Exploration of the design space for a sustainable Overhead Contact Line support structure on the Dutch main rail network

An Integrated Approach to Sustainable Design: Multi-Disciplinary Analysis and Multi-Objective Optimisation using the NSGA-II Algorithm

TU Delft

SWECO

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An Integrated Approach to Sustainable Design:

Multi-Disciplinary Analysis and Multi-Objective Optimisation using the NSGA-II Algorithm

By

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in partial fulfilment of the requirements for the degree of

Master of Science

in Transport, Infrastructure and Logistics

at the Delft University of Technology,

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Contents

Summary

The overhead contact line system (OCLS) is one of the key systems of an electrified railway network. Due to the importance of the OCLS in relation to the operational status of the rail network, the reliability and maintenance of the system are important factors to maintain an operational network. However, due to the complexity of the design process, the design space and key design variables for a sustainable support structure are not well defined. Therefore, this research aims to develop a multi-objective optimisation model which can be used to define and quantify the sustainability of the support structure. The model uses the NSGA-II algorithm to explore the design spaces and determine the Pareto frontier.

Problem Statement

ProRail is tasked with replacing and enhancing the sustainability of the Overhead Catenary System Line Structures (OCLS) within its rail network. Studies conducted by Ecofys in 2010 and TNO in 2011, cited as [1] and [2] respectively, explored the carbon footprint and potential sustainable designs of these structures. The findings indicated that concrete structures could significantly reduce CO2 emissions, though no subsequent changes were implemented in the main rail network. Current pressures from climate regulations and the need for sustainable infrastructure highlight the urgency of addressing these issues. Key unresolved questions include sustainable manufacturing methods for support structures and potential design improvements to enhance sustainability.

The main objective of this research is to identify the key design variables that contribute to the sustainable design of support structures for Overhead Contact Lines System within the Dutch railway network.

Literature Review

The literature review on overhead contact line support structures is presented. The review is carried out using a keyword based search method. A taxonomy proposed by Sedghi, Kauppila, Bergquist, *et al.* is used to classify the research. The main knowledge gaps identified indicate a general need for more in-depth research on the impact and influence of sustainability, particularly during the design and lifecycle of these structures. There is also interest in a more systematic approach to maintenance planning using decision frameworks/systems, and a trend towards more complex models to take into account different aspects that influence decision making. However, despite the increasing importance of sustainability and the research interest in related areas, there is limited information on this topic in the reviewed literature.

Design Proccess and Stakeholders

The design of support structures for the OCLS is a complex process which involves a variety of stakeholders. The purpose of this chapter is to enhance the understanding of the context surrounding the design process for a new and sustainable support structure for the OCLS and to identify the roles of each stakeholder involved in this process. In particular, it explains ProRail's established design protocols and the systematic approach to designing a support structure. The stakeholder analysis highlights the critical role of collaborative efforts in achieving successful design outcomes.

Design Requirements and Specifications

An overview and review of the design requirements and specifications for OCLS is provided on the main Dutch railway network. The aim is to identify the essential requirements and specification for the design of a new superstructure that complies with the relevant regulations and standards. The main focus of the requirements is to achieve an acceptable level of reliability in an economically viable manner, ensuring a robust design to improve safety and minimise the risk of human injury. These requirements are then categorised into functional, nonfunctional and constraint types, providing further insight into their purpose and impact on potential designs of the support structure. This provides valuable insights into the limitations and opportunities for designing a support structure that is both feasible and compliant with regulatory standards. Designers can achieve an optimal solution that prioritises both safety and cost efficiency by carefully assessing trade-offs so that, in addition to safety requirements, economic ones could also be identified as essential.

Sustainability within the Dutch Rail Branch

The concept of sustainability within the Dutch railway branch is explored, including its definition, objectives, and measurement methods. Through an examination of various policy documents and initiatives, including the Brundtland Report, the Paris Climate Agreement, the European Green Deal, the Dutch Climate Agreement and the National Circular Economy Programme, valuable insights are gained into the fundamental principles and dimensions of sustainability provided by these documents. In addition, the importance of equity, inclusivity, and responsible stewardship of natural resources in shaping a sustainable future is highlighted. ProRail provides an example within the rail sector of a proactive approach to integrating sustainability into core business practices. Furthermore, methodologies such as LCA, the ECI, and the circularity indicator provide systematic approaches to assess and quantify the environmental impacts of railway projects and offer a standardised framework for evaluating the protection of material stocks, environmental impact, and preservation of existing value throughout the project lifecycle.

Formulation of Multi-Objective Optimisation Model

The formulation of a multi-objective optimisation problem for the design of support structures with minimal environmental and economic impact, focussing on safety, sustainability, and cost-effectiveness. The assumptions and methodologies used in developing a model for a support structure along the Dutch rail network are described, focussing on the design for the pole. The formulation of objective functions for the design of a pole with minimal environmental and economic impacts is described. The optimisation algorithm NSGA-II (Non-Dominate Sorting Genetic Algorithm II) used for multiobjective optimisation (MOO) is discussed. To test these states, the design is validated by formulating a structural and load model taking into account the design conditions and load cases specified in the RLN0009 and NEN-EN 50119 for support structures.

Implementation of Multi-Objective Optimisation Model

The framework incorporates advanced filtering mechanisms and uses a robust fitness function that integrates constraint scores to evaluate the feasibility of solutions. Design variables such as the material, shape, and dimensions of the pole are defined to specify the gene space. An initial population is generated randomly from this gene space and population filtering is applied to enhance solution quality by focussing on feasibility. The fitness function is detailed, emphasising the evaluation of solutions against defined constraints, with a scoring system that penalises constraint violations. This model aims to optimise design solutions by balancing structural requirements and design constraints, thus ensuring that only the most feasible solutions are carried forward in the genetic algorithm process.

The model utilises the NSGA-II genetic algorithm, integrating structural analysis and environmental impact assessment. The material data used for the model was obtained from Granta Edupack. Ten pole shapes are considered, with dimensions constrained within practical limits. The model is implemented in Python, using PyGad for optimisation and PyNite for structural analysis. Validation encompasses structural, environmental, and optimisation aspects. Structural analysis is validated against expert review and reference calculations, while the environmental data is compared with the results of the NMD life cycle assessment on the current poles used in a support structure. The optimisation model is validated through consistency checks and hyper-volume analysis. Results indicate stability and consistency in finding non-dominated solutions, despite the observed fluctuations. In general, the model provides valuable insight for pole design, serving as a base framework for future research and practical applications.

Two cases were formulated within the scope of the research, differing in the design of the support structure: one with a single-pole configuration and the other with a portal design. The model optimised only the pole design, considering various parameters and material properties. Simulations were performed for different material datasets, including all materials, ceramics, and metals, to evaluate their impact on the objectives.

