Shadow cost optimization of the main bearing construction of industrial halls

MSc thesis

J.J.J. Wolbert

TU Delft

ARCADIS

Shadow cost optimization of the main bearing construction of industrial halls

Development of an optimization methodology for industrial halls that combines shadow price data with a structural parametric model and generative design

by

Jorick Jeroen Johannes Wolbert

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Thesis committee:	Prof. dr. M. Veljkovic,	TU Delft
	Ir. S. Pasterkamp,	TU Delft
	Dr. H. Jonkers,	TU Delft
	Ir. E. den Hartog,	Arcadis

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Graduation student

Name	Jorick Wolbert
Student number	4444132
E-mail	jorickw@gmail.com

Educational institution

Name	Delft University of Technology
Faculty	Civil Engineering and Geosciences (CEG)
Address	Stevinweg 1
	2628CN Delft
	the Netherlands
Department	Structural Engineering

Graduation company

Name	Arcadis Nederland B.V.
Addres	Weena 505
	3013 AL Rotterdam
	the Netherlands
Department	Structural Design & Engineering

Preface

This thesis marks the end of my master's program Structural Engineering, with the specialisation steel and composite structures at Delft University of Technology. Performing this research during the Covid-19 pandemic was challenging, but looking back at the project, I am very proud of what I have achieved.

Throughout my studies I've learned a lot about the theoretical side of structural engineering and deepened my knowledge on specific construction materials. However, I was missing a more practical application in which I could use my gathered knowledge. The environmental impact of structures was a recurring subject in my courses, but from my point of view it seemed to lack efficiency. Therefore, I decided to combine these two aspects in my master's thesis in the form of a structural parametric model for the optimization of shadow costs.

This thesis has been created in collaboration with Arcadis Nederland BV, where I was supervised by Eline den Hartog. I would like to express my gratitude towards her and all the other people at Arcadis for their time, effort and the great working environment, which helped me during my research. I want to extend a special thanks to Michael van Telgen and Igor Pecanac for getting me started with the DynamoStructural tool and for their feedback and suggestions which helped me to improve my parametric model.

I would also like to thank the rest of my committee, Milan Veljkovic, Sander Pasterkamp and Henk Jonkers for all the insights, remarks and feedback that they have provided throughout this project. Their guidance and criticism have helped me to improve the quality of the research and inspired me to strive towards better results.

Then, would like to thank Pelecon structural Engineers and Hercuton Bedrijfsbouw for providing me with building reports and floor plans of existing industrial halls.

A final thank you goes out to everyone who has been there to support me during this final journey. My family, my friends, my girlfriend and all the other people who have been around me. Thank you very much. Without you it would have been much more difficult.

Hopefully, this thesis serves as inspiration for an increase the efficiency of environmental impact reduction in structural designs.

J.J.J. Wolbert
Delft, March 2022

Abstract

The purpose of this thesis is to determine the most optimal material use and configuration of structural elements with regard to minimizing shadow costs associated with the main bearing construction of industrial halls. Central themes in thesis are reusability, parametric modelling and generative design.

The construction sector is responsible for a large amount of pollution due to its high energy consumption during extraction and transportation of raw materials [3, 4]. Paradoxically, this offers the construction sector a unique opportunity to notably decrease its negative environmental impact. Since the implementation of the European energy performance of buildings directive in 2020, all new buildings are required to have nearly zero-energy demands. Consequently the relative impact share of construction materials on the overall environmental impact of buildings is growing progressively. Hence, material shadow costs are starting to become increasingly more governing.

The current inefficiency in shadow cost reductions of main load bearing elements presents a problem regarding the ambition of the European union to decrease the significant amount of harmful emissions as a consequence of construction. One of the most effective ways to reduce shadow costs of buildings is to implement changes in the early design stages [13–15]. Structural parametric modelling is a quite new development in civil engineering and its uses have yet to be discovered on the scale of entire structures. Parametric design is remarkably useful for quick variant studies as it enables structural designers to swiftly adapt their structural design based on the specified input parameters and boundary conditions. Generative design tools can use these parametric models to generate a multitude of different design alternatives. Using a genetic algorithm, these alternatives can be computationally optimized to obtain a configuration of structural elements and materials that result in a design with minimized shadow costs. When implemented during early design stages, this process can provide an optimized starting point towards a definitive design.

Shadow costs associated with structural elements decrease as a result of reuse. Connection types have been identified as the most influential factor for reusability. Therefore, a connection reusability factor was developed which was given according to four material independent criteria and based on the experiences of structural designers from Arcadis Nederland BV. Subsequently, a corrected shadow cost (CSC) can be calculated by multiplication of this reusability factor with the original ECI. As such, this CSC includes the reusability of construction elements through their connection types as well as their recyclability through their original ECI values. Although the reusability scores of connection types are given based on experience, they are heavily influenced by the subjective interpretation from Arcadis designers. The debatable veracity of these scores is recognised and an Alma mater reusability score is provided for comparison, which will be referred to as the J.W. reusability score. Evidently, a change in the reusability scores will result in very different CSC values. During the inventory of relevant connection types, it was identified that creating rigid demountable connections using a few additional bolts is a very effective connection type to increase cross section efficiency in steel elements. However, for timber elements, rigid connections are only possible by using large amounts of bolts or dowels or by using DVW-reinforced joints combined with steel tube fasteners. The former decreases the effective stiffness of the element and is impractical to demount due to the extensive amount of bolts that are used. The latter does retain the original stiffness but it cannot be demounted without destroying the element since the steel tubes are expanded inside the timber to create the connection. Since no rigid timber connection technique is considered (economically) demountable and using rigid connections exclusively for steel elements would give it a rather large and unfair advantage over timber elements, it was decided not to include rigid connections in the optimization process. It is recognised that the benefits of steel elements is underestimated by this decision and the outcomes of the optimization as such do not reflect their full potential.

Dynamo Sandbox was used to create the parametric model that is used in this thesis. This parametric model featured a connection with finite element software RFEM for structural verification. Subsequently, the model could be optimized using a genetic algorithm in Autodesk generative design in order to minimize shadow costs. Due to limitations in the application programming interface of RFEM 2.6 it was not possible to include concrete elements in the parametric model. Consequently only steel and timber elements were assessed during the optimization process. Table 1 provides an overview of the values that were used for the ECI and the price of all considered materials. The ECI values in this table have been taken from the Dutch national environmental database (NMD) and the prices were provided by an Arcadis cost manager. The NMD was identified as the most suitable database since in addition to individual EPDs it also contains branch average data of construction elements suppliers which is the most appropriate data to use for preliminary designs. In the NMD, the effect of biogenic carbon storage in timber elements is not accounted for since the justification of its inclusion is debated amongst experts due to the high dependency on the benefits beyond the end of life which are often unknown. Nevertheless, it should be noted that the inclusion of biogenic carbon storage will lead to a significant reduction of the ECI of timber elements which immanently changes the outcomes of the shadow cost optimization process in this thesis drastically.

Table 1: ECI and price input per material [in €/m^3]

	Rolled steel	Cold formed steel	Timber
ECI	271.84	273.85	56.23
Price	29045	58875	1800

Single and multi objective optimizations were performed on a single storey arbitrary but realistic industrial hall in order to test the optimization processes and to establish which configuration and materials can best be used in the respective optimizations to increase their effectiveness. The hall has a width, length and internal free height of 45 m and 100 m and 10 m respectively, a snow load of 0.56 kN/m^2 was considered and the hall was assumed to be located in a rural area of the Dutch wind zone II. For the self-weight of the roof and facade elements 0.38 kN/m^2 and 0.5 kN/m^2 was used respectively. Fire protection

measures have been accounted for in neither price nor ECI and only hinged connections were considered. Based on the optimization results, for similar halls with similar (boundary) conditions it can be concluded that steel performs significantly better than timber in terms of ECI as well as CSC and contradictory to popular belief, timber performs better in terms of material costs. In exclusively steel multi objective optimized designs, rolled steel sections are consistently preferred for elements which are predominantly loaded in single bending while cold formed steel sections were preferred for elements which were loaded in double bending even though the price of these sections is higher. This indicates that the efficiency per kg of cold formed sections in double bending outweighs the price difference with rolled sections. Moreover, in mixed material multi objective optimized designs it proves most beneficial to use cold formed steel in members that are loaded in double bending such as edge purlins, side rails and edge beams and to use timber for members that bend in a single direction such as columns and purlins. It should be noted that considering the reusability potential and the subsequent elongated lifespan of demountable structural elements, the inclusion of biogenic carbon storage for timber construction elements would reduce their ECI considerably and the outcomes of this optimization might have resulted in more favourable conclusions regarding timber elements.

Two case studies on existing industrial halls were performed in which the effectiveness of the optimization methodology was tested. In order to retain the original functional unit, the length, width, height and internal column positions were assumed to be static during the optimization process. Variables which the algorithm was able to change during the optimization included centre to centre distances between outer columns, purlins and side rails as well as material use and cross section size. For the sake of comparability, the permanent and variable loads acting on the structure were copied from the original design. When interpreting the results of the case studies, it must be recognised that the original design was not verified in a finite element software in its entirety. Therefore, it is plausible that the optimized designs are more conservatively designed than the original industrial hall, thus resulting in a relatively higher ECI, CSC and price. The results from the two case studies are presented in Table 2. Slight differences are noticeable between J.W. and Arcadis CSC's, which are explained by the fact that steel bolted connections result in marginally better reusability scores according to the latter.

Table 2: ECI, CSC, price and weight comparison of case study designs

		Case study 1		**Case study 2**	
		Original	Optimized	Original	Optimized
ECI	[€]	11744.3	9886.9	10297.5	15384.0
Arcadis CSC	[€]	2121.6	1779.6	8855.9	2769.1
J.W. CSC	[€]	2357.3	1977.4	7723.2	3076.8
Price	[€]	1648598.0	1463254.0	1595451.5	2647957.0
Weight	[kg]	378901.5	316240.3	330848.6	485622.5

In the first case study it is observed that the generatively optimized design reduces the ECI of the original hall by 16% which consequently also resulted in lower CSCs. In addition, the construction price is also 11% lower compared to the original hall. The generatively opti-

mized design as well as the original design consisted solely of elements with hinged connections, therefore the results are quite accurately comparable. Thus, it can be concluded that for single span, single storey, steel industrial halls that consist of solely of elements with hinged connections, the optimization methodology as presented in this thesis has a beneficial effect on the total ECI of the hall. However, it should be noted that no tests have been performed on similar kinds of halls in different wind or snow zones. The results of this case study can therefore not be generalized to apply to similar halls in different regions without further testing.

In the second case study, it is observed that the optimized design performs almost 50% worse with regard to ECI compared to the original design. This result can be explained by the fact that all connections in the original design are fixed welded connections, resulting in rigid connections through which more efficient use of the cross sections is enabled, thus resulting in a significantly lower volume of material. Since the connections in the optimized design are all assumed to be hinged, it provides greater potential for reuse. Therefore it is more relevant to compare the corrected shadow costs of both buildings for a fair comparison. By comparison of the results it becomes clear that the optimized design is able to reduce the CSC of the original hall by about 69%. The construction price of the optimized design is significantly larger. However, this comparison is potentially unfair given the material savings due to connection types in the original design. No undivided conclusions can be drawn from this case study, but it does demonstrate the degree of sensitivity that the proposed methodology has regarding the assumptions that are made about the connection types and reusability factors in this thesis.

The results of the optimizations in this thesis are based on the previously described loads, connection types, boundary conditions and configuration of the halls. The conclusions that are drawn in this thesis are therefore only valid in case similar halls with similar boundary and load conditions are assessed. In addition, the conclusions are subject to interpretation as a consequence of the sensitivity of the methodology to the assumptions and simplifications that are made regarding connection types and reusability factors.

Contents

Glossary

ADP	Abiotic depletion potential
A.M.	Alma mater
AP	Acidification potential
API	Application programming interface
BCS	Biogenic carbon storage
BGD	Batch gradient descent
BIM	Building information modelling
CE	Circular economy
CML	Chemical markup language
CSC	Corrected shadow costs
CRF	Connection reusability factor
DfD	Design for deconstruction
DVW	Densified veneer wood
ECI	Environmental cost indicator
EMAF	Ellen MacArthur foundation
EP	Eutrophication potential
EPDB	European energy performance of buildings directive
EPD	Environmental product declaration
ERA	Environmental risk assessment
FEATP	Freshwater aquatic eco-toxicity potential
FEA	Finite element analysis
GWP	Global warming potential
HTP	Human toxicity potential
IBC	Injection bolted connection
IOA	Input-output analysis
J.W. reusability score	Jorick Wolbert's reusability score
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MAETP	Marine aquatic eco-toxicity potential
MCI	Material circularity indicator
MBGD	Mini batch gradient descent
MFA	Material flow analysis
MOE	Modulus of elasticity
MMO	Multi objective optimization
MOR	Modulus of rupture
MPG	Milieu prestatie gebouw
NMD	Nationale milieu database
NSGA-II	Non-dominated sorting genetic algorithm II
ODP	Ozone layer depletion

PCR	Product catagory rules
POCP	Photochemical ozone creation potential
POF	Pareto optimal front
POP	Persistant organic pollutants
PROGRESS	Provisions for greater reuse of steel structures
SBK	Stichting bouwkwaliteit
SEEA	System of economic and environmental accounting
SGD	Stochastic gradient descent
SOO	Single objective optimization
TETP	Terrestrial eco-toxicity potential
TRACI	An environmental impact assessment tool
ReCiPe	An environmental impact assessment tool
RVB	Rijksvastgoedbedrijf
RWS	Rijkswaterstaat
VOC	Volatile organic compound
WSSD	World summit on sustainable development

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Introduction

Section 1.1 of this chapter introduces the thesis by giving background information on the subject and explaining its relevance. A definition of the research is given in section 1.2, this section elaborates on the objectives, research questions and the methodology that is used in this thesis. The methodology is closely related to the assumptions and limitations that are provided. Finally, in section 1.3, the thesis structure is disclosed.

1.1. Background & relevance

Constructing industrial halls whilst keeping environmental damage to a minimum. Currently, this presents a major challenge for the Dutch construction sector. Consumers are increasingly requesting shorter delivery times for consumer goods, in some cases opting for a few hours or minutes of delivery time instead of days. This prompts the introduction of newly build distribution centres scattered throughout a city [1]. Accelerated by the steady growth in e-commerce and the increase in large scale industrial operations, construction companies receive progressively more assignments to build industrial halls [2]. An increase in the amount of newly built industrial halls inevitably leads to an increase in harmful emissions as a consequence of construction. The construction sector is responsible for a large amount of pollution as a result of its high energy consumption during extraction and transportation of raw materials [3, 4]. It is estimated that the Dutch construction branch accounts for 50% of resource use and 40% of energy use in the Netherlands. On top of that, it is responsible for 40% of demolition waste and 35% of CO2 emissions in the Netherlands [5]. Paradoxically, this offers the construction sector a unique opportunity to notably decrease its negative environmental impact.

It has been identified that energy usage during the operation phase is the largest contributor to the total environmental impact of a building [6]. However, since the implementation of the European energy performance of buildings directive in 2020, all new buildings are required to have nearly zero-energy demands. The general prospect is that by the end of the year 2050 all new buildings will have to comply with net zero energy demands [7]. Consequently, the relative impact share of construction materials on the overall environmental impact of buildings is growing progressively. Hence, material shadow costs are starting to become increasingly more governing, especially when the reusability aspect of elements can be included in the calculation.

Research from 1997 states that very few construction companies at that time spent efforts on considering the environmental impact of the building materials in their projects. Most contractors considered completion time and cost reduction as their top priority [8]. According to more recent research, significant improvements have been made in the environmental awareness of the construction sector through the introduction of numerous regulations and directives by governments [9] and overall environmental awareness is at an all-time high due to the global Covid-19 pandemic [10]. However, in the field of construction, shadow cost calculations are usually not performed until after the final design choices have been made [11]. As a result, those calculations are effectively useless for the design process, providing a mere statistic to quantify the end result instead of a benchmark on which improvements can be made. Moreover, as the design advances, the costs corresponding to alterations increase progressively. Should it turn out that the final design does not satisfy the mandatory goals as imposed by the government, this can result in rather costly adjustments [12].

One of the most effective ways to reduce shadow costs of buildings is to implement changes in the early design stages [13–15]. These stages are nowadays typically performed in Building Information Modelling (BIM) programs. Such computer programs are helpful to create a model which simulates planning, design and construction operation of a building. It should be noted that BIM technology could potentially also be used to incorporate shadow cost data into the model which could enable the software to promptly calculate the shadow costs during each design stage as a result. This can assist structural designers produce designs that comply with the established environmental impact goals. BIM therefore has the potential to reduce the costs and time associated with shadow cost analyses by making the information that is required routinely available as a by-product of the standard design process [16]. However, BIM programs generally do not include shadow costs as a feature of individual construction elements. This lack of integration leads to an inefficient design process requiring numerous iterations of fully fledged designs until the compulsory environmental performance criteria have been met. For the sake of the environment, costs and time, it is essential to increase the efficiency of shadow cost calculations. Several studies have pointed out that environmental data should be integrated in already existing software tools rather than developing new programs focused specifically on environmental impact [17]. Recent software compatibility developments have enabled the import of structural designs from different software's to BIM. Therefore, it has become possible to create parametrically optimized designs in an appropriate software and subsequently transfer these designs to an editable building information model.

The concept of parametric design is remarkably useful for quick variant studies, as it is able to adapt a constructive design based on several input parameters and boundary conditions. When environmental data is included in such parametric models, the shadow costs corresponding to various design alternatives can immediately be calculated and compared. Industrial halls lend themselves especially well to parametric modelling due to their uniform dimensions and their relatively simple load bearing construction. The efficiency of this ideology can be pushed to an even higher level when generative design is incorporated into the process. Generative design tools can use the input and output of parametric models to generate a multitude of different design alternatives. These design alternatives can be computationally optimized to obtain a configuration of structural elements that leads to a design with minimal shadow costs within certain specified boundary conditions. This process can provide an optimized starting point for a preliminary design. When the parametrically optimized preliminary design is exported to a building information model, alterations can be made according developments in the subsequent design stages and incorporated environmental data can be used to swiftly determine the effect of design alterations on the shadow costs.

The subject of this thesis emerges from the current inefficiency around shadow cost analyses and the subsequent ignorance of environmental improvement that could be realised during the early design phases. Additionally, it provides a great opportunity to research the suitability of parametric and generative software in the optimization of constructions.

1.2. Research definition

1.2.1. Objectives

When a new building has to be designed within certain boundary conditions, it is often unknown which combination of construction elements and materials will result in a design with the lowest shadow costs. In order to create the best possible design, the starting points of the structural designer should be as good as possible. This MSc thesis aims to fill this knowledge gap by developing and testing a methodology in which parametric and generative design are critical components and which can be used to create shadow cost optimised preliminary structural designs for industrial halls that can be used as starting point for subsequent design stages. This methodology could potentially be used to generate either a design that features the lowest absolute shadow costs or a design which minimizes shadow costs within a certain budget. In this methodology, a consecutive process is provided that should enable detailed design optimization during later design stages.

1.2.2. Research questions

Main research question

Which combination of structural elements and materials result in the lowest shadow cost of the main bearing construction of industrial halls?

Sub-questions

1. What are the relevant properties of industrial halls?
2. Which materials, connection types and loads are assessed?
3. What is the most suitable strategy to evaluate the shadow cost of structural components and what input does the calculation require?
4. What constructive elements and materials are assessed and what are their average individual shadow cost and construction cost including their reusability?
5. What algorithm should generative design use during the optimisation process and will this result in the most optimised design alternatives?
6. How much can the average shadow costs of existing industrial halls be lowered within the same boundary conditions?

1.2.3. Research methodology

The first five research questions of this thesis are addressed through a literature review. The first part of the literature review studies reference projects of industrial halls in order to determine the functional requirements that industrial halls need to fulfil and to enable unambiguous comparison on the basis of a functional unit. The second part is aimed at identifying the most suitable strategy to evaluate shadow costs of individual elements including their reuse and recycling properties whilst taking into account the demountability of their connections. The third part of the literature review identifies the most suitable algorithm for generative design. In order to determine which combination of structural elements and materials lead to the lowest shadow costs for the main bearing construction of an industrial hall, several structural design alternatives need to be created and their shadow costs need to be analysed. This will be done using the proposed methodology that is illustrated in Figure 1.1.

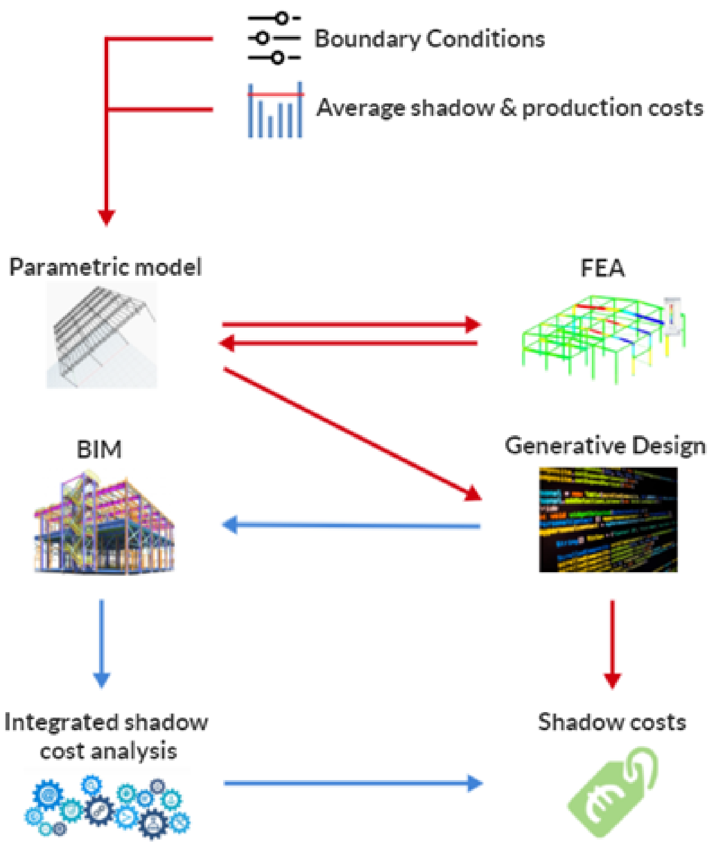


Figure 1.1: Proposed research methodology

The complete methodology consists of two stages: a preliminary design stage and a definitive design stage which are marked in red and blue respectively. In the preliminary design stage, a parametric model of an arbitrary industrial hall is optimized using generative design. This hall has a width of 45 m, a length of 100 m, a free internal height of 10 m, and consists of two main spans of 22.5 m each. The parametric model takes into account all boundary conditions, assumptions and limitations that are specified in section 1.2.4. The cumulative average shadow costs and construction costs can be automatically calculated as the sum of all components in the structural parametric model. Structural designs that are made using this model are exported to a finite element software for structural verification. The results of the finite element analysis (FEA) are returned to the parametric model in order to perform unity checks according to the Eurocode. Generative design software is used to generatively create structural design alternatives that are optimised to obtain minimal shadow costs within the given boundary conditions. From these design alternatives, the most optimal preliminary design can be identified. The definitive design stage as shown in Figure 1.1 is not included in the results of this thesis but is provided as an option for subsequent design stages. During this definitive design stage, the optimised preliminary design can be used as a starting point for definitive design by exporting it to a building information model. In the BIM software, the design can be modified and improved according to new information that becomes available during subsequent design stages. A BIM integrated shadow costs analysis can swiftly determine shadow costs associated with the definitive design. Alterations can be made with regard to specific environmental product declarations of structural elements based on their impact according to the integrated shadow cost calculation. Since the starting point has been optimised, it is expected that this process will promptly lead to an optimised detailed design.

In order to evaluate the effectiveness of the methodology that is proposed in this MSc thesis, two case studies on an existing industrial halls are performed. This is done by analysing the components of the existing industrial halls and converting them into boundary conditions, total shadow costs and total construction costs. The boundary conditions are used to define a functional unit that the computationally generated designs should adhere to. Consequently, a quantification of the magnitude of improvement for the preliminary design of the existing industrial hall is made in case the proposed methodology had been used for the design of the existing hall.

1.2.4. Assumptions & Limitations

This MSc thesis focuses on the shadow cost optimization of generic industrial halls. Since foundation and isolation requirements of industrial halls depend heavily on their exact function, the ECI and price of the flooring and the skin of the hall will not be taken into account. The optimization and verification process will thus only account for the main load bearing elements of the industrial hall design. These structural elements include: columns, trusses, purlins and side rails.

The magnitude of the loads that will be accounted for in all optimizations are 0.38 kN/m^2 for roofing, 0.5 kN/m^2 for facade elements, 0.25 kN/m^2 for solar panels and 0.56 kN/m^2 for snow load. All halls are assumed to be located in a rural part of Dutch wind zone II, thus the wind loads of zones D and E of the halls amount to 0.593 kN/m^2 and -0.371 kN/m^2 respectively. Self-weight is determined by RFEM based on the selected cross sections and included in the calculations.

As will be clarified in subsection 3.5 of this thesis, the design rules for reusable structures state that demountable connections are paramount for the reusability of construction elements. Two connection reusability factors are discussed in this thesis, an Arcadis reusability factor which is based on the experience of structural designers and a J.W. reusability factor which is based on literature and engineering knowledge to provide an unbiased comparison. Evidently, change in the reusability scores will result in very different corrected shadow costs. Furthermore, it is assumed that a corrected shadow cost can be calculated by multiplying the reusability score of an element by its original ECI. One might argue that according to this system a perfectly demountable connection would result in a CSC of zero. However, according to the assessment criteria, connection reusability scores are also based on the life expectancy of the material. Materials degrade over time and there is always a chance of accidental loading which results in unsuitability for reuse, thus a connection reduction factor of zero can never be reached.

While it is potentially possible to create demountable connections in every material, they can currently only realistically be used for steel members. This is mainly due to the fact that contemporary rigid timber connections either reduce the stiffness of the element or produce non-demountable elements. As such, the results of accounting for demountable rigid connections will provide an unfair comparison between material types. Therefore, rigid demountable connections have not been included in the optimization process in this thesis. As a result, given the outcomes of the Arcadis and J.W. reusability scores as provided by section 3.4.3 of this thesis, only single span elements with bolted hinged connections have been considered during optimization.

In the volumetric ECI values of timber that were taken from the NMD and used in this thesis, biogenic carbon storage was not accounted for. It should be noted that the inclusion of biogenic carbon storage will lead to a significant reduction of the ECI of timber elements which immanently changes the outcomes of the shadow cost optimization process in this thesis drastically. The material and connection prices that are used in this thesis are provided by an Arcadis cost manager and are assumed to represent a realistic average price at the time of writing.

Due to software limitations in the application programming interface (API) of RFEM 2.6, the buckling lengths of elements which have intermediate supports in one direction of the profile cross section cannot be exported correctly to RFEM and will instead use its total unsupported length as buckling length. Due to this error, the buckling checks do not reflect the actual behaviour of the intermediately supported structural elements. Therefore, these unity checks are filtered out of the RFEM analysis and are performed manually in Dynamo. This method is slightly less accurate but it reflects the actual behaviour much better. The same API also prevents concrete elements to be correctly exported from Dynamo to RFEM, therefore concrete elements cannot be considered in the design optimization of industrial halls in this MSc thesis.

The configuration of appropriate wind bracing is very dependent on configuration of structural elements. In the parametric model, wind bracing is constructed as semi static and will thus not result in an optimal configuration resulting in larger compressive forces in elements than normally would be the case. However, axial compressive forces due to wind bracing act on a negligible amount of local purlins. Since the optimization is performed for preliminary design, and the compressive force due to unfavourably placed wind bracing is unrealistic, it is acceptable to remove the buckling check for these purlins without major consequence.

1.3. Thesis structure

The flow diagram in Figure 1.2 shows the thesis outline. It can be divided into four main phases. Phase 1 consists of a literature review section that provides a compendium of reference projects of industrial halls in which the current requirements, technologies and construction elements of industrial halls are defined. It also presents a functional unit that can be used to compare alternatives. Subsequently, it provides an overview of the current strategies for shadow cost analyses, a quantification of the effect of reusability and recyclability on the shadow costs of elements, Dutch legislation and a description of environmental impact categories. Phase 2 explains the ideology behind the research methodology and describes what exact software is used during the execution of this Msc thesis. Moreover, in this phase the structural parametric model is constructed and its function, application, input and output is described. Furthermore, the connection of the parametric model with different software programs is elaborated. During phase 3 the shadow cost optimization is performed. This includes a computer generated alternative analysis, a building cost versus shadow cost analysis, and a comparative case study to quantify the effectiveness of the proposed research methodology. In the final phase, conclusions are drawn from the research, followed by a discussion and a series of recommendations for future research.

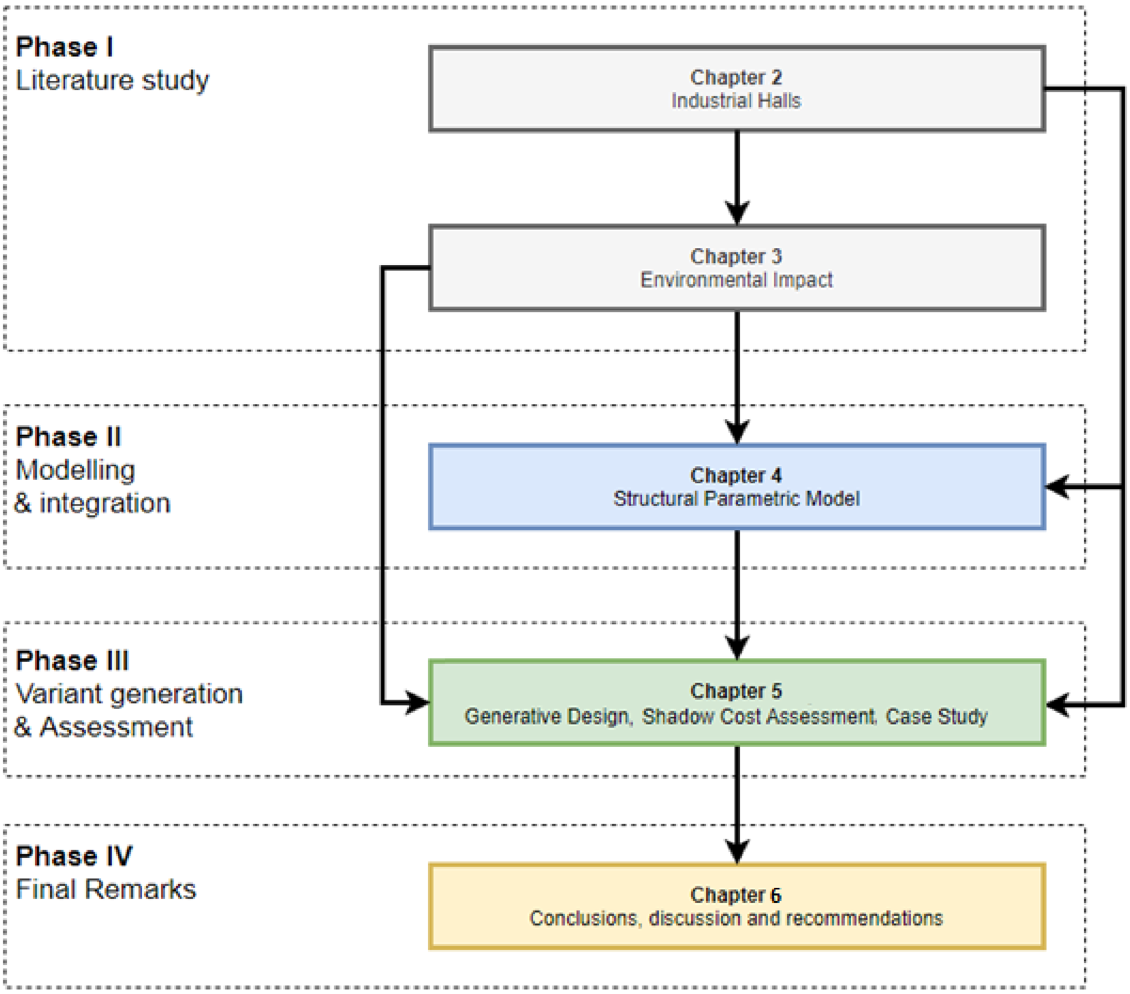


Figure 1.2: Thesis structure

2
Industrial halls

In this chapter a literature study is performed on industrial halls. Section 2.1 of this chapter provides an overview of different business processes that can take place inside industrial halls. Section 2.2 describes five reference projects which are analysed to formulate the relevant properties of industrial halls. The result of these analyses and additional literature on one-storey industrial buildings, is discussed in section 2.3 to determine the most appropriate manner in which the functional requirements can be implemented in a parametric model. Finally, in section 2.4 a definition of a functional unit will be provided in order to enable comparison of alternatives.

2.1. Business processes

Industrial halls exist in numerous shapes and sizes. They are usually box shaped, single storey buildings with a large surface area. While they might all look similar from the outside, they can have very different functions and therefore different requirements. The functional requirements associated with industrial buildings depend primarily on the business processes that have to be accommodated inside. Examples of different functions include [18]:

Distribution centres
Location is a key factor, usually near highways. Nowadays often require automated sorting processes for incoming goods as well as for order picking. This should be considered during the design process through appropriate column spacing, roof height and additional weight of installations.

Assembly & Manufacturing facilities
These types of facilities often require specialized infrastructure and finishes. Depending on its exact function, processes may require specific solutions for drainage, ventilation, chemical substances and may require machinery to be suspended from the roof.

Warehouses
Warehouses are mainly used for storage of goods with limited distribution. Normally little to no climate control is present. Column placement in warehouses is often determined by supply and distribution routes. Storage rack height is often governing for its structural height.

Cold storage
Unlike normal warehouses, cold storage buildings are well insulated and use large amounts of energy for climate control. Cold storage may require specialized flooring since the sub-zero temperatures can cause cracking of normal concrete floor slabs. Seals on loading docks and doors are required to keep low temperatures. Some materials might not be appropriate to use in cold storage halls since they become brittle at low temperatures.

Data centers
Typical for data centers are the numerous rows in which massive amounts of computer servers are placed. Usually there are very few employees present during operation which has an influence on its consequence class. They are normally placed in areas with redundant power sources to ensure zero downtime in case of power failure and may require a special raised flooring system to ensure sufficient cooling. Generally, their height is limited for server maintenance.

2.2. Reference projects

In order to determine the most governing properties and the most common structural elements that are used in industrial halls, several case studies are performed. The goal of these case studies is to determine what input parameters need to be included in the parametric model in order to achieve a realistic representation of an industrial hall. For this purpose, the layout, stability, load transfer and connections of existing halls are assessed. A selection was made to obtain sufficient diversity in geometrical configurations as well as to study potential differences between older halls and newer ones. In total, 5 reference projects are analysed. Their locations are indicated in Figure 2.1.

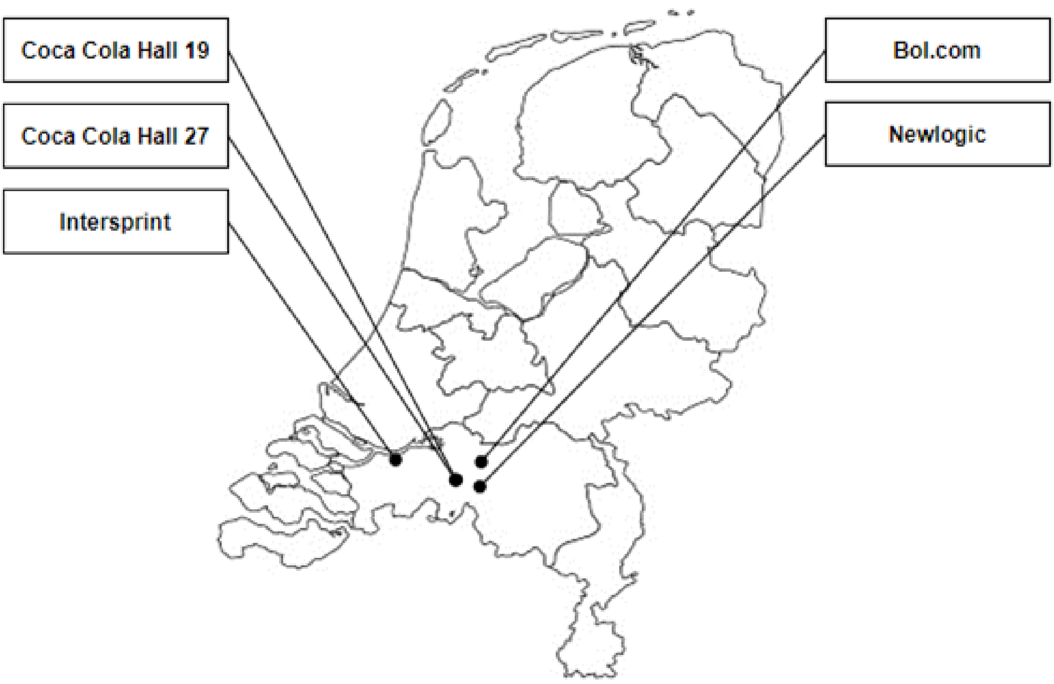


Figure 2.1: Locations of the selection of reference projects in the Netherlands [19]

2.2.1. Coca Cola Dongen building 19

Details

Function:	Automatic warehouse storage
Location:	Dongen, The Netherlands
Year of complection:	1994
Surface area:	5225m2
Structural Design:	Ingenieursbureau v.d. Mast BV

Description

This warehouse was originally built in 1994 and in 2013 it was combined with hall 27 to form one automatic warehouse storage. The construction consists of a single-storey steel structure which is characterized by its open structure with repetitive steel trusses. It is closed on all sides by a facade. The ground floor consists of a concrete floor on a natural foundation. The facade features steel columns with siding on a piled foundation. The hall has a length of about 95m and a width of 55m. The internal free height of the hall is 13m. It features three-span portal frames (c.t.c. 12 m) with intermediate steel columns, the distances between which are covered by steel trusses which have a length of 15m in the mid-span and 20m in the side-spans. On top of the trusses, purlins (c.t.c. 5m) are applied to which the roofing sheets are attached. Along the perimeter of the building, slightly smaller constructive elements are used.

Layout

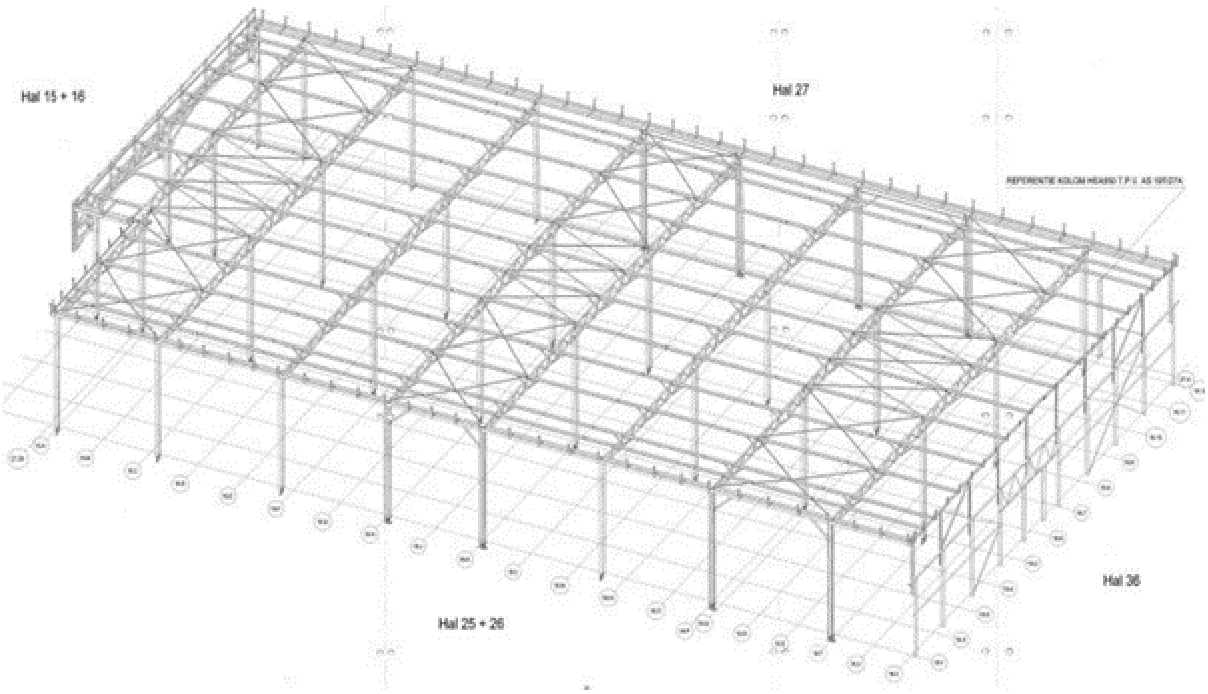


Figure 2.2: Perspective of Coca Cola Dongen building 19 [20]

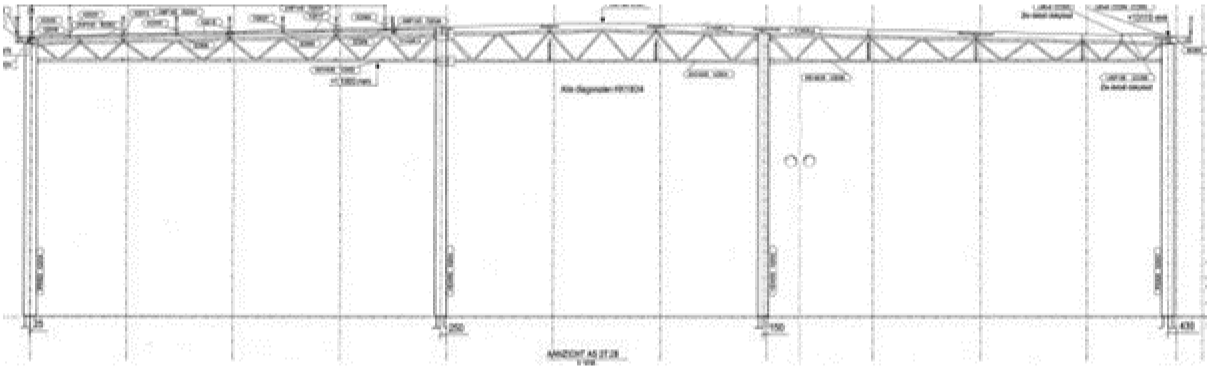


Figure 2.3: Portal frame of Coca Cola Dongen building 19 [20]

Stability system
The global stability is provided by structural bracings in the walls in longitudinal direction and by rigid frames and structural bracings in transverse direction. Structural bracings in both directions of the hall are fixed to the foundation. Due to the connection of the purlins to the trusses, the out of plane buckling length of the top chord is substantially lowered.

