	56	10	25688	95.78	24539.76	43.8659	442.17	31.8712	321.26
		200x200		25.00	0.20	0.20	3.25	0.13	331.29	7	8	56	112	15	37105	95.78	35446.32	43.8659	638.69	31.8712	464.04
	total													**1133**	**2888481**		**597701.88**		**25860.99**		**24413.63**
														m3	kg		euro		euro		euro
7	Steel S355																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	steel deck:																*(no information, assume same as for LCA A+C+D)*		2.6793	8439.80
		finishing layer		0.70	0.035	30.00	5.00	5.25	10703.36	1	7	7	21	110	224771	7.82	24633.00				
		plate material		0.10	0.020	30.00	5.00	3.00	1529.05	1	7	7	21	63	32110	5.84	18396.00				
				self-weight [kN/m3]	area [m2]		span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**				
		steel C-sections		78.500	0.00588		5.00	0.03	235.26	30	7	210	630	19	148214	66.90	210735				
				self-weight [kN/m3]	area [m2]		span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	IPE 300		78.50	0.00538		5.00	0.03	215.25	6	8	48	144	3.87	30997	61.55	44316.00	911.3850	3530.34	146.7950	568.63
				self-weight [kN/m3]	area [m2]		length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	HE 160 A		78.50	0.00388		4.50	0.02	139.72	7	8	56	56	0.98	7824	43.88	11057.76	911.3850	891.12	146.7950	143.53
		HE 160 A		78.50	0.00388		3.25	0.01	100.91	7	8	56	112	1.41	11301	43.88	15972.32	911.3850	1287.17	146.7950	207.32
	total													**198**	**455217**		**325110.08**		**14148.42**		**9359.27**
														m3	kg		euro		euro		euro
8	Aluminium 6061-T6																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	aluminium deck:																*(no information, assume same as for LCA A+C+D)*		5.427	17095.05
		finishing layer		0.70	0.035	30.00	5.00	5.25	10703.36	1	7	7	21	110	224771	7.82	24633.00				
		plate material		0.10	0.020	30.00	5.00	3.00	1529.05	1	7	7	21	63	32110	5.84	18396.00				
				self-weight [kN/m3]	area [m2]		span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**				
		aluminium C-sections		27.000	0.00588		5.00	0.03	80.92	30	7	210	630	19	50978	200.70	632205.00				
				self-weight [kN/m3]	area [m2]		span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	IPE 450		27.00	0.00988		5.00	0.05	135.96	6	8	48	144	7.11	19579	355.98	256305.60	2451.6000	17439.70	374.4900	2663.97
				self-weight [kN/m3]	area [m2]		length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	HE 180 A		27.00	0.00453		4.50	0.02	56.11	7	8	56	56	1.14	3142	153.63	38714.76	2451.6000	2798.65	374.4900	427.50
		HE 180 A		27.00	0.00453		3.25	0.01	40.52	7	8	56	112	1.65	4538	153.63	55921.32	2451.6000	4042.49	374.4900	617.50
	total													**202**	**335118**		**1026175.68**		**41375.89**		**20804.03**
														m3	kg		euro		euro		euro
9	Timber (GL32h + CLT)																	LCA module A		LCA module A+C+D	
				self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	CLT panels		0.60	0.14	3.00	5.00	2.10	917.43	10	7	70	210	441	192661	34.50	108675.00	*(no information, assume same as for LCA A+C+D)*		5.3837	16958.66
				self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m3]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	185x500		4.60	0.50	0.185	5.00	0.46	216.87	6	8	48	144	67	31229	1000.00	66600.00	28.6580	1908.62	28.6580	1908.62
				self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	110x250		4.60	0.25	0.11	4.50	0.12	58.03	7	8	56	56	7	3250	1000.00	6930.00	28.6580	198.60	28.6580	198.60
		110x250		4.60	0.25	0.11	3.25	0.09	41.91	7	8	56	112	10	4694	1000.00	10010.00	28.6580	286.87	28.6580	286.87
	total													**525**	**231833**		**192215.00**		**19352.74**		**19352.74**
														m3	kg		euro		euro		euro

10	Timber (LVL50P + CLT)																LCA module A		LCA module A+C+D	
			self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	CLT panels	0.60	0.14	3.00	5.00	2.10	917.43	10	7	70	210	441	192661	34.50	108675.00	*(no information, assume same as for LCA A+C+D)*		5.3837	16958.66
			self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m3]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	160x550	6.00	0.55	0.16	5.00	0.44	269.11	6	8	48	144	63	38752	900.00	57024.00	37.3800	2368.40	37.3800	2368.40
			self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m3]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	80x300	6.00	0.30	0.08	4.50	0.11	66.06	7	8	56	56	6	3699	900.00	5443.20	37.3800	226.07	37.3800	226.07
		80x300	6.00	0.30	0.08	3.25	0.08	47.71	7	8	56	112	9	5343	900.00	7862.40	37.3800	326.55	37.3800	326.55
	total												**519**	**240455**		**179004.60**		**19879.68**		**19879.68**
													m3	kg		euro		euro		euro