Results

The results show significant differences in performance on the basis of material selection. Metal (non-ferrous) designs generally exhibited higher costs and CO_2 footprints compared to other materials. Ceramic (non-technical) materials showed potential for reducing costs and emissions. Deflection analysis revealed that all material designs adhered to specified constraints, with non-ferrous metals exhibiting superior circular efficiency. Analysis of pole shape properties and parameters highlighted trade-offs between material properties, structural designs, and sustainability objectives. The T beam and ferrous materials dominated the designs, emphasising the importance of material selection in optimising sustainability. Challenges such as deflection on the contact wire underscored the need for ongoing assessment and modification during the design process.

In general, the results emphasises a balanced approach to material and shape selection to meet specific requirements and environmental impact. It underscores the effectiveness of certain materials and designs in achieving optimal performance and advancing sustainable design in rail infrastructure. This research contributes to the advancement of the sustainability of rail infrastructure by highlighting key factors for sustainable support structures and highlighting the crucial role of collaboration, regulatory compliance, and stakeholder participation in achieving sustainable rail infrastructure solutions.

Discussion

The Dutch rail network is highly regulated. This research aims to highlight the significant roles of sustainability and circulation in rail infrastructure. The study identified the potential to integrate these aspects into the design. The integration of these aspects contributes to efficient and environmentally sustainable rail network. The design process and stakeholders were reviewed. In addition, a detailed analysis of the relevant standards and design specifications was performed. The essential requirements identified are a balance between safety and economic considerations. The results also indicated the importance of circularity as an aspect of the sustainability of the design space.

Conclusion

The essential requirements and design specifications for an OCLS support structure in the Dutch rail network, focussing on balancing safety and economic considerations. It highlights the importance of sustainability, emphasising Life Cycle Assessment (LCA) and circularity in material reuse. Key design parameters include material properties, pole shape, and the interaction between these elements to optimise design and sustainability. The research also discusses the influence of material selection on sustainability, noting the trade-offs between cost, structural integrity, and environmental impact. The main design variables identified for sustainable OCLS support structures are material choice, cost-CO2 footprint trade-offs, and material circularity, with an emphasis on optimising material selection to enhance sustainability while considering cost implications.

Recommendations

Further research and development in sustainable rail infrastructure, the following recommendations improving the sustainability of rail systems to meet current specifications, conducting comparative sustainability studies between different train systems, and implementing circular design principles for net zero emissions. In addition, the study suggests integrating environmental cost indicators and specific material standards into models to improve decision making and sustainability in industry practices. Future research should also explore material properties per functional unit and expand datasets to enhance structural solutions.

Preface

This thesis marks the end of the study in Delft and is the last step in my academic career. It also marks the day which most people thought would never come, after my studying for almost 12.5 years in Delft, combined for the last years with work as well as being a father to Luuk. As my brother said whilst I was writing this thesis, 'Well, it wasn't complex enough for Bram, so he thought he'd combine this as well'. That reflects my study in Delft along with my inexhaustible optimism, which , together with my stubbornness, has not always resulted in the best choices. However, it finally resulted in this thesis, and I would like to take this opportunity to thank everyone who helped me over the years with my studies.

For me, this thesis period has had its ups and downs, but it also motivated me to complete my studies at TU Delft. Nonetheless, without the help of many people, the completion of the research would not have been possible.

First, I would like to thank my graduation committee at TU Delft, consisting of Valeri Markine, Hongrui Wang, and Wijnand Veeneman. Thank you for your guidance and patience during the project, especially in trying to understand the more frequent chaotic presentations of my progress and the delays during my thesis. To Valeri, thank you for letting me graduate under your responsibility, providing guidance throughout each stage of the process, particularly the insightful feedback you gave during our meetings and the freedom you allowed for my research. To Hongrui, thank you for your supervision and support during our weekly meetings in the past months, which provided opportunities to share my thoughts on my research. Your help kept me focussed when I found another interesting side track. To Wijnand, thank you for joining us at a later stage as a replacement for Epek and also for challenging me in the later phases of my research and helping me place it in a broader context. Your useful feedback during our meetings helped me greatly clarify my thoughts and ideas.

I also would like to extend a thank you to all the colleagues I met at the Department Rail and Stations at Sweco but specifically to Jaap Jan Krikken and Wim Golverdingen of the Bovenleiding team (as my supervisors) and Ariaan Heiningen. To Jaap Jan, thank you for having enthusiasm for my project, pushing me to get over the finish line, and providing me with a place to conduct my thesis project. Thank you also for all the talks we had during my thesis. To Wim, thank you for your calming guidance throughout the entire process and in-depth discussions we had on the cantenary systems and support structures, placing my research into a practical perspective. I would also like to thank Ariaan for all the talks and time when I had questions about the rail branch. It was more than pleasant working next to you during my thesis process.

Special thanks go to all my family and friends, who are very close to my heart. Specifically, thanks to my parents, Johan and Will, for their unconditional love and constant support throughout my studies. I thank my brother, Peter, and his wife, Nikita, for their support as well during my thesis. Another person I would like to thank is my girlfriend, Gwen, who is the mother to our son, Luuk. She has shown more love, support, and patience during this thesis period than I could have ever asked for. Once more, I would like to thank everyone for making this thesis possible.

Bram Goudkuil
Utrecht, 28th May, 2024

List of Figures

List of Tables

List of Abbreviations

OCL	Overhead Contact Line
OCLS	Overhead Contact Line System
OVS	Design regulations of ProRail (*Dutch: Ontwerp Voorschrift*)
SE	System Engineering
RVOI	Regulation of Relationship between Principal and Consulting Engineering Firm
RAMS	Reliability, Availability, Maintainability and Safety
CEF	Consulting Engineering Firms
TSI	Technical Specifications for Interoperability
CEN	European Committee for Standardisation
CENELEX	European Committee for Electrotechnical Standardisation
NEN	Stichting Koninklijk Nederlands Normalisatie Instituut
FOCL	Flexible Overhead Contact Line
ROCL	Rigid Overhead Contact Line
OVS	Design regulation
BID	Business Information Document
BEA	Order and intake form
RLN	Directive
SPC	Product specification
ACD	AKI Contractdocument
ISV	Installation regulation
PRC	Procedure
ACP	Acceptation protocol
PRD	Product documentation
GVS	Usage regulation
TKG	Drawing
IRA	Conservation Risk Analysis
OHD	Maintenance document
SLV	Demolition regulation
SKAO	Foundation for Climate-Friendly Procurement and Business
LCA	Lifecycle Assessment
NMD	Dutch National Milieu Database
EPI	Environmental Performance Indicator for Buildings
ECI	Environmental Cost Indicator
MOO	Multi-Objective Optimisation Model
GA	Genetic Algorithm
NSGA-II	Non-Dominated Sorting Algorithm - II