Connections
The trusses are connected to the columns by means of a bolted connection with welded steel end plates and are able to transfer bending moments from the roof to the columns. All wind bracing elements are attached to the columns and beams with a bolted connection. Movement of the columns is horizontally and vertically restrained by the foundation.

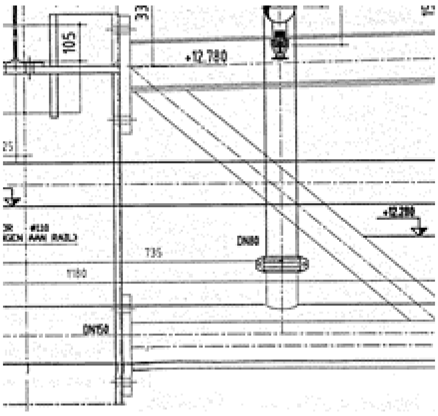


Figure 2.4: Connection detail truss-column [20]

Loads
This industrial hall was calculated with formerly applicable Dutch standards using safety class 2 and a reference time of 30 Years. The loads that were accounted for are: self-weight, snow load and wind load. No collision or accumulation loads were considered in the design of this hall.

2.2.2. Coca Cola Dongen building 27

Details

Function:	Automatic warehouse storage
Location:	Dongen, The Netherlands
Year of complection:	2001
Surface area:	9900 m2
Structural Design:	Arcadis Nederland BV

Description

The construction consists of a single-storey steel structure which is characterized by its open structure with repetitive steel trusses. The warehouse is closed on all sides. The ground floor consists of a concrete floor on a natural foundation. The facade consists of steel columns with siding that is founded on piles. The hall has a length of about 220m and a width of 45m. It has an internal free height of 14m. It features a 45m long single span portal frame, the distance of which is covered by a large steel truss. The spacing between the trusses varies between 9.3, 10 and 13m. On top of the trusses, purlins (c.t.c. 5m) are applied to which the roofing sheets are attached. Along the perimeter of the building, slightly smaller constructive elements are used.

Layout

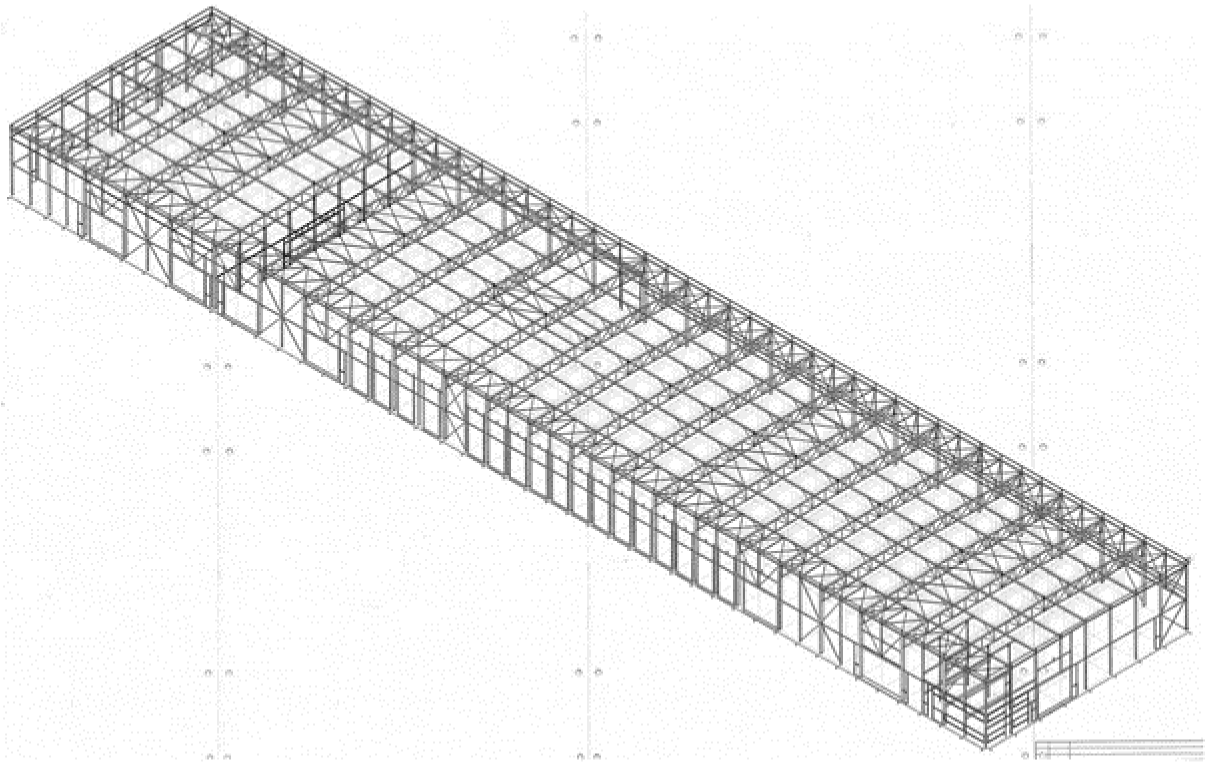


Figure 2.5: Perspective of Coca Cola Dongen building 27 [20]

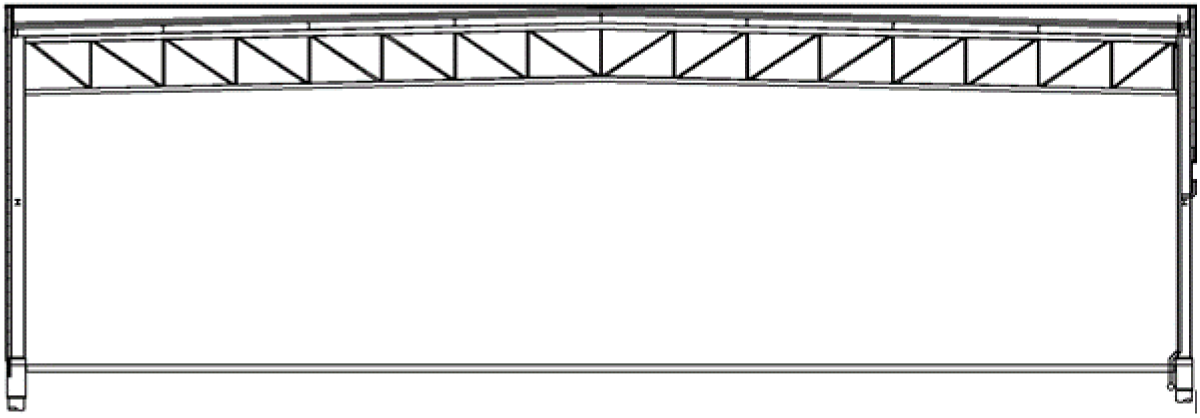
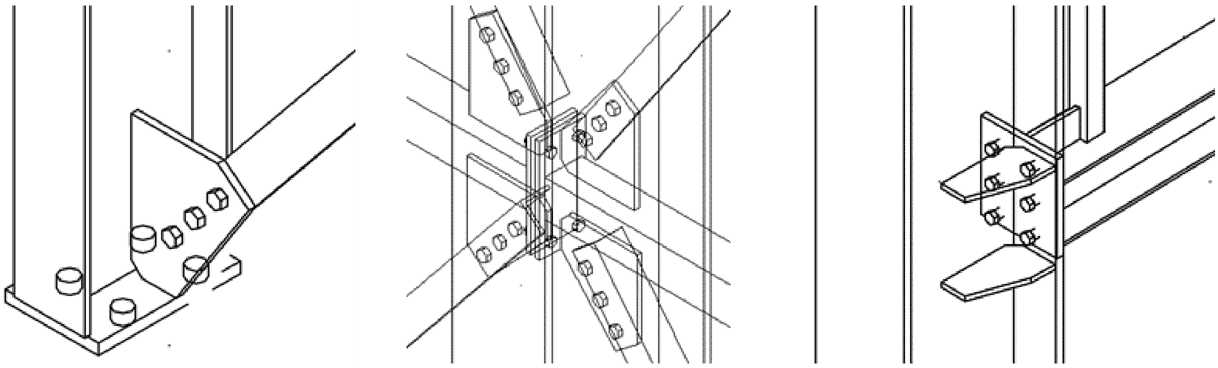


Figure 2.6: Portal frame of Coca Cola Dongen building 27 [20]

Stability system
The stability is provided by the structural bracings in the walls in longitudinal direction and transverse direction. The structural bracings are in both directions of the hall mounted to the foundation. In the determination of the wind actions on the facade, the adjacent buildings have to be taken into account which is why the full wind action is not calculated on both façades. Lower- and upper beams of the trusses are horizontally supported every 2 spans. Steel roof cladding is lateral torsional buckling prevention for the purlins.

Connections
Most connections between the superstructure elements of this hall are bolted connections, which effectively makes this hall a completely demountable building. The exceptions being the end-plates which are welded to the edges of elements and the plates that are welded to the columns to accommodate the bolts for the attachment of wind bracings. The columns are horizontally and vertically restrained by the foundation.



(a) (b) (c)

Figure 2.7: (a) Columnbase-windbrace connection, (b) Windbrace intersection connection, (c) Truss-column connection [20]

Loads
This industrial hall was calculated with formerly applicable Dutch standards using safety class 2 and a reference time of 30 Years. The loads that were accounted for are: self-weight, snow load and wind load.

2.2.3. Bol.com Distribution Centre Waalwijk

Details

Function:	Distribution centre
Location:	Waalwijk, The Netherlands
Year of complection:	2020
Surface area:	14.250 m2
Structural Design:	Pelecon Structural Engineers

Description

This distribution center features several industrial halls that are combined into one building. This case study is focused on the main hub as highlighted in blue in Figure 2.8. Its main load bearing construction consists of a steel skeleton. It has a length of 150m, a width of 95m and an internal free height of 32m. It features multi-span portal frames (c.t.c. 32m) that is constructed with a heavy top beam and lighter intermediate beams. Wind bracing inside the frames increases the stability of the frames but prevents free movement through the portal frames except at the lower left side. On top of the frames, heavy purlins (c.t.c. 6.75m) are applied to which the steel roof plates are attached. The ground floor is made of a 450mm thick monolithic concrete floor on top of vibro foundation piles.

Layout

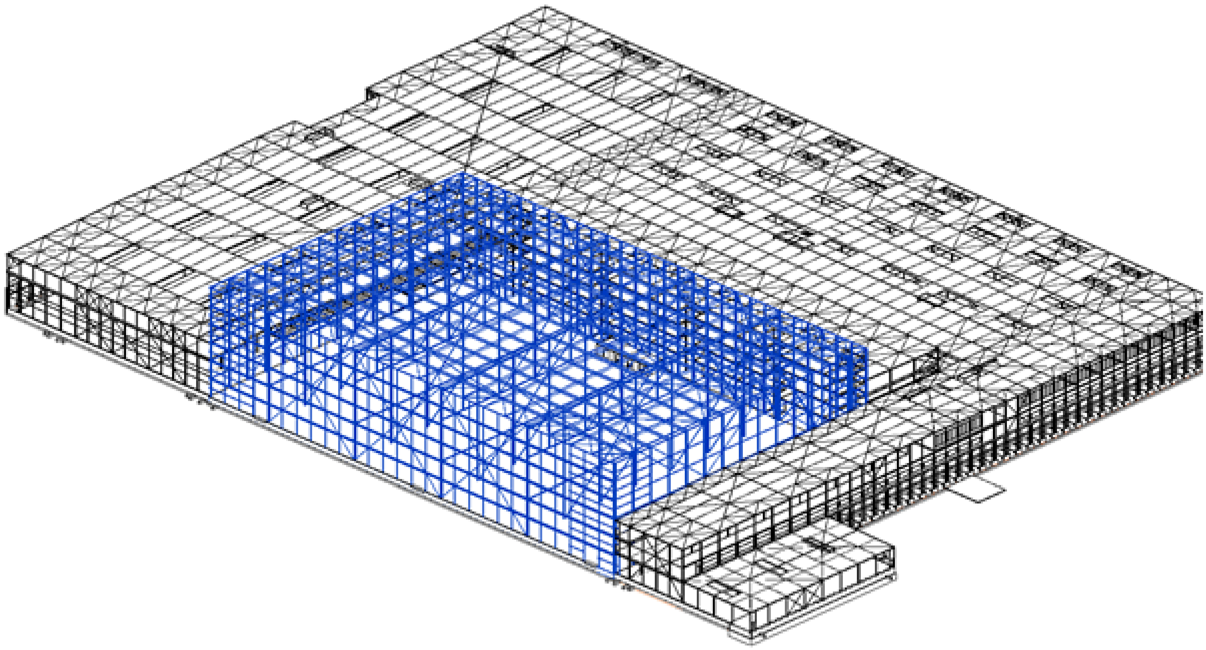


Figure 2.8: Perspective of distribution center Bol.com Waalwijk [21]

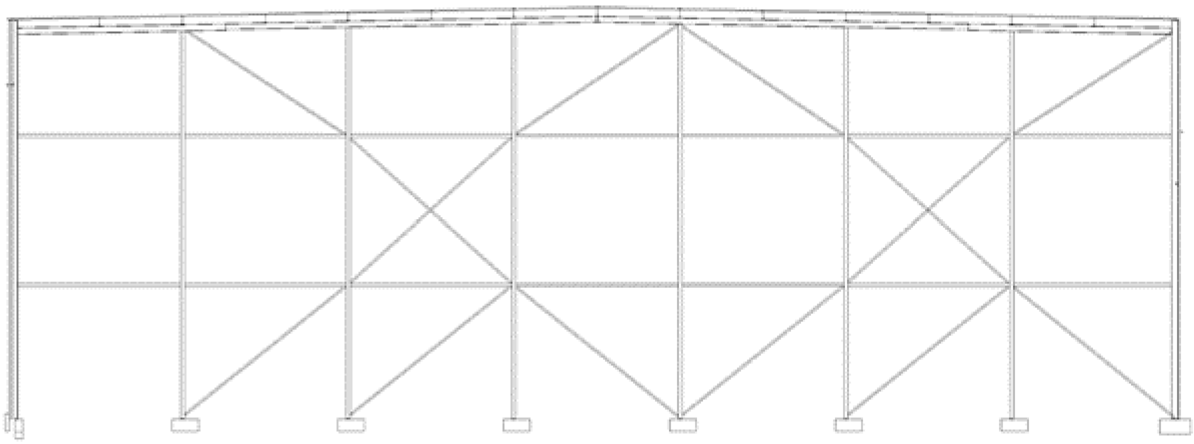


Figure 2.9: Portal frame of distribution center Bol.com Waalwijk [21]

Stability system

The surrounding halls contribute to the stability of the main hub. The main hub is stabilized by means of horizontal and vertical stability braces in the roof, in the facades and inside the portal frames. The purlins are supported by the steel roof plates for kip stability. The purlins support the top beam of the portal against buckling in the lateral direction.

Connections

The connection between the beams and columns of the portal frame can transfer bending moments. All wind bracing elements are attached to the beams and columns by means of bolted hinged connections. The columns are horizontally and vertically restrained by the foundation. Trough its connection to the adjacent low-rise, additional stability is provided for the main hub. In high rise buildings this is often referred to as a 'table structure' and is often applied to reduce the maximum absolute bending moments that occur.

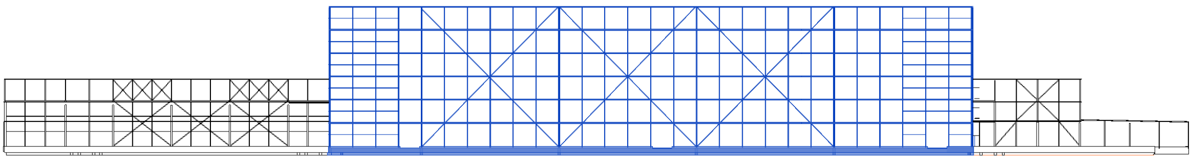


Figure 2.10: Connection main hub to low rise [21]

Loads

This industrial hall was calculated with the current Dutch-European standards using reliability class RC2, consequence class CC2a and a reference period of 50 Years. The main loads that are accounted for are: self-weight, snow load and wind load.

2.2.4. NewLogic III

Details

Function:	Distribution centre
Location:	Tilburg, The Netherlands
Year of complection:	2018
Surface area:	11.664 m2
Structural Design:	Pelecon Structural Engineers

Description
NewLogic III is a distribution center that exists of several compartments which are combined into one building. This case study is focused on the main storage warehouse as highlighted in blue in Figure 2.11. Its main load bearing construction consists of a steel skeleton and the ground floor is constructed with cast in situ concrete. It has a length of 108m, a width of 108m and an internal free height of 12.5m. It features multi-span portal frames (c.t.c. 18m), the spans of which are covered by steel trusses which also have a length of 18m. Purlins (c.t.c. 6.0m) are applied on top of the trusses to which the steel roofing sheets are attached. The column distances in the main warehouse are equal in both directions for the purpose of maximum efficiency and effectiveness. Due to this selected grid size and the use of an ESFR sprinkler installation instead of rack sprinklers, the flexibility in layout is high.

Layout

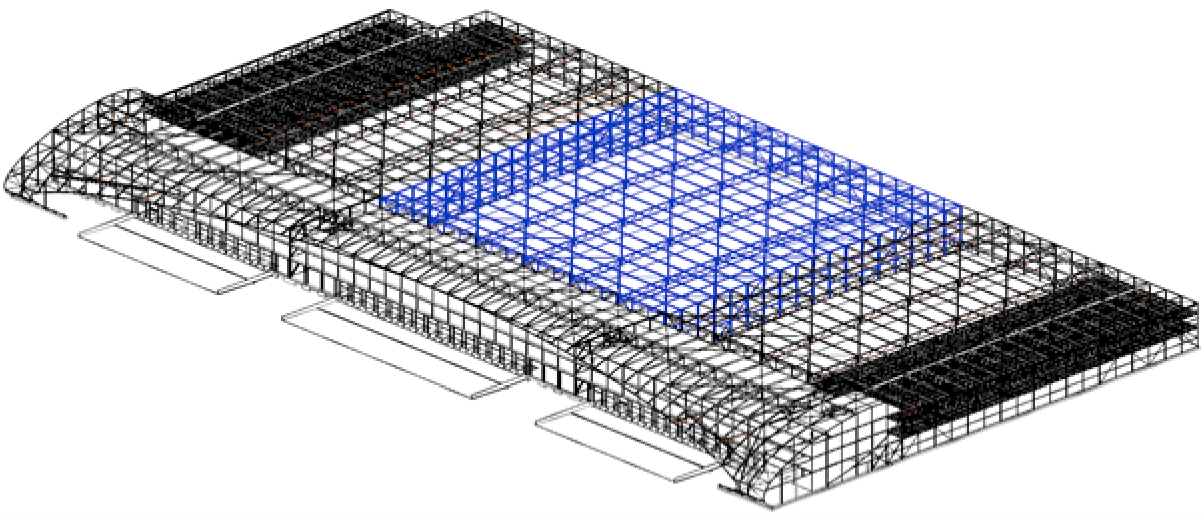


Figure 2.11: Perspective of distribution center Newlogic III Tilburg [21]

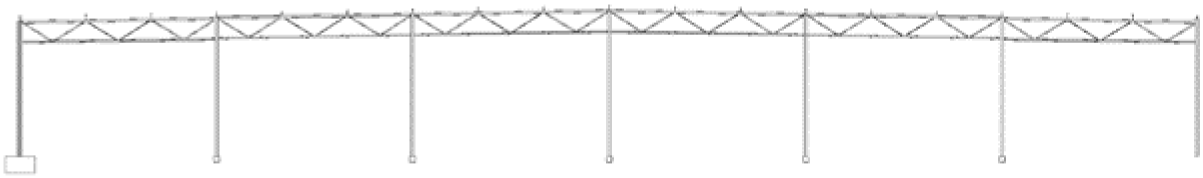


Figure 2.12: Portal frame of distribution center Newlogic III Tilburg [21]

Stability system

The surrounding compartments contribute to the stability of the main warehouse. The main warehouse is stabilized by horizontal and vertical bracings. The purlins are laterally supported at the location of the trusses and at their midspan by an additional SHS 90.90.4 profile that is attached to every purlin it crosses. The purlins in turn stabilize the trusses against buckling in their lateral direction.

Connections

Welds are used to connect the individual steel elements that the trusses are made of. The trusses are connected to the columns in such a manner that they are able to transfer bending moments. All wind bracing elements are connected to the beams and columns by means of bolted connections. The columns are horizontally and vertically restrained by the foundation. Its connection to the adjacent compartments over its full height provides supplementary stability to the main warehouse.

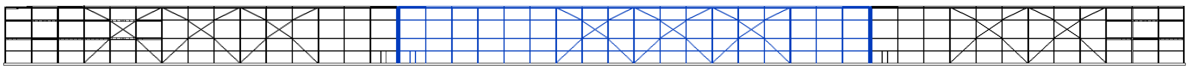


Figure 2.13: Connection main warehouse to adjacent compartments [21]

Loads

This industrial hall was calculated with the current Dutch-European standards using reliability class RC2, consequence class CC2a and a reference period of 50 Years. The main loads that are accounted for are: self-weight, snow load and wind load. However, for the main storage warehouse, wind load is not really appropriate, since three of its four sides are encapsulated by other structures of the same height.

2.2.5. Intersprint V

Details

Function:	Distribution centre
Location:	Moerdijk, The Netherlands
Year of complection:	2019
Surface area:	22.042 m2
Structural Design:	Hercuton Bedrijfsbouw

Description
This industrial hall can be divided into two parts, a storage part and a distribution part. For this case study, only the main bearing construction of the first part is assessed. Its main load bearing construction exclusively consists of concrete elements. The 30m distance between the columns is spanned by concrete IV beams (c.t.c. 12m) on top of which TT roof slabs are applied. The outer spans of the building's portal frame structure are about half the size of the main spans. The hall has a concrete floor which is supported by a foundation of prefab concrete piles. It has a length of 206m, a width of 107m and an internal free height of 10m. Along the perimeter of the building, slightly smaller constructive elements are used.

Layout

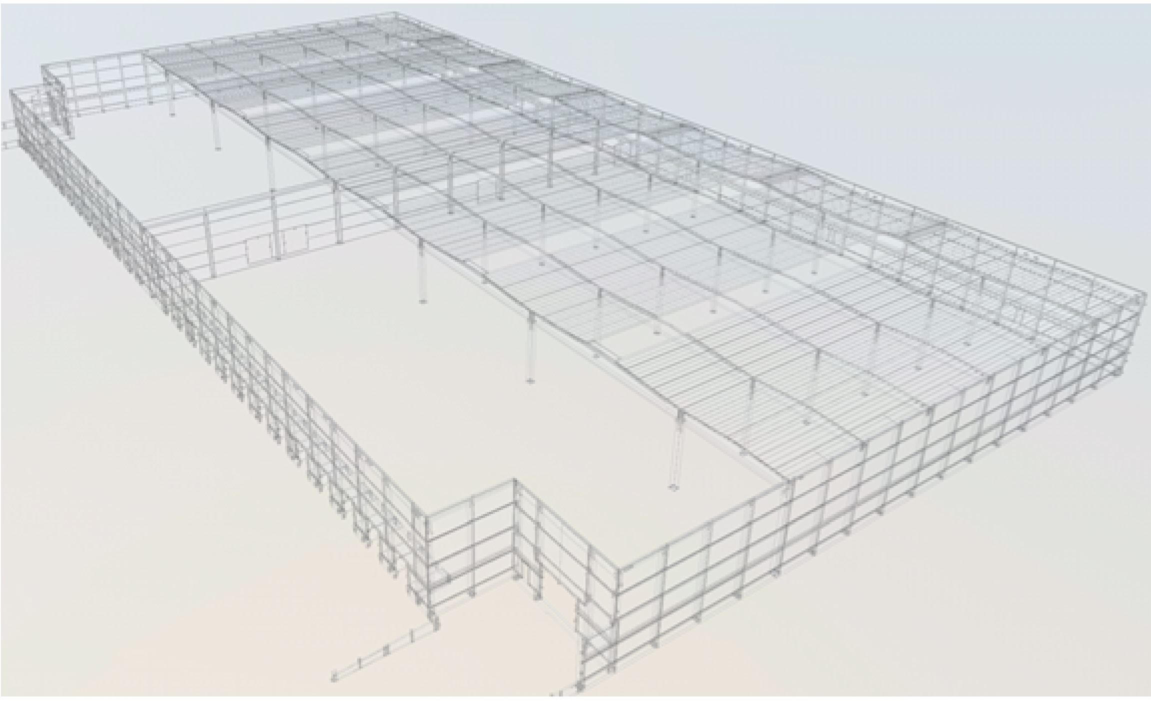


Figure 2.14: Perspective of distribution center Intersprint V Moerdijk [22]

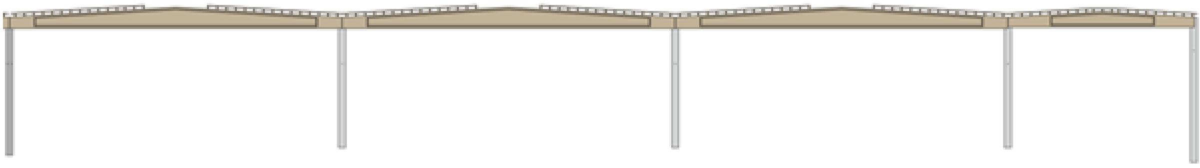
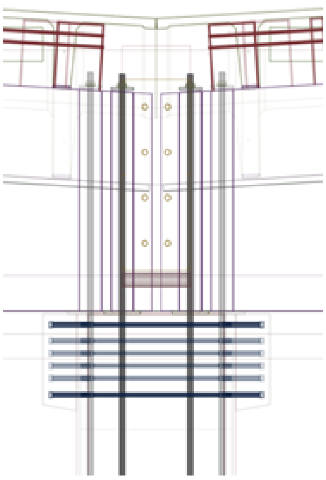


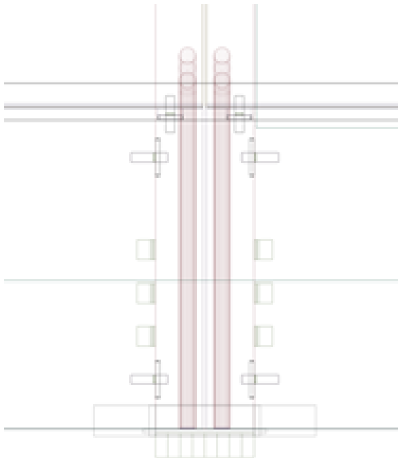
Figure 2.15: Right half of portal frame of distribution center Intersprint V Moerdijk [22]

Stability
This construction makes use of prefab concrete stability walls, which are located at the midsection of the hall and in the facades to provide stability in the transverse and longitudinal direction of the building respectively. The TT slabs support the IV beams in their lateral direction to reduce out of plane buckling length.

Connections
The portal frame columns are horizontally and vertically restrained by the foundation with anchors at the column base. The concrete IV beams are connected to the top of the columns by means of steel anchors which pass through the consoles and the facade elements are attached to the columns with steel angle cleats and screws as illustrated by Figures 2.16a and 2.16b respectively.



(a)



(b)

Figure 2.16: (a) Beam-column connection, (b) Facade-columnbase connection [22]

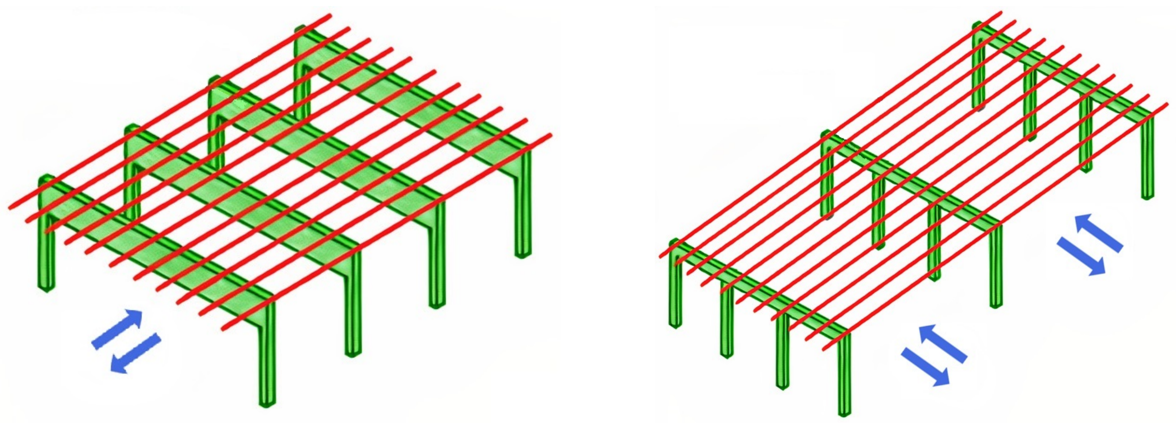
Loads
This industrial hall was calculated with the current Dutch-European standards using reliability class RC2, consequence class CC2a and a relatively short reference period of 15 Years. The main loads that are accounted for are: self-weight, snow load and wind load.

2.3. Structural typologies

This section uses the results of the case study analyses and literature on single-storey industrial buildings by S. Pasterkamp [23], to discuss the requirements of the main bearing construction of industrial halls.

In general, industrial halls are single-storey buildings which are characterised by a relatively large floor area, large headroom and large column free spans. Geometrical properties largely determine the nature and size of the structural elements that the hall comprises of. Due to their single-storey configuration, the height of construction elements in the roof is not governing. It is therefore not uncommon that roof beams have a large structural height. The internal free height of a hall is often determined by the processes that have to take place inside and several psychological factors including the aspect ratio between height and line of sight. Industrial buildings are most commonly made with prefabricated elements. The main reason for this is that the formwork and temporary support structures that would have to be created for cast in situ elements at large heights would be too costly. Additionally, the large degree of repetition of building elements makes prefab solutions more economical. Structural height also influences the stability assessment. For halls that are taller than roughly 10 meters, wind bracing should be considered while for structures with a smaller height, column clamping to the foundation can be sufficient.

From the reference cases two basic typical typologies of industrial halls can be identified. The first is observed in the case studies of Coca Cola and Intersprint. It consists of portal frames that span the largest distances on top of which secondary beams are applied that span the distance between the main portal frames. Figure 2.17(a) illustrates this typology including its main direction of movement. The reference case of Newlogic III provides a special version of the first typology, as it has no main direction of movement since the distances between the columns are equal in both directions. The second typology is shown in Figure 2.17(b) and is observed in the case study of bol.com. It consists of relatively light primary beams with a limited span on top of which relatively heavy secondary beams are required to cover the main span.



(a) (b)

Figure 2.17: Configuration of primary and secondary beams (a) Single hall typology (b) Sub hall typology

Usually braces need to be placed inside this kind of portal frame which limits movement in the transverse direction, therefore the suitability of this typology is limited to specific business processes. Both typologies can be constructed in plural, i.e. multiple portal frames side to side.

The most commonly used material in industrial hall construction is steel. However, in some cases, structural designers opt for concrete or timber in their designs. This choice is greatly influenced by the purpose of the hall. The large mass of concrete elements can provide a building with better thermal and acoustical properties. This can be favourable for cooled warehouses and industrial halls located in an urban area that houses processes which produce a lot of noise. An additional benefit of heavy weight construction elements is their lower vulnerability to live loads, as the share of the live load is often substantially lower than the self-weight. Timber elements can also be used in industrial hall construction, it is a renewable resource which is often more aesthetically pleasing than steel and concrete. However, the use of timber will generally lead to much larger cross sections and higher costs. In any case, the foundations of industrial halls are made of concrete. This is due to the fact that steel and timber are not suitable materials when moisture originating from the sub-soil is factored in.

2.3.1. Main bearing construction

Arguably the most important design choice for the load bearing construction is the number and position of columns. This choice is related to the envisioned function of the hall and the project's budget. Priority in the design should be given to the possible business processes in the hall. Large column-free spans provide the greatest flexibility in this regard. However, large column-free spans cause a substantial increase in costs due to increased dimensions in the roof structure. Moreover, a thicker roof construction results in a larger surface area of the facade and therefore it leads to additional costs. The ultimate design is often a compromise between costs and flexibility. Most designs start out with no intermediate columns, nonetheless in many cases cost pressure eventually leads to the allocation of such supports. In this regard parametric- and generative design can be very helpful. Generative design can optimize the construction for flexibility within a certain budget. During the column grid definition process it might be useful to account for any functional changes that could take place in the future in order to improve the reusability of the hall.

From the reference cases, two basic roof configurations can be identified: Truss portal frames and beam portal frames. Both typologies can both be executed with a different number of spans, yet the feasible length of these spans is often larger for truss frames since it uses the material in a more efficient manner. Depending on the materials that are used, other typologies can be a better choice in some cases. A typology that is not found in the reference cases is an inclined three hinged frame. Nevertheless, for timber halls this type of frame can often be very beneficial. Figure 2.18 illustrates the typical structural elements that are used in single storey industrial buildings as well as a possible interpretation of the aforementioned roof configurations. It should be noted that lattice girders are only produced from steel and timber and cannot be made with concrete. Pitched roofs can be constructed with all three materials. However, in case of concrete, this usually requires an IV beam as identified by the case study on Intersprint V in subsection 2.2.5. The material and profile choices of all other typical elements that are displayed in Figure 2.18 can freely be interchanged according to the vision of the structural designer.

Spacing between secondary bearing elements like purlins and side rails depend on the type and span length of roof and cladding elements. Centre-to-centre distances for purlins are usually between 1.2 and 2.5m. For side rails this range is a bit smaller, namely 1.2 to 1.8m.

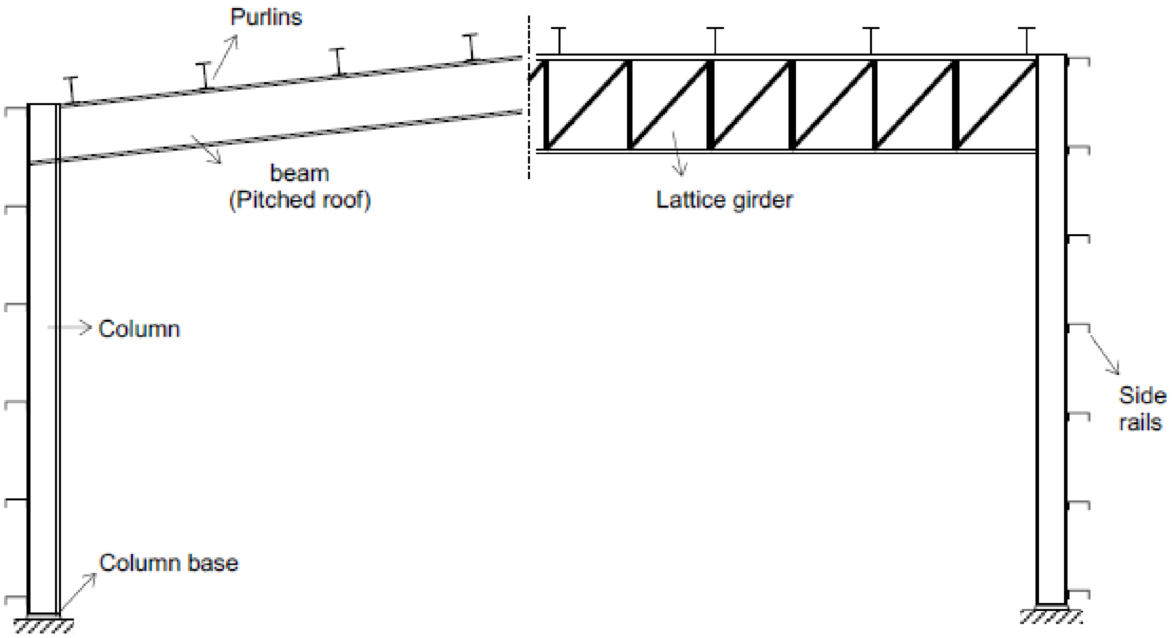


Figure 2.18: Typical structural elements in single storey industrial halls [24]

In all reference projects it is observed that the cross sections of most elements are constant throughout the construction which contributes to a standardised building process that leaves little possibility for execution errors. Along the perimeter of the halls, structural cross sections are usually a little smaller since the forces are roughly halved in comparison with an interior element. Moreover, it can be seen that there is not a lot of difference between the main bearing constructions of older industrial halls and new ones. This goes to show that there have not been many changes in requirements of industrial halls, thus a parametric model of an industrial hall will retain its value in the future.

Another factor that contributes to the choices in structural design of industrial halls is fire safety. Relatively small industrial buildings do not require fire protection if they have a sufficient number of short exit paths. However, larger buildings require additional fire safety measures because fire compartments are not permitted to be larger than 1000m^2. Restricting the size of compartments to fit this requirement greatly decreases functionality, therefore larger compartments are allowed if the necessary precautionary measures have been fulfilled. For steel structures, the costs associated with these measures are substantially higher than for concrete structures since they have a certain level of natural fire resistance. Furthermore, facade openings influence the forces on buildings as they could cause an overpressure due to wind inside the building which generates uplift of the roof. The severity of this phenomenon depends on the weight of the roof elements, it is therefore less governing for concrete elements than for steel or timber.

2.3.2. Stability system

Horizontal loads on industrial halls are most commonly caused by wind loads and are absorbed by the facade elements through which they are transferred to the main bearing construction. The exact way in which this happens depends on the orientation of the facade elements with respect to the columns. In order to limit the span of the elements, the optimal orientation is given by the lowest value of either building height or column distances in the facade. For low buildings this usually means that the facade spans between the foundation and the roof. In higher buildings the facade is more often supported by the columns. When the spans in either direction become too large, intermediate beams are required to which the facade elements can be mounted.

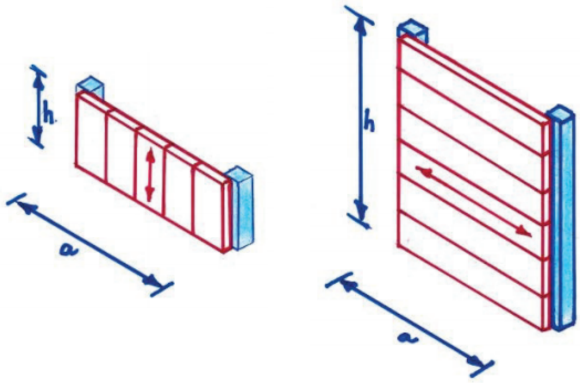


Figure 2.19: Span directions of facade elements [Adapted from 23]

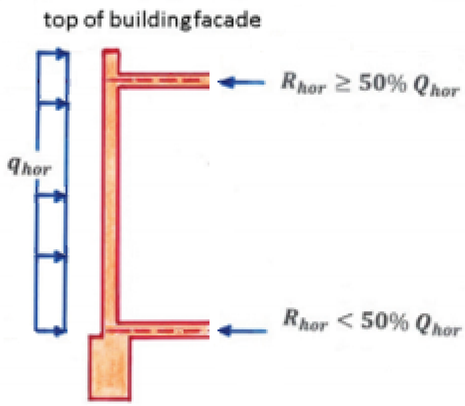


Figure 2.20: Transfer of horizontal loads on the facade to the roof and foundation [Adapted from 23]

In both orientations about half of the total horizontal force can be transferred directly to the foundation, the residual share of the load has to be absorbed by the wind braces in the roof. This principle is illustrated in Figure 2.20. The manner in which the forces are transferred from the main bearing construction to the foundation depends on the chosen stability system. There are two common stability systems for single-storey industrial halls: Braced and unbraced. The main difference between these systems are the deflections. In unbraced systems, the horizontal forces that act on the rigid roof are transferred by means of bending moments through columns that are clamped in the foundation which acts like a rotational spring with a certain stiffness. Stiffer foundations and a larger bending rigidity of the columns enable a greater construction height but will also increase costs significantly. As a result, an unbraced stability system is an uneconomical solution for industrial halls with a height larger than 10m. Thus it is unsurprising that this type of stability system has not been observed in any of the reference projects.

The most common stability system for industrial halls is a braced frame that is constructed by combining horizontal and vertical bracing with a rigid roof system. Bracings often create shape-retaining triangles, which decrease the magnitude of the deflections. This is clearly illustrated in Figure 2.21 and its frequent use is confirmed by the case studies, since four out of five reference projects use this as the main stability system. Generally, bracings are very slender which means that they can exclusively transfer tensile loads which means that they are often designed in diagonally intersecting pairs to be able to transfer loads from both directions. Braced action can also be achieved by the placement of massive stability walls. The stability system of the Intersprint building is an example of this.

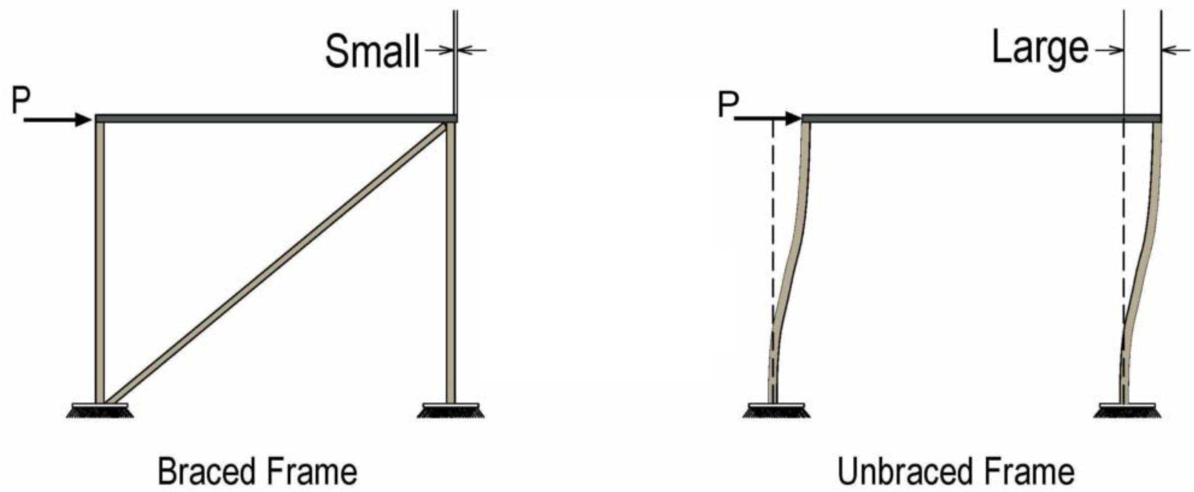


Figure 2.21: Braced and unbraced stability systems [Adapted from 25]

2.3.3. Connections

In order to keep the detailing of connections uncomplicated, industrial halls are often designed to be statically determinate. Unbraced stability systems require clamped column bases which are prone to connection complexity. Shadow costs, to a certain degree, depend on the reusability of structural elements which in turn depends on the demountability of those individual elements. Therefore the type of connections that are used, directly influence the shadow costs of the industrial hall. Generally, bolted connections improve demountability and will thus increase the residual value of components whereas welded connections cannot be taken apart without damaging structural elements and are more prone to fatigue damage as a result of residual stresses in the weld. However, sometimes welded connections are inevitable. This is clearly illustrated in the case studies on the reference projects. The connection between a steel end-plate and a rolled profile can hardly be performed by using bolts and the same can be said about the connection between a steel profile and a fin-plate that has to accommodate wind bracings. Moreover, finite element software requires input on the type of connections that are used to properly model the behaviour and the synergy of structural components due to differences in force transfer.