11	Timber (CL28h + CLT)																LCA module A		LCA module A+C+D	
			self-weight [kN/m2]	thickness [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number in 1 storey	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m2]	**total price [€]**	**ECI [€/m2]**	**total ECI [€]**	**ECI [€/m2]**	**total ECI [€]**
	floor	CLT panels	0.60	0.14	3.00	5.00	2.10	917.43	10	7	70	210	441	192661	34.50	108675.00	*(no information, assume same as for LCA A+C+D)*		5.3837	16958.66
			self-weight [kN/m3]	height [m]	width [m]	span [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m3]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	beams	160x550	4.12	0.55	0.16	5.00	0.44	184.79	6	8	48	144	63	26610	700.00	44352.00	31.2897	1982.52	25.7102	1629.00
			self-weight [kN/m3]	height [m]	width [m]	length [m]	volume [m3]	weight [kg]	number in width	number in length	total number (1 storey)	total number (all storeys)	**total [m3]**	**total [kg]**	price [€/m3]	**total price [€]**	**ECI [€/m3]**	**total ECI [€]**	**ECI [€/m3]**	**total ECI [€]**
	columns	85x350	4.12	0.35	0.085	4.50	0.13	56.22	7	8	56	56	7	3149	700.00	5247.90	31.2897	234.58	25.7102	192.75
		85x350	4.12	0.35	0.085	3.25	0.10	40.61	7	8	56	112	11	4548	700.00	7580.30	31.2897	338.84	25.7102	278.42
	total												**523**	**226967**		**165855.20**		**19514.59**		**19058.82**
													m3	kg		euro		euro		euro

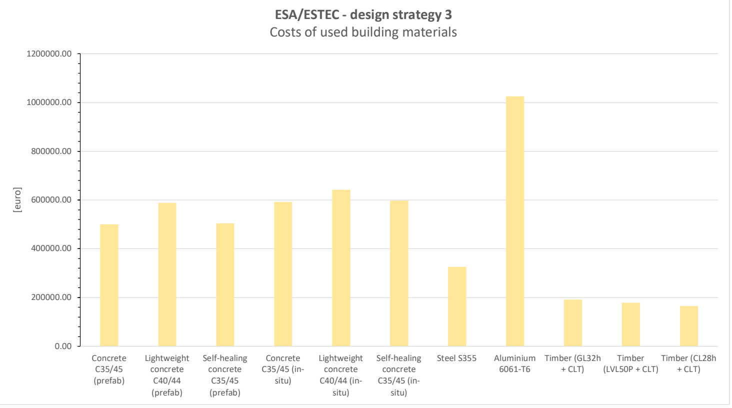
	Volume [m3]	bl	bl	Weight [kg]			
Concrete C35/45 (prefab)	678			1727931	761	%	**0.30**
Lightweight concrete C40/44 (prefab)	678			1637378	721	%	**0.30**
Self-healing concrete C35/45 (prefab)	678			1727931	761	%	**0.30**
Concrete C35/45 (in-situ)	1133			2888481	1273	%	**0.10**
Lightweight concrete C40/44 (in-situ)	1133			2786186	1228	%	**0.10**
Self-healing concrete C35/45 (in-situ)	1133			2888481	1273	%	**0.10**
Steel S355	198			455217	201	%	**0.60**
Aluminium 6061-T6	202			335118	148	%	**0.80**
Timber (GL32h + CLT)	525			231833	102	%	**0.90**
Timber (LVL50P + CLT)	519			240455	106	%	**0.90**
Timber (CL28h + CLT)	523			226967	100	%	**1.00**

Percentage		Score
100	%	1.00
100-125	%	0.90
125-150	%	0.80
150-200	%	0.70
200-300	%	0.60
300-400	%	0.50
400-600	%	0.40
600-800	%	0.30
800-1000	%	0.20
>1000	%	0.10