Notations

Notation used in Model formulation

Sets	
Notation	**Description**
D	Set of axis in the structural model
O	Set of all the objectives
M	Set of materials
B	Set of beam designs
I	Set of design variants of the support structure
J	Set of points in structure model
L	Set of load case
S	Set of solutions per generation of algorithm
G	Set of generations the algorithm
Indexers	
d	Index indicating the direction of the deflection
i	Index indicating type design variant of the pole or the portal
l	Index indicating type of load case applied in the support structure
j	Index indicating point number in structural model of design variants
s	Index indicating the number of solutions within the generation of the genetic algorithm.
g	Index indicating the number of generation of genetic algorithms.
t	Index indicating the track number in the case of a portal design variant
Parameters	
L_{Pole}	Fixed length of the pole of the support structure
$V_{\text{Max,track}}$	Maximum track speed
Design Variables	
H	Height of the beam for the design of the pole.
W	Width of the beam for the design of the pole
Tf	Outer flange thickness
Tw	Centre flange thickness
Tt	Wall thickness of the pole design
b	Selected beam type is selected for design.
m	Indicator of which material is selected for the design

Notation used in Structural assessment

Notation	**Description**	**Unit**
F_G	Permanent loads working on the structure	N
m_i	Mass of component i of the support structure	kg
M	Set containing all the mass of each element of the supporting structure	
g	Gravitational acceleration, [9.81 m/s^2]	m/s^2
Ψ_w	Correction factor for wind loads	
K	Shape parameter for wind correction factor	
ρ	Specified technical lifetime	years
n	Exponent for wind correction factor	
H_{ocl}	Height of the overhead contact line system/support structure	m
h_{cw}	Height of the contact wire of the catenary system	m
h_{cs}	Height of the catenary system	m
$Q_{W,c}$	Resultant force due to wind pressure on the catenary system	N
q_p	Ultimate wind pressure	N/m^2
G_c	Dimensional and dynamic factor for conductors	
d	Diameter of the conductor wire	m
C_c	Pressure coefficient for conductors	
L_1, L_2	Length of adjacent cantenary fields	m
$Q_{W,ins}$	Resultant force due to wind pressure on the insulators	N
G_{ins}	Dimensional and dynamic factor for insulators	
C_{ins}	Pressure coefficient for insulators	
A_{ins}	Surface area on which the wind pressure acts	m^2
$Q_{W,structure}$	Resultant force due to wind pressure on the support structure	N
ϕ	Angle of wind direction on the rail track	$^\circ$
$A_{perpendicular}$	Effective surface area of the support structure perpendicular to railway	m^2
$A_{parallel}$	Effective surface area of the support structure parallel to railway	m^2
$Q_{W,structure}$	Resultant force due to wind pressure on single pole or beam of structure	N
$A_{structure}$	Effective surface area of pole or beam of the support structure	m^2
q_{ice}	Ice load on the catenary system due to icing	N
Ψ_{ice}	Correction factor for icing	
C_{ice}	Coefficient for ice load calculation	

Chapter 1

Introduction

This chapter introduces the thesis topic of the Overhead Contact Line support structure. First, the motivation for this graduate research is presented. This is followed by the context of the research, problem definition, research objective and scope, research questions, and outline of the thesis.

1.1 Motivation

The overhead contact line system is one of the key systems of an electrified railway network. The system ensures that the train has a continuous supply of electrical energy. This is achieved by means of a sliding contact between a fixed catenary wire along the track and current-collection equipment on the roof of the train. The system is generally referred to as the overhead contact line system (OCLS) but may also be referred to as overhead line equipment (UK), overhead contact system (Europe and US), or overhead wiring system (New Zealand). For the purposes of this research, it was decided to use the generic name OCLS.

Due to the importance of OCLS in relation to the operational status of the rail network, the reliability and maintenance of the system are important factors to maintain an operational network. The literature shows research interest in these topics, with a focus on how to plan and schedule the maintenance. The aim of the research is in most cases to either reduce the cost or extend the technical lifetime. Whilst replacement is inevitable at some point, with the increasing capacity of and traffic on the rail network, it is becoming a more complex operation.

As in the case of the market consultation on the replacement task conducted by the Dutch infrastructure manager ProRail, the current OCLSs in various sections in the south and east of the Netherlands are reaching the end of their technical lifetime. Together, these sections form a total of almost 500 km which are to be replaced in the coming years to avoid future delays or failures in the network [4].

Given the current constraints, conventional methods are not suitable as they would, for example, take too much time and cause too many delays. ProRail is therefore considering new methods for the replacement as well as innovations for the OCLS. In addition, the newly installed OCLS should contribute to the improvement of the reliability, sustainability, and affordability of the railway network.

Sustainability is an increasingly important factor to consider in the design of a support structure, despite being a relatively new factor in this context. However, it is one of the identified knowledge gaps in the reviewed literature on support structures for OCLS. The influence and effects it would have on OCLS and the design of the support structure are currently unknown. Therefore, this research aims to fill the knowledge gap and gain more insight into the influence of sustainability by developing a multi-objective optimisation model, which can be used to define and quantify the design space and key design variables for a sustainable support structure.

1.2 Research Context

In preparation for this study, an extensive literature review was conducted on the topic of support structures for OCLS, focussing on the recently published scientific literature in the period 2013–2022. To classify the reviewed literature, the taxonomy proposed by Sedghi, Kauppila, Bergquist, *et al.* has been used as a basis [3]. The following classes are thus formulated: structural characteristics, maintenance management and monitoring, and evaluations and decision support systems and decision-making frameworks.

The literature review shows that a solid foundation of knowledge has been developed on support structures for OCLS. However, based on the analysis, the following four knowledge gaps have been identified:

- Further understanding and development of methods on the structural condition of the structures
- Use of condition-based maintenance using structural models and new monitoring methods
- Further development of multi-objective decision-making models, as well as the implementation of more complex algorithms
- Impact and influence of sustainability on the design and maintenance of support structures

The full literature review can found in chapter 2.

1.3 Problem Definition

As mentioned in section 1.1, ProRail has the significant task of replacing the OCLS within its rail network. In addition, the company has the ambition and need to make OCLS more sustainable.

However, in 2010, ProRail conducted research on the life-cycle assessment of the support structure of the OCLS, which was performed by Ecofys [1]. The study aimed to determine the total carbon footprint of the support structures, which could be used to calculate the carbon footprint of the entire organisation. A distinction was made between steel and concrete portal structures. The study showed that the main contribution to emissions occurs during the production phase, and concrete was identified as the most potential option to reduce CO2 emissions.