From literature, it can be identified that the connection between the superstructure and the foundation is crucial for the performance of a building, especially since it is often the interface between two different materials. It is therefore imperative to include connection types into the parametric model for preliminary design.

2.3.4. Loads

All reference projects except for the older Coca Cola halls were calculated using the current Dutch-European standards and are applicable to the structural design of industrial halls that are made using steel, concrete and timber are:

NEN-EN 1990 Eurocode 0 Basis of structural design
NEN-EN 1991 Eurocode 1 Actions on structures
NEN-EN 1992 Eurocode 2 Design of concrete structures
NEN-EN 1993 Eurocode 3 Design of steel structures
NEN-EN 1994 Eurocode 4 Design of composite steel- and concrete structures
NEN-EN 1995 Eurocode 5 Design of timber structures
NEN-EN 1997 Eurocode 7 Geotechnical design

According to Eurocode 0, industrial halls are allocated to consequence class CC2a - 'risk group low'. This class is meant for buildings with a moderate consequence with regard to human lives or considerable damage can occur to economical aspects, social aspects or the environment. This class requires a safety factor of 1.1 for permanent loads and 1.35 for variable loads.

Roof loads are determined in the same manner in all five reference projects. The sole difference is given by unique properties such as the weight of installations and the possibility to suspend certain heavy equipment from the roof. The occurrence of these additional loads may lead to local divergence of main bearing construction which should not be included in the preliminary design stage. Presently, an increasing number of roofs are equipped with water storage, photo-voltaic panels or are executed as green roofs. In existing constructions, the additional load due to these measures was usually not taken into consideration for future application. Part of sustainable design, as will be discussed in section 3.1, is constructing with an eye on the future. Therefore, these supplementary optional loads should be considered in all new designs. The variable loads that act on the roof are usually limited to wind, water and snow loads. The flatness and large surface area of industrial hall roofs make them particularly interesting for the placement of solar panels, however, this can hinder the blow off of snow, therefore increasing the chance of concurrency with other governing loads.

It is interesting to note that the reference periods that are observed in the case studies differ quite a lot. This shows that there is no standard commonly accepted lifespan for industrial halls.

2.3.5. Conclusions

Literature study on one-storey industrial buildings in combination with the analyses of the reference case studies has resulted in a number of conclusions with regard to the most appropriate methods in which the functional requirements of industrial halls can be incorporated in a structural parametric model in order to achieve a realistic construction. Additionally, several conclusions can be drawn with regard to shadow cost optimization using parametric models and generative design.

- It has been identified that the typology shown in Figure 2.17a can accommodate the largest amount of different business processes and is therefore the most appropriate typology to model. Thus, the parametric model should feature primary beams that span the main distances between the columns with secondary beams on top which should span between the main portal frames.

- Components that need to be accounted for in the parametric model are: Columns, trusses, purlins, side rails and wind bracings.

- During the column grid definition phase it might be useful to account for any functional changes that could take place in the future in order to improve the reusability and flexibility of the hall.

- Local adjustments to the main bearing construction due to irregular column or beam placement as a result of facade openings or other constraints, are not part of the preliminary design stage and have a negligible effect on the shadow cost optimization process since they involve only a small piece of the entire construction. Therefore they should not be incorporated as a variable in the parametric model. This aspect can be included in later design stages, e.g. during the definitive design using BIM software.

- Permanent deformations of construction elements have a negative influence on their reusability since their residual strength and especially their stiffness is lower. Thus, deformation is a factor that should be considered in the calculation of shadow costs.

- The most dominant loads as identified by the case studies are: self-weight, wind loads and snow load.

- Lastly, it is readily apparent that there are no large differences between the type of construction elements that are used in older industrial halls and new ones. This goes to show that there have not been many changes in requirements of industrial halls, thus it can be concluded that a parametric model of an industrial hall will retain its value in the future.

2.4. Functional unit

A functional unit is defined in order to enable unambiguous comparison of alternatives. The definition of industrial hall design alternatives with the same functional unit including deviation margin that will be used in this Msc thesis is given by the following conditions:

1. Function of the hall is the same
2. The intended lifespan is equal (±<1%)
3. The usable floor area is equal (±<1%)
4. Internal column distances, width and length are within the specified limits
5. Variable loads of equal magnitude (±<1%)
6. Internal free height is equal (±<1%)

When these six conditions are met, the design is considered to be fit for comparison with alternatives that meet the same conditions. Apart from that, in the search for a structural design that results in the lowest shadow costs in absolute sense, condition seven may be neglected. This is an interesting tactic from an academic point of view, since studies could be performed on the applicability of construction materials in certain projects. However, in practise, such designs will often not be economically viable as their price is likely significantly higher and they are therefore exclusively coveted by philanthropists or as prestige projects.

3
Environmental impact

In this chapter a literature study is performed regarding the environmental impact of constructions. Section 3.1 describes common impressions of sustainable design. Current sustainability strategies that are used to assess environmental performance are presented in section 3.2, this includes the life cycle assessment framework, environmental impact categories, environmental product declaration and Dutch legislation on sustainability. Circularity aspects of building constructions are clarified in section 3.3. Section 3.4 addresses the reusability of construction elements and in section 3.5, the demountability of designs is discussed. Lastly, the average shadow costs and prices of materials that are used in this thesis are stated in section 3.6

3.1. Sustainable design

Due to its nature, the construction industry is a large consumer of natural resources. Ever growing concerns regarding climate change and the increased scarcity of resources implores structural engineering firms to strive towards more sustainable designs. Sustainable development was already brought to the attention of the public by the Brundtland commission when they released their famous report: "Our Common Future" in 1987 which states that sustainable development meets the needs of the present without compromising the ability of future generations to do the same. In 2002, the World Summit on Sustainable Development (WSSD) marked an expansion of the definition of sustainability given by the Brundtland commission. The WSSD defined three pillars of sustainable development: Economic development, social development and environmental protection [26].

More recently, on the 12th of May 2021 the European Commission adopted the EU action plan: "Towards zero pollution for air, water and soil". This plan is a key part of the European green deal. It describes the vision and goals for sustainable development towards 2050, as well as the steps that need to be taken to get there. This vision contemplates a world where pollution is reduced to levels that are no longer harmful to human health and natural ecosystems [27].

Executive Vice-President for the European Green Deal, Frans Timmermans, said:

> *"The Green Deal aims to build a healthy planet for all. To provide a toxic-free environment for people and planet, we have to act now. This plan will guide our work to get there. New green technologies already here can help reduce pollution and offer new business opportunities. Europe's efforts to build back a cleaner, fairer, and more sustainable economy must likewise contribute to achieving the zero pollution ambition." [28]*

The statement by Timmermans touches upon all three aspects of sustainable development as described by the WSSD. A visualisation of these environmental, social and economic aspects and their four interfaces shown in Figure 3.1. From this figure, it can clearly be seen that only the integration of all three sustainability aspects leads to sustainable development and thus sustainable design. The integration of these three aspects lead to a philosophy that promotes decisions at each design phase that reduce damage to the environment and social wellbeing without compromising too much on economic levels.

Figure 3.1: Three aspects leading to sustainable development [Adapted from 29]

Sustainable design should start in the early design stages, as the optimization potential in these early phases is much higher and the consequences of changes on the construction costs are lower. By choosing an approach in the early stages of a project that would normally not be considered, a contribution can be made to the improvement of the final design in terms of performance and reduce its total costs as a result. Sustainable development requires a more involved and integrated effort of all stakeholders than a traditional design process. Thus, the early design stages are critical since it includes most decisions that will influence the building's performance [12].

Sustainability has a multitude of interpretations, it therefore lacks a unique and official definition, thus the meaning can be adapted to the context in which it is considered at any particular time [30]. Since the definition of sustainability is ambiguous, so is its assessment. Nevertheless, in general, sustainability assessments can be described as the process of identifying, measuring and evaluating the probable impact of a construction on the environment [31]. In order for sustainability analyses to calculate potential impacts, a set of sustainability indicators are required. Several of these sets have been developed, yet no agreements have been made about a universal measure [32]. Nevertheless, Figure 3.2 provides an overview of numerous sustainability aspects that are all equally valid components in sustainable design. However, not all of these aspects could nor should be incorporated as input into the structural parametric model that characterises this Msc thesis, as some of these components are not directly measurable or quantifiable and others depend on architectural- rather than structural choices.

Figure 3.2: Overview of sustainability aspects [Adapted from 33]

Some 'people' aspects under the sub-categories health and user quality are unmeasurable and the rest of them mainly depend on architectural decisions or installations required for the operation phase. As identified in chapter 2, these decisions depend heavily on the type of business process that will take place inside a building. In a general parametric model for the structural design of industrial halls, these aspects should therefore not be included as input parameters.

In the Netherlands, more than 50% of available raw resources is utilized for the production of building materials [34]. The corresponding environmental impact differs between structural elements. Therefore the choice of materials plays an important role in sustainable development, but sustainable design does not end when the construction phase of a building is complete. In conventional buildings, the operation phase is often the most polluting phase of the building life cycle, simply because all processes within a building require some form of energy and this phase accounts for the longest period of time [6]. However, since the implementation of the European energy performance of buildings directive (EPBD) in 2020, all new buildings are required to have nearly zero-energy demands. This means that nearly all of the energy that a building requires for its operation should come from sustainable sources. The general prospect is that by the end of the year 2050 all new buildings will have to comply with net zero energy demands [35]. This development will eventually eliminate energy usage entirely from a building's environmental impact analysis. Consequently, the relative impact share of construction materials on the overall sustainability of a building is growing progressively. Figure 3.3 illustrates the shift from energy dominated- to material dominated environmental impact in a new building's life cycle.

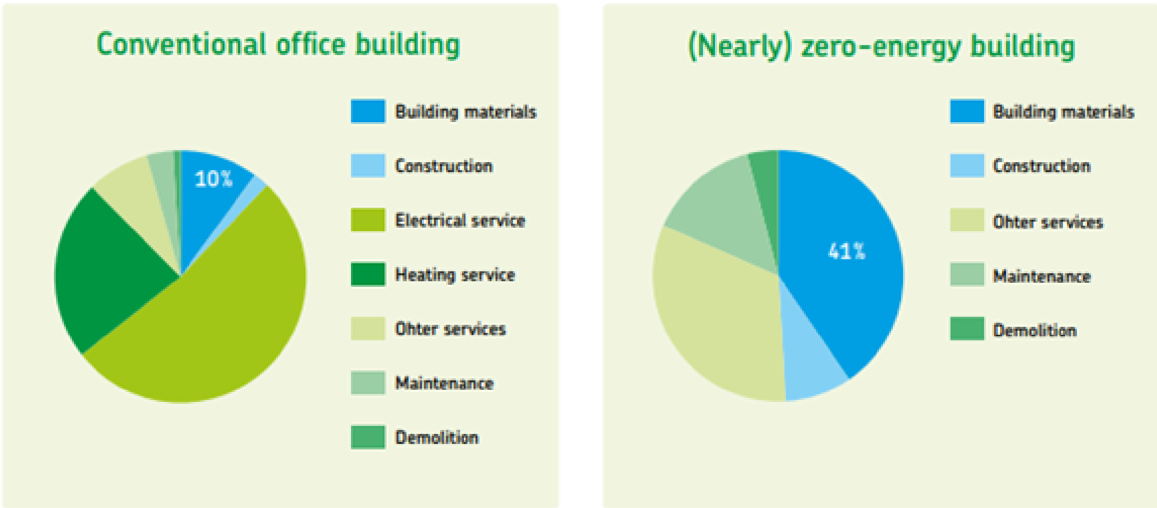


Figure 3.3: Environmental impact over a building's life cycle [36]

Apparently, the relative contribution of construction materials to the total environmental impact of nearly zero energy buildings, is over four times larger than it was in conventional buildings. Environmental impact due to construction materials is often represented as a shadow cost. Hence, it can be said that shadow costs are starting to become increasingly more governing for new constructions, especially when reusability of elements is factored in. In addition to its declining influence on environmental impact, energy performance depends largely on the type of business process in a building, thus it is a legitimate assumption to disregard this aspect. With regard to the 'profit' aspect of sustainable design, it is important to include a project budget in order to maintain economical viability. Therefore, the environmental input of the structural parametric model should be limited exclusively to circularity corrected shadow costs of building materials and their production costs.

3.2. Shadow costs

Market prices are an important guiding variable for economical processes, they reflect what consumers are prepared to pay for a product or service. Though, not all goods and services are traded through markets. Examples of this include scenery, decency, safety, and a clean environment. Regardless of their positive influence on human welfare, no explicit price exists for them. The construction branche cannot recognise the economic repercussions of environmental damage and provide economically efficient solutions for them if ecosystem services are not quantified with an empirical price. For this purpose, shadow prices have been developed. These are prices that quantify the marginal societal cost for the prevention of environmental damage and express them in euros per kilogram of polluting substance [37]. Shadow costs can be presented on three different levels: on substance-level as emissions of environmentally hazardous compounds; on midpoint-level as valuation of environmental themes such as global warming or eutrophication; and on endpoint-level as valuation of the effects of environmental pollution on human health or ecosystems [37]. The most appropriate level is chosen based on the application in which the shadow costs will be used. Common applications include social cost-benefit analyses, socially acceptable entrepreneurship and life cycle analyses. The latter is of particular interest in the construction industry, for the purpose of determining the environmental impact of building materials.

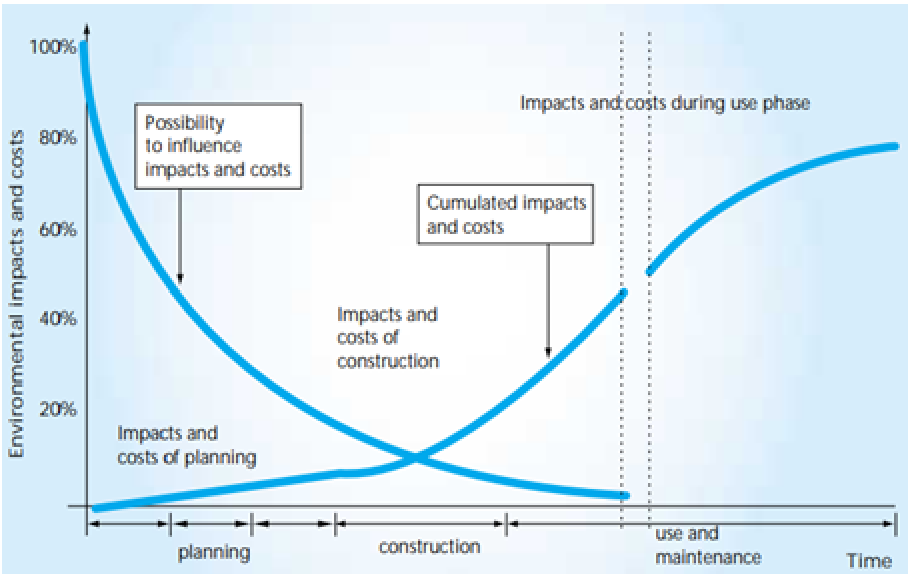


Figure 3.4: Influence of design decisions on costs with each stage of design [38]

Through the years, several tools for assessing environmental impacts of manufactured products have been developed. Besides Life Cycle Analysis (LCA), these include: Material Flow Analysis (MFA), Input-Output Analysis (IOA), System of Economic and Environmental Accounting (SEEA) and Environmental Risk Assessment (ERA). The application of such assessments contribute to the quality of the built environment [39, 40]. Sadly, the objectivity of some of these methods is not always guaranteed. Research has shown that sustainability assessment results are largely influenced by the assessors' point of view and their time limitations. Consequently, a transparent and objective assessment method is considered necessary [30]. Among these tools, LCA is the only internationally standardized method and is considered to be the most objective and suitable practise for the environmental assessment of buildings over their full life cycle [41, 42]. However, as a result of its complexity it is usually only used as a post-design evaluation rather than an optimization method for early design stages [42]. Parametric design allows for swift variant studies during the preliminary design stages. Thus by incorporating an LCA based shadow cost assessment into a structural parametric model and generative design, improvements can be made on both objectivity and optimization whilst saving time and costs. The significance of the latter is clearly illustrated in Figure 3.4, which shows that the influence on the design decreases significantly during the development of the design whereas the corresponding costs increase.

3.2.1. Life Cycle Assessment

LCA is a procedure to evaluate the environmental impact related to all life cycle stages of a product or building. Its outcome can be used to compare products on the basis of functional quality and through redesign the opportunity arises to optimize the product by concentrating on the contributions with the largest environmental impact.

An LCA consists of four phases as described in the international ISO 14040:2006 standard. The goal and definition phase, the life cycle inventory (LCI), the life cycle impact assessment (LCIA) and the interpretation phase. During the first phase, the reason for executing the LCA is described and an exact definition of the product's life cycle and system boundaries are given. Additionally, a functional unit is defined for the outcome to be able to compare the results to other LCA's. The LCI phase deals with all the environmental inputs and outputs associated with the product [43]. Its inputs can be described by the use of raw materials and energy consumption during fabrication processes. Its output consists of the emission of pollutants and waste. In the LCIA phase, LCI data is transformed into environmental impacts using a characterisation method such as CML, ReCiPe or TRACI [44]. These methods all use a different combination of environmental impact categories (EICs) and the choice between them is made based on the specific application in which it will be used. During the final phase, the conclusions are presented and a verification is made whether the outcomes are sufficiently supported by reliable data.

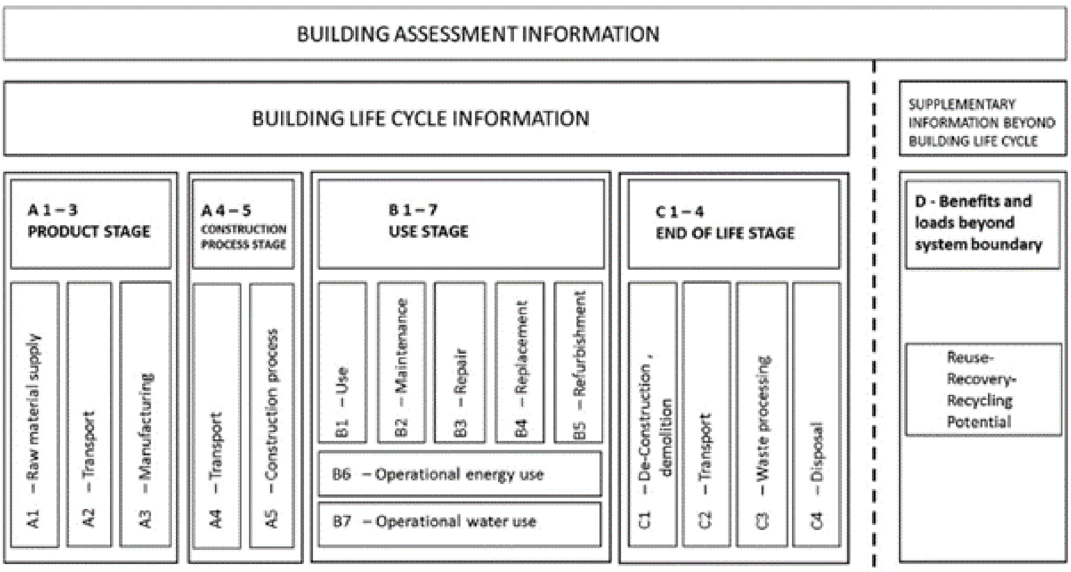


Figure 3.5: Stages in life cycle assessment according to EN 15978 and EN 15804 [46]

In a building life cycle, five main stages can be identified: The product stage, the construction process stage, the use stage, the end of life stage and the effects beyond the building life. The latter can be described by re-use, recycling and recovery potential. Figure 3.5 depicts all sub-stages of the building life cycle. Modules A-C represent the initial building life cycle. Module D is usually calculated separately and is often the most difficult part of an LCA. According to NEN-EN 15804 for all construction products it is required to declare input for at least modules A1-A3, C1-C4 and module D [45].

The classical LCA approach as described in ISO 14040 is an elaborate procedure which takes specialists at least 2-3 months to complete and costs a significant amount of money. For most projects that require a large number of different elements, it is unthinkable to perform a separate complete LCA for every element. In these cases often a so-called 'fast track LCA' is used for which various tools are available. This type of LCA uses the output of the calculations of classical LCAs that are previously performed by others as input for the fast track calculations. Its methodological focus is aimed at comparison of design alternatives instead of the creation of LCI and LCIA data. By performing a fast track LCA, a lot of time and money can be saved without losing out too much on accuracy compared to formal LCAs [47].

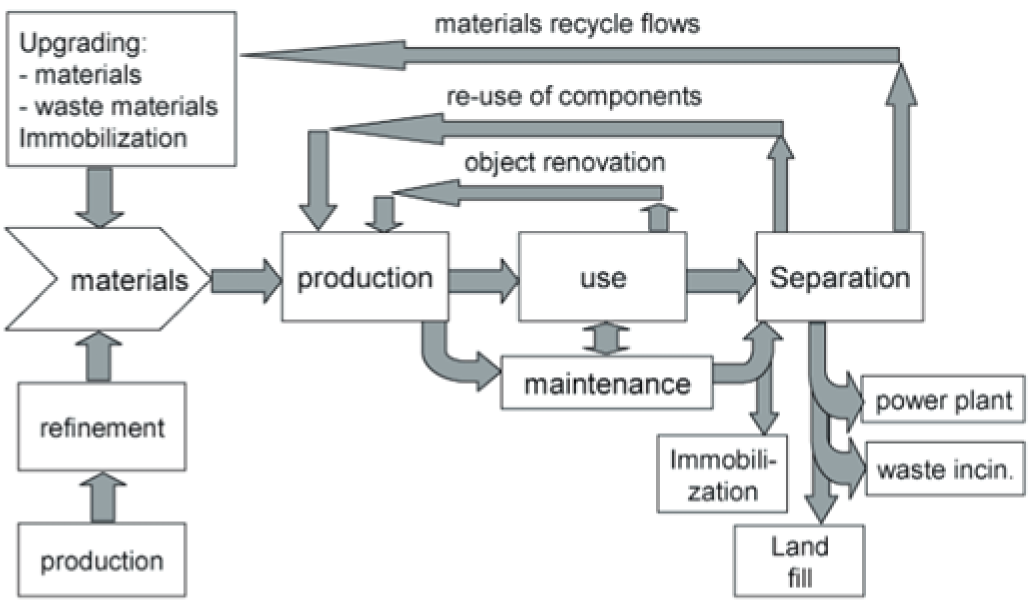


Figure 3.6: Building blocks of an LCA [47]

Traditionally, LCAs only account for the life cycles from cradle to grave and it is often presumed that it is not possible to create an LCA for a cradle-to-cradle system. However, this assumption is flawed, the only barrier for such a system is an LCA practitioner's knowledge gap which makes the correct selection of databases difficult since it requires supplementary information beyond the building life cycle and therefore a more extensive understanding of recycling and reuse processes [47]. Figure 3.6 depicts the building blocks of a cradle-to-cradle LCA and illustrates the material flows that need to be taken into account. There is still a lot of controversy amongst LCA experts about the backflow of materials in the form of reuse and recycling that are declared in LCA module D since its outcome depends heavily on the assumptions that are made by the LCA performer about the future of the building components which are uncertain to a large extent and as a result the environmental benefits are often overestimated [48]. The contribution of this stage, nonetheless, has a significant effect on the total shadow costs and will be further elaborated upon in section 3.3.

3.2.2. Environmental Product Declarations

The output of an LCA is characterised by certain environmental impact categories (EICs) and can be documented in an Environmental Product Declaration (EPD), which is a declaration of the environmental impact of a product according to ISO 14025 standards. All EPDs are required to be verified by a licensed and independent LCA expert and have a validity of five years [49]. The content of EPDs is required to follow a specific format as described by product category rules (PCRs) to ensure comparability for groups of similar products [50]. Several different types of EPDs exist, the most important distinction is made between the following types of analyses: cradle-to-gate, which only takes into account sub stages A1-A3; cradle-to-grave, which takes into account sub stages A, B and C; and cradle-to-cradle assessments, which includes stages A, B, C and D [45]. The latter is the most suitable for the life cycle of buildings like industrial halls. Industrial halls consist of a myriad of construction elements, it is therefore unconceivable to determine their environmental burden from scratch every single time by means of an LCA. Therefore, EPD databases like Ecoinvent, Environdec, Ökobau and Nationale Milieudatabase (NMD) have been developed. These databases, amongst other data, provide access to verified EPDs that can be used to calculate the environmental performance of a building and are extended with new EPDs each year. The European standard EN15804 was initiated to standardize the EPD generation process [45]. However, individual countries can still employ different assumptions and scenarios which leads to more favourable outcomes. In order to provide a fair comparison, further homogenisation of EPDs is required [51].

3.2.3. Nationale Milieu Database

For the purpose of standardising environmental performance calculations of Dutch buildings, the NMD has been created. It consists of numerous product cards that have been composed using the ‘bepalingsmethode’ of SBK and which relate to environmental profiles. By applying the corresponding calculation rules, these product cards can be used in different tools to create reproducible, verifiable outcomes. The ’bepalingsmethode’ provides directions for the composition of EPDs for Dutch applications in a manner that makes their environmental information suitable for inclusion into the NMD [52].

The NMD database consists of EPDs from multiple sources. Not all assumptions and data behind the EPDs in the NMD are made publicly available by manufacturers due to their fear that competitors might gather valuable information from them. This is why the EPDs are bound to a certain category. Category 1 consists of proprietary data which has been tested by an independent, qualified third party and its underlying data is not publicly available. Category 2 consists of unbranded industry average data, which is tested by a qualified third party with mention of its representativity in a certain market. Its underlying data is not publicly available. Category 3 includes unbranded data which has not been tested by a third party but its underlying data is freely accessible [52]. One might argue that the lack of transparency in the first two categories makes the EPDs unreliable since no verification can be made whether all required life cycle phases have been included. However, for both cases it is legally required to get the assumptions and origins of the data verified by an independent licensed LCA expert. Thus, while the exact assumptions that are used are unknown for the general public, the EPDs that are declared in these categories are double checked and therefore valid.

However, there are some differences between the three categories with regard to their accuracy which leads to category 1 data generally being more favourable than category 3 data. This has to do with the level of detail in which production companies can perform their LCAs. These companies know the exact techniques that they use for the production of their building elements and can therefore give a more realistic estimate for the respective LCAs in category 1. This is also the reason why the underlying data is not publicly available. While category 3 data is freely accessible, it often not based upon the state of the art production methods and thus it leads to higher shadow costs.

EPDs from category 2 consist of branche average environmental data which eliminates potential outliers. A drawback for this category is the fact that it does not exist for every structural element so it cannot always be used. Nevertheless, category 2 data, if available, can be considered the most appropriate type for estimation of environmental impacts during preliminary design. For the building components that are not accommodated in category 2 data, the most appropriate solution for preliminary design would be to randomly choose 5 category 1 elements and calculate their average value.

3.2.4. Environmental Impact Categories

As stated in section 3.2, life cycle assessments for building components are based on environmental themes which are characterised by environmental impact categories, therefore mid-point level shadow prices should be used. Several categorisation methods are available which each contain different EICs and which use different normalisation and weighting criteria for the input [44]. Worldwide, the CML2-baseline method is the most commonly used method for LCIA categorisation. The EPDs in the NMD are also based on the CML2-baseline which manifests itself in eleven EICs. A summary and description of which is given based on EN15804+A2 and a reader by H. Jonkers [45, 53]:

Global Warming Potential (GWP)
The GWP is defined as the human induced effect on the heat radiation absorbing capacity of the lower atmosphere and are therefore often called greenhouse gasses. EN15804+A2 distinguishes between GWP contributions from fossil fuels, biogenic storage, land use and land use change (luluc). The main greenhouse gasses are Carbon dioxide (CO2), Nitrous oxide (N2O), methane (CH4), Chloro-fluoro-carbons (CFC's) and Ozone (O3). In order to measure the combined effect, these gases are converted into a reference unit: kg CO2 equivalent. Global warming leads to temperature change and consequently in sea level rise and loss of biodiversity.

Ozone Layer Depletion (ODP)
In contrast to its global warming potential, ozone is a very useful gas in the higher atmosphere as it protects life on earth against harmful ultraviolet (UV) radiation. Due to their chemical stability, halogenated gasses like CFC's, HCFC's and halons can reach the upper atmosphere where they are decomposed by UV radiation. As a result, they catalyse the decomposition of ozone. The reference unit for ozone depleting gasses is: kg CFC-11 equivalent.

Acidification Potential (AP)
Some emitted compounds can produce acids when dissolved in water. These acids can have detrimental effects on soil, groundwater and ecosystems and are also damaging to structures as they possess corrosive properties. Nitrogen oxides (NOx), ammonium (NH4) and sulphur dioxide (SO2) are examples of such compounds. The combined effect of these substances is measured in the reference unit: kg SO2 equivalent.

Eutrophication Potential (EP)
Eutrophication is the process of disproportional organic growth by elevated levels of nutrients in an ecological environment. EP accounts for aquatic freshwater, aquatic marine and terrestrial eutrophication. In the agricultural sector many fertilizers are used containing nitrogen (N) and phosphorous (P) which eventually end up in the groundwater or surface water. Due to eutrophication usually one plant type starts to overgrow others which locally results in low biodiversity. In aqueous bodies this may cause oxygen depletion and subsequently animal mortality and malodorous water. EP is captured in the reference unit: kg PO43+ equivalent.

Photochemical Ozone Creation Potential (POCP)
Sunlight can cause a reaction with several airborne pollutants which can result in chemically reactive compounds. These can be damaging for both human health and the environment. Volatile organic compounds (VOCs), Nitrogen oxides (NOx) and carbon monoxide (CO) are examples of compounds that are sensitive to photochemical oxidation. The result of this process is the creation of ozone in the lower atmosphere which next to its GWP is also toxic to humans and the natural environment in high concentrations. The airborne compounds that lie at the root of this problem are often emitted by diesel fuelled engines. The reference unit for this impact category is: kg C2H4 equivalent.

Abiotic Depletion Potential (ADP-non fuel, ADP fuel)
ADP is a measure to express the scarcity of abiotic finite resources. There is no endless supply of these resources so their consumptions should be limited. ADP can be divided into abiotic depletion for fossil fuels and non-fuels such as metals and minerals. The reference unit for non-fuel and fuels can be expressed as: kg Sb equivalent. For fuels an additional reference unit can be used: MJ, net calorific value.

Freshwater Aquatic Eco-Toxicity Potential (FAETP)
FAETP quantifies toxic substances in freshwater environments as a consequence

of wastewater dumps, heavy metal accumulation and deposited aerial compounds. These substances affect organisms living in freshwater ecosystems. The reference unit given in: kg 1,4 dichlorobenzene equivalent.

Marine Aquatic Eco-Toxicity Potential (MAETP)
Like FAETP, specific compounds can be especially detrimental for marine habitat. Most of these toxic compounds dilute in the enormous quantity of water that is stored by seas and oceans. However, persistent organic pollutants (POPs) only slowly degrade and will accumulate throughout the food chain resulting in highly toxic levels in the biggest predators. POPs are often a by-product of industrial processes. The reference unit given in: kg 1,4 dichlorobenzene equivalent.

Terrestrial Eco-Toxicity Potential (TETP)
Similar to the freshwater and marine environment, there are numerous compounds that cause problems on land. Agricultural activities often leave behind pesticides and insecticides which at a certain level can become toxic for plants and animals. Just like POPs in the marine environment, insecticides like DDT can accumulate in the food chain and disrupt natural processes. The reference unit given in: kg 1,4 dichlorobenzene equivalent.

Human Toxicity Potential (HTP)
HTP relates to substances which have a negative influence on human health. They can be found in air, water and soil as a result of emissions by industry and traffic. Depending on their concentration and toxicity their relative contribution to their HTP is determined. This is measured in: 1,4 dichlorobenzene equivalent.

Without expert knowledge, it is relatively hard to understand the functional reference units of EICs. A simplification needs to be made in order for the general public to work with and understand the results. To that end, so-called ‘shadow price models’ have been constructed by Dutch organisations such as TNO, CE Delft and NIBE. These shadow prices reflect the costs that society is willing to pay to prevent the environmental damage in question [54]. The exact shadow prices may differ depending on the selected source, but the discrepancies are so small that they are negligible, especially for preliminary design purposes. The shadow prices for the aforementioned eleven EICs that can be quantified by the CML2-baseline are shown in Table 3.1.

The amount of reference unit that is produced as a consequence of a certain project is multiplied with their corresponding shadow price. By summing all contributions, a single score shadow cost can be calculated. This score can be used by companies to determine which combination of materials and construction elements lead to the lowest environmental damage [37].

Table 3.1: CML2-baseline shadow prices [55]

Environmental impact category	Reference unit	Shadow price	Source
GWP	kg CO2 eq.	€ 0.05	CE
ODP	kg CFC-11 eq.	€ 30.00	CE
AP	kg SO2 eq.	€ 4.00	CE
EP	kg PO43- eq.	€ 9.00	CE
POCP	kg C2H4 eq.	€ 2.00	CE
ADP non fuel	kg Sb eq.	€ 0.16	TNO
ADP fuel	kg Sb eq.	€ 0.16	TNO
FAETP	kg 1,4 DB eq.	€ 0.03	TNO
MAETP	kg 1,4 DB eq.	€ 0.0001	TNO
TETP	kg 1,4 DB eq.	€ 0.06	TNO
HTP	kg 1,4 DB eq.	€ 0.09	TNO

3.2.5. Dutch Construction sector

Since 2018, the Dutch construction sector is obligated to perform at least a fast track LCA for buildings of 100 m2 or more [56]. This can be done by means of an environmental performance criterion better known as 'MilieuPrestatie Gebouwen' (MPG). MPG was developed by stichting Bouwkwaliteit (SBK) in order to unambiguously determine the material related environmental performance of buildings and civil engineering works over their entire lifecycle. It is based on the EN15804:2012+A2:2019 guideline and uses the Nationale Milieudatabase as data source [52]. The outcome of an MPG calculation is expressed in shadow cost per square meter gross floor area per year [€ / m2 GFA / year]. When MPG was first introduced, its limit value was set to 1.0. This value is reached for every building that does not take into account additional measures to increase the sustainability of the building. However, since July 2021, the limit value for an MPG has decreased to 0.8 [56]. This change is part of a plan of the government to gradually increase the sustainability requirements of building constructions in order to achieve 50% reduction in environmental impacts by the year 2030. Since MPG is normally only used for housing and offices, the underlying environmental cost indicator (ECI) is a more appropriate measure for industrial halls.

3.3. Circular design

In the Dutch construction sector, approximately 25 million tonnes of waste is produced per year, which is three times as much as the amount of waste that is produced by households [34]. These substantial waste flows are generated by the construction, renovation and demolition of buildings. In the Netherlands 95% of this waste is already being recycled, concrete waste is usually used as foundation material for ground works, roads and has several purposes in hydraulic engineering works [57]. However, high recycling percentages do not automatically substantiate a circular economy (CE). While the lion's share of construction waste is being recycled, only 3% is used again for its initially intended purpose. Thus, over time, the market for secondary recycled material will saturate [57]. This is especially true for cementitious waste, which is generally downgraded to applications without a true structural function. This secondary grade material market saturation actually resembles a modified scheme of a traditional linear economy, in which the main concept still postulates infinite resource availability. The sole difference is given by an additional buffer of second grade materials with limited capacity that is added to the material life cycle. This initially does lead to a decrease in waste material. However, once the buffer has been saturated, the same amount of landfill will be produced as before. Ergo, waste generation is merely delayed for a particular portion of construction materials. This modified version of a linear economy is illustrated in Figure 3.7.

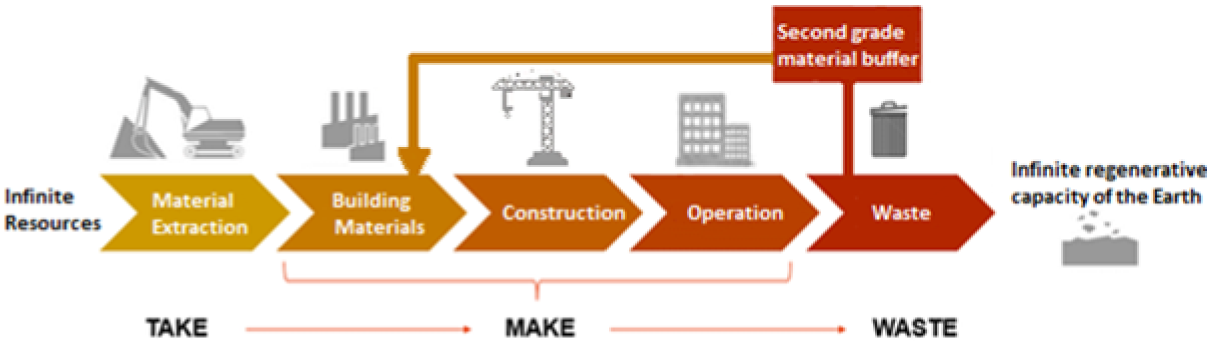


Figure 3.7: Modified version of a linear economy [Adapted from 58]

The Ellen MacArthur Foundation (EMAF) is internationally recognised as an authority on circular concepts. They describe a circular economy as follows:

> *"A circular economy is an industrial system that is restorative or regenerative by intention and design It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models." [59]*

The EMAF distinguishes between two circularity cycles that are relevant for the construction industry: a technical cycle, which is valid for all construction materials with a finite source of raw materials and a biological cycle which is an addition to the technical cycle for construction materials that are made of regrowable resources such as timber. These cycles are depicted by the butterfly diagram in Figure 3.8.

By keeping materials in these loops for as long as possible, virgin resource extraction is slowed down and linear non-sustainable processes such as land-filling and energy recovery are therefore minimized. Circular design not only takes into account every phase of the building life-cycle but also the subsequent and recurring phases. To that end, it aims to keep products, components and materials at their highest utility and value at all times. To achieve circular design, the transition from every design phase to the next needs fit seamlessly together. In the case of new and existing buildings, this requires an integral endeavour of customers, architects, engineers, managers, (demolition) contractors and recyclers. As a result, circular design changes from a technical challenge to a process in which cooperation and knowledge sharing are the main fulcrums. According to research from 'Nederlandse Organisatie voor toegepast natuurwetenschappelijk onderzoek' (TNO), alteration of business models leads to change in the nature of many jobs to a certain extent. Consequently, the change towards a circular economy requires restructuring society [61].

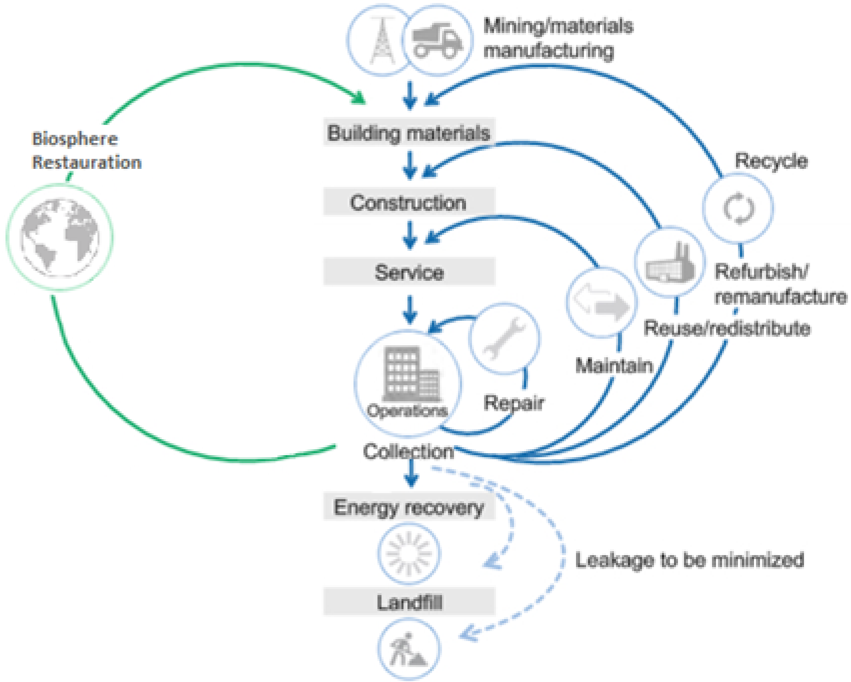


Figure 3.8: Modified version of the butterfly diagram by EMAF [Adapted from 60]

A pitfall of the contemporary construction industry is that every phase of a building lifetime is financed except for demolition and recycling. Most buildings are designed to be permanent and robust structures in order to last an indefinite period of time. Whenever such a building is deemed unfit for its purpose, the price of decommissioning befalls the new investor or a community as a whole. Building on an empty plot of land is generally cheaper, so old buildings are left vacant which obstructs urban renewal and leaves a source of potential building materials untouched [34]. To counter this, the Dutch cabinet introduced the program ‘Nederland circulair in 2050’. This program states that by the year 2030, 50% less raw materials should be used and by the year 2050 the Netherlands should be a fully circular economy [62]. This program was followed by a letter of intent from 180 different governmental- and business-parties called the ‘Grondstoffenakkoord’ to make the Dutch economy run on reusable raw materials [63]. To that end, in 2018, together with the undersigned of the ‘Grondstoffenakkoord’, the Dutch government has drawn up a transition agenda for the 5 main industrial sectors. For the construction sector this resulted in the introduction of a material passport, circularity criteria in building regulations such as the ‘Milieuprestatie-eis voor gebouwen’ (MPG) and an exemplary role of governmental institutions like ‘Rijksvastgoedbedrijf’ (RVB) and ‘Rijkswaterstaat’ (RWS) to make the entire government office portfolio and all their tenders circular before the end of 2030. All these measures should lead to a positive impulse of circular applications in the construction industry [64].