	Costs [€]			
Concrete C35/45 (prefab)	499737.58	301	%	**0.30**
Lightweight concrete C40/44 (prefab)	588784.62	355	%	**0.30**
Self-healing concrete C35/45 (prefab)	504179.18	304	%	**0.30**
Concrete C35/45 (in-situ)	592684.28	357	%	**0.30**
Lightweight concrete C40/44 (in-situ)	641880.92	387	%	**0.30**
Self-healing concrete C35/45 (in-situ)	597701.88	360	%	**0.30**
Steel S355	325110.08	196	%	**0.60**
Aluminium 6061-T6	1026175.68	619	%	**0.10**
Timber (GL32h + CLT)	192215.00	116	%	**0.80**
Timber (LVL50P + CLT)	179004.60	108	%	**0.90**
Timber (CL28h + CLT)	165855.20	100	%	**1.00**

Percentage		Score
100	%	1.00
100-110	%	0.90
110-125	%	0.80
125-150	%	0.70
150-200	%	0.60
200-250	%	0.50
250-300	%	0.40
300-400	%	0.30
400-500	%	0.20
>500	%	0.10

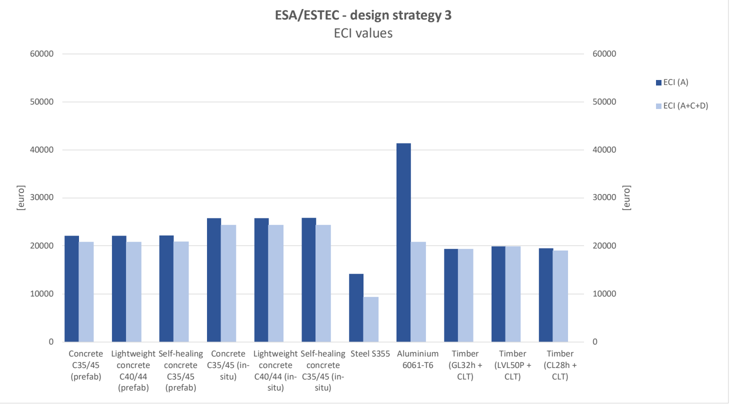


	ECI (A)	bl	bl	ECI (A+C+D)	**ECI (A)**		
Concrete C35/45 (prefab)	22127			20840	156	%	**0.60**
Lightweight concrete C40/44 (prefab)	22127			20840	156	%	**0.60**
Self-healing concrete C35/45 (prefab)	22172			20889	157	%	**0.60**
Concrete C35/45 (in-situ)	25810			24356	182	%	**0.60**
Lightweight concrete C40/44 (in-situ)	25810			24356	182	%	**0.60**
Self-healing concrete C35/45 (in-situ)	25861			24414	183	%	**0.60**
Steel S355	14148			9359	100	%	**1.00**
Aluminium 6061-T6	41376			20804	292	%	**0.30**
Timber (GL32h + CLT)	19353			19353	137	%	**0.80**
Timber (LVL50P + CLT)	19880			19880	141	%	**0.70**
Timber (CL28h + CLT)	19515			19059	138	%	**0.70**

Percentage		Score
100	%	1.00
100-110	%	0.90
110-125	%	0.80
125-150	%	0.70
150-200	%	0.60
200-250	%	0.50
250-300	%	0.40
300-400	%	0.30
400-500	%	0.20
>500	%	0.10

ECI (A+C+D)		
223	%	**0.50**
223	%	**0.50**
223	%	**0.50**
260	%	**0.40**
260	%	**0.40**
261	%	**0.40**
100	%	**1.00**
222	%	**0.50**
207	%	**0.50**
212	%	**0.50**
204	%	**0.50**

Percentage		Score
100	%	1.00
100-110	%	0.90
110-125	%	0.80
125-150	%	0.70
150-200	%	0.60
200-250	%	0.50
250-300	%	0.40
300-400	%	0.30
400-500	%	0.20
>500	%	0.10