In 2011, TNO conducted a study on potential sustainable support structure designs commissioned by ProRail, with a focus on reducing CO2 emissions [2]. In the study, five different potential designs were analysed structurally and environmentally. Designs varied in material (steel, concrete, wood) and connection type (fixed, hinged). The study showed that the concrete variant would be the most beneficial in terms of emissions for the portal structures, but the steel or wood variant could also be favourable depending on the design life-cycle assessment. However, although previous studies by Ecofys and TNO provided valuable information on the environmental impact of OCLS support structures and potential directions to reduce CO2 emissions, these studies did not result in changes in support structures manufactured in the main rail network in recent years. In addition to the evolving climate regulations and agreements from governments and European Union bodies, ProRail faces renewed pressure to improve the sustainability of its OCLS infrastructure. Furthermore, one of the identified knowledge gaps is the lack of research on the impact and influence of sustainability on the design of support structures. This raises the following issues:

- How can the support structure be made in a sustainable manner?
- What are the potential design directions to increase the sustainability of the support structure?
- What is the potential design space for designing a sustainable support structure?

1.4 Research Objective and Scope

Research objective

The purpose of this research is to develop a multi-objective optimisation model which can be used to explore and quantify the design space and key design variables for a sustainable support structure for OCLS. The scope of the research is limited to the support structure due to its importance within the OCLS and its unique characteristics as a structure.

To further clarify the concept of design space, that for a generic system is illustrated in Figure 1.1 from a system engineering point of view in terms of the system boundary. The solution space represents those elements which can be directly designed and modified or implemented, and the design space includes other elements which could have been part of the solution. The problem space includes all the elements which could directly or indirectly be affected by the proposed system or could influence the system [5]. In this research, the area enclosed by the problem space represents all possible designs for a support structure for OCLS.

To define and quantify the design space, an optimisation model is developed, for which it is important to accurately define and formulate the different objectives, related constraints, and decision variables considering the various aspects and disciplines involved in designing a support structure. Therefore, the design variables are identified which impact and influence the sustainability of the design of the support structure.

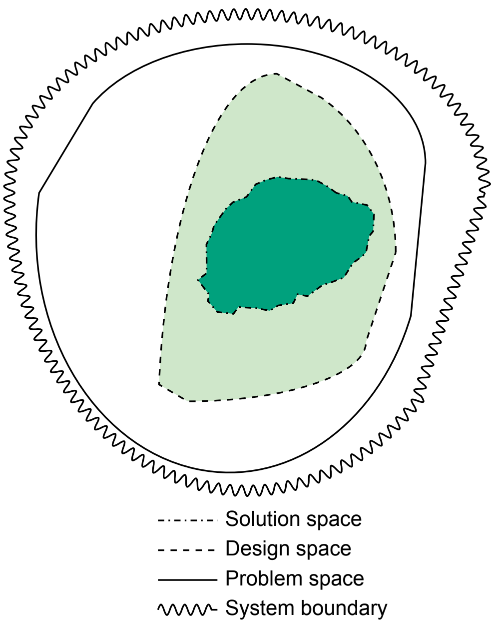


Figure 1.1: The design space, solution space and problem space given a system boundary

Scope

The research scope is defined contextually and geographically by focussing on the case of the Dutch main railway network. Physically, the scope is demarcated in the context of OCLS by analysing only the structural elements of the support structure, namely the poles above the foundation and the beams in the case of a portal structure. The structural elements of catenary systems are not taken into account in this research as they depend on the installed catenary system.

1.5 Research Questions

Based on the knowledge gaps established and the objective formulated for this research, the following main research question is posed:

What are the key design variables for the sustainable design of a support structure for an OCLS?

To answer this question, the following sub-questions have been formulated:

1. What are the essential requirements and design specifications to be met when designing a supporting structure for an OCLS on the main rail network in the Netherlands?
2. What are the methods which can be used to determine the sustainability of the design of a supporting structure for an OCLS?
3. Which parameters and variables define the design of the OCLS supporting structure?
4. How can the degree of sustainability be influenced when designing the OCLS supporting structure?
5. What are the implications of sustainability on the current design of the OCLS supporting structure?

1.6 Thesis Outline

As stated, the aim of this research is to explore the design space for sustainable OCLS structures on the main Dutch rail network. To do so, the thesis is structured as follows, and a graphic overview of the outline is presented in Figure 1.2. In the overview, the relationships among the different chapters are provided, as well as the research questions and in which chapters they are answered.

Chapter 2 presents an extensive review of the state of the art of support structures for the OCLS using the following classification from the literature: structural characteristics, maintenance management practices, decision support systems, and frameworks prevalent in the field. Chapter 3 focusses on the design process for OCLSs within ProRail, and a stakeholder analysis is discussed to identify the different interests and perspectives which influence the design of support structures.

The design requirements and specifications for OCLS structures are discussed in chapter 4, with an emphasis on technical specifications, European and national standards, and regulations which govern their design. Essential requirements are identified through a comprehensive analysis of design specifications. As a result, this chapter provides answers regarding the essential requirements and design specifications of the support structure which must be met when designing a support structure in the context of the main Dutch rail network.

The aspect of sustainability is explored in chapter 5 in the context of OCLS structures to provide a definition aligning with the ambitions of the rail branch and ProRail. In addition, various sustainability assessment methodologies and criteria are discussed to determine how sustainability can be evaluated in the design of the support structure. The chapter provides an answer to the sub-question of which methods can be used to determine the sustainability of a design for a support structure.

Building on the insights described in preceding chapters, a multi-objective optimisation model is formulated to determine the potential sustainable design space for OCLS structures. Chapter 6 discusses the theoretical foundations, including the problem statement regarding the model, assumptions, objectives, and constraints. The formulated model uses the NSGA-II genetic algorithm for optimisation to explore the design space. Details on the algorithm's standard framework and the implementation of crossover and mutation elements are elaborated in the chapter.

Further description of the model implementation for optimisation regarding these problem is provided in chapter 7. It also introduces the formulated framework of the model, outlining the modifications to the standard NSGA-II framework and the designed fitness function. It also covers the model's implementation in Python and its validation. The results of the model are presented in chapter 8, along with the trade-offs for the design of a sustainable support structure, based on the Pareto Frontier. Further analyses of the results are also discussed to provide an answer about the parameters and variables which define the design of the support structure.

Chapter 9 discusses the interpretations and implications of the results, placing them in a broader context. Furthermore, it describes how the degree of sustainability can be influenced on the basis of the results, as well as its implications for the current design of the OCLS support structure, thus addressing the final sub-questions.

Based on the discussion, the conclusion of the research regarding the key design variables for the sustainable design of a support structure for an OCLS is drawn and presented in chapter 10. Finally, recommendations are given for future research.