In order to indicate the degree of circularity of a product, the EMAF has developed a material circularity indicator (MCI). This indicator has been developed on both a product and a company level. The MCI provides a value in the range of 0 to 1. The lower bound represents a fully linear product that uses only virgin feed-stock and ends up as landfill at the end of its use. The upper bound is given by a fully circular product that contains no virgin feed-stock and is completely reused or recycled at the end of its life cycle. The MCI score is therefore based on extension of lifespan, use of secondary raw materials, recycling efficiency and waste creation [60] as indicated in Figure 3.9.

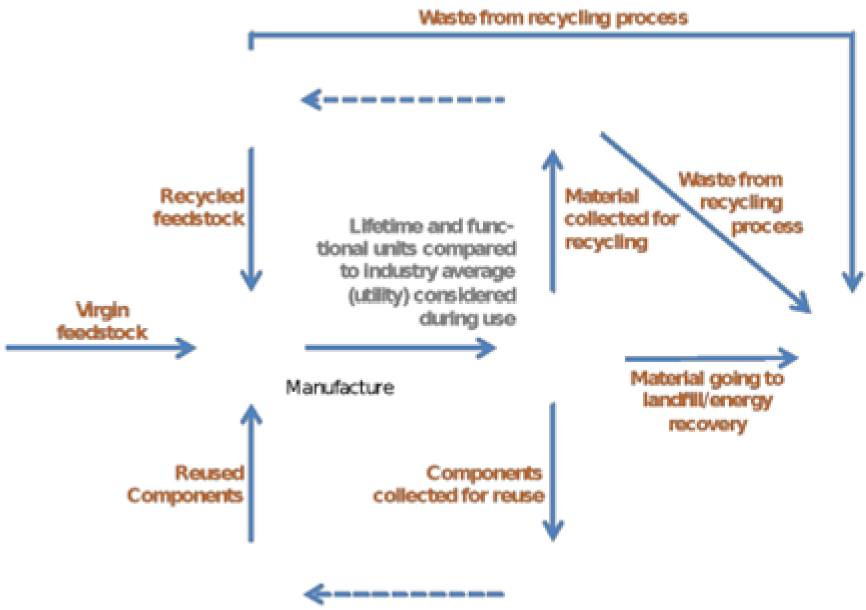


Figure 3.9: EMAF circularity indicators methodology [65]

The information that is necessary for EMAF's MCI model is usually well known and also a part of an LCA analysis [66]. As a result, the MCI value could be included as an additional EIC in the output of an LCA. However, in most LCAs the calculation of this indicator is not common practise. Moreover, the method as proposed by the EMAF might be applicable for individual products but it is not necessarily accurate for buildings with combined structural elements since their reusability depends on the type of connection that is used and the degree of deformation that has occurred during the use stage. Both of these aspects cannot be specified in an LCA. Thus whereas the ideology is valuable, EMAF's MCI cannot be used as a circularity indicator for the structural components of industrial halls. Presently, no official circularity indicator exists that takes into account structural connection types and damage to components. Given that the recyclability of the materials in building components can already be accounted for by their LCAs, reusability is a more governing aspect for a circularity indicator. Therefore, some reasonable assumptions have to be made to include reusability of structural elements in shadow cost calculations.

3.4. Reusability

Reuse, in contrast to recycling, does not require structural elements to be broken down, processed and built up again. It is an alternative to recycling with the goal to support the recovery process of building materials in such a way that no downgrading occurs. In some cases, a bit of remanufacturing is required, but the cost and environmental impact corresponding to this will generally be much lower compared to recycling. Re-entrance of building components in the built environment is an intricate process which affects all parties that are associated with the building's life cycle [67, 68]. The most important role is fulfilled by the designers, who have to consider a new material source and thoroughly assess the deconstructability of their designs. The difficulty of their role depends on the size of the building elements destined for re-use and their corresponding complexity.

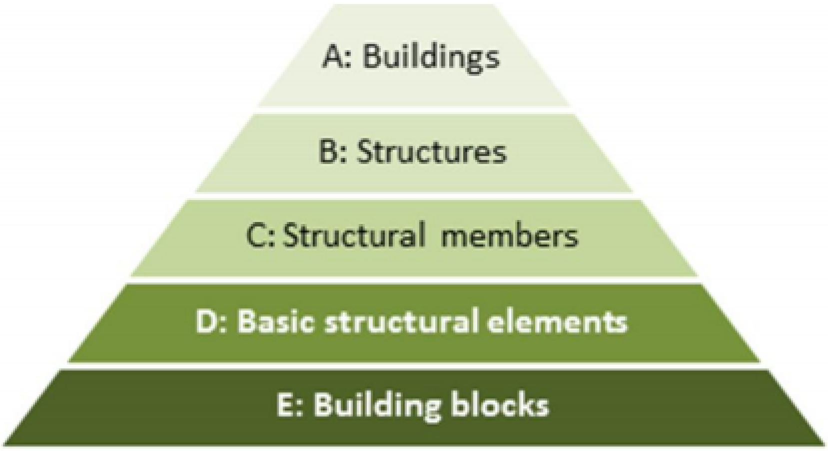


Figure 3.10: Categories of structural elements [68]

From literature, five size categories can be identified as shown in Figure 3.10 [68]. Whilst the elements in one of the higher categories are often more valuable than the sum of its separate components, it is usually more efficient to take them apart since it might be hard to find an appropriate application for them in their next life cycle. With regard to the components of industrial halls, categories B and C are the most appropriate for analysis. When the viability of reuse of different elements is taken into account, some materials and components have a higher potential than others. Structural steel framing, glued laminated timber and traditional timber have been marked as high potential components while precast concrete elements and steel roof trusses are considered to have medium reusability potential since they are often rather specific custom made elements [68–71].

Reuse of components is an example of a closed-loop future scenario. The component is used in a similar application after it has been prepared for reuse. Activities relating to reuse preparation include deconstruction, transport, cleaning and cutting. Especially transport distance has a significant contribution to the viability of component reuse. Previous research has developed estimates for the maximum transport distances of reclaimed material before the environmental advantage is lost [72]. An overview of five common materials can be seen in Table 3.2. It is obvious that for materials with low self-weight the maximum distance is larger than for heavy materials. Nevertheless, materials from demolished buildings need to be transported regardless of their next function, so there is no clear difference between environmental transport costs of reusable materials or materials headed for landfill. The use of such maximum transport distances for reclaimed materials is therefore erroneous.

Table 3.2: Estimated maximum transport distance of reclaimed material before the environmental advantage is lost [72]

Aggregates	**Distance [km]**
Bricks	400
Timber	1.600
Steel	4.000
Aluminium	12.000

Single storey buildings like industrial halls are considered to be particularly suitable for reclaiming and reuse of structural elements. This is well addressed in the project 'PROGRESS' (PROvisions for Greater REuse of Steel Structures) which was spearheaded by the Finnish research institution VTT [24]. The repetitive structural system of industrial halls allows for good standardisation in their geometry and the use of primary components. Since they are often low occupancy structures, the joints and structural members do not have to be hidden for safety and they are therefore usually visually exposed which allows for good accessibility for assembly and disassembly. Additionally, the relatively low fire safety requirements in such buildings eliminate the need for intumescent coatings or other safety measures that might hinder the reusability of elements. Altough 'PROGRESS' was focused on steel buildings, all benefits that were addressed are equally valid for timber and prefab concrete constructions since they are independent of material characteristics.

Literature states that the environmental gain from reuse can be calculated by subtracting the burden related to preparation for reuse from the production burden [68]. Thus, for elements that can sustain the reuse process an infinite number of times, the environmental burden that remains can be expressed as solely their reuse preparation burden. However, the physical state of building products after dismantling and their resilience to ageing or reuse preparation depends on their mechanical properties, which are finite. Therefore, realistically, infinite iterations can never be achieved and thus a part of the original shadow cost always has to be accounted for. How much depends on the number of subsequent life cycles a certain structural element can achieve.

For the development of a reusability indicator it is important to distinguish between two different reuse scenario's. The two most relevant scenario's that are discussed in literature are:

- Relocation: Disassembly of a building in order to reconstruct the same building on another location
- Individual reuse: Disassembly of a building for the purpose of using the individual elements in a different configuration for different new buildings

Both scenario's have their own advantages and disadvantages and are not always equally applicable. Relocation ensures reuse of all the elements in a building but freedom in redesign is very limited, as such, it presupposes that the same exact building design will be required in a different location in the future. As identified in chapter 2, this most likely is not the case since the required size and column placement of industrial halls depend heavily on the exact nature of the envisioned business processes associated with the new owner. Furthermore, connection types for this scenario are limited to demountable connections since all elements are required to be reused in their original state. In case of individual reuse, elements can be sold more easily to a new owner since they can be used in all sorts of new buildings due to the fact that they are not bound to a single configuration. Therefore, individual reuse does not require any assumptions for their next application. Furthermore, it allows for the use of permanent connection types because the affected part of the element can simply be cut off. While this leads to a reduction in length and thus value, the rest of the element can be reused for a different application. The main obstacle for individual reuse is that the current market for second hand construction elements is still small which compromises the effectiveness of this scenario. However, in some European countries a few pioneering companies have identified reuse as a business opportunity with great potential and have started to assemble an inventory of reused components. Much to the benefit of these companies, the problem of the limited supply of disassembled elements is being addressed through new standards for disassembly as well as through increased costs for disposal of construction waste [73]. This implies that the value and supply of disassembled building components is slowly increasing. Given that the service life of industrial halls generally amounts to 50 years, it is probable that the main obstacle for individual reuse will be cleared before the first hall is scheduled for disassembly. As a consequence, individual reuse can be considered the most appropriate scenario for industrial halls.

3.4.1. Reusability of materials

As identified in chapter 2, the most common building parts in industrial halls can be divided into three groups: steel-, concrete- and timber-elements. Thus, these are the materials that should be focused upon in the development of a reusability indicator for structural elements of industrial halls. Given the fact that impact of damage to construction elements due to connections and the deformations manifests itself in different ways for different construction materials, a separate projected reusability score needs to be developed for all three of the previously mentioned materials.

Steel

Reuse of steel construction elements avoids the negative environmental impacts associated with recycling in scrap melting furnaces. Regardless, there are some limiting factors that prevent its reuse in some cases. In low carbon steel (up to 0.2%), thermal ageing embrittlement can lead to decreased ductility, notch toughness and fracture toughness [24]. However, steels types that are used for construction are generally class S235 or higher for which the carbon content is higher than 0.2%. Since the mechanical and physical properties of construction steel do not change significantly due to ageing, reuse can be considered to be relatively easy. Still, structural steel elements could suffer from corrosion, significant permanent deformations or fatigue damage and thus need to be protected appropriately to be considered suitable for reuse. Additionally, reclaimed steel elements that have localised cross sectional loss or that have holes in certain locations where new holes are required are generally considered to be less valuable [68, 71]. Permanent deformations can to a great degree be prevented by designing with the elastic limit of the material. Corrosion can largely be prevented by preparation with surface paint or by applying metallic coatings such as galvanisation. Fatigue normally does not occur in structural components of industrial halls, but steel components originating from applications with cyclic loading like bridges may not be reused. Reclaimed steel elements are allowed to be reused in structural design when in accordance of the provisions in EN1993. To comply with this, the steel needs to have specific performance and quality requirements. Existing bolts from previous applications should not be reused.

Timber

Material degradation is a significant factor in the reuse potential of timber building components. Due to its organic nature, timber elements are at risk of fungi or insect attack [74]. These effects can be limited by means of preservatives or coatings which usually contain pesticides or toxic chemicals and as a consequence are not very ecologically friendly products. Alternatively, hardwoods could be used since they are denser and more durable than softwoods. However, availability of hardwood is limited in Europe and the associated costs are significantly higher compared to softwoods.

Several researchers have tried to quantify the change in the mechanical properties of timber. It is interesting to note that whereas for small specimens no concluding evidence can be provided for any kind of degradation, it is clear that for structural timber the reduction in modulus of elasticity (MOE) and modulus of rupture (MOR) is relatively high when compared to new structural timber from the same strength class [75]. This confirms the in-service influence of load duration and state of conservation on the mechanical properties of structural timber. Since timber gradually loses ductility over time, reuse applications where brittle failure is governing should be avoided [68, 70]. This includes elements with long rows of bolts. Additionally, large holes and notches reduce the reusability of timber elements since it negatively affects its strength in bending and tension. Furthermore, damage could occur in structural timber members as a consequence of mounting and dismantling procedures which may affect its original mechanical properties [76, 77].

Given that timber is a regrowable resource it is favourable to use cascading strategies after its reuse cycles as a main load bearing element to further decrease its environmental impact. Cascading is a form of reusing in which the timber is reprocessed into a different, slightly less valuable element. This is especially relevant for timber products since the amount of energy that is required to cascade a timber element is much lower compared to similar processes for steel or concrete and the subsequent drop in value is much lower. Although it degrades over time, the same amount of timber can be regrown in less time than it takes to complete all its consecutive life phases. Of course, some energy is required to reshape the material. However, the net effect on carbon sequestration is positive, thus more carbon is captured than emitted to the atmosphere [78]. An example of a cascading strategy for timber is given in Figure 3.11. A drawback of the carbon sequestration method is given by the fact that only carbon emissions are assessed and whereas timber products mostly consist of carbon, some additional substances are used and emitted during its (re)production which should not be overlooked. Unfortunately, the exact effect of cascading scenarios is very hard to determine and may sometimes already be included in the end-of-life scenario in LCAs [79]. Therefore it should not be included again in a reusability indicator for the initial structural timber element. It should be noted that the actual environmental effect of timber elements would probably be even smaller than predicted in case cascading strategies are implemented.

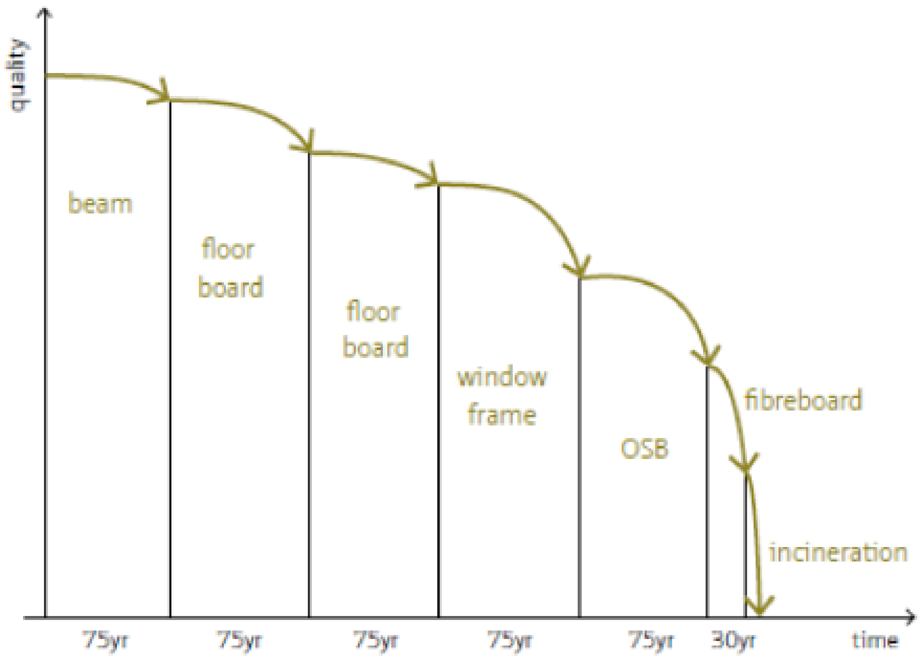


Figure 3.11: Cascading strategy of a timber beam [78]

Prefab concrete
Mechanical properties of prefab concrete can be influenced by many time dependent processes. A part of these processes interact with the concrete itself and another part with its embedded reinforcing steel like rebars and anchors.

Carbonation changes the characteristics of concrete over time and is caused by carbon dioxide in the atmosphere. Carbonation starts at the concrete surface and causes a drop in pH value. When it reaches the embedded steel rebars or anchors, they are depassivated and corrosion commences. The rate of carbonation depends on the temperature, relative humidity, permeability of the concrete and carbon dioxide concentration. It is accompanied with a local increase in compressive concrete strength close to the affected surface. Repeated Freeze and thaw cycles gradually decrease the mechanical properties of concrete due to expansion of capillary water which causes micro cracks [80]. However, generally the main bearing construction of industrial halls is protected and insulated by the facade and roof. Therefore it is safe to assume that the temperature within industrial halls does not reach sub zero temperatures. The temperature in cold storage warehouses is constantly kept below zero, which means that no thaw cycles occur and therefore no damage is expected. Chlorides that are present in the concrete as a consequence of the used aggregate or introduction by the environment can cause corrosion in embedded steel reinforcement. Transport of chlorides through the concrete can take place by capillary suction and diffusion. The former is caused by wetting and drying cycles and can be disregarded since the concrete elements in industrial halls are protected by the facade and roof elements. However, the latter slowly transports chloride ions throughout the concrete element, degrading the steel over time [80]. Creep is defined as deformation under sustained load. Shrinkage is the consequence of water loss and relaxation and leads to shortening. The sensitivity of constructions to both phenomena varies widely. Industrial halls are considered to be less susceptible to these effects. Steel relaxation in reinforcing steel manifests itself in the form of visco-plastic strain and is independent of stress or strain history. It only occurs in pre-stressed concrete like pretentioned beams and leads to prestress losses. The effect can be calculated and compensated for in the design stage [80]. Concrete elements with localized cross sectional loss or large holes can lead to high stress concentrations. Moreover, cracks at the location of connections may lead to corrosion in the future [68].

In general, concrete building elements are amongst the heaviest in their sort since they have massive cross sections and relatively high material density. Workers protection during disassembly has priority over the preservation of structural elements. The deconstruction of heavy concrete components can be regarded as relatively dangerous which therefore complicates deconstruction and therefore reuse. Deconstruction usually requires strong cranes and machinery which increases its price significantly. Additionally, an entire industry has formed around the recycling of concrete elements to make crushed aggregate [81]. This process is often cheaper than careful deconstruction which provides an extra barrier for reuse.

3.4.2. Cost of reuse

Demolition is a quick and straightforward process in which a construction is torn down, debris shipped away and the site cleared for subsequent use. Reuse on the other hand, requires more complex processes like deconstruction, material handling, inspection, modification and transport. All of these processes are associated with a certain cost. According to a Msc thesis by I.Jabeen, deconstruction costs are considered to be the biggest money sink, followed by modification, storage and transportation [82]. It also states that in order for reuse to be economically feasible, the net cost of reuse has to be lower than or equal to the cost of end-of-life treatment in traditional demolition. However, this statement is flawed, since reuse in fact not only has economic burdens but is also accompanied with economic benefits. Components can be sold to collection companies or used by the same owner in a new project which reduces the construction costs of the new building.

The same thesis rightfully distinguishes between different reuse scenario's. Direct on-site reuse, direct off-site reuse and indirect reuse are three scenario's that bring about different costs. The first scenario does not involve storage or transportation and therefore provides the highest cost savings. The second scenario is slightly less advantageous since transportation is still required. However, there is already a demand for the deconstructed components. The last scenario requires the products to be stored at a collection facility until a buyer is found after which it needs to be transported again. Although this is economically less favourable, it is currently the most common practise and as discussed in section 3.4 it is the most appropriate scenario for industrial halls.

Another study [83] has identified that reuse would be considered an economically superior alternative to recycling if the deconstruction costs are reduced by 20% or if the residual value of used steel components is valued 330% higher. However, it should be noted that the assumptions that are made in this paper with regard to upstream processes and their implications on structural steel reuse analyses should be tested on more specific projects or structure types in order to achieve more relevant data. In addition, the results were gathered using constructions that were not designed according to the designing for deconstruction (DfD) philosophy. DfD will ensure that the costs associated with deconstruction are much lower and will thus result in more economical reuse scenarios.

3.4.3. Influence of connections

It is self evident that not all possible connection types have been considered in this thesis. The reason for this is twofold. Firstly, not all connection types are suitable to be used in industrial hall design. The collection of the assessed connections consists of a combination of frequently used connections and connection types which have shown promising results regarding reusability. Secondly, in order to provide a fair comparison between construction materials, no rigid demountable connections are considered during the optimization process in this thesis. This aspect is further elaborated upon in section 4.3.

As a part of project 'PROGRESS', Hradil et al [84] have constructed an elaborate table which contains all categories that influence connection reusability of steel elements and have subsequently developed a scoring system that can be found in Figure A.1 of Appendix A. Given careful thought, this system can be generalised to four most prominent criteria that suit timber and concrete as well as steel. It is suggested that the suitability of different types of connections for the reuse of their respective structural components depends on the following four criteria:

- Ease of disassembly
- Damage to the element due to disassembly
- Difficulty/cost of element preparation for reuse
- Expected lifespan of the element

Arcadis reusability score

Ten types of connections that are relevant for industrial halls were assessed based on their reusability. A score is given to each connection based upon a survey that was filled out by 10 structural designers from Arcadis Nederland BV based on their experiences. A blank copy of this survey can be found in Appendix C. The survey was constructed in order to develop a practical estimate for the degree of reusability of construction elements that have been fastened using a certain connection type. The scoring system is based upon a scoring system that was made solely for steel connections by Hradil et al [84]. After generalisation of the criteria used in this research, it is considered applicable for steel as well as timber and concrete construction elements. The results of this survey fills a gap in published literature with regard to the influence of connections on the reusability of steel, timber and concrete structural elements. The participants were asked to score the performance of the connections based on the previously mentioned criteria and according to Table 3.3. Despite the fact that the resulting scores typically had a small standard deviation, additional research is considered necessary in order to gain any statistical relevance.

Table 3.3: Connection assessment scores

Assessment	Score
Excellent	100
Very good	80
Good	60
Moderate	40
Poor	20
Very poor	0

Table 3.4: Average connection scores

Connection type	Arcadis score	Arcadis reusability factor
Steel		
Welded	14	0.86
Bolted	82	0.18
Slip resistant bolted	72	0.28
Resin injected bolted	40	0.6
Timber		
Bolted	66	0.34
Doweled	50	0.50
Prefab concrete		
Bolted	58	0.42
Embedded steel hinge	62	0.38
Pinned	30	0.70
Grouted	2	0.98

Similar connection types in different kinds of materials can lead to a dissimilar damage or wear. Therefore, the scores of a bolted connection in steel, timber or concrete can be different and the connections must therefore be assessed individually for each material. The average scores per connection type from the survey as well as the ECI reduction factor that is calculated from it can both be found in Table 3.4. The assumption is made that the connection based ECI reduction factor can be calculated by dividing the connection score of the survey by 100 and subsequently subtracting it from 1. This enables the scores to be used directly to calculate the reduction of ECI value for a particular construction element. E.g. an average connection score of 65 will result in an ECI connection reduction factor of 1-(65/100) = 0.35 which corresponds to a shadow cost reduction of 65% for an individual construction element. One might argue that, in theory, a 100% reusable connection will lead to a reusability factor of zero, therefore reducing the ECI of an element to zero as well. However, this theory is flawed, because the connection factors are based on four criteria, one of which is the expected lifespan of the element. These criteria are further elaborated upon in the next paragraph. Construction elements inevitably degrade over time, therefore, reusability factors can never reach zero.

In addition to these scores, the structural designers were asked to provide the relative weights that they allocated to the four criterion's in their assessment as well as how frequent all connections occur in practice. The average of the criteria weights that were indicated by the structural designers are shown in the pie chart in Figure 3.12. The percentages in this figure mark the relative importance of the four criteria in the assessment of the connections by the structural designers independent of material use. It is rather clear that ease of disassembly and damage to the element are considered as the most important aspects for reusability. Cost of construction element preparation after damage has a smaller role and it seems that reusing a construction element in another structure using the same fastening technique is not necessarily very important.

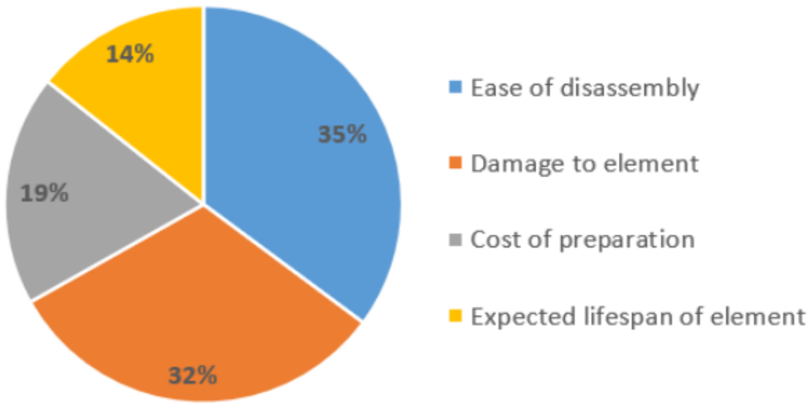


Figure 3.12: Average criterion weights from survey in percentage

From the results shown in Figure 3.12 can be concluded that the ease of disassembly and the damage to the element are considered to be the most important criterion weights. This indicates that structures which are designed for disassembly (DfD) are far more suitable for ECI reduction than conventional buildings. Consequently, in order to maximize the ECI reduction industrial hall designs should adhere to the general principles of DfD which are elaborated upon in section 3.5.

Figure 3.13 plots the ECI reduction factor of all assessed connections versus their relative occurrence in practice. The positions of connections in steel, timber and concrete in this plot are indicated by a blue, orange or gray marker respectively. The exact specifications of the connections that were scored can be found in the blank survey in Appendix C. As a general rule for lowering the ECI of a structure, the connections in the upper two quadrants should be avoided as they are assumed to be less effective in reducing the ECI score of the elements they are connecting. It can be seen that there exist several types of connections that are not frequently used but can provide a rather good option with regard to reusability. Especially for prefab concrete large ECI reductions can be realised by using embedded hinges or bolted connections.

The results from Figure 3.13 can be corroborated by the comments which the structural designers wrote down in the remarks section of the survey. Grouted connections are almost impossible to disconnect without destroying the elements that are attached to it which makes them highly unsuitable for reuse. Concrete elements with an embedded hinge or bolts can be disassembled without damage to the element but the their large weight decreases their reusability potential in terms of transportation and ease of disassembly. Pinned concrete elements are less suitable since the pins are generally grouted and cannot be taken out without cutting. Dowelled and bolted timber elements score relatively well, the slight difference between the two can be explained by the fact that dowels tend to do more damage to the element than bolts. Steel bolted connections are generally considered easy to disassemble since the nuts can simply be loosened and only the bolt itself can not be reused. There are some arguments that after long periods of time it might be difficult to unscrew them due to deflections. However, when careful thought is given to the design this can be prevented. Welds are not separable without damaging and shortening the element which makes this connection unsuitable for reuse of the elements in relocation. Slip resistant bolts are considered non-damaging to structural elements but they are can only be applied in very specific cases and are generally unsuitable for industrial halls. Resin injected bolts are generally only used when normal bolts in steel elements are not strong enough and do not damage the plate material. From conclusions of the thesis of Martin Nijgh [85] it becomes apparent that resin injected bolts including a release agent have a high potential for reuse of structural elements. It seems that structural designers are not yet aware of the findings in recent research on connections and consequently this fastening method is scored worse than it may in fact be. It can therefore be concluded that the ECI reduction factors for less common connection types that result from the survey are less accurate than the more commonly used fastening techniques.

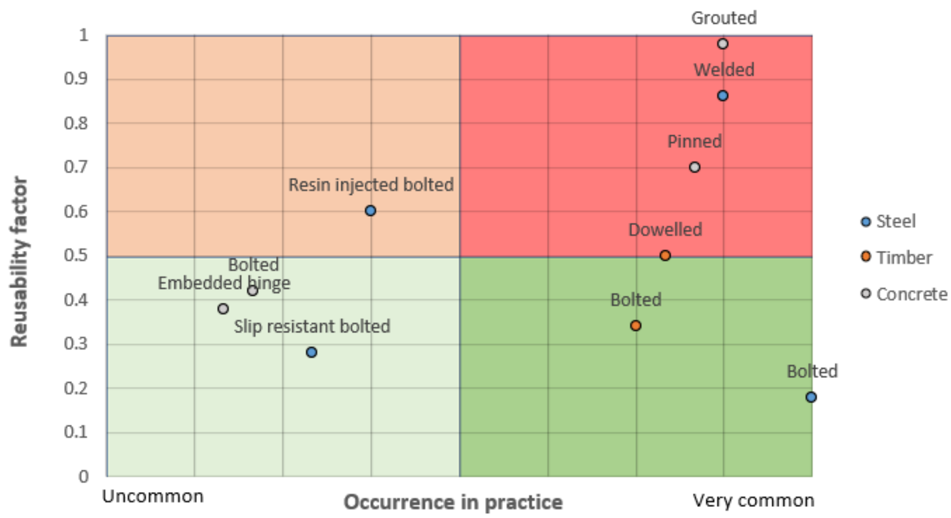


Figure 3.13: Reusability factors of different connection types plotted against their occurrence in practice

It should be noted that slip resistant connections are not very applicable to industrial halls, which is why many structural designers labeled them as uncommon connection types. This does not mean that they are uncommon in general. For example, slip resistant connections are very common in fields of construction where fatigue damage is a major factor.

J.W. reusability score

Since the reusability scores that are provided in the previous paragraph are exclusively based on the viewpoints of structural designers employed by Arcadis, thus they should not be mistakenly interpreted as academically unbiased scores. Therefore, for comparison, a J.W. reusability score is provided based on literature and engineering knowledge. They are given based on the same criteria as the Arcadis scores. However, the relative importance of these criteria differs as can be seen in Figure 3.14.

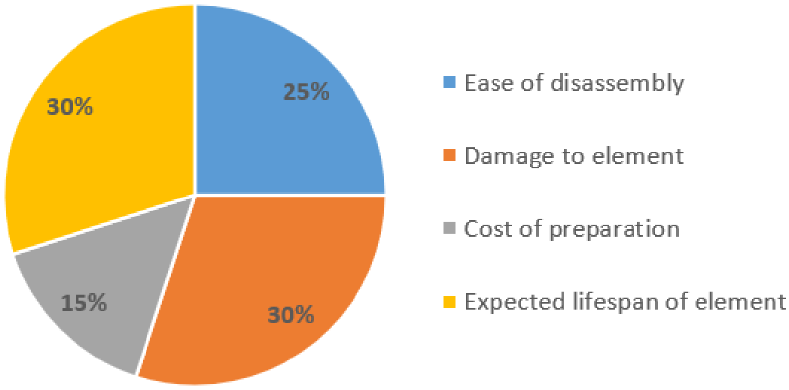


Figure 3.14: J.W. criterion weights in percentages

Damage to the element and cost of preparation have a similar relative importance in the J.W. criterion weights compared to the Arcadis designers average weights. This can be explained by the fact that the relative importance of these criterion weights is corroborated by the limited literature that was available on this topic [84]. Therefore no large changes are proposed in the J.W. criterion weights. The major difference is given by the weights of expected lifespan and ease of disassembly. The former being 16% larger and the latter being 10% smaller compared to the Arcadis average weights. This can be explained by the fact that material characteristics govern the expected lifespan of an element. Timber generally degrades more quickly than steel or concrete even though all appropriate durability measures have been taken. Thus, the number of life cycles an element can endure differs per material. This should be reflected in the reusability scores, therefore, the expected lifespan of an element therefore takes precedence over its ease of disassembly in the J.W. reusability score.

The values of the J.W. scores are provided in Table 3.5. In steel welded elements, cutting off the heat affected area of the welds results in loss of standardised size which means that its reusability potential decreases significantly. This potential of course also depends on the original element length the amount of smaller standardised lengths that it can be cut to. Additionally, there is a high risk of damage to the element during deconstruction which is inherent to its deconstruction process [68]. Steel bolted elements are generally considered to be very good for reuse. The reusability potential partly depends on ease of accessibility and the amount of bolts. When properly designed, almost no damage should occur to the element. Slight deformations of bolt holes are possible but this can be solved locally by adding additional steel plates. Slip resistant bolted connections generally do not damage the element due to disassembly. However, it can be said that in many cases, the ease of disassembly is slightly limited by the vast amount of bolts that are required to produce this connection. This is also the reason why the J.W. score of slip resistant connections is slightly lower than for bolted connections. A study on resin injected bolted connections has indicated that they are a very good option for reuse of elements when they are combined with a release agent [85]. No damage to the connected elements occurs because all deformation is taken up by the injection material and the forces are distributed evenly to the connected element. This connection type is especially useful for very heavily loaded members. However, it is more expensive compared to a regular bolted connection and requires a larger amount of man hours during construction and deconstruction which limits its reusability score.

Table 3.5: J.W. connection reusability scores

Connection type	J.W. score	J.W. reusability factor
Steel		
Welded	25	0.75
Bolted	80	0.20
Slip resistant bolted	70	0.30
Resin injected bolted	80	0.20
Timber		
Bolted	70	0.30
Doweled	50	0.50
Prefab concrete		
Bolted	70	0.30
Embedded steel hinge	70	0.30
Pinned	15	0.85
Grouted	0	1.00

Given enough thought, it is possible to create timber bolted connections that behave similar to steel bolted connections and could therefore produce the same reusability score. However, timber elements degrade faster than steel elements which means that the number of times an element can be reused is smaller, which should be reflected in its reusability score according to the assessment criteria. In timber dowelled connections, the amount of dowels that is needed is generally quite large, which reduces their ease of disassembly significantly. Moreover, dowel deformation is quite common which reduces their reusability potential even further since it is very hard to remove deformed dowels without damaging element severely [86]. Concrete bolted elements can be used to create rigid joints since the reinforcement can be activated by a row of bolts located behind the reinforcing steel and subsequently the force can be transferred through a steel plate to another element. This connection has a multitude of applications. However, concrete elements are rather heavy which provides a challenge for construction and disassembly [87]. Concrete elements with an embedded steel hinge are considered to be quite good in terms of reuse potential. Concrete generally does not degrade very fast and elements with an embedded steel hinge can be removed without damaging the element itself. Since only single spans are possible due to the nature of the connection design, elements need to have a rather large size to accommodate all forces which decreases their ease of disassembly. In pinned concrete connections, the pins are usually grouted in place which means that the connection has to be broken before reuse is possible which has a high potential of damaging the element as a result. Additionally the ease of disassembly is relatively low and the cost of preparation for reuse can be quite high, ultimately leading to a low reusability score. Grouted concrete connections are inherently incompatible with the disassembly ideology. Deconstruction of these elements usually results in shattered elements which can then only be recycled. While it is technically possible to 'cut' the element including the reinforcing steel, it is very difficult to produce a similar connection using the cut element and in practise this is never profitable. Therefore this connection type is considered not to be demountable at all.

It should be noted that not a single connection can ever reach a score of 100 since this would correspond with an everlasting element. Every material degrades over time thus this is realistically not possible. Moreover, there is always a chance of accidental loads which can render an element unsuitable for reuse. both these phenomena are accounted for in the 'expected lifespan' assessment criterion.

3.4.4. Permanent deformations

Permanent deformations in structures develop as a consequence of multiple effects, the most prominent ones are design load exceedance and creep. Permanent deformations reduce the reusability potential of structural elements as a result of aberrations and increased eccentricities. Its effect should therefore be included in the calculation of the actual shadow costs of construction elements.

Design load exceedance

In every structure there exists a certain probability that the occurring load is larger than the load it has been designed for. When all required variables are known, this probability can be calculated. Since this thesis focuses on design generation, not all required variables are known beforehand and consequently it is impossible to perform a reliable calculation for the probability of design load exceedance for each design. In addition, this probability will be the same regardless of the materials that are used which means that material choice has no influence on this phenomenon, thus the relative shadow costs will also not be influenced by it. Therefore, the probability of design load exceedance should not be accounted for when calculating the effect of permanent deformations on the shadow costs of structural elements.

Creep

Creep manifests itself differently in different materials and some are more prone to creep deformation than others. Generally, safety factors are used that mitigate the effect of creep on the deformation of virgin structural elements. The same safety factors can be used in a subsequent life cycle, but thought should be given not to place these elements in the exact same position as before since the creep life for which it has been calculated will be extended beyond the initial calculations. Therefore, beams should be rotated 180 degrees with respect to their original position which will ensure that the creep that occurs during the second life cycle does not consolidate the creep of the first life cycle.

Suggested deformation score

Since design load exceedance cannot be reliably be calculated and creep effects can be mitigated by smart design, a deformation score is not necessary to account for decreased reusability. Therefore the only influencing factor is the connection score.

3.4.5. Reusability scoring system

As a consequence of reuse, the shadow costs associated with structural elements decreases. Therefore, a corrected shadow cost has to be calculated. The ECI reduction factor of an element only depends on its connection which makes it easy to calculate the new shadow cost.

> **Suggested corrected shadow cost**
> The corrected shadow cost (CSC) of a structural element can be calculated as its original ECI multiplied by the connection reusability factor (CRF) as shown in Equation 3.1. The environmental damage associated with remanufacuring of elements is already implicitly included in their ECI reduction factors.
>
> $$CSC = ECI * CRF \tag{3.1}$$

As such, the CSC includes the reusability of construction elements through their reusability factors as well as their recyclability through their original ECI values and can therefore be used used as additional output for the shadow cost calculations in the structural parametric model of this MSc thesis and subsequently for its generative design process.

3.5. Design for disassembly

Despite the clear environmental benefits related to reuse, salvage of structural components is often referred to as labour intensive and costs are typically mentioned as its main barrier for widespread application in the EU. Other obstacles that are mentioned are inconsistent quality and quantity of structural elements [68]. This is mainly due to the fact that the current decommissioned buildings were not designed for disassembly. Moreover, industrial halls are especially suitable for disassembly since they usually consist of large quantities of identical elements which makes it easy to generate enough structural elements for secondary use in new buildings. The end of life scenarios for concrete, timber and steel buildings do not include a lot of reuse. This is mainly because the current reused material supply chain is weak and fragmented [88].

By designing for disasssembly (DfD), this supply chain could greatly be improved for the future. Architect Frank Duffy created a concept in which he identified four shearing layers in a building. An expansion to this concept by Stewart Brand resulted in the six layers that are illustrated in Figure 3.15.

Each of the shearing layers represents a different component and has a different service-life expectancy. In general, from longest service life to shortest, the components can be ranked in the following order: site, structure, skin, services, space plan and stuff. With regard to

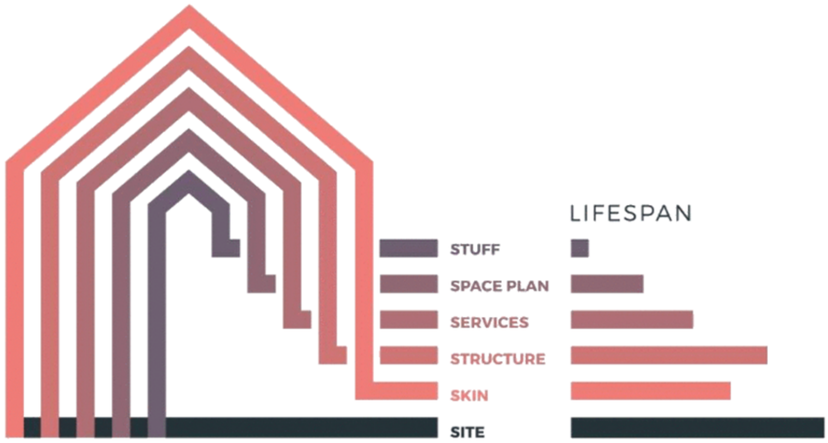


Figure 3.15: Shearing layers by Steward Brand [Adapted from 90]

DfD, the most important of which are structure and skin. The exact durability of these elements differ per structural design and for every application but the general consensus is that the estimated life span of exterior surfaces ranges from 20 to 60 years and for main load bearing elements a range of 30 to 300 years is given [91, 92]. Although these ranges are quite broad, it is clear that exterior surfaces generally have a much shorter longevity. Another factor which influences the life span of facades is its appearance. Once it does not satisfy the aesthetic requirements set by the client or neighbourhood it often has to be replaced [93]. However, industrial halls are usually not located in area's where aesthetic requirements are held in the highest esteem and owners are more interested in its functional capabilities so this normally does not provide any problems. Nevertheless, due to its shorter life span, facades will require good demountability for the purpose of designing for deconstruction.

Pulaski et al [94] have identified in which design stages it is most relevant to include certain design principles. This outcomes are shown in Table 3.6 and can be used to determine what principles need to be considered in a parametric model for the preliminary design of an industrial hall that will be used to optimize shadow costs. Preliminary design most closely matches the phase 'schematic design' from the table. Therefore the principles that are highlighted under schematic design are most valuable for this thesis.
The nature of the structural configuration of industrial halls is very consistent and requires elements with similar measurements, it is therefore quite easy to use standardised profiles and lengths. This is a large benefit for the availability of compatible building materials in the future. In spite of that, these valuable elements could be damaged when non-demountable connections are used. Fortunately, new types of demountable connections are being developed and tested in order to provide better reusability to construction elements. An example of this is the MSc thesis of M.P. Nijgh [85] which aimed to investigate the behaviour of injected bolted connections (IBCs) with oversized holes using various injection materials. IBCs with oversized holes make demounting and remounting of structural elements easier since the deviation tolerances are higher whilst the injection material makes sure that the connection remains stiff. Injection resin normally adheres very strongly to the surface it is applied upon, but by treating the connection members with a release agent, the IBCs can be demounted with relative ease. Nijgh also investigated a new

Table 3.6: Relevance of design principles per design stage [94]

	Design Principles	Program Development	Schematic Design	35% Design Development	70% Design Development	100% Design Development	Construction Documents	Construction
1	Design for prefabrication, preassembly and modular construction	Medium relevance	High relevance	Medium relevance	Medium relevance	Medium relevance	Medium relevance	
2	Simplify and standardize connection details			High relevance	Medium relevance	Medium relevance	Medium relevance	
3	Simplify and separate building systems	Medium relevance	High relevance	Medium relevance				
4	Consider worker safety during deconstruction & construction			Medium relevance	Medium relevance	Medium relevance	Medium relevance	High relevance
5	Minimize building components and materials	High relevance	High relevance	Medium relevance	Medium relevance	Medium relevance	Medium relevance	
6	Select fittings, fasteners, adhesives and sealants that allow for quicker disassembly and facilitate the removal of reusable materials				Medium relevance	Medium relevance	Medium relevance	Medium relevance
7	Design to accommodate deconstruction logistics	Medium relevance	Medium relevance	Medium relevance	Medium relevance			Medium relevance
8	Reduce building complexity	High relevance	High relevance	Medium relevance				
9	Design to reusable materials	Medium relevance	Medium relevance	High relevance	Medium relevance	Medium relevance	Medium relevance	
10	Design for flexibility and adaptability	High relevance	High relevance	Medium relevance				

High relevance
Medium relevance

injection material: resin reinforced with steel shot. The short and long term performance of this material was observed to be significantly better than that of ordinary resin. However, the quantity of tests was too small to obtain any statistical significance. Nevertheless, connection types such as these provide good reusability potential.