		Concrete						Metal				Timber					
		Prefab			In-situ			Welded connections		Bolted connections		Bolted connections			Nailed/ doweled connections		
		Standard reinforced concrete (prefab)	Lightweight concrete (prefab)	Self-healing concrete (prefab)	Standard reinforced concrete (in-situ)	Lightweight concrete (in-situ)	Self-healing concrete (in-situ)	Steel (welded)	Aluminium (welded)	Steel (bolted)	Aluminium (bolted)	Glulam (bolted)	LVL (bolted)	CLT (bolted)	Glulam (nailed/ doweled)	LVL (nailed/ doweled)	CLT (nailed/ doweled)
Lifespan of a building material		**0.90**	**0.90**	**1.00**	**0.80**	**0.80**	**0.90**	**0.60**	**0.70**	**0.90**	**1.00**	**0.80**	**0.80**	**0.80**	**0.60**	**0.60**	**0.60**
Estimated service life [ESL, years]		55	55	61	50	50	54	41	45	54	60	50	50	50	41	41	41
Reference service life [RSL, years]		50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
A.1 Inherent performance level		1	1	1	1	1	1	1	1	1	1	0.9	0.9	0.9	0.9	0.9	0.9
A.2 Inherent performance level		1	1	1.1	1	1	1.1	1	1.1	1	1.1	1	1	1	1	1	1
B. Design level		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
C. Work execution level		1.1	1.1	1.1	0.9	0.9	0.9	0.9	0.9	1.1	1.1	1	1	1	0.9	0.9	0.9
D. Indoor Environment		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
E. Outdoor Environment		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
F. Usage conditions		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
G. Maintenance level		1	1	1	1	1	1	1	1	1.1	1.1	1.1	1.1	1.1	1	1	1
H. Fire resistance		1	1	1	1.1	1.1	1.1	0.9	0.9	0.9	0.9	1	1	1	1	1	1
Building material's potential for recycling [I_recycling]		**0.595**	**0.595**	**0.595**	**0.595**	**0.595**	**0.595**	**0.650**	**0.705**	**0.650**	**0.705**	**0.590**	**0.590**	**0.590**	**0.590**	**0.590**	**0.590**
Index for benefits from recycling [BR]		0.47	0.47	0.47	0.47	0.47	0.47	0.63	0.70	0.63	0.70	0.49	0.49	0.49	0.49	0.49	0.49
Index for suitability for recycling [SR]		0.72	0.72	0.72	0.72	0.72	0.72	0.67	0.71	0.67	0.71	0.69	0.69	0.69	0.69	0.69	0.69
Type of connection [TC]		**0.80**	**0.80**	**0.80**	**0.10**	**0.10**	**0.10**	**0.10**	**0.10**	**0.80**	**0.80**	**0.80**	**0.80**	**0.80**	**0.60**	**0.60**	**0.60**
Accessibility of connection [AC]		**0.80**	**0.80**	**0.80**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.80**	**0.80**	**0.80**	**0.80**	**0.80**	**0.60**	**0.60**	**0.60**
Removability-index of a connection [I_connection_removability]		**0.80**	**0.80**	**0.80**	**0.16**	**0.16**	**0.16**	**0.16**	**0.16**	**0.80**	**0.80**	**0.80**	**0.80**	**0.80**	**0.60**	**0.60**	**0.60**
Total weight of used building material		**0.30**	**0.30**	**0.30**	**0.10**	**0.10**	**0.10**	**0.60**	**0.80**	**0.60**	**0.80**	**0.90**	**0.90**	**1.00**	**0.90**	**0.90**	**1.00**
Total price of used building material		**0.30**	**0.30**	**0.30**	**0.30**	**0.30**	**0.30**	**0.60**	**0.10**	**0.60**	**0.10**	**0.80**	**0.90**	**1.00**	**0.80**	**0.90**	**1.00**
ECI value for production process (LCA module A1-A3)		**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**1.00**	**0.30**	**1.00**	**0.30**	**0.80**	**0.70**	**0.70**	**0.80**	**0.70**	**0.70**
ECI value at end-of-life stage (LCA module A1-3 + C + D)		**0.50**	**0.50**	**0.50**	**0.40**	**0.40**	**0.40**	**1.00**	**0.50**	**1.00**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**
MCA criteria * weights for design strategy 2	weights																
Lifespan of a building material	**0**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Building material's potential for recycling [I_recycling]	**2**	1.19	1.19	1.19	1.19	1.19	1.19	1.30	1.41	1.30	1.41	1.18	1.18	1.18	1.18	1.18	1.18
Type of connection [TC]	**0**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Accessibility of connection [AC]	**0**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Removability-index of a connection [I_connection_removability]	**4**	3.20	3.20	3.20	0.64	0.64	0.64	0.64	0.64	3.20	3.20	3.20	3.20	3.20	2.40	2.40	2.40
Total weight of used building material	**2**	0.60	0.60	0.60	0.20	0.20	0.20	1.20	1.60	1.20	1.60	1.80	1.80	2.00	1.80	1.80	2.00
Total price of used building material	**1**	0.30	0.30	0.30	0.30	0.30	0.30	0.60	0.10	0.60	0.10	0.80	0.90	1.00	0.80	0.90	1.00
ECI value for production process (LCA module A1-A3)	**0**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ECI value at end-of-life stage (LCA module A1-3 + C + D)	**1**	0.50	0.50	0.50	0.40	0.40	0.40	1.00	0.50	1.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Total MCA score	**10**	**5.79**	**5.79**	**5.79**	**2.73**	**2.73**	**2.73**	**4.74**	**4.25**	**7.30**	**6.81**	**7.48**	**7.58**	**7.88**	**6.68**	**6.78**	**7.08**