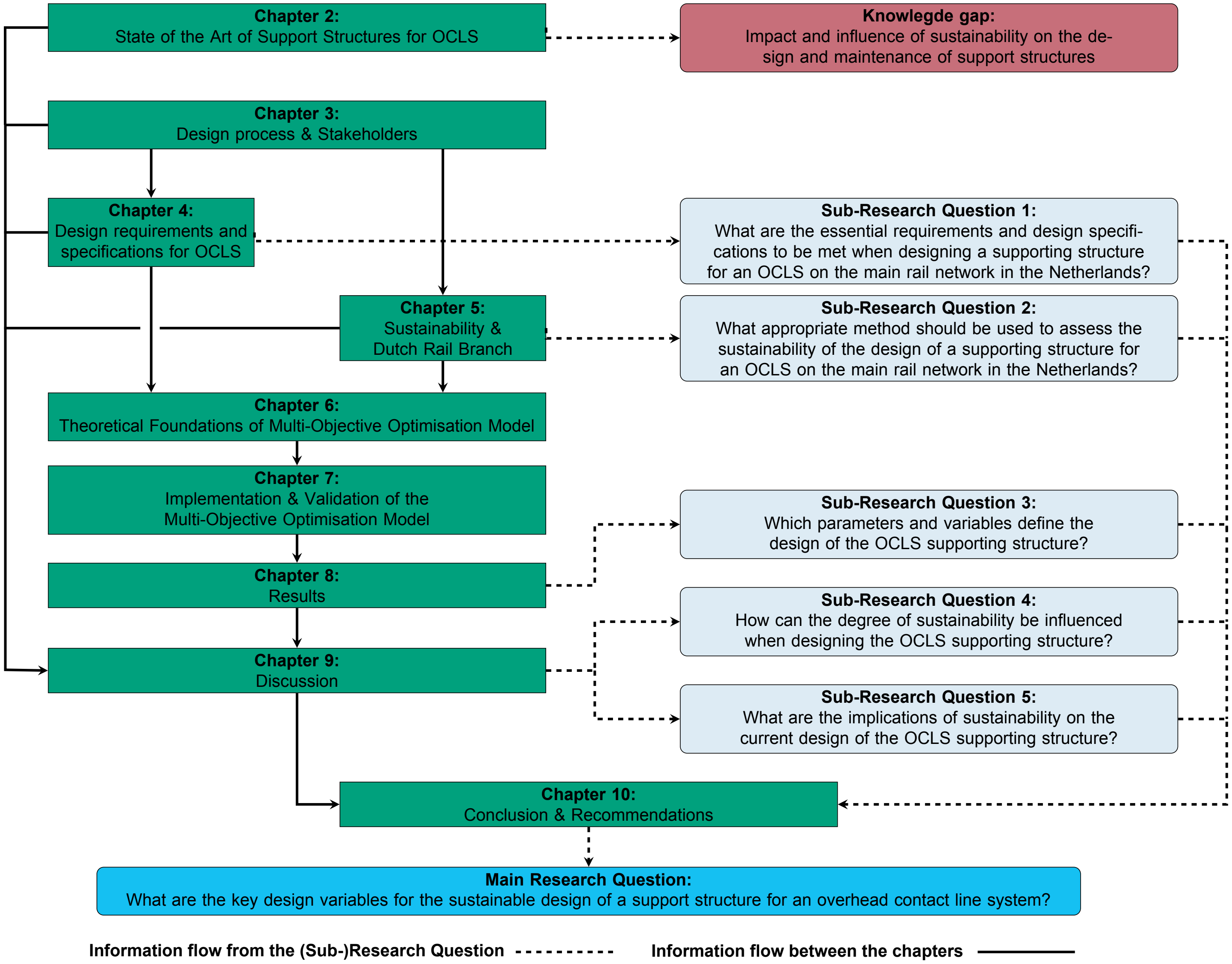


Figure 1.2: Overview of the relations and information flows between chapters and research questions

Chapter 2

State of the Art of Support Structures for OCLS

The chapter provides an overview of the state of the art and related studies on the topic of support structures for OCLS in the scientific literature. As an inclusion criterion for currency, the reviewed texts and studies are from 2013–2022 using a keyword-based search method.

To structure this chapter and classify the reviewed literature and studies, a taxonomy proposed by Sedghi, Kauppila, Bergquist, *et al.* is used to classify research in the field of planning and scheduling of railway track maintenance. Three main classes are defined: structural characteristics of the railway system, maintenance management decisions, and decision-making frameworks. These classes are adapted with respect to the support structures for OCLS.

Section 2.1 discusses literature on the structural aspect of the support structure. Section 2.2 describes maintenance with respect to OCLS and the support structure, as well as the methods developed for its management, monitoring, and evaluation. Section 2.3 presents the decision-making models and framework regarding the support structure and OCLS. The chapter ends with a conclusion on the literature review. A more detailed description of the keyword-based search method used and an overview of the reviewed literature can be found in Appendix B.

2.1 Structural characteristics

The definition of an OCLS is given in the standard NEN-EN 50119 as a 'support system and contact line that supply electric energy to vehicles through current collection equipment'. One of the major components of the system is the support structures. The main requirements for these structures in the Netherlands and Europe are specified in NEN-EN 50119 [6]. However, a distinction is made in the standard amongst the requirements related to reliability, safety, and security. A similar distinction can be seen in the reviewed literature. In other parts of the world, similar standards have been developed in relation to OCLS. On the basis of these regulations, several 'standard' texts have been published over the years. For example, the work of Kiessling, Puschmann, Schmieder, *et al.* is considered the main standard reference work for the contact line system used on the German railways [7]. Other work by Keenor focusses on the general aspect of electrifying the railway system in Great Britain [8]. Nonetheless, both studies provide a practical approach combining the experience and knowledge of the authors with the standard requirements of the time and can be used as a handbook during the design or analysis of an OCLS

In addition, several reports and articles give an overview of the support structures used in a railway network. Given presents a clear overview of the different support structures used in the Great Britain rail network and their characteristics [9]. Hu and Chan do the same in Australia, stating that support structures should be seen as a vital part of an OCLS [10].

Despite this, most of these structures are often viewed as simple, though, in most cases, according to Hu and Chan, a large capital investment is required for their replacement or construction. This can be explained by the costs for design, construction, and maintenance and is mainly due to the fact that a large number of these structures are involved in a network. As these are typically spaced at 50–70 metres, in the Melbourne region alone there are more than 13,000 structures [10]. As they are a vital part of the OCLS, their reliability is critical to the safe operation of the rail network [10].

In all the works mentioned above, the standardisation of the design of the support structure for the OCLS can be seen. One of the main advantages of standardisation is that, in general, it reduces almost all costs during different phases of a product, but according to Perera, Nagarur, and Tabucanon, when making the decision for standardisation, one should properly evaluate the effect on the various costs of a product [11].

Regarding OCLSs, Rechena, Infante, Sousa, *et al.* confirm the positive effects on catenary cantilevers in terms of costs. They argue that standardisation is particularly beneficial for infrastructure managers of smaller railway networks. A successful case study of a design for the standardisation of catenary cantilevers is presented, in which they show that in the wide variety of other designs, the cantilever could be successfully replaced by its standard design and still achieve similar functionality [12].