The conclusions from this section in combination with additional literature [88, 95] can be summarized in seven base design rules that structural designers should adhere to when designing for deconstruction:

- A building should be built in such a way that components can be removed without damaging them.
- The main load bearing frame should act as a self-supporting construction and should not include wall elements since they make replacement of elements difficult.
- When selecting the element sizes, special consideration needs to be given to the potential need for manual removal. Lifting equipment for heavy elements should be designed so they can also be used during disassembly works.
- Joints should be easily accessible and the amount of different kinds of connections should be minimized.

- Claddings like roofs and facades should be attached using mechanical connections instead of adhesives or sealants. This is especially important because the outer shell of a construction usually has the lowest life span.
- Structural members should have long expected life-spans and should remain available for maintenance.
- The number of different structural components should be kept to a minimum, in order to retain a good quantity of similar elements for reuse.

3.6. Average costs

The average building costs and shadow costs of the most important construction materials for industrial halls need to be determined to provide as input for the parametric model. This section describes the method that is used to determine those costs.

3.6.1. Average building costs

Building costs of elements depend upon their strength class, the amount that is ordered and the finishes that are applied. Shapes also influence costs, round elements for example are usually more expensive than rectangular elements due to their increased difficulty in production [23]. Table B.1 provides a range of costs for several construction elements commonly used in industrial halls based upon estimates from a cost manager from Arcadis Nederland BV.

Table 3.7: Average building costs per structural element

Elements	Average Price [€]	Unit
Prefab reinforced concrete	750-1100	m^3
Steel rolled profile	2.4-5	kg
Steel box profile	6-9	kg
Laminated softwood	1800	m^3
Roofing	28-32	m^2
Facade	80-160	m^2
Welded connection	175	m^1
Bolted connection	100-140	piece
Injection bolt connection	180-220	piece
Slip resistant bolt connection	160-200	piece
Dowelled connection	100-200	piece
Pinned connection	100-200	piece
Grouted connection	200-300	piece
Truss	1.1 * constituents	piece

Some of the elements in Table B.1 correspond to a range in pricing, for these elements the average price that will be used in the structural parametric model will be calculated as the mean of the upper and lower bound price. The prices per connection are given based on the average amount of bolts, dowels, grout and pins that are required in a typical connection including installation. The price of trusses will be calculated as the average price of its constituents multiplied by a factor of 1.1 to account for the cost of its assembly. Furthermore, to retain a certain level of simplicity in the parametric model, it will be assumed that the average length of a welded connection is 1m.

3.6.2. Average shadow costs

The average ECI values in Table 3.8 are determined from the NMD. LCA data included in Appendix B. Connections are not included since they have a negligible weight compared to the total weight of the building and therefore their effect on the total ECI is assumed to be limited. The NMD does not account for biogenic carbon storage in its assessment of timber elements. It should be noted that the inclusion of biogenic carbon storage will lead to a significant reduction of the ECI of timber elements which immanently changes the outcomes of the shadow costs optimization process in this thesis drastically.

Table 3.8: Average ECI per structural element

Elements	**Average ECI [€]**	**Unit**
Prefab reinforced concrete	73.08	m^3
Steel rolled profile	271.84	m^3
Steel box profile	273.85	m^3
Laminated softwood	56.23	m^3
Roofing	8.00	m^2
Facade	3.93	m^2

4

Structural parametric model

In this chapter all the aspects with regard to the structural parametric model are discussed. Section 4.1 describes the workflow that is used for the inputs and outputs of the parametric model. Section 4.2 elaborates on the engineering method that is used to create the model and explains the interaction between different software connections, these include Microsoft Excel, RFEM, Autodesk Refinery. The most important boundary conditions are stated in section 4.3 and all the model inputs and efficiency measures are discussed in section 4.4.

4.1. Workflow

The structural parametric model is the basis for generative design and needs to be constructed based upon the requirements from the research methodology that is described in section 1.2.3. Figure 4.1 indicates the data transfer that needs to be performed between different software programs in order to generate valid design alternatives during the preliminary design stage.

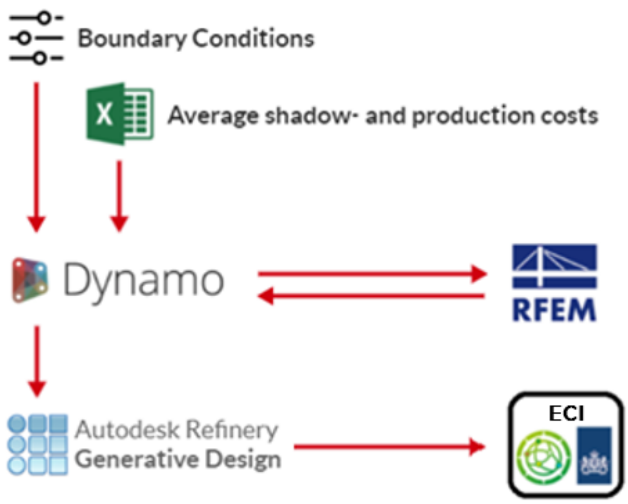


Figure 4.1: Research methodology translated to practical workflow

The boundary conditions are determined by the functional unit and can be inputted directly in Dynamo. Shadow costs and building costs of structural elements and connections are inserted into Dynamo through an Excel file. Dynamo is connected with RFEM which can perform a structural verification by means of a finite element analysis. Ultimately, Autodesk Refinery uses the parametric model in Dynamo to compute the most optimized design alternatives.

4.2. The parametric model

Parametric models can be made using several different kinds of software. Dynamo Sandbox was identified as the most suitable option for this MSc thesis since helpful add-ons and assistance can be provided by Arcadis Nederland BV. It acts as the central component of the workflow and communicates with all other software packages.

4.2.1. Dynamo Sandbox

Dynamo Sandbox is a software that can be used for visual programming and is free to use. The programming is done by connecting several so called 'Dynamo nodes' with each other by means of wires. Nodes can perform different actions and can be set up in such a way that it creates a parametric model of an industrial hall. In Figure 4.2, several node groups are shown which are indicated with different colours. A brief walk-through starting from the left of the model: In the blue group, the boundary conditions of the model can be specified. The green group hosts all variables that can be altered in order to change the design. In the grey group a trial calculation is made to estimate the required surface area and inertia of all structural elements, this estimation is subsequently used by the nodes in the orange group to select a range of appropriate profiles. The nodes in the beryl green groups create the geometry along which the columns, trusses, beams, purlins, side rails and wind bracings should be placed. The light-purple group hosts all the load definitions, load cases and load combinations. The nodes in the cyan group calculate the ECI and the price of the structural design. The small purple group hosts the model-to-RFEM node which is used to export all structural information from Dynamo to RFEM. Finally, in the yellow group, all results from the structural verification in RFEM are gathered and filtered for relevance.

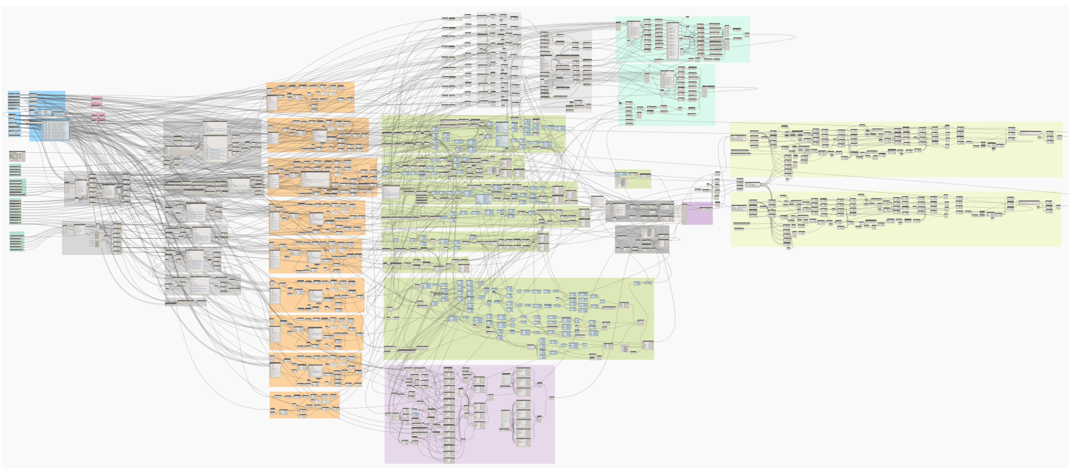


Figure 4.2: Dynamo Sandbox script

4.2.2. Geometric roof configuration

The main difference between industrial halls is given by the configuration of their roof construction. Common variants are: straight beam roof, inclined beam roof and truss roof. All three variants have their own advantages and disadvantages and are suitable to a greater or lesser extend based on the materials and cross sections that are used to create them. With regard to the required variables in each roof, length, width and purlin type are the variables that are applicable to all roof-based variants but each variant may have its own individual additional variables. In variants that use a straight beam roof, the only extra variables are the cross section and material that will be used for the main beams. In the case of inclined beam roofs, the inclination angle is considered as an additional variable. For truss roofs, the height of the truss as well as the cross sections that the truss comprises of are additional variables. In case wind bracings are applied to a design, it is constructed using an I-pattern. Given that it is often more economical to increase the length of the hall than to increase the span length of the portal frames to achieve surface area gain, this configuration provides the best solution.

It is a great challenge to build a parametric model on the scale of an entire industrial hall including all its components and consequently a lot of time and effort has to be spend on making it suitable for generative design. Therefore it is not efficient to construct three individual models to test the suitability of generative design for ECI optimization of industrial halls. Since a truss roof typology is suitable for most industrial hall configurations, it is also deemed to be the most relevant to perform research on. Thus the truss roof typology will be investigated and optimized exclusively.

4.2.3. Software connections preliminary design

In order for the parametric model to work properly and receive its input from the appropriate sources, some software connections have to be made. The software's that need to be connected include Microsoft Excel for the input of shadow costs and construction costs, RFEM for the numerical structural verification of the industrial hall and Autodesk Refinery as a tool to perform generative design optimization. Additionally, a connection with Autodesk Revit is made in order to export the preliminary parametric design into a software where the design can be finalized and subsequently be evaluated through the One Click LCA plugin.

Dynamo - Excel

Information regarding cross sections are inputted into the parametric model by means of Excel sheet input. Figure 4.3 shows how this is done.

Dynamo - RFEM

The parametric model can be exported to finite element analysis software through the DynamoStructural add-on package that is supplied by Arcadis Nederland BV. This package is able to transfer geometry as well as cross sections and materials from Dynamo to RFEM.

Dynamo - Refinery

Autodesk Refinery is able to use the parametric Dynamo model and change parameters that have been labeled as input nodes. It will subsequently run the Dynamo graph and return the results to provide the optimal solutions within the stated boundary conditions.

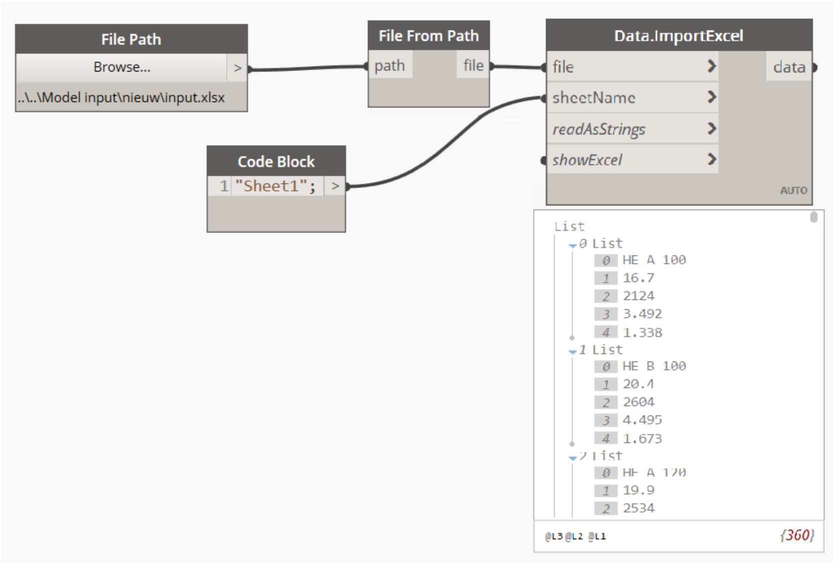


Figure 4.3: Excel input in Dynamo

4.2.4. Software connections definitive design

For the application of the parametric model and generative design, only the early design steps are relevant. After the early design phase, the optimized design with the lowest shadow cost can be exported to Autodesk Revit where it can be customized for a particular project and optimized even further for its specific application using the One Click LCA plugin.

Dynamo - Revit

Revit cannot 'read' the direct input from the dynamo model as it is made through the DynamoStructural tool from Arcadis. Though using similar steps the Revit input could be generated using appopriate input nodes.

Revit - One Click LCA

One Click LCA is a plugin for Revit which automatically assesses the shadow costs of the entire model and identifies which elements have the largest contribution. These elements can subsequently be optimized by changing the supplier.

4.3. Boundary conditions

The boundary conditions of the parametric model are outlined by the functional unit that is defined in section 2.4. The main goal of the boundary conditions is to provide adequate input for the parametric model. These are based on several assumptions that are elaborated upon per aspect. It is important to denote them for proper analysis and discussion of the results but also in case additional research will be done based on this MSc thesis.

Function

This criterion is important since a specific function can influence the requirements for its column spacing, height and insulation. However, it is inordinate to determine the exact requirements for each type of hall and although its function has a certain influence on the structural configuration of the industrial hall, taking them all into account will result in too many separate results which cannot be compared. Therefore it judicious to assume that all design alternatives will have the same generic function with no special individual requirements.

Internal column spacing
Minimum internal column spacing depends on the function of the hall and might be different in transverse or longitudinal direction. Since it is wise to generalise function, an average minimum column spacing should be determined. From the reference projects in section 2.2 an average column spacing can be calculated which amounts to roughly 18m when the projects with single span portal frames are not included. Therefore this value will be used during the design generation process.

Facade & Roof
As discussed in chapter 2, the choice for specific facade and roof panels associated with certain insulation values is highly dependant on the function that the industrial hall has to fulfill. As stated before, applying a generic function to all halls will provide the best data for analysis. Thus, the parametric model will use a mean value of ECI, price and dead load that is calculated as the average of 4 typical roof and facade elements. A disadvantage of this generalisation is that these elements will not have a specific bearing length and as a result, the minimum and maximum center to center distances of purlins and side rails are unknown. Fortunately, in section 2.3.1, frequently used spacing's for these elements have been identified. For purlins those distances amount to 1.5 m to 5 m and for side rails 1.0 m to 3 m is commonly used. Therefore, these values will be used as boundaries in the parametric model. One might argue that this provides a certain limitation to the degree of optimization that can be achieved by generative design since the algorithm will most likely always opt for the maximum distances as this requires the least amount of material. However, this is not strictly true since still different cross sections and different materials can be chosen for which the optimum span and spacing may differ depending their characteristics. Additionally, the difference in strength and stiffness as well as shadow costs of the structural elements differ greatly, therefore it can be said that enough room for optimization remains.

Lifespan
It was concluded in chapter 2 that the average life span of industrial halls is 50 years, thus for the purpose of preliminary design, the same life span will be used during the generation of design alternatives.

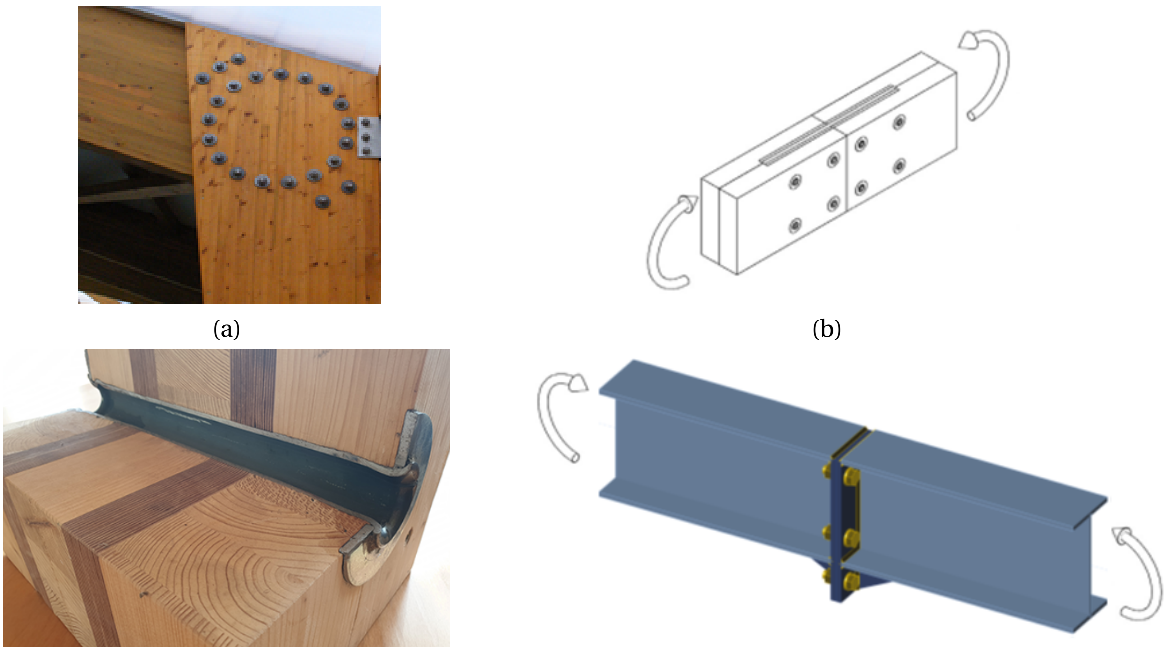
Size
It should be noted that the size of a hall has a significant influence on the configuration of structural elements. For halls with a limited width (ca. 20m) it is usually most efficient to use a single span roof construction with no intermediate columns. In halls with a longer width (ca. 40m), single span with a heavy roof construction or multi span with lighter elements is both realistic. Very wide halls (>100m) are often executed as a combination of several medium sized industrial halls since dilatation's have to be applied to mitigate stresses as a result of thermal expansion.

Loads
Although not all industrial halls are located in the same area with the same characteristic

wind and snow loads, to provide fair comparison the assumption is made that all halls are located in a rural part of wind area II in the Netherlands. This is a valid assumption since industrial halls are often not located in residential areas. Section 4.4.4 explains the loads that are used in this thesis more explicitly.

Production costs
In the search for the absolute lowest shadow cost design, production costs are not a factor. However, in reality, price is a major factor during the decision making process of a client. Therefore, a separate analysis needs to be performed that takes into account costs and that generates designs to minimize costs as well as shadow costs.

Connections
To enable fair comparison of materials during the optimization process, not all connection types are considered. Figure **??** shows the most relevant rigid connections for steel and timber elements.



(a) (b) (c) (d)

Figure 4.4: Examples of demountable connection types in steel and timber [97], [96], [98]

Figure 4.4 (a) shows a ring bolt connection between a laminated timber column and beam. The use of this connection type at this particular location results moment transfer without reducing the effectiveness of the cross sections. However, the element height that is necessary for this connection is normally very large which makes it unsuitable for most applications. Additionally, the amount of bolts that are required is considerable, resulting in uneconomical reusability scenario's. Figure **??** (b) and (c) illustrate a densified veneer wood joint with hollow steel fasteners which retains 100% of the cross section capacity. In order to make this connection, the steel fasteners are expanded inside the timber and the DVW is glued to the laminated timber elements. Therefore, it cannot be demounted without destroying a large part of the construction element. In Figure **??** (d), a bolted rigid steel connection is shown. This connection results in a 100% effective cross section and is easily demountable. It is currently only possible to construct demountable rigid connections that retain cross section efficiency in steel elements. The inclusion of demountable rigid connections would give steel an unfair advantage over timber. Therefore only demountable hinged connection types are assessed in the optimization process of this thesis.

4.4. Model input

The input of the parametric model is provided in this section in order to elaborate on the assumptions that are made as well as to provide the required information to ensure reproducibility of the research. Basic requirements of the hall have to be given in terms of surface area, minimum column spacing in both directions, minimum internal free height and whether an intermediate column is allowed. These requirements are normally decided by the client and are therefore generalised according to three sizes as described under section 4.3. Input regarding materials characteristics, cross sections, (shadow) costs and loads are provided in sections 4.4.1 through 4.4.4.

4.4.1. Material characteristics

Certain material properties need to be assumed in order to perform structural verification of elements. In chapter 3, the average ECI of materials and cross sections is determined irrespective of their material strength. Therefore, to provide a fair comparison, the material properties of the most common strength class of steel and glulam will be considered. This results in strength classes of S355, GL32h for steel and glulam respectively. The material characteristics that are associated with these strength classes are provided in Tables 4.1, 4.2 and which will be used in the parametric model accordingly.

Table 4.1: Glulam GL32h material properties [100]

Material Property	**Symbol**	**GL32h**	**Unit**
Bending strength	$f_{m,g,k}$	32	MPa
Tensile strength	$f_{t,0,g,k}$	25.5	MPa
	$f_{t,90,g,k}$	0.5	MPa
Compressive strength	$f_{c,0,g,k}$	29	MPa
	$f_{c,90,g,k}$	3.3	MPa
Shear strength	$f_{v,g,k}$	3.8	MPa
Rolling shear strength	$f_{c,g,k}$	1.2	MPa
Modulus of elasticity	$E_{0,g,mean}$	13700	MPa
	$E_{90,g,mean}$	460	MPa
Shear modulus	$G_{g,mean}$	850	MPa
Rolling shear modulus	$G_{t,g,mean}$	65	MPa
Density	$\rho_{g,mean}$	450	kg/m^3

Table 4.2: Steel S355 material properties [99]

Material Property	Symbol	S355	Unit
Yield strength	f_y	355	MPa
Ultimate strength	f_u	460	MPa
Modulus of elasticity	E	210000	MPa
Shear modulus	G	81000	MPa
Density	ρ	7850	kg/m^3

4.4.2. Cross sections

Cross section sizes of structural elements are determined by the supplier. Divergent and custom sizes are available but they defeat the purpose of reuse and thus prevent shadow cost optimization. Therefore, the only most commonly used steel and timber cross sections will be considered which are readily available products that can be provided by most manufacturers. Tables containing all profiles that are considered in design generation are provided in Appendix C.

Sections per category:

- Steel rolled sections: HEA, HEB, HEM and IPE
- Steel hollow sections: CHS, SHS and RHS
- Glulam sections: Rectuanglur sections, See Table C.3

4.4.3. (Shadow) Costs

All input with regard to shadow costs and building costs is provided in sections: 3.4.3, 3.4.4, 3.4.5, 3.6.1 and 3.6.2.

4.4.4. Loads

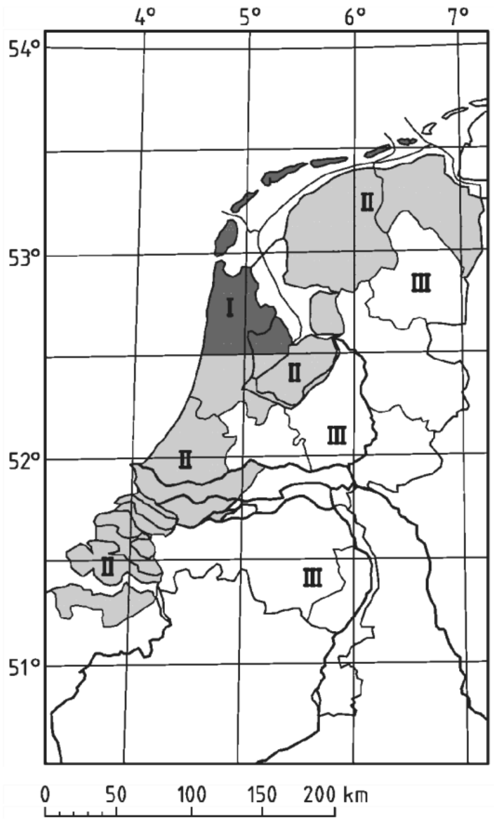
The loads that will be assessed in the parametric model are dead load, wind load and snow load. Loads as a consequence of temperature gradients, local impact or seismic activity are negated for preliminary design. The calculation will be performed using the safety factors for permanent and variable loads as prescribed by the Eurocode. Roof configuration has an influence on the force distribution of the the construction. Therefore, the effect of inclined roofs on the active components of the acting loads needs to be considered separately.

Dead load

The dead load of the main bearing construction is given by the self-weight of columns, beams, trusses, purlins, side rails and wind bracings. All self-weights can be calculated automatically by the parametric model based on the cross section that is used and the corresponding density of the chosen material. Since the roofing and facade panels are generalized, an average weight should be used to account for their dead loads. These loads are respectively 0.38 kN/m^2 and 0.50 kN/m^2 and are calculated based upon the same products that were used to determine their average ECI. As stipulated in section 2.3.4, an additional dead load as a consequence of optional requirements needs to be considered. Green roofs are rather heavy because its water-saturated weight needs to be taken into account. The spans of industrial halls are usually quite large which decreases the applicability of green roofs. Photo-voltaic panels on the other hand, weigh much less and in addition they have the capability to reduce the energy usage of the hall considerably. The associated average self-weight of PV panels including ballast is 0.25 kN/m^2 and will be accounted for in all designs.

Wind load

As discussed in section 4.3, for the purpose of preliminary design it is assumed that all industrial halls are located in a rural area of wind zone II in the Netherlands according to NEN-EN 1991-1-4+A1+C2. The Dutch wind zones are indicated on the map in Figure 4.5 and the wind pressures associated with wind zone II are shown next to it. These are the values that will be used during design generation. In between the indicated heights, linear interpolation can be used to determine the wind pressures.



Height m	Zone II Rural kN/m^2
1	0.60
2	0.60
3	0.60
4	0.60
5	0.66
6	0.71
7	0.75
8	0.79
9	0.82
10	0.85
15	0.98
20	1.07
25	1.14
30	1.20
35	1.25
40	1.30
45	1.34

Figure 4.5: Wind areas in the Netherlands with associated wind pressures for Area II Rural [101]

Snow load

Based on NEN-EN 1991-1-3+C1+A1, the amount of snow load that should be taken into account depends on a multitude of factors like the thermal properties and roughness of the roof. However, for preliminary design these are not always known. Therefore, only the shape of the roof will be accounted for. Taking into account the geometric roof variants, only 2 different kinds of roofs have to be considered: flat roofs and inclined roofs. Furthermore, it will be assumed that all industrial halls are located in the Netherlands at sea level. According to the Dutch National annex, the Netherlands is part of the central west snow area. This means that the characteristic snow load on the ground can be calculated as:

$$S_k = 0.164 * Z - 0.082 + \frac{A}{966} \tag{4.1}$$

In which Z is the number of the snow zone (No.2) and A is the altitude above sea level (0m). Therefore, using equation 4.1, $S_k = 0.246\ \mathrm{kN/m^2}$. These values are determined from Figures B.19 and B.20 that can be found in Appendix B. Ultimately, the snow load on a roof should be calculated according to equation 4.2.

$$S = \mu_1 * C_e * C_t * S_k \tag{4.2}$$

In which μ_1 is the snow load shape coefficient and depends on the shape of the roof. For roof inclination angles between 0 and 30 degrees its recommended value is 0.8. C_e is the exposure coefficient which is 0.8 for rural areas. C_t is the warmth coefficient which is assumed to be 1.0 since no specific roofing will be chosen during design generation. Assuming that the angle of inclined roofs stay below 30 degrees, the roof snow load of both types of roofs is given by $S = 0.157\ \mathrm{kN/m^2}$.

Load combinations

It is assumed that large wind loads will cause removal of any snow that is present on the roof structure. Thus, maximum wind and snow load do not occur at the same time. Consequently, there are only two load combinations that need to be assessed. Permanent loads combined with wind loads and permanent loads combined with snow loads. Concurrency factors do not need to be considered since both load combinations consist of only one variable load since maximum snow load does not occur at the same time of heavy wind due to snow blow-off. The load combinations that are used in the load definition of the parametric model for ULS are shown in Table 4.3. For SLS, the same load combinations are used. However, both factors are set to zero for this limit state in accordance with the Eurocode.

Table 4.3: ULS load combinations and factors

Load combinations ULS	**Factor 1**	**Factor 2**
Permanent + Uplift	0.9	1.5
Permanent + Snow	1.2	1.5
Permanent + Wind-x	1.2	1.5
Permanent + Wind-y	1.2	1.5
Permanent	1.35	-

Furthermore, all surfaces on which a load is active are assumed to be loaded equally. This is a valid assumption since wind and snow act as homogeneously distributed loads, thus alternative load cases on roof and facade such as shown in Figure 4.6 do not have to be considered. This assumption is beneficial since these load configurations often lead to locally increased bending moments.

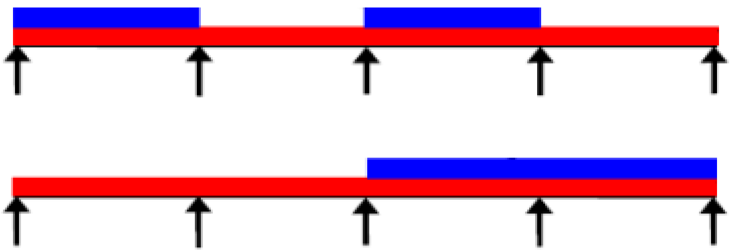


Figure 4.6: Alternative load cases

4.4.5. Model efficiency

To reduce the amount of options and therefore lower the computing time during generative design, not all materials and cross sections will be considered in the three geometric variants of the roof construction. A decomposition as to what structural components are useful to assess is provided based on engineering knowledge combined with the findings from chapter 2.

Different materials and cross sections have deviating configurations in which their properties are most effectively used. This results in the possibility to eliminate certain cross sections and materials from the variants. Ordinary softwood relatively weak and not available in large sizes which makes it unsuitable for large spans and therefore it should be excluded as an option for all main spans. It is rather difficult to use concrete beams in an inclined roof structure due to the connection detailing. Furthermore, prefab-concrete is not a common material for trusses and it would be difficult to transport a large prefab-concrete truss to the construction site. Thus, prefab-concrete should not be considered as inclined roof beams or trusses. Steel box sections are considered unsuitable as roof beams since it is nearly impossible to attach purlins or roofing to them using another connection method than welding. After the exclusion of certain materials and profiles for certain roof configurations, the following options remain: Straight beam roof variants can feature prefab-concrete, glued laminated timber and rolled steel beams. Inclined beam variants can consist of glued laminated timber or rolled steel sections and the constituents of the truss alternatives can consist of steel box profiles, steel rolled profiles or glulam.

The limitations for beams and trusses in each roof geometry lead to a reduction in possibilities and subsequently in a significantly reduced computing time. However, still an incredibly large amount of combinations remain for other structural elements. Therefore it is wise to perform a similar analysis for the cross section and material options for the columns, purlins and side rails. These structural elements experience different types of loading and thus different kinds of profiles will be suitable for each application.

Inner columns mainly experience axial loads originating from the roof structure, but in outer columns bending moments occur as well as a result of wind loads on the facade. Therefore columns require a cross section that has a good buckling resistance and is able to withstand bending moments from both main directions. Steel rolled IPE profiles are especially effective in bending due to their slim webs in combination with thick flanges but the webs tend to buckle easily under compression loads as a consequence, which makes them unsuitable as columns. Although hollow sections are effective in both criteria, connecting them to other elements is notoriously hard and time consuming. Taking into account the design recommendations from section 3.5 they are disregarded as suitable sections for all applications except for trusses and internal columns. Under normal conditions, purlins are only loaded with bending moments in the vertical direction. Circular hollow sections and square hollow sections have the same second moment of inertia in horizontal and vertical directions. As a result of their shape, they will never be as effective in vertical bending as rolled sections or rectangular hollow sections and should therefore be negated as purlin options. Purlins also require some lateral torsional buckling resistance but stability is usually provided by the roof elements. Side rails should be able to resist vertical bending moments as a result of the weight of the facade as well as horizontal bending moments due to wind loads. The governing direction depends on the design wind load and the weight of the facade. Circular hollow sections are not suitable for this application since facade elements cannot easily be fastened to them due to their shape. With regard to bracing types, only steel bracings are considered since the rest of the materials are not particularly suitable for this function. The cross sections that remain per function are shown in Table 4.4. For the sake of simplicity, for wind bracings only steel unequal leg angles are considered.

Table 4.4: Profile options within design alternatives

Columns	**Internal Columns**	**Edge Beams**	**Trusses**	**Purlins**	**Side rails**
HEA	HEA	HEA	HEA	HEA	HEA
HEB	HEB	HEB	HEB	HEB	HEB
HEM	HEM	HEM	HEM	HEM	HEM
-	-	-	-	IPE	-
-	-	-	CHS	-	-
-	SHS	-	SHS	-	SHS
-	-	RHS	-	RHS	RHS
Glulam	Glulam	Glulam	Glulam	Glulam	Glulam

Although some column, purlin and side rail options are eliminated, still not all remaining cross sections should be assessed. It makes no sense to evaluate the effect of a side rail that is constructed from an equally heavy profile as the main beams when its span is considerably smaller. Thus, it is important that the parametric model can determine the suitable cross sections per function. To this end, a best guess method is implemented to determine a logical initial cross section for each material considering its length and estimated loading. The generative design algorithm will then proceed to make iterations around this initial guess. This best guess will be calculated based on the estimated required inertia due to deformations as well as the estimated inertia required for stability of the cross section. Since only single span elements are considered in the assessment, calculation is quite straightforward and can be done by modification of the basic formulas for deformation and stability requirements.

Deformation requirements state that the maximum deflection of a beam may not be larger than the length divided by 250. Equation 4.3 states the deflection of a simply supported beam with a distributed load.

$$I_{bending} = \frac{5}{384} * \frac{q * L^4}{E * I} \tag{4.3}$$

This formula can be rewritten in order to obtain the required inertia that corresponds to the deflection limit. This adapted formula is shown in equation 4.4. For members in double bending, two separate calculations are performed in order to find the required inertia for both the major and the minor axis of the cross section.

$$\frac{1250}{384} * q * L^3 / E \tag{4.4}$$

Additionally, for compression members such as columns and the top chords of trusses, the required inertia to prevent buckling needs to be calculated. This is done by rewriting the formula for the Euler buckling load as shown in equation 4.5

$$I_{buckling} = P_{axial} * L_{buckling}^2 / (\pi^2 * E) \tag{4.5}$$

For build up members like trusses, the strength check might be governing. Therefore for truss elements an additional calculation is performed. Firstly, the bending moment in the middle of the truss at the height of the neutral axis is calculated by means of equation 4.6.

$$M = 1/8 * q * L^2 \tag{4.6}$$

Equation 4.7 shows the Euler-Bernoulli equation for bending in which z represents the distance from the neutral axis of the truss towards its edges which corresponds with half the truss height. For preliminary calculations on trusses, Steiner's rule can be used to rewrite this equation as shown in equation 4.8.

$$\sigma = \frac{M * z}{I} \tag{4.7}$$

$$\sigma = \frac{M * \frac{1}{2} h_{truss}}{2 * A_{profile} * \frac{h_{truss}}{2}^2} \longrightarrow \sigma = \frac{M}{A_{profile} * h_{truss}} \tag{4.8}$$

Subsequently, substituting the steel design strength for the maximum occuring stress, the required surface area of the cross section can be calculated according to equation 4.9.

$$A_{profile} = \frac{M}{h_{truss} * f_{yd}} \tag{4.9}$$

As a consequence of these combined measures, the realistic choices of the generative design algorithm will reduce drastically and therefore the optimization efficiency will increase greatly.

5

Generative design

This chapter describes the concept of generative design. Section 5.1 describes different algorithms that can be used in this process. The generative design process in Autodesk Refinery is discussed in section 5.2 and in section 5.3 the results of an optimization on an arbitrary hall are discussed. Section 5.4 consists of two comparative case studies of optimized structural design versus existing industrial halls.

5.1. Optimization algorithms

Generative design can be described as an iterative design process that involves an algorithm which generates a number of outputs that meet certain boundary conditions [102]. These iterations can be performed in such a way that they converge towards a predefined goal such as the optimization of shadow costs, construction price or both at the same time. These predefined goals are called objective functions. When only a single objective has to be evaluated, the optimization process is rather straightforward. For example, a structurally sound design with the lowest shadow costs can be considered as the best design. However, when shadow costs as well as price needs to be minimized simultaneously, a multi objective optimization is required. In this case, optimization is more complex because it becomes a matter of searching for the most advantageous trade-off between the two objectives whilst remaining within the boundary conditions.

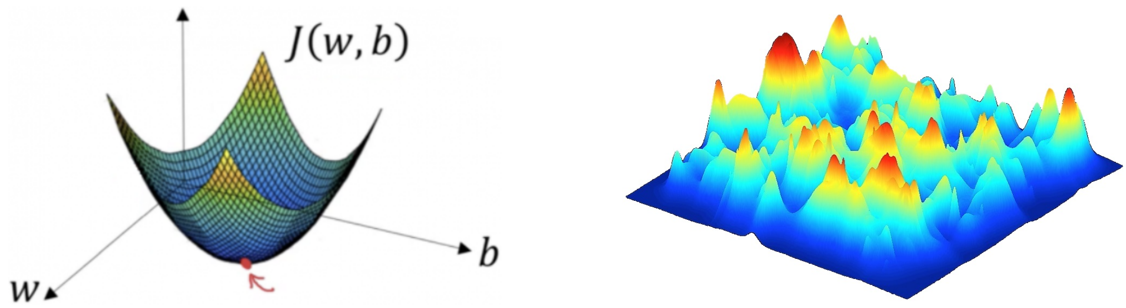
Although all optimization algorithms are different, they have three things in common. They all consist of a generator, an evaluator and a solver. A generator creates new solutions based on the input variables. In case of a parametric model of an industrial halls these variables are height, width, length, column distance, and type of construction elements. Different input for those variables will lead to alternative designs. The designs from the generators are fed to an evaluator which assesses the quality of the design [102]. In this thesis the quality of a design is measured as the shadow costs and/or price. The evaluator enables the comparison of design alternatives. Solvers can automatically run scripts containing a generator and evaluator many times and search for the best solution. Different kinds of optimization algorithms have been developed and each has their own advantages and disadvantages which make them suitable to a greater or lesser extend for a particular purpose. In this thesis a distinction is made between single objective optimization (SOO) i.e. shadow cost minimization and multi objective optimization (MOO) i.e. combined shadow cost and construction price minimization. In both cases, the input parameters are the same and the boundary conditions should be respected. Nevertheless, they benefit from different types of optimization algorithms, especially since not all algorithms are equally suitable for either type of optimization.

5.1.1. Single objective optimization

For the purpose of minimizing single objective functions, a link can be made with gradient descent. This is a mathematical optimization algorithm that iteratively searches for the parameters that lead to a local minimum of an objective function. Equation 5.1 describes the mathematical function that is used during gradient descent, in which 'b' indicates the next position of the iteration, 'a' indicates the current position, the minus represents the minimization of the function, the γ is a waiting factor and ∇ 'f(a)' is the direction of steepest descent.

$$b = a - \gamma * \nabla f(a) \tag{5.1}$$

In Figure 5.1a, a certain function J(w,b) is shown on the vertical axis and it has a local minimum for a certain combination of its variables 'w' and 'b'. In order to find the optimum values of 'w' and 'b', a starting point is required. Gradient descent will proceed to make iterations from the starting point in the steepest downside direction until it reaches the lowest point of objective function J(w,b).



(a) (b)

Figure 5.1: (a) Gradient descent with two variables [103], (b) Solution landscape [Adapted from 104]

However, more often than not, the solution landscape consists of multiple valleys of varying size (See Figure 5.1b) and the algorithm might get stuck trying to get the the bottom of the initial valley that it has identified and will therefore ignore potentially lower valleys of the so called fitness landscape. Thus, the starting point potentially has an influence on the solutions that are considered. To ensure that the actual optimum solution will be found, gradient descent needs to be combined with a randomizer which randomly chooses different input parameters and starts optimizing from the new starting point. By combining these methods, the local optimum solutions can be eliminated and the true best solution can be found.

The three most popular types of gradient descent are named batch gradient descent (BGD), stochastic gradient descent (SGD) and mini-batch gradient descent (MBGD). The main difference between them is given by the amount of data they use and their subsequent difference in speed. Batch gradient descent considers the whole data set for each iteration, which is useful for finding the global minimum with great accuracy. However, for large data sets, the amount of computation time becomes an issue. In SGD, a single set of variables is chosen from the data set and its gradient is used to take a single step. Although SGD converges relatively fast for large data sets, it will not reach an absolute minimum as the outcomes keep fluctuating. Mini batch gradient descent is a combination of BGD and SGD. In MBGD, a few samples are selected randomly from the whole data to perform an iteration. By using a predefined sample size containing randomized variables, the path that is taken by the algorithm is noisier than in batch gradient descent but the outcomes are usually comparable and the total computation time is much smaller. The large amount of variables that are used in the design optimization process in this thesis result in a large amount of possible solutions. Therefore, in order to reach good convergence on a global optimum within a reasonable amount of time, MBGD is considered the most appropriate optimization technique.

5.1.2. Multi objective optimization

MOO problems can be solved using multiple methods that simultaneously account for the performance of all objectives that are considered. In practise, often the Pareto method and scalarization are used which both work in a different manner. The former is used if the objective functions have to be considered separately and a trade-off has to be made. The latter combines the objectives in a performance indicator that forms a scalar function. Since it is beneficial to be able to see the effect of design choices on the shadow costs and construction price separately, the Pareto method is considered the best option. During optimization, the Pareto method separates the objective functions and differentiates between dominated and non-dominated solutions. A non-dominated solution has an optimal value for all considered criteria and is reached when one objective function cannot be increased without reducing another. A dominated solution is also called a non-Pareto optimal solution and is characterised by the possibility to improve one or more objectives without reducing another [105].

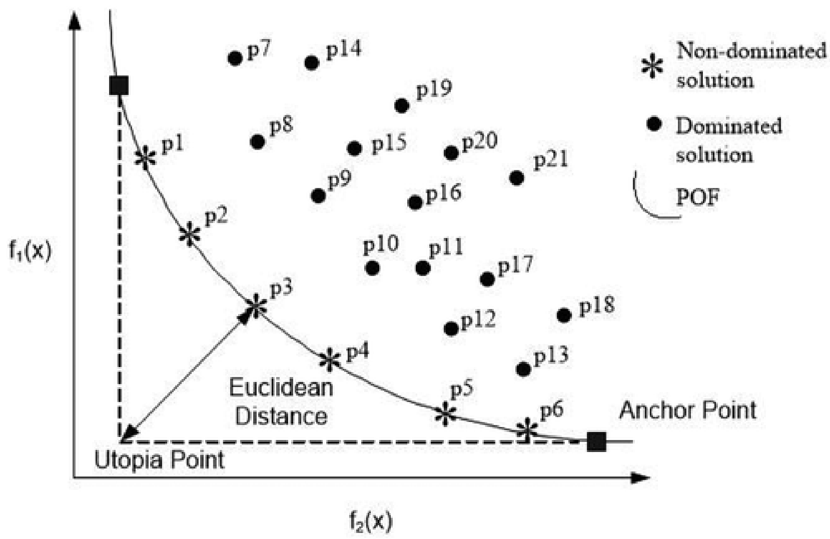


Figure 5.2: Pareto optimal front for two objective functions [105]

In order to choose the best solution regarding shadow costs and construction price, a Pareto optimal front (POF) can be used. Figure 5.2 illustrates a POF of two objective functions. Anchor points are obtained by optimizing for a single objective function only and thus indicate the boundaries in the solution landscape. The utopia point is defined as the intersection of the optimum value of both objective functions and can most likely not be reached in practise for non-trivial solutions since objective functions are often conflicting. This means that there exist a certain number of Pareto optimal solutions. The most favourable Pareto optimal solution is different for each project but in this thesis the outcome with the shortest Euclidean distance to the utopia point is considered the absolute optimal solution.

5.1.3. Constrained optimization

In addition to optimization of particular objective functions, all solutions should adhere to the given boundary conditions (constraints). Unconstrained optimization may provide better solutions in terms of shadow cost or construction price but they may consist of absurd designs that cannot be considered viable options and should therefore not be excluded. The constraints are provided in the form of:

- Fixed length and width
- Minimum internal height
- Internal column distances
- Unity checks

Unity checks need to be smaller than 1 for any design, whilst the other constraints differ depending on the prospected function of the hall as defined in section 4.3. Furthermore, all options for mathematically trivial solutions need to be eliminated since they do not actually provide viable solutions. In case of industrial hall design, a trivial solution could be to design nothing by using no materials. In this example, shadow costs and construction price are both fully optimized (zero) but it does not actually result in a usable design.

5.2. Generative design in Refinery

Autodesk refinery provides several different kinds of solvers that can be used to generate and evaluate design alternatives. The solver that is most appropriate for a particular function depends on the type of optimization (SOO or MOO) and is chosen based on whose functionality most closely matches the algorithms discussed in section 5.1. These solvers all work in a different manner and an overview of available solvers is provided below.

- Randomize
- Optimize
- Cross-product
- Like this

Randomize generates a specified amount of alternatives by randomly choosing values for all input parameters [102]. It is often used in applications where it is not yet clear what parameters need to be optimized. It provides an optioneering process in which a designer is able to explore a broad range of possibilities within predefined constraints.

Optimize develops the design based on the output from the evaluators. Each new iteration will use the input configuration that was previously used. For this, Autodesk Refinery uses the non-dominated sorting genetic algorithm II (NSGA-II) [102]. The three major benefits of NSGA-II are its reduced computational complexity, its elitism and the fact that there is no need to specify a sharing parameter (see scalarization in section 5.1.2). It features a selection operator that creates a mating pool that combines parent and offspring populations (designs) and chooses a certain amount of optimal solutions with respect to fitness and parameter spread. After each generation, a portion of the existing solutions is selected to conceive a new generation which typically share many of the characteristics of its parents. Individual solutions are chosen by means of a fitness based process in which fitter solutions are more likely to be selected. Generally, the fitness increases with each iteration since only the best solutions from the previous generation are selected for the next generation [106]. According to simulation results on complex test problems, NSGA-II is able to identify a larger spread of solutions and has a better convergence towards the Pareto utopia point compared to other multi objective optimization algorithms [107].

Cross-product explores the design space by combining every parameter with all other parameters. In this process, evenly spaced values are used to generate a specified amount of results [102]. Whereas this results in a very large amount of design configurations, it doesn't necessarily provide any kind of optimization. However, it can be useful for determining what parameters exclude certain other parameters from being viable options. For engineering purposes for example, it can be used to identify what range of span lengths are applicable to a beam that is made from a certain material since unsuitable results will not show up in the analysis. However, for large data inputs it does require an enormous amount of computing time to assess all the available options.

Like this creates slight variations to a previous design. Once a suitable outcome has been generated by optimization, it can be used to explore variations of that design [102]. These variations will not manifest themselves as the absolute optimum with regard to the initial optimization criteria but they could possibly bring about a number of advantages concerning any secondary design criteria which are not considered equally important in the optimization process. Therefore, non-structurally speaking, they might result in preferable designs. However, secondary design criteria are incredibly dependent on the specific function of a building and should therefore not be included.

It can be concluded that for constrained optimization, the best results will be generated if *Optimize* is used. This method requires input of a 'parent' population size and the amount of 'offspring' generations. Increasing the population size will increase the chance that the location of the global optimum is found while increasing the amount of generations will increase the convergence towards an optimum. However, increasing the population size also causes the amount of generations to reach sufficient convergence to increase. In literature [108], it is proven that the optimal population for a given problem is the point of inflection where the benefit of fast convergence is negated by an increase in inaccuracy. Since several analyses need to be performed it is important to keep computation time at a reasonable level. Therefore a consideration needs to be made between population size and amount of generations. Since the amount of variables is quite high, it is advised to use a rather large population size compared to the amount of generations. During testing of the model it was found that as a rule of thumb, a population size of 36 combined with 3 generations to get relatively good convergence at a global optimum in a reasonable amount of time. The exact computing time varies strongly depending on the size of the model and thus the amount of structural elements that have to be modelled. For small models with fewer than 500 elements this computing time amounts to roughly 3 hours. For bigger models with more than 1500 elements, the computing time increases to 4.5 hours using the same population size and amount of generations. These computing times are based on the usage of a laptop with the following specifications for processor, graphics card and amount of RAM respectively: Intel Core i9-10885H, Nvidia Quadro RTX 3000, 64GB.

5.3. Arbitrary hall

The main goal of the optimization in this MSc thesis is to identify the most suitable construction materials and profiles for every set of boundary conditions within the field of industrial hall constructions. For the purpose of testing the parametric model and generative design, this thesis will consider a realistic but arbitrary hall of 108 meters long, 45 meters wide which has an internal free height of 10 meters. Internal column positions are normally stated in the boundary conditions, therefore the reasonable assumption is made that the the width of the hall will be divided into two spans of 22.5 meters and that the centre to centre distance of the portal frames that cover these spans will amount to 12 meters. A birds-eye view of the geometry of the previously described hall is shown in Figure 5.3, where the trusses that cover the main spans are highlighted in blue.

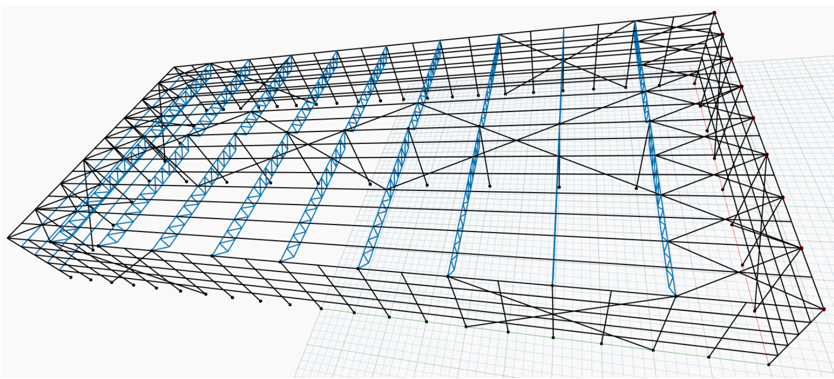


Figure 5.3: Realistic arbitrary hall in Dynamo

Next to the static geometrical boundary conditions, the hall has several variables that can be freely chosen by the generative design algorithm. These are: centre to centre distances of purlins, side rails and outer columns; materials of all element categories; and cross section sizes of all element categories. The magnitude of the loads that will be accounted for in all arbitrary hall optimizations are 0.38 kN/m^2 for roofing, 0.5 kN/m^2 for facade elements, 0.25 kN/m^2 for solar panels, 0.56 kN/m^2 for snow load and loads of wind zones D and E amount to 0.593 kN/m^2 and -0.371 kN/m^2 respectively. Self-weight is determined by RFEM based on the selected cross sections and included in the calculations.

Several tests will be performed using this standardised model to find the optimal design solutions. Since this thesis aims to find the optimal design solution regardless of contemporary design philosophies, a combination of steel and timber elements will be assessed. A single objective optimization will be performed to find the design corresponding with the lowest ECI value. Additionally, a multi criteria optimization with regard to ECI and price will be performed in order for the costs to remain within a reasonable and thus realistic price range. Since it is common for industrial halls to be designed out of a single material, additional analyses will be performed on halls that are made of either steel or timber exclusively. This will shed some light on how the optimal solutions within a single material relate to the combined optimum which might help in determining the efficiency of either material with regard to ECI as well as a combination of both ECI and structural element costs.

5.3.1. Randomized designs

In order to determine whether the parametric model combined with generative design is able to generate sufficient structural designs without crashing, a test run was performed for all three cases that are previously described in section 5.3 which consisted of 40 random sample designs. The results from this test run differ depending on the materials that were allowed in the design generation process and are therefore split into three separate categories. In Figures 5.4, 5.5 and 5.6, filled circles indicate a design with a maximum unity check smaller than 1 while open circles indicate a design which does not satisfy all structural verification checks.

Steel

The randomly generated designs in this category consist of structural elements that could either be made from rolled steel or cold formed steel. There is little difference between these steel types with regard to ECI value. However, the difference in price is rather significant. Figure 5.4 shows the ECI vs price distribution of 40 steel hall designs.

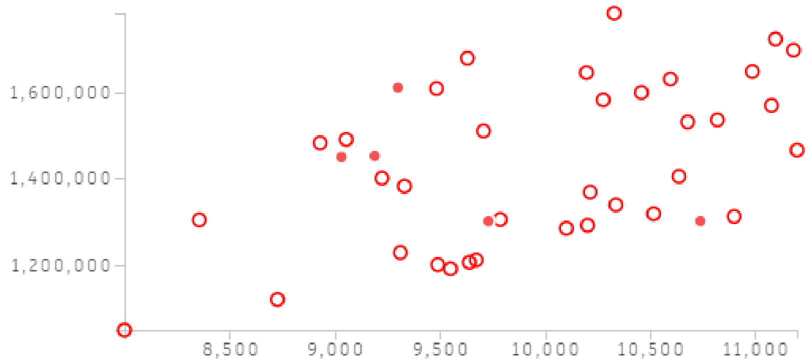


Figure 5.4: ECI and price of 40 random steel hall designs

Timber

In this category, the randomly generated designs could solely consist of glued laminated timber elements. It is clear from Figure 5.5 that the ECI and price of the 40 random designs are linearly correlated as a consequence of their shared single dependency: volume.

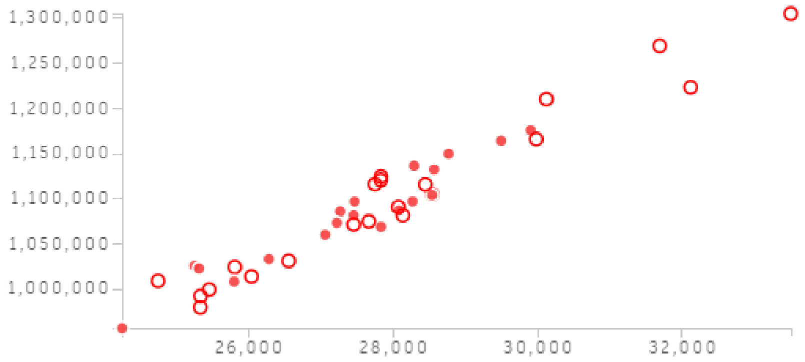


Figure 5.5: ECI and price of 40 random timber hall designs

Mixed materials

The randomly generated designs in this category consist of structural elements that could be made from either type of steel or glued laminated timber. Figure 5.6 depicts the results from the random generation of mixed timber and steel structural elements. It shows a completely different distribution of ECI and price values compared to the previous graphs in which only one material was used.

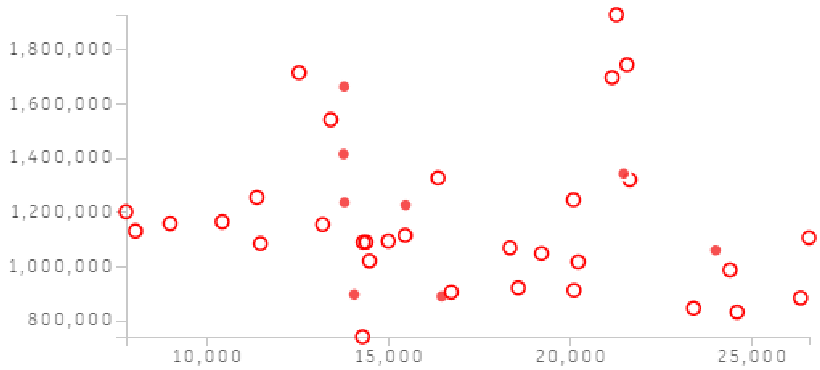


Figure 5.6: ECI and price of 40 random mixed material hall designs

A number of conclusions can be drawn from the graphs in Figures 5.4, 5.5 and 5.6. The smaller amount of valid unity check designs in the steel design category seem to be due to a greater sensitivity to decreases in cross section size since they are usually a lot more slender than glulam cross sections. Due to the fact that the inertia of the cross section range from which the parametric model can choose decreases linearly while the slenderness may increase quadratically as a result. Therefore, for steel elements, the algorithm is more prone to select a cross section which is too slender for the occurring load. The difference in scatter between the timber and steel category is explained by the fact that the steel category consists of two steel cross section types which differ in price but not in ECI.

Furthermore, from the randomized results it can be concluded that if a single material is used, a multi criteria optimization in terms of ECI and price is in essence not contradictory since both objectives scale linearly with the material volume. However, when multiple materials are used, a decrease in ECI does not necessarily lead to a decrease in price. This consideration is clearly demonstrated by the absence of data points in the lower left corner of Figure 5.6. This indicates that using mixed materials is probably the most beneficial method for a multi criteria optimization.

5.3.2. ECI optimization

An ECI optimization of the arbitrary industrial hall was performed for the same three material categories as explained in section 5.3. The optimizations consisted of a population size of 36 with 3 generations. From each of these categories one design was selected as most optimal and their results are portrayed in Figures 5.7, 5.8 and 5.9 in terms of ECI, reusability corrected shadow cost and price respectively. It should be noted that the optimization that dealt with a combination of timber and steel elements inherently consisted of notably more design possibilities than the single material optimizations. Therefore it is plausible that the mixed material optimization could have resulted in a more optimal design if a larger population size had been used. This also provides a possible explanation regarding the large deviation in purlin price results. Nevertheless, in most element groups the results seem to be quite clear as to which materials perform best.

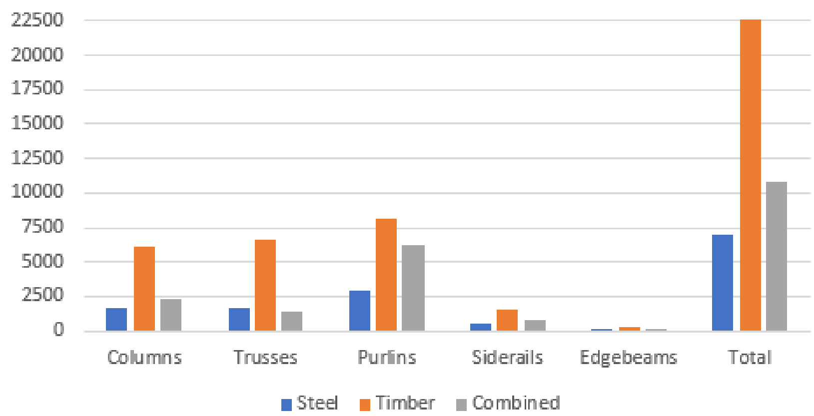


Figure 5.7: ECI of main element groups

Contrary to popular belief, steel seems to perform best with regard to ECI and timber designs seem to be cheaper. Therefore it can be concluded that a multi objective optimization which that includes a mixture of both materials will result in a cost effective environmentally friendly design provided that the population size and amount of generations are large enough to reach a global optimum.

An in depth analysis of the generatively optimized halls was performed to determine whether certain conclusions could be drawn with regard to the optimal centre to centre distances the structural elements. Since the internal column grid was assumed to be static, the only centre to centre distances that were variable were those of the outer columns, purlins and side rails. It is interesting to note that in all optimized designs these distances were roughly equal. The only outlier being the purlin centre to centre distances of the under-optimized

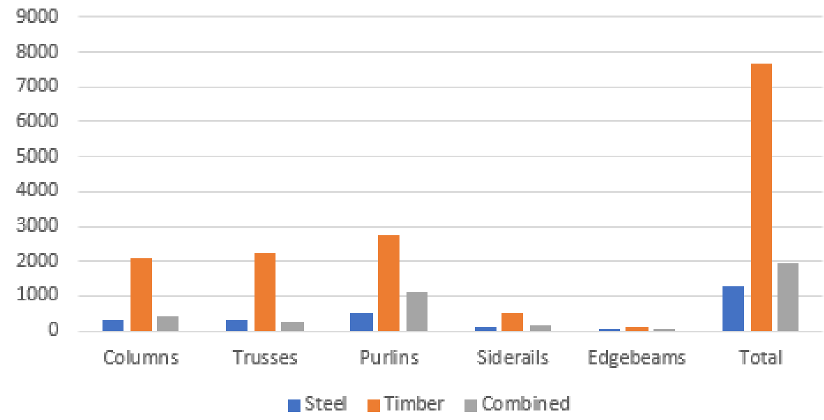


Figure 5.8: Reusability corrected shadow costs of main element groups

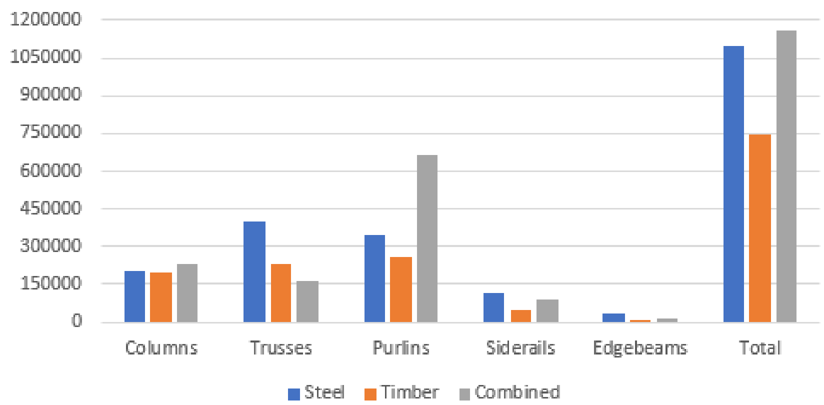


Figure 5.9: Price of main element groups

mixed material variant which in turn might explain its inconsistently high purlin price. Therefore, the results of the optimizations indicate that for halls with similar boundary and load conditions there might exist an optimum configuration regarding element lengths and spans which is independent of material characteristics.

From a cross section analysis of the optimized results it can be concluded that for elements which predominantly require stiffness in their major axis, rolled sections are preferable to cold formed sections, with regard to both price and ECI. For cross sections which require stiffness in both their major as well as minor axis, cold formed sections are preferable in terms of ECI but not in terms of price.

5.3.3. Multi objective optimization

In section 5.3.2 it was concluded that a mixed material optimization is most beneficial to reach an optimum for both the price and ECI of industrial hall designs. This method is therefore used to determine the combined price and ECI optimum of the arbitrary hall. Figure 5.10 depicts the main bearing construction of the arbitrary hall that was optimized according to the previously mentioned method. Since the choice between steel or timber elements is a consideration between respectively lower ECI or lower price, it makes sense that the hall exists out of a combination of steel and timber elements. It is logical that the trusses in this design are made out of steel since timber trusses require a larger height to span the same distance, which would result in an increase the required height of all columns.

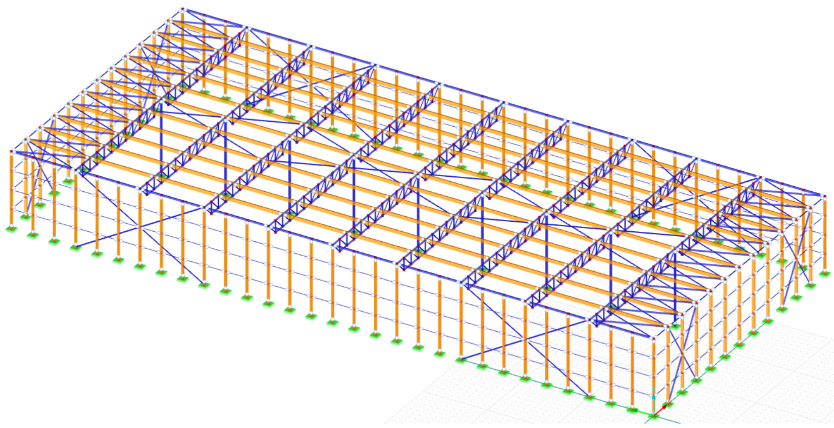


Figure 5.10: RFEM model of multi objective optimized hall

It is interesting to note that all steel elements are made from cold formed steel which is more expensive than rolled steel but has a similar ECI per cubic meter. This higher price is apparently negated by the more efficient cross sectional shape of the profiles regarding their minor axis. From the different loading scenarios it becomes clear that all steel elements in this design require stiffness in their major as well as in their minor direction. I.e. edge purlins, side rails and edge beams are all loaded in double bending by facade weight and wind load. Trusses and internal columns require stiffness in both their major and minor axes as well since they are prone to buckling under compressive loads. It is therefore beneficial that their axes have roughly the same stiffness. The most interesting conclusion from this multi objective optimization is probably that it is most beneficial to use cold formed steel in members that are loaded in double bending and to use timber for members that bend in a single direction such as columns and purlins.

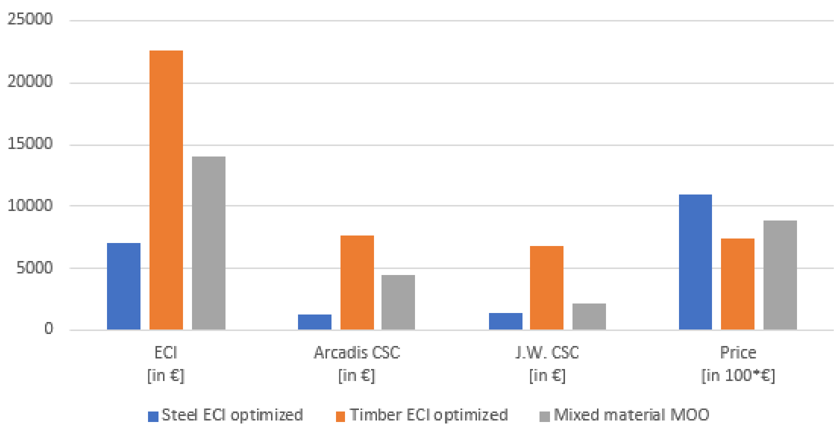


Figure 5.11: Comparison of total ECI, CSC and price

When comparing the total ECI, CSC and price of the mixed material MOO with the single objective ECI optimization from section 5.3.2 it is noticeable that the mixed material MMO produces scores for all categories that are roughly the average of the ECI optimized steel and timber designs, which is clearly visible in Figure 5.11. It can therefore be concluded that the mixed material method will produce the best results in terms of multi objective optimization with regard to price and ECI for the case studies. As for the absolute ECI optimum of a hall, only steel elements need to be assessed since they score produce inherently better ECI values than timber elements.

5.4. Comparative case studies

In order to establish how much an existing design could have been improved by using the optimization method that is presented in this MSc thesis, two reference projects are evaluated and compared to an generatively optimized variant with the same boundary conditions. As identified in section 5.3, to get the most promising results in single objective ECI optimization, only steel elements should be considered and for multi objective optimization, mixed materials should be used. The case studies are performed in two phases. First the average ECI and price of the original industrial hall are calculated using the same quantitative method as used in the parametric model. Subsequently, the functional requirements and boundary conditions of the original hall are used as input for the generative design process. The design output is then compared to the original hall in terms of ECI and construction price, after which possible improvements can be discussed. This method exists of two main phases as explained below.

Phase 1

- Determine the boundary conditions of the hall
- Determine which and how many main construction elements are used
- Determine which kind of connections are used
- Determine average ECI and price for every individual element
- Calculate ECI and price associated with all elements combined

Phase 2

- Using the requirements and boundary conditions of the original hall as input for generative design
- Perform single and multi objective generative design optimizations
- Determine possible improvements in the design

5.4.1. Coca-Cola hall 27

Phase 1

Coca Cola hall 27 has a length of 220 m and a width of 45 m which is spanned without the use of intermediate columns. From its design report all necessary load assumptions can be determined. It is located in a rural part of Dutch wind area III which leads to a Zone D and E wind load of 0.593 kN/m2 and -0.371 kN/m2 respectively. The weight of the roofing amounts to 0,35 kN/m2 and the snow load which was used in the calculations is 0,56 kN/m2. Its total ECI is estimated at € 10773.7 while its corrected shadow costs amount to € 4642.9. The total construction element price is estimated at € 1628387.2. An overview of all construction elements with regard to ECI and price calculations can be found in Table 5.1. A more detailed version can be found in Table C.4 in Appendix C.

Table 5.1: Breakdown of structural element contributions in the original Coca Cola 27 hall

		Columns	Trusses	Purlins	Side rails	**Total**
ECI	[€]	4747.3	2904.6	3025.0	1047.0	**11724.0**
Arcadis CSC	[€]	854.5	522.8	544.5	188.5	**2110.3**
J.W. CSC	[€]	949.5	580.9	605.0	209.4	**2344.8**
Price	[€]	533153.0	562923.2	372889.8	162359.6	**1631325.6**

Phase 2

Directed by the results from section 5.3, an ECI optimization was performed using solely steel elements. This resulted in a design which is shown in Figure 5.12. Additionally a multi objective optimization was performed using mixed material elements which resulted in a design that is shown in Figure 5.13. In these figures, blue colours represent steel elements and orange colours represent timber elements. The ECI, CSC and price contribution per element group of these two designs are shown in Table 5.2 and 5.3 respectively.

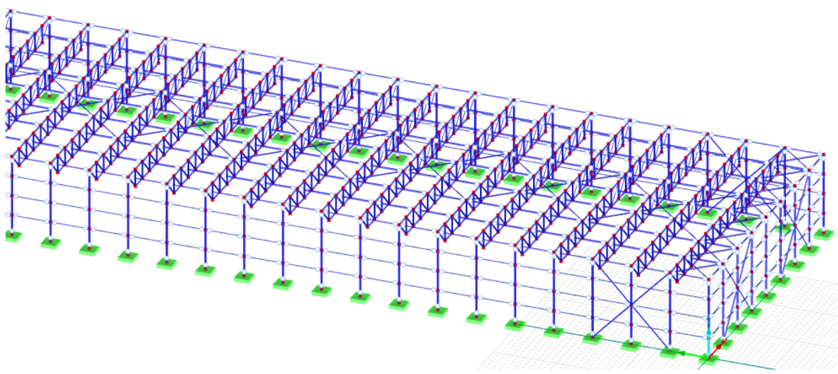


Figure 5.12: ECI optimized design for Coca Cola 27 in RFEM

Table 5.2: Breakdown of structural element contributions in the ECI optimized hall

		Columns	Trusses	Purlins	Side rails	**Total**
ECI	[€]	2782.3	4550.0	1788.0	717.4	**9837.8**
Arcadis CSC	[€]	500.8	819.0	321.8	129.1	**1770.8**
J.W. CSC	[€]	556.5	910.0	357.6	143.5	**1967.6**
Price	[€]	245707.2	889363.7	191970.6	127487.5	**1454529.0**

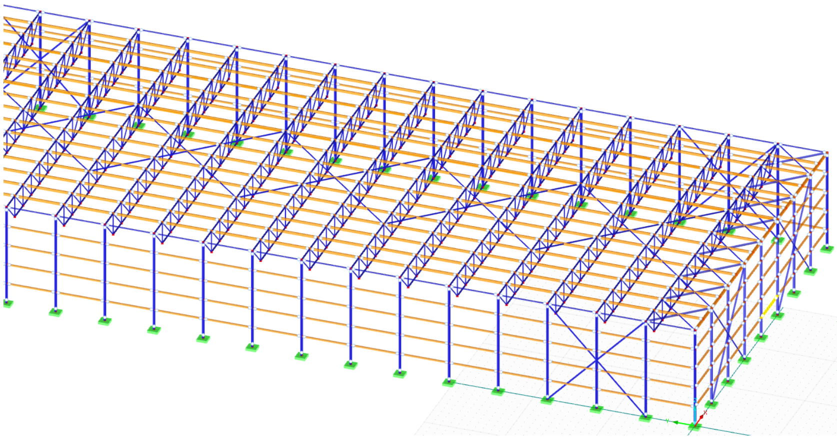


Figure 5.13: Multi objective optimized design for Coca Cola 27 in RFEM

Table 5.3: Breakdown of structural element contributions in the multi objective optimized hall

		Columns	Trusses	Purlins	Side rails	**Total**
ECI	[€]	3237.9	4645.8	7762.4	3726.7	**19372.8**
Arcadis CSC	[€]	582.8	836.2	2537.3	1267.1	**5223.4**
J.W. CSC	[€]	647.6	929.2	2328.7	1118.0	**5023.5**
Price	[€]	345960.8	546024.3	296146.4	119296.0	**1307427.5**

It is observed that the single objective ECI optimized design reduces the ECI of the original hall by 16% which consequently also resulted in lower CSCs as can be seen when comparing Tables 5.1 and 5.2. Both the original and the optimized hall consist solely of single span hinged elements which makes the results quite accurately comparable. Since the connection reusability factors for these connection types are equal, it comes as no surprise that the corrected shadow costs of the original design does not differ too much from the ECI optimized design. An additional benefit of the ECI optimized design is given by the financial aspect, as the construction price of the optimized design is approximately 11% lower than that of the original hall.

The multi objective optimized design resulted in a higher ECI score than the original design but its price was approximately 19% lower. The ratio between its ECI increase and price reduction compared to the original design might indicate that a multi objective optimization method gravitates a bit more towards price reduction than ECI reduction. This might have something to do with the order of magnitude of both numbers. Therefore, it might also not necessarily provide the best solution regarding the combination of the two objectives. Figure 5.14 graphically depicts the differences between the discussed designs in terms of ECI, CSC and price. When interpreting the results of both optimization methods, it must be recognised that the original design was not verified in a finite element software in its entirety. Therefore, it is plausible that the optimized designs are more conservatively designed than the original industrial hall, thus resulting in a relatively higher ECI and price than would have been the case when the designs had been calculated manually. Furthermore, both optimizations used a limited population size and amount of generations to retain an acceptable time frame. Thus, it is conceivable that both designs could have been optimized to a greater extend which would probably have resulted in lower ECI and prices.

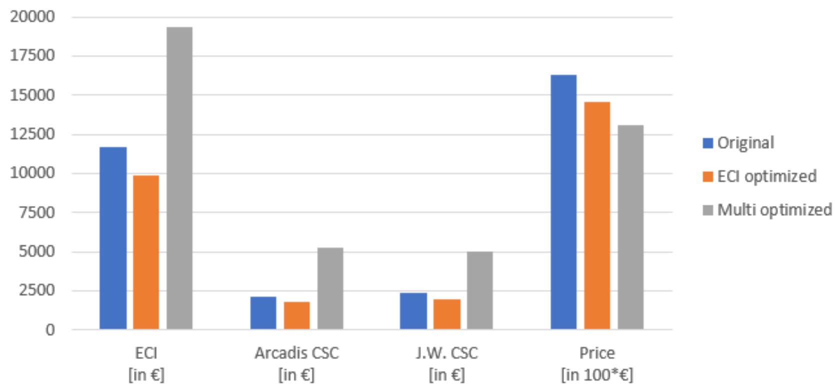


Figure 5.14: Relative ECI, CSC and price comparison of different Coca Cola hall 27 designs

5.4.2. Newlogic III

Phase 1

The relevant part of the Newlogic III distribution centre has a length of 108 m and a width of 108 m. This hall has features 6 spans in both directions, therefore the internal column grid is 18 x 18 m. From its design report all necessary load assumptions can be determined. It is located in a rural part of Dutch wind area III which leads to a Zone D and E wind load of 0.593 kN/m2 and -0.371 kN/m2 respectively. The weight of the roofing amounts to 0,35 kN/m2 and the snow load which was used in the calculations is 0,56 kN/m2. Its total ECI is estimated at € 12211.1 while its corrected shadow costs amount to € 10270.6 due to its large use of welded connections. The total construction element price is estimated at € 1778191.7. An overview of all construction elements with regard to ECI and price calculations can be found in Table 5.4. A more detailed version can be found in Table C.5 in Appendix C.

Table 5.4: Breakdown of structural element contributions in the original Newlogic III hall

		Columns	Trusses	Purlins	Side rails	**Total**
ECI	[€]	2747.8	1892.0	4480.9	949.4	**10070.1**
Arcadis CSC	[€]	2363.1	1627.2	3853.5	816.5	**8660.3**
J.W. CSC	[€]	2060.9	1419.0	3360.6	712.1	**7552.6**
Price	[€]	419438.4	313311.2	518660.8	279720.0	**1531130.4**

Phase 2

Directed by the results from section 5.3, an ECI optimization was performed using solely steel elements. This resulted in a design which is shown in Figure 5.15. Additionally a multi objective optimization was performed using mixed material elements which resulted in a design that is shown in Figure 5.16. In these figures, blue colours represent steel elements and orange colours represent timber elements. The ECI, CSC and price contribution per element group of these two designs are shown in Table 5.5 and 5.6 respectively.

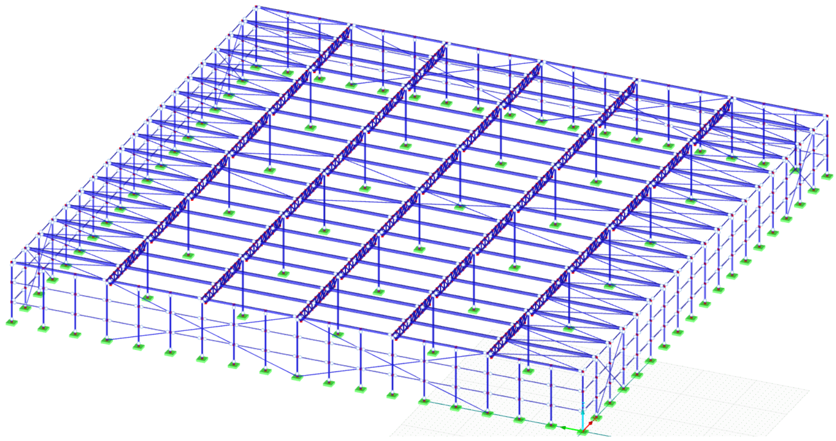


Figure 5.15: ECI optimized design for Newlogic in RFEM

Table 5.5: Breakdown of structural element contributions in the ECI optimized hall

		Columns	Trusses	Purlins	Side rails	**Total**
ECI	[€]	2218.0	3062.8	9282.7	543.6	**15107.0**
Arcadis CSC	[€]	399.2	551.3	1670.9	97.8	**2719.3**
J.W. CSC	[€]	443.6	612.6	1856.5	108.7	**3021.4**
Price	[€]	376651.8	929079.5	1385023.2	149908.6	**2840663.0**

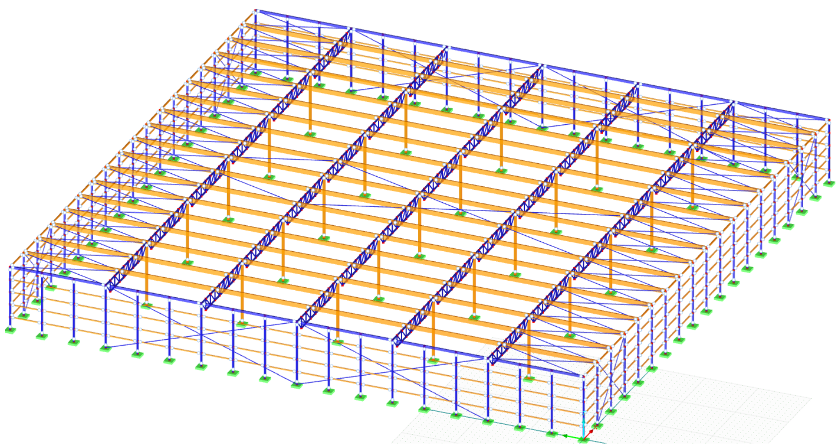


Figure 5.16: Multi objective optimized design for Newlogic III in RFEM

Table 5.6: Breakdown of structural element contributions in the multi objective optimized hall

		Columns	Trusses	Purlins	Side rails	**Total**
ECI	[€]	5026.4	6716.2	21928.0	3497.9	**37168.5**
Arcadis CSC	[€]	1340.2	1208.9	7656.2	1189.3	**11394.6**
J.W. CSC	[€]	1256.6	1343.2	6578.4	1049.4	**10227.6**
Price	[€]	333390.8	789361.8	906007.7	111974.4	**2140734.7**

It is observed that the ECI optimized design performs 50% worse with regard to ECI value compared to the original design. This result was more or less expected since all connections in the original are fixed connections. By using fixed connections and thus creating rigid connections, the cross sections of the structural elements can be used more effectively compared to hinged elements. The connections in the ECI optimized design are all assumed to be hinged since this provides greater potential for reuse. Therefore it is more relevant to compare the corrected shadow costs of both buildings for a more fair comparison. From the CSC it is clear that the ECI optimized design performs 69% better than the original. The only drawback is given by the total price which is considerably higher. However the price of the optimized design is negatively influenced by the type of connections that are used which makes this comparison difficult and unfair.

The multi objective optimization resulted in a design with a higher ECI, CSCs and price compared to the ECI optimized variant. The difference in connection types between the original hall and the optimized hall deteriorates the degree of comparability of the results in this particular case study. Since no optimization is achieved in either of the two criteria for this optimization method, no useful conclusions can be drawn from it. The inability of the genetic algorithm to come up with better design solutions are probably caused by the assumptions around connection types but the relatively short computation time can also be a factor. Additionally, the fact that the original hall was not verified in a finite element software in its entirety may result in an underestimation of the shadow costs and price compared to the optimized design.

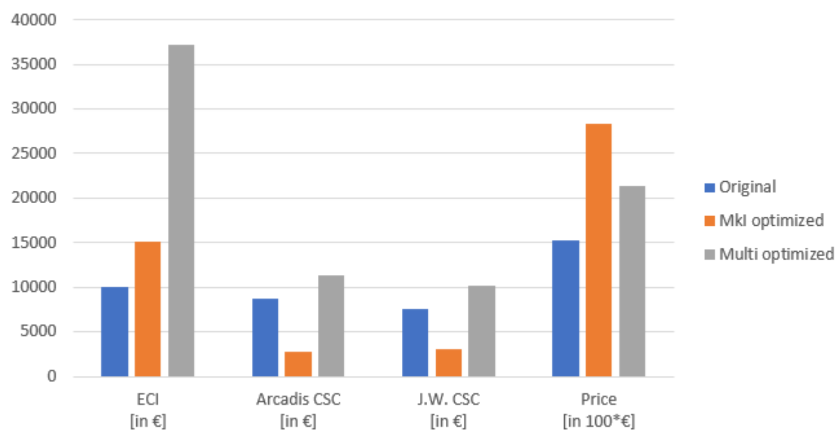


Figure 5.17: Relative ECI, CSC and price comparison of different designs

Figure 5.17 depicts the differences between the discussed designs. When interpreting the results of both optimization methods, it must be recognised that the original design was not verified in a finite element software in its entirety. Therefore, it is plausible that the optimized designs are more conservatively designed than the original industrial hall, thus resulting in a relatively higher ECI and price than would have been the case when the designs had been calculated manually. Moreover, the difference in connection types negatively influences the comparability of the original design with the optimized results. Furthermore, both optimizations used a limited population size and amount of generations to retain an acceptable time frame. Thus, it is conceivable that both designs could have been optimized to a greater extend which would probably have resulted in lower ECI and prices.

6
Final remarks

In this chapter some final remarks are made. Section 6.1 provides the conclusions that are found during the generative design optimization. These conclusions are discussed in section 5.2 and in section 5.3 some recommendations are made for future research.

6.1. Conclusion

Since the implementation of the European energy performance of buildings directive in 2020, all new buildings are required to have nearly zero-energy demands. The general prospect is that by the end of the year 2050 all new buildings will have to comply with net zero energy demands [7]. Consequently, the relative impact share of construction materials on the overall environmental impact of buildings is growing progressively. Hence, material shadow costs are starting to become increasingly more governing, especially when the reusability aspect of elements can be included in the calculation. The current inefficiency with regard to the reduction of shadow costs in industrial hall designs poses a barrier to further decrease its negative impacts. The objective of this study was to create and test a methodology with which shadow costs of preliminary structural designs of industrial halls could be minimized using a parametric model and generative design.