The wide variety of designs of OCLS structures could be explained by the role of the visual aspect of the design. According to Boorse, the visual aspect is an important factor in the design of these structures. As structures have an impact on public space, the visual aspect plays a role in people's acceptance of such new infrastructure in public. The visual aspect is particularly applicable in the case of light rail and trolley buses as these operate in more urban areas. To reduce the impact, designers should be more sensitive to this factor during the design process, as well as being open to using different techniques which can minimise the visual impact [13].

From a structural engineering point of view, the support structures for OCLSs are relatively exceptional structural objects due to their simplicity in design, their relatively long useful technical life, and their exposure to all elements [10]. An example of this can be seen in the case study presented by Hu and Chan, where a structural assessment is conducted on a century-old portal structure for OCLS. Despite its age and severe deterioration of some points of the structure as a result of corrosion, it was still structurally sound. According to the researchers, this can be interpreted as a reassuring result in relation to similar structures of this age and design [10]. On the other hand, they also argue the importance of the reliability of the structures as they are vital to the safe operation of the network.

Such support structures should be able to withstand the effects of extreme events to some degree to maintain safe operation of the network. For events such as earthquakes and hurricanes, Ngamkhanong, Kaewunruen, Calçada, *et al.* showed the various effects they can have on the support structure. Their research used a cantilever mast structure as a support structure. This typical design is particularly vulnerable to vibrations from earthquakes [14]. However, in addition to these externally induced vibrations, other vibrations induced by train traffic itself can also have damaging effects. Examples of these are given by Matsuoka, Tokunaga, and Tsunemoto and Ngamkhanong and Kaewunruen. Support structures such as poles located on bridges, especially those at the end of a bridge, are more affected by these types of vibrations [15]. However, ground-borne vibrations caused by high-speed trains have been shown to not be strong enough to cause damage to the support structures [16].

In addition to the effects of vibration, other forces can affect the support structure such as wind, which is generally resisted by the structures. However, in extreme cases such as a hurricane, these loads can have catastrophic consequences. Even in such cases, the structure-soil interaction is an important factor to consider, according to Ngamkhanong, Kaewunruen, Calçada, *et al.* They show that if the rotational stiffness between the soil and the structure is less than 3000 kN/rad, the structure has a higher probability of failure due to wind loads in the case of a hurricane [17].

These are just several examples of the variety of different loads which can affect the support structure of an OCLS. One of the ways to address these situations in the design of the structure is through the choice of material. Over the years, different materials have been used for support structures. In the early days of rail electrification, wood or steel was mainly used for poles. Concrete poles, introduced later, have numerous advantages, according to McSaveney, as they are similar in strength to steel poles and can be prestressed, which further improves their strength. Concrete is also non-conductive, and these poles can be produced relatively inexpensively [18]. As a result, prestressed concrete poles are now widely used as a support structure for OCLSs [19], [20]. An example of this is Russia, where, with more than 86,000 km of railway, of which 43,400 km is electrified, I-shaped and round reinforced concrete centrifuged poles are widely used.

Moreover, different types have been designed and used along the rails in Russia. Variations in the concrete have resulted in differences in strength. Initially, the focus was on high production numbers and the acceptance of low operational reliability. This has changed to a demand for high operational reliability of the structures used [19].

However, in the Russian railway network, there are still older support structures in use. To assess these structures, Zheltenkov, Li, Demina, *et al.* propose the use of a 3D model of one of the poles to model the effects of operational factors (e.g., temperature fluctuations, sun radiation, wind, and rain). They found various design flaws and potential hazards which could occur if the loads exceeded the safety factor [19]. As the effects of operational factors are different for each design, the researchers generalised these factors for concrete poles and basic damage types according to the Russian RailNetwork [21].

Similar to the work of Zheltenkov, Li, Demina, *et al.*, Tsunemoto, Shimizu, Kudo, *et al.* performed the same assessment in Japan and developed a method to determine whether a concrete pole should be replaced. Based on a field survey of 475 concrete poles on commercial lines in Japan, they distinguished the most common types of damage, which was spontaneous cracking, followed by deterioration of the concrete [20].

Finally, another aspect which influences the structural state and is easily overlooked is the construction process of the support structure. According to Pennings, dimensional accuracy is a key factor in the construction of the support structures. To achieve a high level of precision during construction, a new working method has been developed. The method involves step-by-step check forms that can be filled in on location. Thus, ensure consistency in the evaluation of the installation of the support structure during construction [22].

2.2 Maintenance Management, Monitoring and Evaluations

With the current ageing railway infrastructure in among others The Netherlands, the increasing demand for safety, and the pursuit of continuous track availability, performance evaluation and maintenance planning have become important fields of research in recent years. In both fields, it has been observed that the heterogeneity or variety of designs used for the structures of OCLSs and other railway infrastructures has an increasing impact on the complexity of the problems [23], and the heterogeneity is also noted by Rechena, Infante, Sousa, *et al.*'s paper on standardisation [12].

With regard to the maintenance aspect, Shang, Nogal, Wang, *et al.* propose a systems thinking approach which integrates both micro and macro levels of asset management to structure the synthesis. To gain more insight into different aspects of degradation and more maintenance knowledge, a mechanistic and data-driven approach is used. The mechanistic approach is used for micro-level issues, and the data-driven approach is used for the macro level [23].

Various studies have also been undertaken in the area of performance evaluation and determination of the state of various support structures. For prestressed concrete poles, both deterministic and probabilistic approaches are currently being used. One deterministic method is the Markov estimator [24]. For a probabilistic approach, the Bayesian inference method can be used to estimate the probability distribution of the different parameters [24], [25].

Reliability analysis is another method to determine which components are the most structurally critical and should be monitored more closely [26]. Hu and Chan have developed a reliability-based time-dependent assessment for steel structures. As they note, for steel structures, corrosion causes some of the most common damaging effects on the structure over time. To account for the time factor, they used a power function for the corrosion model to represent steel thickness and a modified corrosion decay model to support the reliability analysis. Another innovation in maintenance management is the use of digitisation, where a digital twin of the infrastructure is created [27].

On the other hand, another strategy is the use of preventive maintenance, as discussed in several articles. One aspect of this is scheduling different maintenance activities which must be performed along the railway line. According to Budai, Huisman, and Dekker, activities should be scheduled together as much as possible to reduce costs and inconvenience for the travelling public. They present a mathematical programming formulation for fixed intervals and one which maximises the interval [28]. Oudshoorn, Koppenberg, and Yorke□Smith, in contrast, propose three generic approaches to this problem: an evolutionary strategy, a greedy metaheuristic approach, and a hybrid combination of the other two strategies [29].

A focus on the reliability and determination of the current state of the OCLS infrastructure can also be seen in the literature as most older OCLSs are approaching the end of their useful life, and replacement is a costly operation [21], [26]. Asset management is a supportive method to extend the technical life of a structure in a safe manner. This can be done in an active monitoring manner using sensors on each of the structures [30].