Arbitrary hall

An arbitrary but realistic industrial hall was optimized in terms of lowest ECI value during a single objective optimization. Additionally, it was optimized for a combination of ECI value and construction price during a multi objective optimization. Both optimizations were performed for a 'steel only' design, a 'timber only' design and a design which used a combination of steel and timber elements. It should be noted that the results of these optimizations are highly sensitive to the assumptions that were made in this thesis and can therefore not be generalised to apply to each industrial hall without additional research.

By randomly generating designs using different kinds of materials an indication was discovered that steel elements are prone to slenderness induced buckling issues in generative design and thus to failed unity checks. The best guess method that was used for the cross section size estimation as discussed in section 4.4.5 was adapted accordingly to provide more viable estimations and thus enable better optimization. Additionally it was identified that optimizations which use a mixture of materials should consist of larger populations size than single material optimizations to get a similar convergence towards an optimum since the amount of possible solutions is far greater. During the optimization of an arbitrary industrial hall that uses the assumptions and boundary conditions that are described in section 1.2.4, it has been found that contrary to popular belief, steel seems to perform best with regard to ECI while timber designs seem to be cheaper. Therefore, for similar halls with similar boundary conditions, it can be concluded that in a multi objective optimization for ECI and price, a mixture of steel and timber elements is required in order to achieve the most cost effective and environmentally friendly structural design. In any case, in order to achieve better convergence towards the global optimum, a larger population size and amount of generations is imperative.

According to an in depth analysis of the structural elements in the generatively optimized arbitrary halls, the centre to centre distances for outer columns, purlins and side rails were roughly equal which indicates that for halls with similar boundary and load conditions there might exist an optimum configuration regarding element lengths and spans which is independent of material characteristics. The sole outlier to this theory is given by the purlin centre to centre distance of a mixed material design which was deemed under-optimized in previous conclusions. Furthermore, several conclusions can be drawn with regard to the most effective cross section types for specific structural applications within industrial hall constructions. In exclusively steel multi objective optimized designs, rolled steel sections are preferred for elements which are predominantly loaded in single bending while cold formed steel sections were preferred for elements which were loaded in double bending even though the price of these sections is higher. This indicates that the efficiency per kg of cold formed sections in double bending outweighs the price difference with rolled sections. Moreover, in mixed material multi objective optimized designs it proves most beneficial to use cold formed steel in members that are loaded in double bending such as edge purlins, side rails and edge beams and to use timber for members that bend in a single direction such as columns and purlins.

Case studies

Using the results and conclusions from the arbitrary hall optimizations, two case studies were performed on existing industrial halls. In these case studies, the existing halls were analysed and their ECI as well as their construction price was estimated. Subsequently, the optimization methodology that is presented in this thesis was used to determine whether these industrial halls could have been constructed in a more beneficial manner with regard to shadow costs. The optimization tactic that is used for these case studies is a result from the optimization of the arbitrary hall, therefore the same caution is advised for generalisation of these results based on different assumptions, boundary conditions or loads.

During the first case study it was observed that the single objective ECI optimized design reduces the ECI of the original hall by 16% which consequently also resulted in lower CSCs as can be seen when comparing Table 6.1 to Table 6.2. In addition, the construction price is also 11% lower compared to the original hall. The generatively optimized design as well as the original design consisted solely of elements with hinged connections, therefore the results are quite accurately comparable. Thus, it can be concluded that for single span, single storey, steel industrial halls that consist of solely of elements with hinged connections, the optimization methodology as presented in this thesis has a beneficial effect on the total ECI of the hall. However, it should be noted that no tests have been performed on similar kinds of halls in different wind or snow zones. The results of this case study can therefore not be generalized to apply to similar halls in different regions without further testing. Since the J.W. reusability score of steel bolted connections are slightly less favourable than the Arcadis reusability score, it comes as no surprise that the total J.W. CSC is marginally higher.

Table 6.1: Breakdown of structural element contributions in the original hall

		Columns	Trusses	Purlins	Side rails	**Total**
ECI	[€]	4747.3	2904.6	3025.0	1047.0	**11724.0**
Arcadis CSC	[€]	854.5	522.8	544.5	188.5	**2110.3**
J.W. CSC	[€]	949.5	580.9	605.0	209.4	**2344.8**
Price	[€]	533153.0	562923.2	372889.8	162359.6	**1631325.6**

Table 6.2: Breakdown of structural element contributions in the ECI optimized hall

		Columns	Trusses	Purlins	Side rails	**Total**
ECI	[€]	2782.3	4550.0	1788.0	717.4	**9837.8**
Arcadis CSC	[€]	500.8	819.0	321.8	129.1	**1770.8**
J.W. CSC	[€]	556.5	910.0	357.6	143.5	**1967.6**
Price	[€]	245707.2	889363.7	191970.6	127487.5	**1454529.0**

Table 6.3: Breakdown of structural element contributions in the multi objective optimized hall

		Columns	Trusses	Purlins	Side rails	**Total**
ECI	[€]	3237.9	4645.8	7762.4	3726.7	**19372.8**
Arcadis CSC	[€]	582.8	836.2	2537.3	1267.1	**5223.4**
J.W. CSC	[€]	647.6	929.2	2328.7	1118.0	**5023.5**
Price	[€]	345960.8	546024.3	296146.4	119296.0	**1307427.5**

Figure 6.1 depicts the relative impact of construction elements on the total ECI of the original and ECI optimized design. Since the ECI optimized design has a lower ECI compared to the original hall, for halls that use identical boundary conditions and assumptions, it can carefully be concluded that its ECI can be minimized by using a larger material volume for trusses by placing the portal frames closer together which leads to less heavily loaded portal columns which subsequently leads to a decrease of their cross section size. Additionally, no intermediate facade columns are required which leads to a significant reduction in the amount of columns in the design. Moreover, since the center to center distance of the portal frames is smaller, purlins and side rails with a smaller cross section can be used which leads to a reduction in material use. It should be noted that this design tactic can only be used for single span halls. In multi span halls, the allowable internal column positions are

often dictated by the client, which means that there is little to no margin in the center to center distances of portal frames. This optimization tactic is therefore unsuitable for multi span industrial halls.

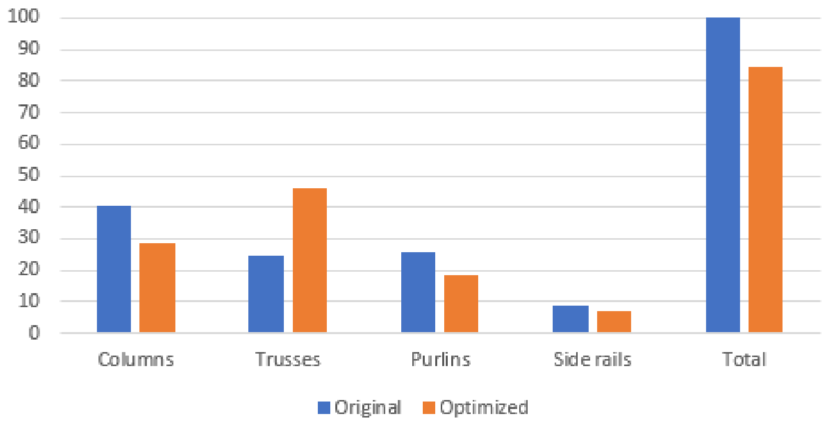


Figure 6.1: Relative impact of construction elements on the total ECI

The multi objective optimized design resulted in a higher ECI score than the original design but its price was approximately 19% lower as can be seen in Table 6.3. The ratio between its ECI increase and price reduction compared to the original design might indicate that a multi objective optimization method gravitates a bit more towards price reduction than ECI reduction. This is probably correlated to the order of magnitude of both numbers which leads to the algorithm prioritising the absolute reduction of the combined outcomes over the relative reduction of the individual shadow cost and price. Therefore, it is probable that it does not necessarily provide the best solution regarding the combination of the two objectives. It is worth mentioning that the J.W. corrected shadow costs are lower compared to the Arcadis CSC, which is directly related to the more favourable J.W. reusability score for bolted timber connections. From this MMO, it can be concluded that considering the ECI assumptions, connection assumptions, boundary conditions and load cases that are used in this thesis, ECI versus price is a consideration between steel and timber respectively. According to the current assumptions, to achieve the best possible combined outcome for both criteria, steel elements should predominantly used in columns and trusses and timber should be used for purlins and side rails. However, the inclusion of biogenic carbon storage will result in timber being more favourable in terms of ECI as well as cheaper which will probably result in a completely timber design as optimal solution for both criteria. A similar statement can be made regarding the inclusion of demountable rigid connections, which will result in much more favourable configurations for steel elements. The inclusion of both previously mentioned conditions at the same time will result in a very interesting but unknown outcome and should be investigated in subsequent research.

During the second case study, it was observed that the ECI optimized design performs almost 50% worse with regard to ECI compared to the original design as can be seen when comparing Table 6.4 to Table 6.5. This result can be explained by the fact that all connections in the original design are fixed welded connections, resulting in rigid connections through which more efficient use of the cross sections is enabled, thus resulting in a significantly lower volume of material. Since the connections in the optimized design are all assumed to be hinged, it provides greater potential for reuse. Therefore it is more relevant to compare the corrected shadow costs of both buildings to achieve a fair comparison. By comparing the results it becomes clear that the optimized design is able to reduce the CSC of the original hall by about 69%. The construction price of the optimized design is significantly larger. However, the price comparison is potentially unfair given the material savings due to the rigid connections in the original design. No undivided conclusions can be drawn from this optimization, but it does demonstrate the degree of sensitivity that the proposed methodology has regarding the assumptions that are made about the connection types and reusability factors in this thesis.

The results of the multi objective optimization in this case study are shown in Table 6.6 and its is clear that this optimization led to a design with higher ECI, CSC's and price compared to the ECI optimized variant. Since optimization is achieved in neither of the two criteria, no useful conclusions can be gathered from this particular optimization. Probable causes for the inability of the genetic algorithm to find a better design solution are given by the assumptions regarding connection types and the relatively short optimization time. The difference in connection types between the original hall and the optimized hall is a major influencing factor in the degree of comparability of the results in this particular case study and lead to an overall higher ECI and price of the optimized designs. Taking into account the large number of variables in the parametric model, the computation time was probably too short which resulted in a lack of convergence towards global optimum and subsequently to a sub optimal configuration regarding ECI and price. Moreover, the original hall was not verified in a global finite element analysis and is therefore less conservatively designed resulting in lower overall ECI and price.

Table 6.4: Breakdown of structural element contributions in the original hall

		Columns	Trusses	Purlins	Side rails	**Total**
ECI	[€]	2747.8	1892.0	4480.9	949.4	**10070.1**
Arcadis CSC	[€]	2363.1	1627.2	3853.5	816.5	**8660.3**
J.W. CSC	[€]	2060.9	1419.0	3360.6	712.1	**7552.6**
Price	[€]	419438.4	313311.2	518660.8	279720.0	**1531130.4**

Table 6.5: Breakdown of structural element contributions in the ECI optimized hall

		Columns	Trusses	Purlins	Side rails	**Total**
ECI	[€]	2218.0	3062.8	9282.7	543.6	**15107.0**
Arcadis CSC	[€]	399.2	551.3	1670.9	97.8	**2719.3**
J.W. CSC	[€]	443.6	612.6	1856.5	108.7	**3021.4**
Price	[€]	376651.8	929079.5	1385023.2	149908.6	**2840663.0**

Table 6.6: Breakdown of structural element contributions in the multi objective optimized hall

		Columns	Trusses	Purlins	Side rails	**Total**
ECI	[€]	5026.4	6716.2	21928.0	3497.9	**37168.5**
Arcadis CSC	[€]	1340.2	1208.9	7656.2	1189.3	**11394.6**
J.W. CSC	[€]	1256.6	1343.2	6578.4	1049.4	**10227.6**
Price	[€]	333390.8	789361.8	906007.7	111974.4	**2140734.7**

When interpreting the results of both optimization methods during the case studies, it must be recognised that the original design was not verified in a finite element software in its entirety. Therefore, it is plausible that the optimized designs are more conservatively designed than the original industrial hall, thus resulting in a relatively higher ECI and price than would have been the case when the designs had been calculated manually. Furthermore, both optimizations used a limited population size and amount of generations to retain an acceptable time frame. Thus, it is conceivable that both designs could have been optimized to a greater extend which would probably have resulted in lower ECI and prices.

The main research question that was formulated in the introduction of this thesis is:

Which combination of structural elements and materials result in the lowest shadow cost of the main bearing construction of industrial halls?

Considering the input data of all materials and connections as well as the assumptions, it can be said that steel elements have the best performance with regard to both ECI and to the corrected shadow cost ideology as presented in section 3.4.5 of this thesis. With regard to construction price, timber seems to be the best option for all structural elements. It can also be concluded that for an optimal combination of price and ECI, a mixed material use is required. However, as the optimizations and case studies have demonstrated, the optimization results are largely influenced by the assumptions that are made at the start of this thesis. Nevertheless, the main research question is answered for industrial halls that use the same boundary conditions, loads and assumptions that are adopted in this thesis.

6.2. Discussion

When interpreting the conclusions that are provided in section 6.1, the assumptions that were made at the start of this thesis in section 1.2.4 should be taken into account. The conclusions cannot be generalised to qualify for every industrial hall but are instead very strongly linked to the assumed ECI input, loading conditions, boundary conditions, the type of connections that are used in the optimization process and the connection reusability scores that are suggested in this thesis.

If the timber elements can be retained for about 100 years, their ECI will be significantly lower than that of comparable steel elements due to carbon sequestration. However, the benefits beyond the end of life of an element are often uncertain and no assurances are in place that timber elements will not be incinerated after initial use. The inclusion of biogenic carbon storage can therefore not be justified. The Dutch national environmental database has been identified as the best data source for this thesis since it does not include carbon sequestration in the calculation of ECI values but does provide branch average data which is the most suitable option for ECI calculation of preliminary designs. Inclusion of biogenically stored carbon in timber elements will undoubtedly lead to a very different results for single objective single material ECI optimizations as well as multi objective mixed material optimizations. When carbon sequestration effects are accounted for, it is possible that an industrial hall design that exists solely of timber elements provides the most optimal ECI value as well as construction price. However, it is worth mentioning that the assumptions regarding rigid connection types that were done in section 1.2.4 negatively impacted the performance of steel elements, hence no evident conclusions can be drawn with regard to the impact of these separate assumptions. It is worth mentioning that the ECI scores that are taken from the Dutch national environmental database have some parallels with so called black box approaches, which means that even tough they are verified by external parties, there is no way to check them in order to ensure their validity. By utilising branch average data, the risk of illegitimate EPD selection is minimized. However, it should be recognised that this provides no 100% guarantee of the correctness of the data. The results of the material choice in the optimizations are rather contradictory to the common consensus regarding the price of materials. Timber is generally viewed as a very costly material compared to steel. However, the results from optimization suggest otherwise. It should be noted that the cost input of materials were solely based on volume and connection costs. Therefore, the price calculation is probably not completely realistic.

Shadow costs associated with structural elements decrease as a benefit of reuse. Connection types have been identified as the most influential factor for reusability. Therefore, a connection reusability factor was developed which was given according to four material independent criteria and based on the experiences of structural designers from Arcadis Nederland BV. Subsequently, a corrected shadow cost (CSC) can be calculated by multiplication of this reusability factor with the original ECI. As such, this CSC includes the reusability of construction elements through their connection types as well as their recyclability through their original ECI values. One might argue that, in theory, a 100% reusable connection will lead to a reusability factor of zero, therefore reducing the ECI of an element to zero as well. However, this theory is flawed, because the connection factors are based on four criteria, one of which is the expected lifespan of the element. Construction elements inevitably degrade over time, therefore, reusability factors can never reach zero. Although the Arcadis reusability scores of connection types are given based on experience, they are heavily influenced by the subjective interpretation from Arcadis designers. The debatable veracity of these scores is recognised and an alternative so called "J.W. reusability score" is provided for comparison which is based on a limited amount of literature as well as engineering knowledge. During the development of the CSC, it was assumed that the connection scores are linearly related to the reusability of their respective elements. This assumption was made since no relevant literature on this subject was available for all considered materials at the time of writing. However, it is presently not corroborated by any published literature and should be more thoroughly investigated before implementing the corrected shadow cost ideology universally. Additionally, it is recognised that the creation of a good survey is very difficult. Although the images and explanations that were used in the survey were selected with great care, it is possible that the answers of the structural designers do not reflect their true opinions as a result of misunderstandings. Evidently, small changes in the reusability scores will result in very different CSC values. Due to the assumptions and uncertainties that are associated with the reusability scores, one should be careful during the interpretation of the CSC values that are presented in this thesis.

During the inventory of relevant connection types, it was identified that creating rigid demountable connections using (additional) bolts is a very effective connection type to increase cross section efficiency in steel elements. However, for timber elements, rigid connections are only possible by using large amounts of bolts or dowels or by using DVW-reinforced joints combined with steel tube fasteners. The former decreases the effective stiffness of the element and is impractical to demount. The latter does retain the original stiffness but it cannot be demounted without destroying the element since the steel tubes are expanded inside the timber to create the connection and the densified veneer wood plates are glued to the timber element. Since no contemporary rigid timber connection technique is considered demountable and using rigid connections exclusively for steel elements would give it a rather large and unfair advantage over timber elements, it was decided not to include rigid connections in the optimization process. It is recognised that the benefits of steel elements is underestimated by this decision and the outcomes of the optimization as such do not reflect their full potential. As a result of this decision, in all optimization processes, all construction elements were executed as hinged single span elements. While this configuration is highly recommended for demountability purposes as discussed in section 3.5, it is definitely not optimal for minimizing material use. Consequently, it is probable that sub-optimal solutions have been found during the optimization processes which potentially reduces the reliability of the conclusions regarding optimal material use that are presented in this thesis.

The results from the optimization of the arbitrary hall were quite clear on optimal material use for ECI reduction considering the assumptions about connection types and ECI input that were made in combination with the used loads and boundary conditions. It is rather safe to state that for ECI optimizations of industrial halls in which the same assumptions and boundary conditions are used, steel is the best option. However, small changes in assumptions or boundary conditions will lead to different optimization results. It should be noted that the optimization of the arbitrary hall was completely based on a single predefined hall with predefined dimensions and number of main spans. Especially the width has a major influence on the main bearing construction of a hall since it determines the span of the portal frames. Consequently, the conclusions about material use in this thesis should be considered only to be valid for similar halls under similar conditions. No reliable conclusions can be drawn with regard to optimal material use for generic industrial halls with generic loads and boundary conditions. In any case, a greater population size is imperative for improvement of the optimization and thus to achieve greater convergence towards a global optimum.

During the first case study, it has been found that the methodology that is presented in this thesis resulted in a total ECI improvement of 16% compared to the original design while during the second case study, the optimization process did not yield an improved design. In the first case study, the original and optimized design are quite accurately comparable since both halls exist solely of hinged single span elements. The conclusions regarding this hall are therefore quite reliable, but should not be taken out of context since they are only valid considering the assumptions that are stated in 1.2.4. The results of the optimization in the second case study are inconclusive since the difference in connection types between the original and optimized hall result in incomparable designs. Taking into account the current assumptions regarding connection types, the hall that is assessed in the second case study, by definition, has less potential for optimization. The rigid connections in the original design already reduce the volume of material that is used compared to a hinged connection design. Computing a design solution using solely hinged connections which embodies less material is therefore difficult and potentially impossible. An alternative comparison can be made in terms of corrected shadow costs. According to this ideology, the optimized hinged design performs more than twice as good as the original welded design due to the reusability factors that are in place. However, the corrected shadow cost ideology is not corroborated by a significant amount of literature and is based on many uncertain assumptions. Conclusions regarding CSCs should therefore be interpreted with great care. The extensive number of variables in the parametric model leads to an enormous amount of possible design solutions during optimization. This makes it difficult to accurately compute the best solution within a reasonable amount of time. During the interpretation of the case study results it was recognised that the output of the optimization processes was most likely more conservative compared to the original designs since those designs were not analysed in their entirety using finite element software. By modelling the original halls in FEA and adapting the cross sections to comply with the structural verification's, a fairer comparison might be provided. Moreover, the wind bracing in the optimized models was not placed in the most advantageous manner resulting in larger forces in trusses and thus requiring larger cross sections which in turn negatively influenced their ECI, CSCs and price. Considering the previously mentioned assumptions and uncertainties, it is clear that more compatible case studies need to be performed in order to determine the effectiveness of the optimization methodology.

A disadvantage of using Autodesk refinery for optimization is the fact that this software does not show the computational path that it takes to arrive at the optimized result. Therefore it cannot be verified whether the genetic algorithm makes logical decisions or missed out on potentially good design solutions. The incorporation of a visible computational path provides valuable insight in the behaviour of the chosen algorithm which enables detailed comparison with different algorithms which can result in an improvement of the optimization process. Furthermore, a limiting factor for the NSGA-II algorithm to reach the optimum design is the fact that the amount of iterations and population size needs to be specified in advance of the generation process. A reasonable estimate needs to be made for this, which is difficult since there is almost no relevant literature to be found on optimizations with an equal order of number of variables as the amount that are used in this thesis. Additionally, the variables that can be chosen are not static but they tend to change according to other variables. This is especially true for the list of cross sections that is used per element because this list changes according to the length and center to center distances of the respective elements. Therefore, the NSGA-II algorithm might not select the most appropriate cross sections in all cases which obstructs potentially viable solutions from reaching the population selection that produces the next generation of design alternatives.

6.3. Recommendations for future research

During the research in this thesis, several assumptions had to be made due to gaps in published literature and time constraints. Additionally, some problems and potential improvements were identified.

- The assumptions that were made at the start of this thesis limit the variety of design solutions by imposing additional boundary conditions. Therefore, in future research, additional optimizations need to be performed that include the influence of biogenic carbon storage and demountable (semi-) rigid connections. This will create a more diverse and realistic supply of designs which presumably leads to an improvement in design optimization.
- The CSC ideology and the connection reusability factor as presented in this theses are based on a series of assumptions. Since no quantitative studies have been performed on reusability factors for timber connections and the literature on steel connections is rather limited. The CSC outcomes in this thesis are therefore not sufficiently reliable. Additional research is required on the reusability score of connections to enable fair comparison of design solutions with different connection types.
- All optimizations that were done in this thesis were performed using a single model that included exportation of the results to finite element analysis software. Inherent to this method is are long computation times as a consequence of FEA for each design. It might prove more efficient to split the optimization into two parts. Firstly, an optimization for materials and centre to centre distances without FEA which provides a credible preliminary optimized design provided that basic design rules for cross section size are in place. Secondly, an optimization that includes FEA to reduce the cross section sizes of the preliminary optimized design. This alternative optimization method reduces computation time significantly and make more competent use of a genetic algorithm. As a result of this bifurcation, more design alternatives can be assessed in a smaller amount of time which will likely increase the convergence of the optimization process towards a global optimum.

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A

Appendix A: Connections and damages

Table 1. Components' reusability categories, based on [8] and modified by the authors

Category	ρ_i = 20% (very difficult)	ρ_i = 40% (difficult)	ρ_i = 60% (moderate)	ρ_i = 80% (easy)	ρ_i = 100% (very easy)
Deconstruction Disassembly[1] w = 35%	Welded connections, high risk of damage during deconstruction	Welded connections between components with difficult access	Mostly welded connections between components	Bolted connections between components with difficult access	Easily accessible bolted connections between components
Handling Manipulation[2] w = 10%	Exceeding standard transport dimensions, prone to damage, requires special protection	Standard transport, prone to damage, requires special protection	Manipulation by crane, not damage sensitive	Small lifting devices	Manipulation by hand
Separation Cleaning[3] w_i = 10%	Machine cleaning/cutting needed to separate other materials	Hand tools for cleaning/cutting can be used to separate other materials	Bolted connections with difficult access for separation	Bolted connections need to be removed for separation	Free-standing components requiring no cleaning
Redesigning[4] w = 10%	No documentation, components would not fulfil the standard design requirements without modification	No documentation available, new design is required	Design documentation available	Detailed documentation available incl. loading and maintenance history	Designed to be reused, documentation and maintenance records in digital format
Another purpose[5] w_i = 10%	Unique sizes and shapes, no other application possible	Possible to reuse for another purpose with some re-manufacturing	Limited possibility to use for another purpose	Possible to use for another purpose even outside the construction sector	There is a larger demand for another application than the original purpose
Modification[6] w = 10%	Sizes are unique, reuse would require complete remanufacturing	Requires removal of welded parts	Requires addition and adjustment of bolt-holes	Requires only addition of new components	Requires no modification
Quality check[7] w_i = 10%	No documentation, demanding environment, loading history is difficult to estimate, laboratory tests are needed	Laboratory tests are needed to check material properties	Documentation available, loading history known, on-site test needed to check material properties	Material documentation available incl. loading and maintenance history	Material documentation available Exploited in less demanding environment
Geometry check[8] w = 5%	Components would not pass geometry requirements without modification	Complex geometry 3D scanning required	Need to confirm positions of bolt-holes, etc.	Straightness and distortion check needed (lasers)	Straightness enough to confirm usability (wire, visual, etc.)

[1] Deconstruction or disassembly is a site operation resulting in transportable parts that will be further handled;
[2] Handling or manipulation means lifting, transporting, storage and protection of the reusable components after the deconstruction process;
[3] Separation and cleaning is a workshop process leading to a reusable component acceptable by the salvage yard or material dealer. It is the pre-process of modification;
[4] Re-design is an office process governed by the new life target, the availability of components and the result of checks. The purpose of re-design is to modify the components or verify that they can sustain loads in the new life scenario;
[6] Modification is an optional workshop process leading to a modified product;
[5] Another purpose category indicates the freedom to use the component in a wider scope, different purpose (e.g. column as a beam), and even different industry;
[7] Quality check is a process supporting re-design by confirming the quality of the materials in the component;
[8] Geometry check is a process supporting re-design by showing that the geometry of components conforms to the tolerances in execution standards;

Figure A.1: Reusability indicator steel connections by Hradil et al [84]

Effect of connections in steel, timber and prefab-concrete construction elements on their reusability

This survey is composed in order to develop a practical estimate for the reusability of construction elements after they have been fastened using a certain connection type. An overview of all connection types is provided on the next page. I kindly ask you to provide a score for every connection type in steel, timber and prefab concrete elements based on your experience as a structural designer. In your assessment, please consider the following criteria:

1. Ease of disassembly
2. Damage to the element due to disassembly
3. Difficulty/cost of element preparation for reuse (if relevant)
4. Lifespan of the element

Use the following table for your scores:

Assessment	Score
Excellent	100
Very good	80
Good	60
Moderate	40
Poor	20
Very poor	0

Indicate the relative weight you assign to each criterion in your assessment.

Criterion	Weight
1	
2	
3	
4	

NOTE: Make sure the weights add up to 100

In the remarks section, in addition to your own comments, please also indicate how often each connection type occurs in practice (**Very Common, Common, Moderate, Uncommon, Rare**).

Steel elements

Connection type	Score	Remarks
1. Welded		
2. Bolted		
3. Slip resistant bolted		
4. Resin injected bolted in oversized hole (with release agent)		

Timber elements

Connection type	Score	Remarks
5. Bolted		
6. Doweled		

Prefab concrete elements

Connection type	Score	Remarks
7. Bolted		
8. Embedded steel hinge		
9. Pinned		
10. Grouted		

Please e-mail the filled-out document back to jorick.wolbert@arcadis.com
Thank you for your time and valuable insights!

Figure A.2: Effect of connections on reusability survey page 1

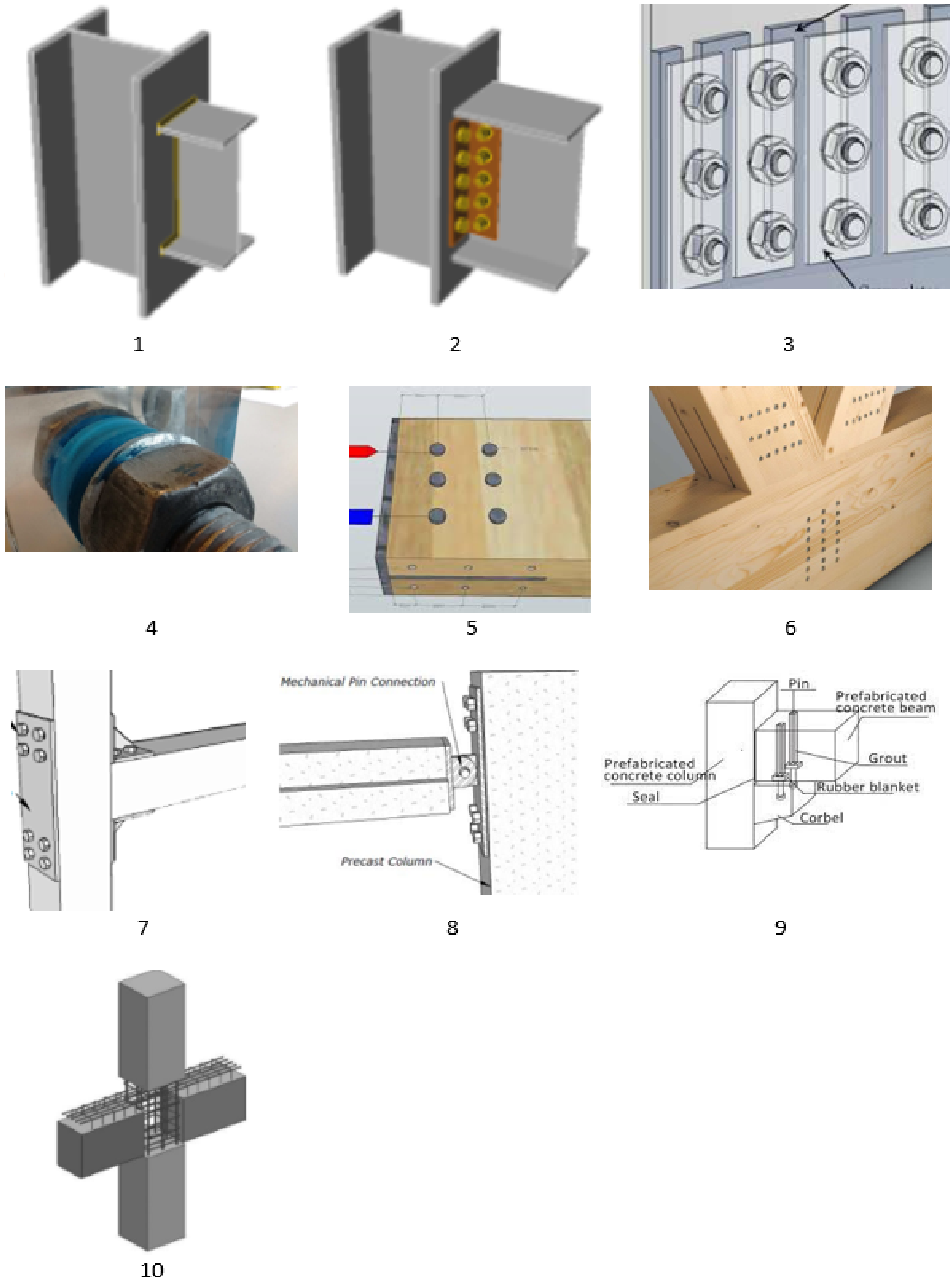

Figure A.3: Effect of connections on reusability survey page 2

B

Appendix B: ECI values from NMD

Table B.1: Average ECI per component type based on NMD product cards

Component	NMD product card	Individual ECI	Unit	ECI in reference unit	Average ECI	Reference unit
Prefab concrete					**73.08**	m3
	Kolom/ligger beton, prefab, Betonhuis (B&U)	6.7495	m	74.9944		
	Kolom/ligger beton, prefab, Betonhuis (GWW)	17.0777	m	71.1571		
Steel rolled profiles					**0.035**	kg
	Consoles, Staal; HEA, HEA200	1.4919	m	0.0346		
	Consoles, Staal; HEB, HEB400	5.4668	m	0.0346		
	Consoles, Staal; HEM, HEM300	8.3942	m	0.0347		
	Consoles, Staal; IPE, IPE300	1.4884	m	0.0346		
Steel box profiles					**0.035**	kg
	Consoles, Staal; RHS150x100	0.6454	m	0.0347		
	Consoles, Staal; SHS300	2.5253	m	0.0347		
	Consoles, Staal; CHS 139.7	0.4736	m	0.0353		
Softwood					**4.92**	m3
	Constructies in kg of m3, Europees naaldhout	0.0107	kg	4.9220		
Laminated softwood					**56.23**	m3
	Constructies in kg of m3, Hout gelamineerd europees naaldhout	0.0466	kg	22.834		
	Constructies in kg of m3, Gelamineerd naaldhout voo rconstructieve toepassingen	0.1829	kg	89.6210		
Roofing					**8.00**	m2
	Platte daken, cellenbeton dakplaten, XellaHebel	7.3667	m2	7.3667		
	Dak sandwichpaneel trapeziumvorming, staal + PIR, gecoat 40mu	10.2733	m2	10.2733		
	Roma PIRisolatie dakpaneel D	7.5779	m2	7.5779		
	Dakelement, stalen dakplaat met coating 40 mu, geperforeerd + steenwol cannelurevulling	6.7695	m2	6.7695		
Façade					**3.93**	m2
	Bekledingen, Sandwich paneel trapeziumvormige, staal + EPS	4.344	m2	4.344		
	Bekledingen, Kingspan AWP Architectural Curvewall QuadCore	3.7113	m2	3.7113		
	Bekledingen, Gevelbekleding van WRC, niet geschilderd	3.9959	m2	3.9959		
	Zinken gevel, Rheinzink, Losangegevel	3.6582	m2	3.6582		
In situ concrete					**58.77**	m3
	Funderingspalen, Beton; in het werk gestort, C2025; incl. wapening	58.7703	m3	58.7703		

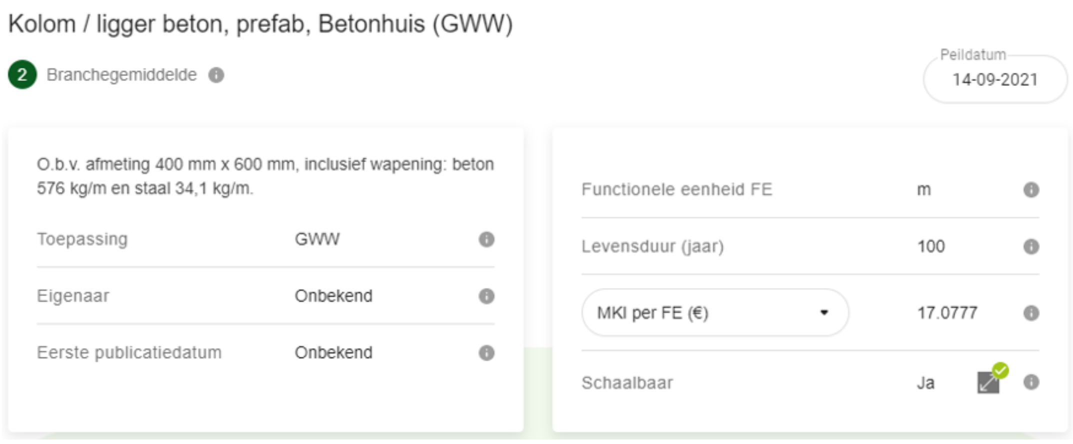

Figure B.1: NMD productcarad prefab reinforced concrete [109]

Figure B.2: NMD productcarad prefab reinforced concrete [109]

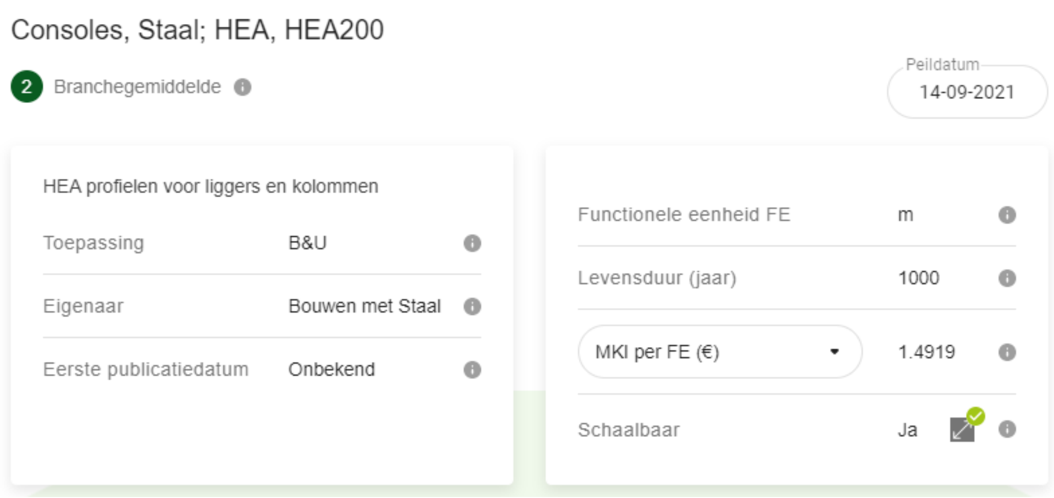

Figure B.3: NMD productcard HEA200 [109]

Figure B.4: NMD productcard HEB400 [109]

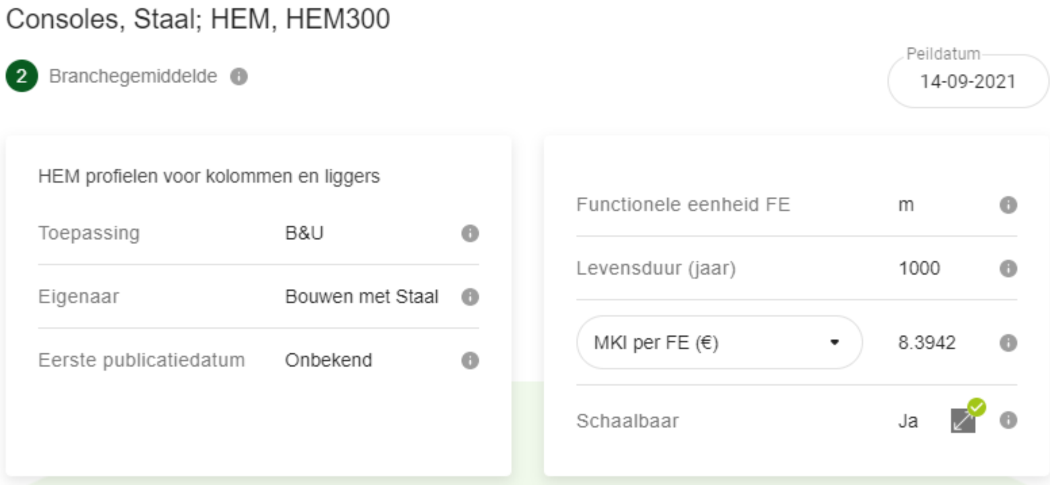

Figure B.5: NMD productcard HEM300 [109]

Figure B.6: NMD productcard IPE200 [109]

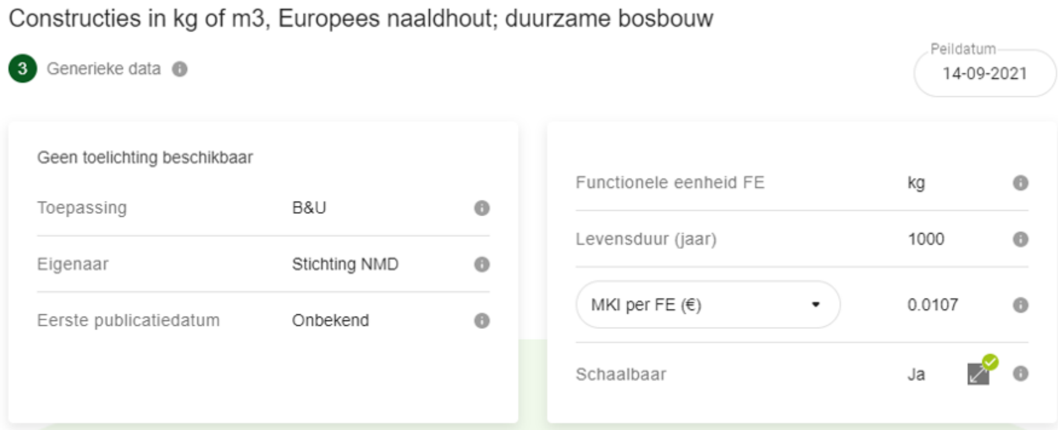

Figure B.7: NMD productcard softwood [109]

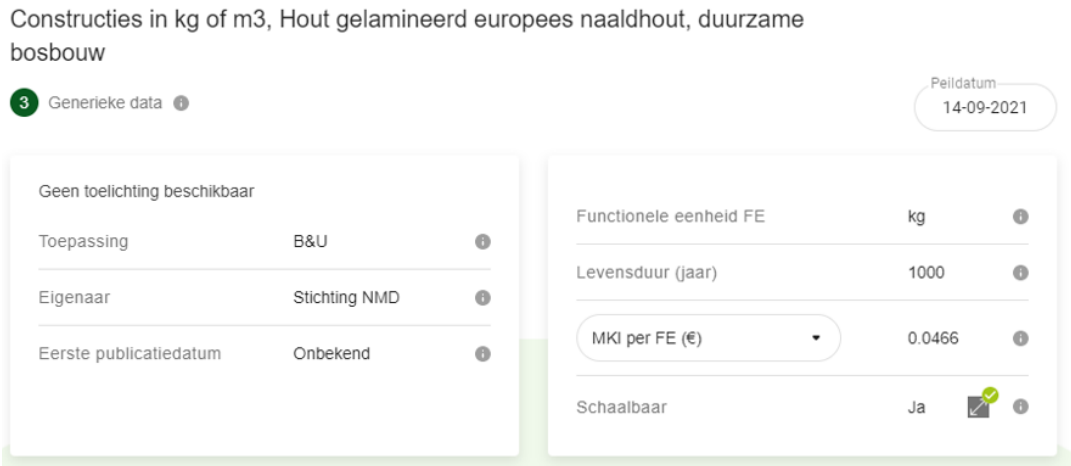

Figure B.8: NMD productcard laminated softwood [109]

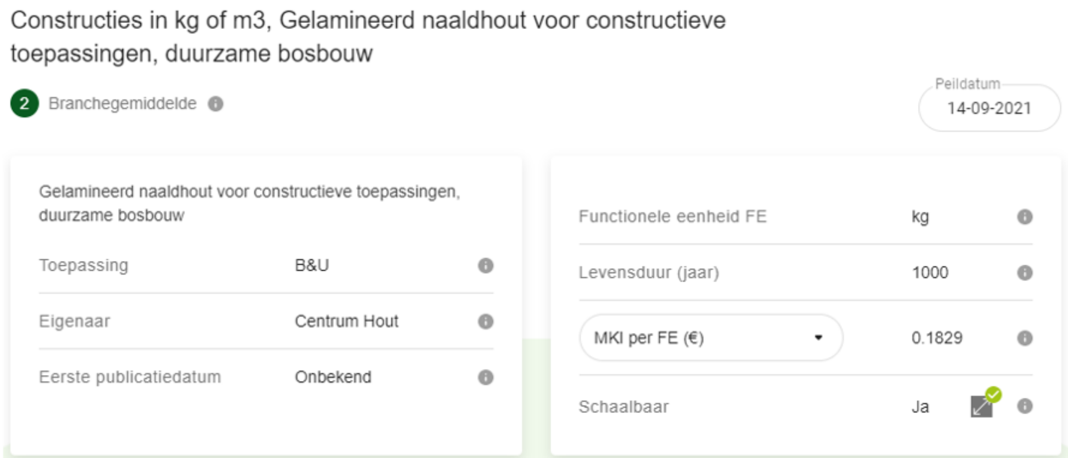

Figure B.9: NMD productcard laminated softwood [109]

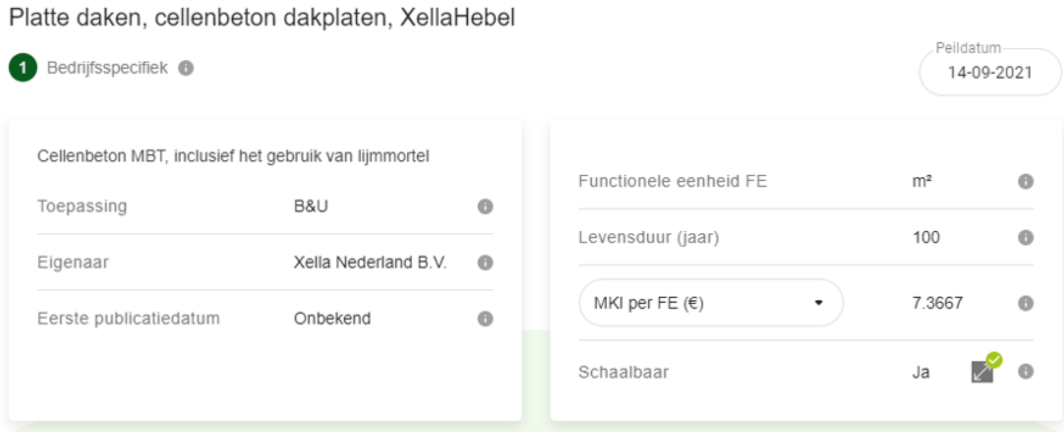

Figure B.10: NMD productcard roofing [109]

Figure B.11: NMD productcard roofing [109]

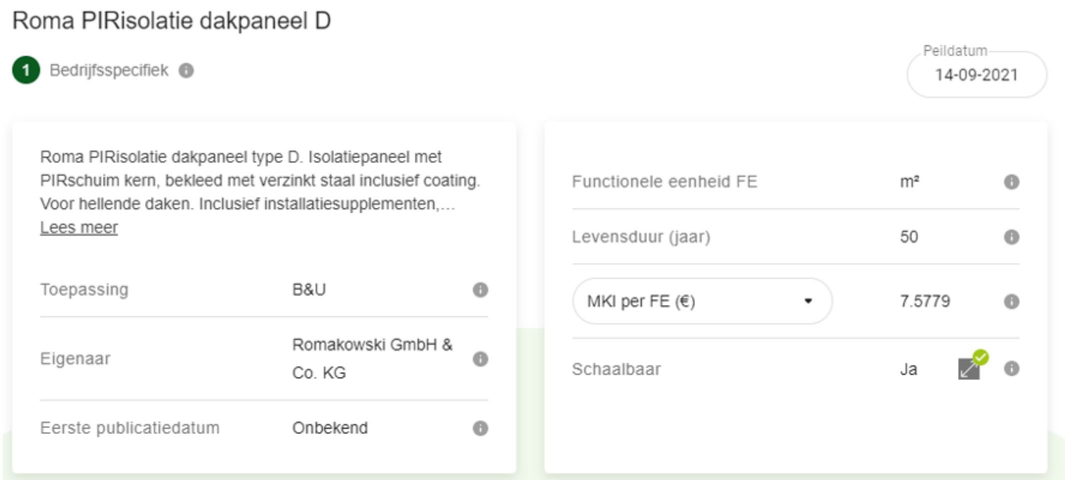

Figure B.12: NMD productcard roofing [109]

Figure B.13: NMD productcard roofing [109]

Figure B.14: NMD productcard facade [109]

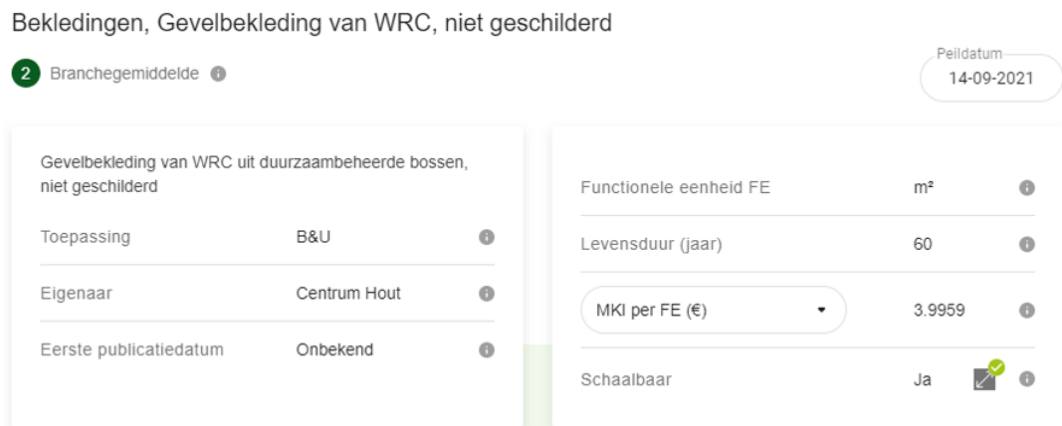

Figure B.15: NMD productcard facade [109]

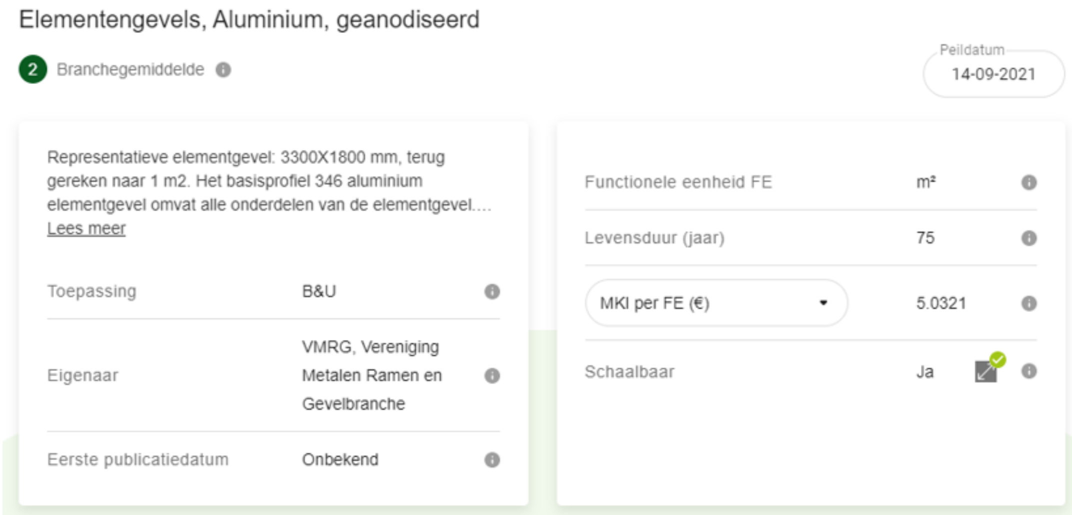

Figure B.16: NMD productcard facade [109]

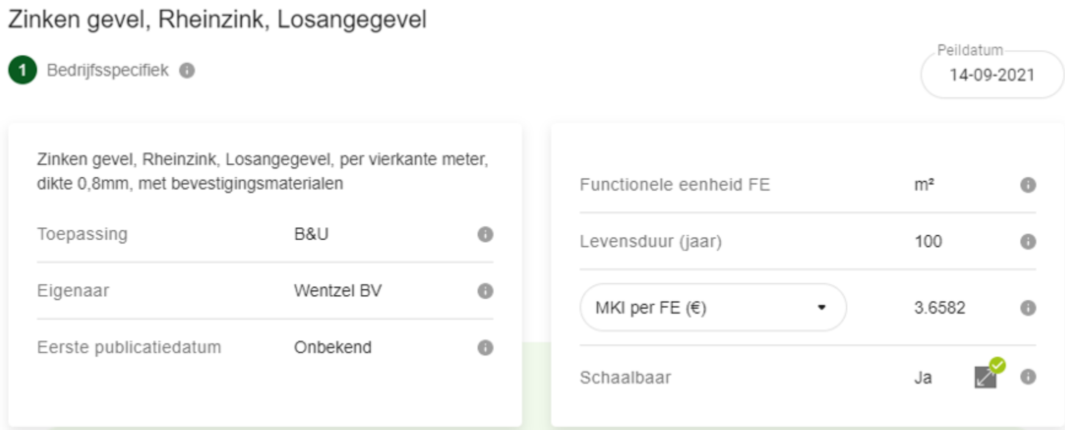

Figure B.17: NMD productcard facade [109]

Figure B.18: NMD productcard in situ concrete [109]

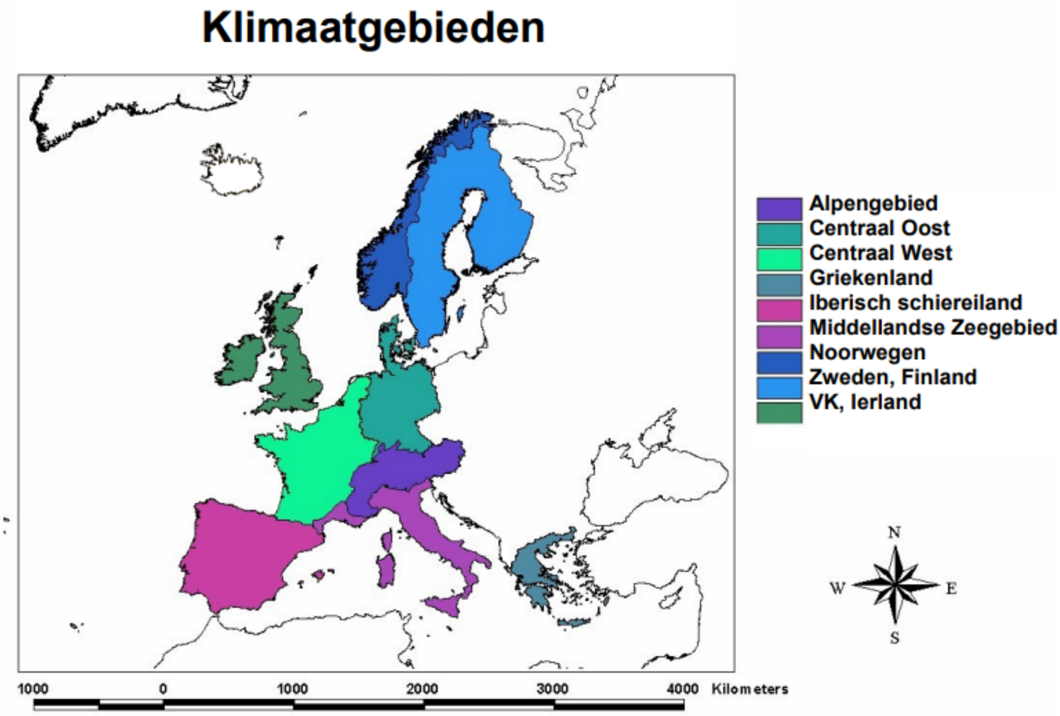

Figure B.19: Climate zones in Europe [111]

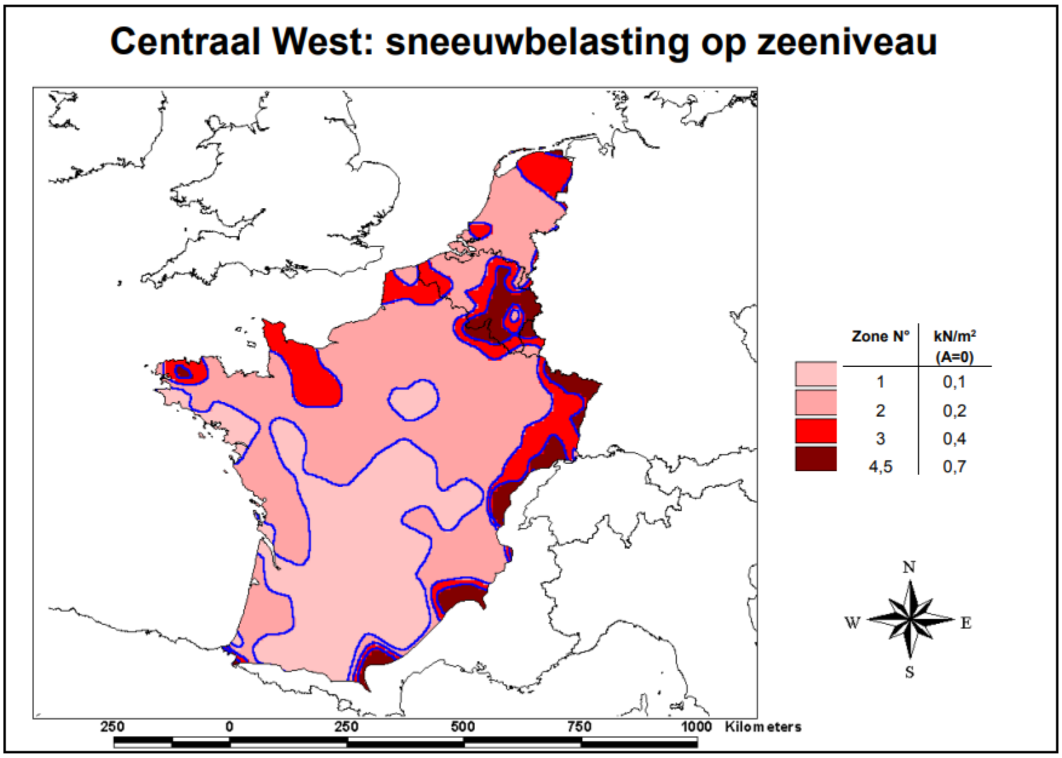

Figure B.20: Central west snow area [111]

C

Appendix C: Cross sections

In this appendix, a summary of the cross sections that will be used for the parametric model is given.

Steel rolled elements:

- HEA 100-1000
- HEB 100-1000
- HEM 100-1000
- IPE 80-600
- L (angle) w x h x t = 40 x 40 x 4 - 80 x 80 x 8 mm

Steel hollow elements:

- SHS w x h = 40-400 mm; t = 2.6-20 mm
- CHS ø= 21-1219 mm; t = 2.3-25 mm
- RHS w x h x t = 50 x 30 x 2.6 - 500 x 300 x 20 mm

Glulam elements:

- Rectangular sections of b x h = 80 x 120 - 240 x 1280 mm

Table C.1: List of steel rolled sections

Steel rolled sections			
IPE 80	HEA 100	HEB 100	HEM 100
IPE 100	HEA 120	HEB 120	HEM 120
IPE 120	HEA 140	HEB 140	HEM 140
IPE 140	HEA 160	HEB 160	HEM 160
IPE 160	HEA 180	HEB 180	HEM 180
IPE 180	HEA 200	HEB 200	HEM 200
IPE 200	HEA 220	HEB 220	HEM 220
IPE 220	HEA 240	HEB 240	HEM 240
IPE 240	HEA 260	HEB 260	HEM 260
IPE 270	HEA 280	HEB 280	HEM 280
IPE 300	HEA 300	HEB 300	HEM 300
IPE 330	HEA 320	HEB 320	HEM 320
IPE 360	HEA 340	HEB 340	HEM 340
IPE 400	HEA 360	HEB 360	HEM 360
IPE 450	HEA 400	HEB 400	HEM 400
IPE 500	HEA 450	HEB 450	HEM 450
IPE 550	HEA 500	HEB 500	HEM 500
IPE 600	HEA 550	HEB 550	HEM 550
	HEA 600	HEB 600	HEM 600
	HEA 650	HEB 650	HEM 650
	HEA 700	HEB 700	HEM 700
	HEA 800	HEB 800	HEM 800
	HEA 900	HEB 900	HEM 900
	HEA 1000	HEB 1000	HEM 1000

Table C.2: List of steel hollow sections

Steel hollow sections		
CHS 21.3 / 2.3	SHS 40 / 2.6	RHS 50x30 / 2.6
CHS 21.3 / 2.6	SHS 40 / 3.2	RHS 50x30 / 3.2
CHS 21.3 / 3.2	SHS 40 / 4	RHS 50x30 / 4
CHS 26.9 / 2.3	SHS 40 / 5	RHS 50x30 / 5
CHS 26.9 / 2.6	SHS 50 / 2.6	RHS 60x40 / 2.6
CHS 26.9 / 3.2	SHS 50 / 3.2	RHS 60x40 / 3.2
CHS 33.7 / 2.6	SHS 50 / 4	RHS 60x40 / 4
CHS 33.7 / 3.2	SHS 50 / 5	RHS 60x40 / 5
CHS 33.7 / 4	SHS 50 / 6.3	RHS 60x40 / 6.3
CHS 42.4 / 2.6	SHS 60 / 2.6	RHS 80x40 / 3.2
CHS 42.4 / 3.2	SHS 60 / 3.2	RHS 80x40 / 4
CHS 42.4 / 4	SHS 60 / 4	RHS 80x40 / 5
CHS 48.3 / 2.6	SHS 60 / 5	RHS 80x40 / 6.3
CHS 48.3 / 3.2	SHS 60 / 6.3	RHS 80x40 / 8
CHS 48.3 / 4	SHS 60 / 8	RHS 90x50 / 3.2
CHS 48.3 / 5	SHS 70 / 3.2	RHS 90x50 / 4
CHS 60.3 / 2.6	SHS 70 / 4	RHS 90x50 / 5
CHS 60.3 / 3.2	SHS 70 / 5	RHS 90x50 / 6.3
CHS 60.3 / 4	SHS 70 / 6.3	RHS 90x50 / 8
CHS 60.3 / 5	SHS 70 / 8	RHS 100x50 / 3.2
CHS 76.1 / 2.6	SHS 80 / 3.2	RHS 100x50 / 4
CHS 76.1 / 3.2	SHS 80 / 4	RHS 100x50 / 5
CHS 76.1 / 4	SHS 80 / 5	RHS 100x50 / 6.3
CHS 76.1 / 5	SHS 80 / 6.3	RHS 100x50 / 8
CHS 88.9 / 3.2	SHS 80 / 8	RHS 100x60 / 3.2
CHS 88.9 / 4	SHS 90 / 4	RHS 100x60 / 4
CHS 88.9 / 5	SHS 90 / 5	RHS 100x60 / 5
CHS 88.9 / 6.3	SHS 90 / 6.3	RHS 100x60 / 6.3
CHS 101.6 / 3.2	SHS 90 / 8	RHS 100x60 / 8
CHS 101.6 / 4	SHS 100 / 4	RHS 120x60 / 4
CHS 101.6 / 5	SHS 100 / 5	RHS 120x60 / 5
CHS 101.6 / 6.3	SHS 100 / 6.3	RHS 120x60 / 6.3
CHS 101.6 / 8	SHS 100 / 8	RHS 120x60 / 8
CHS 101.6 / 10	SHS 100 / 10	RHS 120x60 / 10
CHS 114.3 / 3.2	SHS 120 / 5	RHS 120x80 / 4
CHS 114.3 / 4	SHS 120 / 6.3	RHS 120x80 / 5
CHS 114.3 / 5	SHS 120 / 8	RHS 120x80 / 6.3
CHS 114.3 / 6.3	SHS 120 / 10	RHS 120x80 / 8
CHS 114.3 / 8	SHS 120 / 12.5	RHS 120x80 / 10
CHS 114.3 / 10	SHS 140 / 5	RHS 140x80 / 4
CHS 139.7 / 4	SHS 140 / 6.3	RHS 140x80 / 5
CHS 139.7 / 5	SHS 140 / 8	RHS 140x80 / 6.3
CHS 139.7 / 6.3	SHS 140 / 10	RHS 140x80 / 8
CHS 139.7 / 8	SHS 140 / 12.5	RHS 140x80 / 10
CHS 139.7 / 10	SHS 150 / 5	RHS 150x100 / 4
CHS 139.7 / 12.5	SHS 150 / 6.3	RHS 150x100 / 5
CHS 168.3 / 4	SHS 150 / 8	RHS 150x100 / 6.3
CHS 168.3 / 5	SHS 150 / 10	RHS 150x100 / 8
CHS 168.3 / 6.3	SHS 150 / 12.5	RHS 150x100 / 10
CHS 168.3 / 8	SHS 150 / 14.2	RHS 150x100 / 12.5
CHS 168.3 / 10	SHS 150 / 16	RHS 160x80 / 4
CHS 168.3 / 12.5	SHS 160 / 5	RHS 160x80 / 5
CHS 177.8 / 5	SHS 160 / 6.3	RHS 160x80 / 6.3
CHS 177.8 / 6.3	SHS 160 / 8	RHS 160x80 / 8
CHS 177.8 / 8	SHS 160 / 10	RHS 160x80 / 10
CHS 177.8 / 10	SHS 160 / 12.5	RHS 160x80 / 12.5
CHS 177.8 / 12.5	SHS 160 / 14.2	RHS 180x100 / 4
CHS 193.7 / 5	SHS 160 / 16	RHS 180x100 / 5
CHS 193.7 / 6.3	SHS 180 / 5	RHS 180x100 / 6.3
CHS 193.7 / 8	SHS 180 / 6.3	RHS 180x100 / 8
CHS 193.7 / 10	SHS 180 / 8	RHS 180x100 / 10
CHS 193.7 / 12.5	SHS 180 / 10	RHS 180x100 / 12.5
CHS 193.7 / 14.2	SHS 180 / 12.5	RHS 200x100 / 4
CHS 193.7 / 16	SHS 180 / 14.2	RHS 200x100 / 5
CHS 219.1 / 5	SHS 180 / 16	RHS 200x100 / 6.3
CHS 219.1 / 6.3	SHS 200 / 5	RHS 200x100 / 8
CHS 219.1 / 8	SHS 200 / 6.3	RHS 200x100 / 10
CHS 219.1 / 10	SHS 200 / 8	RHS 200x100 / 12.5
CHS 219.1 / 12.5	SHS 200 / 10	RHS 200x100 / 16
CHS 219.1 / 14.2	SHS 200 / 12.5	RHS 200x120 / 6.3
CHS 219.1 / 16	SHS 200 / 14.2	RHS 200x120 / 8
CHS 219.1 / 20	SHS 200 / 16	RHS 200x120 / 10
CHS 244.5 / 5	SHS 220 / 6.3	RHS 200x120 / 12.5
CHS 244.5 / 6.3	SHS 220 / 8	RHS 250x150 / 6.3
CHS 244.5 / 8	SHS 220 / 10	RHS 250x150 / 8
CHS 244.5 / 10	SHS 220 / 12.5	RHS 250x150 / 10
CHS 244.5 / 12.5	SHS 220 / 14.2	RHS 250x150 / 12.5
CHS 244.5 / 14.2	SHS 220 / 16	RHS 250x150 / 14.2
CHS 244.5 / 16	SHS 250 / 6.3	RHS 250x150 / 16
CHS 244.5 / 20	SHS 250 / 8	RHS 260x180 / 6.3
CHS 244.5 / 25	SHS 250 / 10	RHS 260x180 / 8
CHS 273 / 5	SHS 250 / 12.5	RHS 260x180 / 10
CHS 273 / 6.3	SHS 250 / 14.2	RHS 260x180 / 12.5
CHS 273 / 8	SHS 250 / 16	RHS 260x180 / 14.2
CHS 273 / 10	SHS 260 / 6.3	RHS 260x180 / 16
CHS 273 / 12.5	SHS 260 / 8	RHS 300x200 / 6.3
CHS 273 / 14.2	SHS 260 / 10	RHS 300x200 / 8
CHS 273 / 16	SHS 260 / 12.5	RHS 300x200 / 10
CHS 273 / 20	SHS 260 / 14.2	RHS 300x200 / 12.5
CHS 273 / 25	SHS 260 / 16	RHS 300x200 / 14.2
CHS 323.9 / 5	SHS 300 / 6.3	RHS 300x200 / 16
CHS 323.9 / 6.3	SHS 300 / 8	RHS 350x250 / 6.3
CHS 323.9 / 8	SHS 300 / 10	RHS 350x250 / 8
CHS 323.9 / 10	SHS 300 / 12.5	RHS 350x250 / 10
CHS 323.9 / 12.5	SHS 300 / 14.2	RHS 350x250 / 12.5
CHS 323.9 / 14.2	SHS 300 / 16	RHS 350x250 / 14.2
CHS 323.9 / 16	SHS 350 / 8	RHS 350x250 / 16
CHS 323.9 / 20	SHS 350 / 10	RHS 400x200 / 8
CHS 323.9 / 25	SHS 350 / 12.5	RHS 400x200 / 10
CHS 355.6 / 6.3	SHS 350 / 14.2	RHS 400x200 / 12.5
CHS 355.6 / 8	SHS 350 / 16	RHS 400x200 / 14.2
CHS 355.6 / 10	SHS 400 / 10	RHS 400x200 / 16
CHS 355.6 / 12.5	SHS 400 / 12.5	RHS 450x250 / 8
CHS 355.6 / 14.2	SHS 400 / 14.2	RHS 450x250 / 10
CHS 355.6 / 16	SHS 400 / 16	RHS 450x250 / 12.5
CHS 355.6 / 20	SHS 400 / 20	RHS 450x250 / 14.2
CHS 355.6 / 25		RHS 450x250 / 16
CHS 406.4 / 6.3		RHS 500x300 / 10
CHS 406.4 / 8		RHS 500x300 / 12.5
CHS 406.4 / 10		RHS 500x300 / 14.2
CHS 406.4 / 12.5		RHS 500x300 / 16
CHS 406.4 / 14.2		RHS 500x300 / 20
CHS 406.4 / 16		
CHS 406.4 / 20		
CHS 406.4 / 25		
CHS 406.4 / 30		
CHS 406.4 / 40		
CHS 457 / 6.3		
CHS 457 / 8		
CHS 457 / 10		
CHS 457 / 12.5		
CHS 457 / 14.2		
CHS 457 / 16		
CHS 457 / 20		
CHS 457 / 25		
CHS 457 / 30		
CHS 457 / 40		
CHS 508 / 6.3		
CHS 508 / 8		
CHS 508 / 10		
CHS 508 / 12.5		
CHS 508 / 14.2		
CHS 508 / 16		
CHS 508 / 20		
CHS 508 / 25		
CHS 508 / 30		
CHS 508 / 40		
CHS 508 / 50		
CHS 610 / 6.3		
CHS 610 / 8		
CHS 610 / 10		
CHS 610 / 12.5		
CHS 610 / 14.2		
CHS 610 / 16		
CHS 610 / 20		
CHS 610 / 25		
CHS 610 / 30		
CHS 610 / 40		
CHS 610 / 50		
CHS 711 / 6.3		
CHS 711 / 8		
CHS 711 / 10		
CHS 711 / 12.5		
CHS 711 / 14.2		
CHS 711 / 16		
CHS 711 / 20		
CHS 711 / 25		
CHS 711 / 30		
CHS 711 / 40		
CHS 711 / 50		
CHS 711 / 60		
CHS 762 / 6.3		
CHS 762 / 8		
CHS 762 / 10		
CHS 762 / 12.5		
CHS 762 / 14.2		
CHS 762 / 16		
CHS 762 / 20		
CHS 762 / 25		
CHS 762 / 30		
CHS 762 / 40		
CHS 762 / 50		
CHS 813 / 8		
CHS 813 / 10		
CHS 813 / 12.5		
CHS 813 / 14.2		
CHS 813 / 16		
CHS 813 / 20		
CHS 813 / 25		
CHS 813 / 30		
CHS 914 / 8		
CHS 914 / 10		
CHS 914 / 12.5		
CHS 914 / 14.2		
CHS 914 / 16		
CHS 914 / 20		
CHS 914 / 25		
CHS 914 / 30		

Table C.3: Standard packing units straight glulam beams [110]

Height in mm	t unit	m^3 cm	t unit	m^3 cm	t unit	m^3 cm	t unit	m^3 cm	t unit	m^3 cm	t unit	m^3 cm	t unit	m^3 cm	t unit	m^3 cm
1,280	2.5 **4**	5.5 128 x 32	3.1 **4**	6.9 128 x 40	1.9 **2**	4.1 128 x 24	2.2 **2**	4.8 128 x 28	1.2 **1**	2.8 128 x 16	1.4 **1**	3.1 128 x 18	1.6 **1**	3.5 128 x 20	1.9 **1**	4.1 128 x 24
1,240	2.4 **4**	5.4 124 x 32	3.0 **4**	6.7 124 x 40	1.8 **2**	4.0 124 x 24	2.1 **2**	4.7 124 x 28	2.4 **2**	5.4 124 x 32	1.4 **1**	3.0 124 x 18	1.5 **1**	3.3 124 x 20	1.8 **1**	4.0 124 x 24
1,200	2.3 **4**	5.2 120 x 32	2.9 **4**	6.5 120 x 40	1.7 **2**	3.9 120 x 24	2.0 **2**	4.5 120 x 28	2.3 **2**	5.2 120 x 32	1.3 **1**	2.9 120 x 18	1.5 **1**	3.2 120 x 20	1.7 **1**	3.9 120 x 24
1,160	2.3 **4**	5.0 116 x 32	2.8 **4**	6.3 116 x 40	1.7 **2**	3.8 116 x 24	2.0 **2**	4.4 116 x 28	2.3 **2**	5.0 116 x 32	1.3 **1**	2.8 116 x 18	1.4 **1**	3.1 116 x 20	1.7 **1**	3.8 116 x 24
1,120	2.2 **4**	4.8 112 x 32	2.7 **4**	6.0 112 x 40	1.6 **2**	3.6 112 x 24	1.9 **2**	4.2 112 x 28	2.2 **2**	4.8 112 x 32	2.4 **2**	5.4 112 x 36	1.4 **1**	3.0 112 x 20	1.6 **1**	3.6 112 x 24
1,080	2.1 **4**	4.7 108 x 32	2.6 **4**	5.8 108 x 40	1.6 **2**	3.5 108 x 24	1.8 **2**	4.1 108 x 28	2.1 **2**	4.7 108 x 32	2.4 **2**	5.2 108 x 36	1.3 **1**	2.9 108 x 20	1.6 **1**	3.5 108 x 24
1,040	2.0 **4**	4.5 104 x 32	2.5 **4**	5.6 104 x 40	1.5 **2**	3.4 104 x 24	1.8 **2**	3.9 104 x 28	2.0 **2**	4.5 104 x 32	2.3 **2**	5.1 104 x 36	1.3 **1**	2.8 104 x 20	1.5 **1**	3.4 104 x 24
1,000	1.9 **4**	4.3 100 x 32	2.4 **4**	5.4 100 x 40	1.5 **2**	3.2 100 x 24	1.7 **2**	3.8 100 x 28	1.9 **2**	4.3 100 x 32	2.2 **2**	4.9 100 x 36	2.4 **2**	5.4 100 x 40	2.9 **2**	6.5 100 x 48
960	1.9 **4**	4.1 96 x 32	2.3 **4**	5.2 96 x 40	1.4 **2**	3.1 96 x 24	1.6 **2**	3.6 96 x 28	1.9 **2**	4.1 96 x 32	2.1 **2**	4.7 96 x 36	2.3 **2**	5.2 96 x 40	2.8 **2**	6.2 96 x 48
920	1.8 **4**	4.0 92 x 32	2.2 **4**	5.0 92 x 40	1.3 **2**	3.0 92 x 24	1.6 **2**	3.5 92 x 28	1.8 **2**	4.0 92 x 32	2.0 2	4.5 92 x 36	2.2 **2**	5.0 92 x 40	2.7 **2**	6.0 92 x 48
880	1.7 **4**	3.8 88 x 32	2.1 **4**	4.8 88 x 40	1.3 **2**	2.9 88 x 24	1.5 **2**	3.3 88 x 28	1.7 **2**	3.8 88 x 32	1.9 **2**	4.3 88 x 36	2.1 **2**	4.8 88 x 40	2.6 **2**	5.7 88 x 48
840	1.6 **4**	3.6 84 x 32	2.0 4	4.5 84 x 40	1.2 **2**	2.7 84 x 24	1.4 **2**	3.2 84 x 28	1.6 **2**	3.6 84 x 32	1.8 **2**	4.1 84 x 36	2.0 **2**	4.5 84 x 40	2.4 **2**	5.4 84 x 48
800	1.6 **4**	3.5 80 x 32	1.9 **4**	4.3 80 x 40	1.2 **2**	2.6 80 x 24	1.4 **2**	3.0 80 x 28	1.6 **2**	3.5 80 x 32	1.7 **2**	3.9 80 x 36	1.9 **2**	4.3 80 x 40	2.3 **2**	5.2 80 x 48
760	1.5 **4**	3.3 76 x 32	1.8 **4**	4.1 76 x 40	1.1 **2**	2.5 76 x 24	1.3 **2**	2.9 76 x 28	1.5 **2**	3.3 76 x 32	1.7 **2**	3.7 76 x 36	1.8 **2**	4.1 76 x 40	2.2 **2**	4.9 76 x 48
720	1.4 **4**	3.1 72 x 32	1.7 **4**	3.9 72 x 40	1.0 **2**	2.3 72 x 24	1.2 **2**	2.7 72 x 28	1.4 **2**	3.1 72 x 32	1.6 **2**	3.5 72 x 36	1.7 **2**	3.9 72 x 40	2.1 **2**	4.7 72 x 48
680	1.3 **4**	2.9 68 x 32	1.7 **4**	3.7 68 x 40	1.0 **2**	2.2 68 x 24	1.2 **2**	2.6 68 x 28	1.3 **2**	2.9 68 x 32	1.5 **2**	3.3 68 x 36	1.7 **2**	3.7 68 x 40	2.0 **2**	4.4 68 x 48
640	1.2 **4**	2.8 64 x 32	1.6 **4**	3.5 64 x 40	0.9 **2**	2.1 64 x 24	1.1 **2**	2.4 64 x 28	1.2 **2**	2.8 64 x 32	1.4 **2**	3.1 64 x 36	1.6 **2**	3.5 64 x 40	1.9 **2**	4.1 64 x 48
600	2.3 **8**	5.2 120 x 32	2.9 **8**	6.5 120 x 40	1.7 **4**	3.9 120 x 24	2.0 4	4.5 120 x 28	2.3 **4**	5.2 120 x 32	2.6 **4**	5.8 120 x 36	2.9 **4**	6.5 120 x 40	3.5 **4**	7.8 120 x 48
560	2.2 **8**	4.8 112 x 32	2.7 **8**	6.0 112 x 40	1.6 **4**	3.6 112 x 24	1.9 **4**	4.2 112 x 28	2.2 **4**	4.8 112 x 32	2.4 **4**	5.4 112 x 36	2.7 **4**	6.0 112 x 40	3.3 **4**	7.3 112 x 48
520	2.0 **8**	4.5 104 x 32	2.5 **8**	5.6 104 x 40	1.5 **4**	3.4 104 x 24	1.8 **4**	3.9 104 x 28	2.0 **4**	4.5 104 x 32	2.3 **4**	5.1 104 x 36	2.5 **4**	5.6 104 x 40	3.0 **4**	6.7 104 x 48
480	1.9 **8**	4.1 96 x 32	2.3 **8**	5.2 96 x 40	1.4 **4**	3.1 96 x 24	1.6 **4**	3.6 96 x 28	1.9 **4**	4.1 96 x 32	2.1 **4**	4.7 96 x 36	2.3 **4**	5.2 96 x 40	2.8 **4**	6.2 96 x 48
440	1.7 **8**	3.8 88 x 32	2.1 8	4.8 88 x 40	1.3 **4**	2.9 88 x 24	1.5 **4**	3.3 88 x 28	1.7 **4**	3.8 88 x 32	1.9 **4**	4.3 88 x 36	2.1 **4**	4.8 88 x 40	2.6 **4**	5.7 88 x 48
400	2.3 **12**	5.2 120 x 32	2.9 **12**	6.5 120 x 40	1.7 **6**	3.9 120 x 24	2.0 **6**	4.5 120 x 28	2.3 **6**	5.2 120 x 32	2.6 **6**	5.8 120 x 36	2.9 **6**	6.5 120 x 40	3.5 **6**	7.8 120 x 48
360	2.1 **12**	4.7 108 x 32	2.6 **12**	5.8 108 x 40	1.6 **6**	3.5 108 x 24	1.8 **6**	4.1 108 x 28	2.1 **6**	4.7 108 x 32	2.4 **6**	5.2 108 x 36	2.6 **6**	5.8 108 x 40	3.1 6	7.0 108 x 48
320	1.9 **12**	4.1 96 x 32	2.3 **12**	5.2 96 x 40	1.4 **6**	3.1 96 x 24	1.6 **6**	3.6 96 x 28	1.9 **6**	4.1 96 x 32	2.1 **6**	4.7 96 x 36	2.3 **6**	5.2 96 x 40	2.8 **6**	6.2 96 x 48
280	2.2 **16**	4.8 112 x 32	2.7 **16**	6.0 112 x 40	1.6 **8**	3.6 112 x 24	1.9 **8**	4.2 112 x 28	2.2 **8**	4.8 112 x 32	2.4 **8**	5.4 112 x 36	2.7 **8**	6.0 112 x 40	1.6 **8**	7.3 112 x 48
240	2.3 **20**	5.2 120 x 32	2.9 **20**	6.5 120 x 40	1.7 **10**	3.9 120 x 24	2.0 **10**	4.5 120 x 28	2.3 **10**	5.2 120 x 32	2.6 **10**	5.8 120 x 36	2.9 **10**	6.5 120 x 40	3.5 **10**	7.8 120 x 48
200	2.3 **24**	5.2 120 x 32	2.9 **24**	6.5 120 x 40	1.7 **12**	3.9 120 x 24	2.0 **12**	4.5 120 x 28	2.3 **12**	5.2 120 x 32	2.6 **12**	5.8 120 x 36	2.9 **12**	6.5 120 x 40		
160	2.2 **28**	4.8 112 x 32	2.7 **28**	6.0 112 x 40	1.6 **14**	3.6 112 x 24	1.9 **14**	4.2 112 x 28	2.2 **14**	4.8 112 x 32						
120	2.3 **40**	5.2 120 x 32	2.9 **40**	6.5 120 x 40	1.7 **20**	3.9 120 x 24										
Width in mm	80		100		120		140		160		180		200		240	

260 mm and 280 mm widths are available on request. Can be expanded by block bonding if desired. Heights up to 4.000 mm are possible

Table C.4: Breakdown of structural elements in Coca Cola 27

	OCPF	FC	TTC	TBC	TD	P	LSR	SSR	Total
Type	HEA550	IPE360	HEA160	HEA160	SHS80x4	IPE300	IPE300	SHS120x5	
Weight/m	166,2	57,1	30,4	30,4	9,41	42,2	42,2	17,8	
Length	12,5	12,5	45	45	3,75	10	5	5,625	
Amount	44	64	22	22	660	207	128	32	
Connections	hinged	hinged	-	-	-	hinged	hinged	hinged	
MKI	3165,5	1581,9	1042,2	1049,9	812,5	3025,0	935,3	111,8	**11724,0**
CSC	569,8	284,7	187,6	189,0	146,2	544,5	168,3	20,1	**2110,3**
J.W. CSC	633,092851	316,373279	208,4406787	209,9819006	162,4942175	605,0015633	187,0536234	22,35453248	**2344,8**
Price	348777,0	184376,0	122490,7	248292,0	192140,4	372889,8	130649,6	31710,0	**1631325,6**
Volume	11,6	5,8	3,8	3,8	3,0	11,1	3,4	0,4	**43,1**

Table C.5: Breakdown of structural elements in Newlogic

	OCPF	FC	IC	TTC	TBC	TD	P	EP	SR	Total
Type	HEA260	IPE360	K260/260/10	HEA240	K140/140/5	K120x120x5	IPE400	HEA180	K180/100/5	
Weight/m	68,2	57,1	77,7	60,3	21	17,8	66,3	35,5	21	
Length	12,75	12,75	12,75	18	18	3,3	18	18	6	
Amount	14	58	25	30	30	180	102	12	216	
Connections	hinged	fixed	fixed	-	-	-	fixed	fixed	fixed	
MKI [€]	421,6	1462,2	864,0	1127,6	395,6	368,8	4215,3	265,5	949,4	**10070,1**
CSC [€]	362,5473634	1257,524464	743,0409552	969,7353514	340,2158904	317,2108159	3625,169866	228,3622221	816,5181371	**8660,3**
J.W. CSC [€]	316,1750262	1096,678312	648,000833	845,6994344	296,6999045	276,6373395	3161,485348	199,1531006	712,0797707	**7552,6**
Price [€]	48402,7	176534,2	194501,6	132527,3	93555,0	87228,9	486089,2	32571,6	279720,0	**1531130,4**
Volume [m3]	1,6	5,4	3,2	4,1	1,4	1,3	15,5	1,0	3,5	**37,0**

*The following acronyms were used in the tables above: OCPF = Outer columns portal frame, FC = Facade columns, IC = Internal columns, TTC = Truss top chord, TBC = Truss bottom chord, TD = Truss diagonals, P = Purlins, LSR = Long side rails, SSR = Short side rails, SR = Side rails.


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