Different detection and analysis methods can be used to monitor OCLS structures. In general, the monitoring results are a large multidimensional dataset. Three methods to reduce the dimensionality of the dataset are principal component analysis (PCA), the neural network of the autoencoder, and the stochastic embedding of neighbour t distributed (t-SNE). In Wang, Hendriks, Dollevoet, *et al.*, these three methods are compared in terms of their performance and show that the autoencoder is a promising technique to detect anomalies within the monitoring data [31].

Due to the implementation of the abovementioned methods by different stakeholders in the railway sector in recent years within Europe, the need to implement prognostics and health management (PHM) has arisen.

The railways must modernise their products and need innovative solutions to manage their assets, reduce operational costs, and remain competitive.

PHM uses methods/solutions such as remote monitoring, fault diagnosis techniques, and prognostic technologies [32]. An overview of the different implementations and techniques of PHM used in northwest Europe which focus on OCLSs is provided by Brahimi, Medjaher, Leouatni, *et al.*, who point to the need for standardisation to monitor OCLSs through sensors, further research on the technique used, and comparative studies to gain a deeper understanding of the monitoring results [32].

Examples of these monitoring techniques for on OCLS are also discussed by Hofler, Dambacher, Dimopoulos, *et al.*, who propose the use of optical radar for distance measurements between the different components of an OCLS [33]. Alkam and Lahmer present a different technique for monitoring the poles of OCLSs. They developed a model-free, data-driven approach to determine the condition of prestressed, spun-cast, ultra-high-strength concrete poles, which are mainly used along high-speed railway lines, by using a unified damage index to evaluate different damage characteristics of the poles. A logistic function is used to classify the integrity of the structure, eliminating the need for expensive damage detection methods to determine the integrity of the structure. A similar use of a health index to determine life expectancy is proposed by Na, Jung, and Park, which is used for the feeder cable. In this case, the index is based on a lifecycle assessment [35].

2.3 Decision Support System and Decision-Making Framework

Another aspect is the use of decision support systems (DDSs) and/or decision-making frameworks. In recent years, systems and frameworks have been developed and proposed, an overview of which, in relation to the maintenance of railway tracks, is given by Sedghi, Kauppila, Bergquist, *et al.* With regard to these types of system, Jamshidi argues that in addition to properly defining it' use, it is equally important to define which KPIs should be formulated. According to him, these can be classified into three different levels: technical, tactical, and global [36].

A DDS for annual maintenance planning for OCLS is proposed by Xu, Lai, and Huang, who use a predictive maintenance approach for the planning. In their case study, they achieved a reduction in costs of 25% compared with a preventive maintenance strategy [37]. Another example of a DDS is proposed by Bojda, Dziaduch, Nowakowski, *et al.* to support the maintenance of rail-bus infrastructure [38].

DDSs are also used in the design process of the rail infrastructure and OCLS design decisions, an example of which is the DDS developed by Zoeteman. In this DDS, a lifecycle approach is used to support design and maintenance decisions based on an ex ante evaluation process of infrastructure costs in the long and/or short terms [39].

Other examples of the use of DDS during the design phase are proposed by Garcia, Gomez, Saa, *et al.* and Berthold, both noting that the design process of OCLSs is highly complex [40], [41]. According to Berthold, this is due to the fact that there is a wide variety of requirements from national and international standards, design specifications, and different infrastructure operators/managers. In addition, the complexity of new projects is also increasing due to the client's demand for detailed designs whilst reducing the design time [41].

The DDS proposed by Garcia, Gomez, Saa, *et al.* produces a valid design solution in terms of design and structural constraints. As a result, the total time of the entire design path is reduced, along with the risk of human calculation errors. The presented DDS reduces the invested time by 82.33% compared with the existing process [40]. The DDS developed by Berthold is an add-on for the AUTOCAD CAD programme, called ELBAS OLACAD. The tool supports designers/engineers in creating different drawings in the design process by using various standard drawings and pre-programmed standard objects such as foundations and poles [41].

Most DDSs have a single-objective perspective and employ methods such as integer programming or heuristics. A recent development in this regard is the DDS approach from a multi-objective perspective. This is a more realistic approach; for example, maintenance planning for OCLSs includes not only the cost aspect but also other factors which impact the operation of the railway infrastructure. Other aspects which could be included are serviceability, passenger comfort, and maximum track capacity. To consider these different factors, Peralta, Bergmeir, Krone, *et al.* propose a multi-objective perspective. In their proposed model, they apply a Pareto-based algorithm to determine the optimal schedule, taking into account cost and delay. They compared the developed schedules of the model with those developed by experts in the field; in both cases, the schedules developed by the model outperformed those by experts [42].

A state-of-the-art method for multi-objective models is the use of deep conventional neural networks. Liu, Liu, Núñez, *et al.* developed a model to determine the performance of different components of an OCLS using this method [43]. A multi-objective approach is also taken by Chen, Zhang, Liu, *et al.* who incorporate a condition-based maintenance strategy for OCLS in their proposed model. Instead of using a deep conventional neural network, they employ a particle swarm optimisation algorithm with a multi-search strategy [44]. Besides their use for OCLS, multi-objective algorithms are proposed for the maintenance scheduling of the earthworks of the railways. A risk-based approach is also presented by Stipanovic, Bukhsh, Reale, *et al.* using multi-attribute utility theory. The model shows a more proactive way of scheduling balanced against the needs of the organisation [45].

2.4 Discussion

The knowledge gaps identified indicate a general need for more in-depth research on the impact and influence of sustainability on support structures. Similar to the use of multi-objective decision-making models in the design process of the structures. Furthermore, there is a trend which can be identified regarding the gaps as they are all related to the topic of maintenance and asset management. This can be explained by the fact that most support structures are already placed and in use; thus, maintenance is an important factor during their technical lifetime.

Similarly, research has gained further insights into the structural condition of the structures, which can contribute to a better understanding of how and when maintenance should be performed and how it can be conducted efficiently. For example, one of the outcomes could be to improve the precision of determining the structural condition of the structures. This can also be related to the research interest in condition-based maintenance as the knowledge gained and the methods developed can be used to support and improve this type of maintenance. One of the main advantages of condition-based maintenance is that it is performed when it is actually needed. This increases the efficiency of the maintenance process, for instance, in terms of preventive maintenance.

In addition to the use of structural models, monitoring is another research interest related to condition-based maintenance. One of the reasons for this is that the data provided help to determine the condition and to take decisions about whether maintenance is necessary. With an increasing use of monitoring, the amount of data available will also increase.

This can be seen as an incentive for the development of new models able to handle and use these data in an appropriate way. Furthermore, the complexity with which these models deal is also rising due to the increased use of rail networks and the reduced available maintenance time. As a result, these models should be able to optimise multiple objectives. Therefore, new and more complex algorithms are needed to fully exploit these types of models in the decision-making process.

However, one of the main knowledge gaps is in the area of sustainability, particularly during the design and lifecycle of these structures. As stated in section 1.3, there is a need for a deeper understanding of the implications and implementation of sustainability as it is taken into account in the requirements for future support structures.

2.5 Conclusion

OCLS support structures are a vital part of the railway infrastructure, and much knowledge has been gained about these structures. Recent literature has shown a trend towards standardisation of design. However, there is still a wide variety of designs and methods used within and between railway networks.

From a structural perspective, researchers have been interested in more in-depth structural studies, such as the effects of extreme load cases and the determination of the current structural condition of the structures. In recent years, maintenance planning and scheduling for support structures have attracted more research attention, especially from a multicomponent and network perspective. In addition, there are studies on condition-based maintenance policies with respect to predetermined maintenance and monitoring methods for support structures. There is also interest in a more systematic approach to maintenance planning using decision-making frameworks/systems, along with a trend towards more complex models to account for various aspects which influence decision-taking. However, despite the increasing importance of sustainability and the research interest in related fields, there is limited information on this topic in the reviewed literature. Based on these observations, the following knowledge gaps are identified:

- the need for further understanding and development of methods regarding the structural condition of the structures
- use of condition-based maintenance using structural models and new monitoring methods
- further development of multi-objective decision-making models, as well as the implementation of more complex algorithms
- determining the impact and influence of sustainability on the design and maintenance of support structures

Chapter 3

Design process and Stakeholders

This chapter provides an overview of ProRail's design process for OCLSs in section 3.1. In section 3.2, a stakeholder analysis is performed to identify the different stakeholders involved in the design of support structures. The chapter concludes with a summary of key findings and insights.

The purpose of this chapter is to enhance the understanding of the context surrounding the design process for a new and sustainable support structure for the OCLS and to identify the roles of each stakeholder involved in this process. Additionally, it explains ProRail's established design protocols and the systematic approach to designing a support structure. The stakeholder analysis aims to uncover the perspectives and priorities of key stakeholders, providing valuable context for understanding the decision-taking dynamics inherent in the design of the support structure.

This is a fundamental step towards achieving the broader research objective of identifying the design space for a sustainable support structure for the OCLS. It sets the basis for identifying essential requirements and potential challenges by understanding both the procedural framework and the diverse stakeholder landscape in the pursuit of a sustainable support structure.

3.1 Design Process for OCLSs

In this section, the current design process for the OCLS on the main Dutch railway network is reviewed. As an infrastructure manager, ProRail has established a set of company regulations governing the design process, which is based on the system engineering (SE) approach. This allows for an interdisciplinary approach and the optimisation of the whole system lifecycle, which is described in a handbook [46]. Furthermore, this approach has also been implemented in the Dutch civil engineering sector for each contract form. ProRail was one of the initiators of this initiative; to ensure uniformity nationwide, they published a guideline for it [47].

The design process is part of the process model, in which a distinction is made amongst three main processes: modelling, functional design, and physical design. During the physical design phase, the requirements are translated to physical solutions. During the design, a design loop is implemented between the functional design and the physical design phase.

The handbook defines the design process as part of the development process. This is divided into seven phases, and two models have been developed, one focussing on process and the other on information exchange. The seven phases which comprise the development process are as follow:

- **Needs Analysis**: during this phase, the initial needs and priorities are determined.
- **Concept Exploration**; based on stakeholder needs and objectives, the requirements for the system are defined for potential concepts.
- **Concept Definition**: Potential concepts are evaluated for RAMS, feasibility, and manufacturability. The preferred concept is identified.
- **Working Draft Definition**: the concept is further evaluated by determining sub-systems, costs, and performance.
- **Detailed Elaboration**: the design is fully elaborated so that it can be built during the following phase.
- **Realisation**: the design is realised and validated to evaluate whether it meets all the requirements.
- **Management and Operation**: the system is put into operation, and information and design documents are handed over during this phase.

Based on these phases, the design process for OCLS is defined and described in the design specification OVS00024. Part OVS00024-2.1 describes the process and associated products, which are parts of the regulation of relationship between principal and consulting engineering firm (RVOI) [48]. The RVOI phases of the design process consist of the following:

- **Research Phase**
  During this phase, exploratory studies are conducted to assess various design variants and their feasibility based on functional requirements and indicative track layout designs. The resulting technical report informs the choice of catenary system design and provides recommendations for subsequent phases [48].
- **Preliminary Design Phase**
  A detailed elaboration of promising design variants from the research phase is further developed. This contains a preliminary track design scheme, along with global calculations and the design of the variants. Essential inputs for this phase include functional programme requirements and results of variant studies.
- **Final Design Phase**
  On the basis of an approved design schedule, the final drawings are produced in this phase. The final design should be aligned with the specifications, and adjustments can be made in consultation with the client to optimise financial or technical aspects. Coordination with various disciplines involved, such as train safety and track construction, is crucial during this phase [48].
- **Design Specifications Phase**
  This phase involves the further development of the final design into documents and drawings suitable for use as contract documents for tendering and pricing purposes. ProRail technically assesses the specifications to ensure uniformity and compliance with standards and regulations [48].

The OCLS design process and the SE development process share similarities in their phases. Both processes aim to ensure completeness and clarity in designs and analyses. It is important to describe and justify any assumptions and trade-offs made and to trace them back to the related source or requirement for the design.

Furthermore, throughout the entire design process, it is essential that the design complies with the standards, legislation, and company regulations of ProRail. Activities during the design process should be conducted in accordance with the systems engineering method described in the Civil Engineering Branch Systems Engineering Guideline [47] or the ProRail Handbook for Systems Engineering [46]. It should be noted that ProRail uses an accreditation policy for its subcontractors, which should comply with the accreditation protocol [49]. The result is that only consulting engineering firms accredited for the support structure of OCLS by ProRail can perform design work [50].

The design specification requires the use of ProRail asset-management-approved products, as specified in the associated product specification (SPC). Any alternative products must be requested through ProRail asset management and authorised via the purchase order and acceptance form (BEA). These railway-specific building materials can only be purchased from one of the approved suppliers or manufacturers for the relevant ProRail product [48].

If a product is not described in an SPC or cannot be acquired via BEA but is necessary for the design, the responsible system manager of ProRail asset management must be consulted. The designer should provide the necessary information for the new product and demonstrate whether it meets the required properties for such a product and should be incorporated into the regulations. The time of the ProRail certification or approval process should be taken into account during the design process as this can be time-consuming [48].

3.2 Stakeholder Analysis for OCLS Design Process

This section aims to identify and discuss the stakeholders involved in the design process of support structures for overhead catenary line systems. The NEN-EN50126 standard defines five main categories for stakeholders in a rail system: railway undertakings, infrastructure managers, maintainers, railway supply industry, and safety authorities [51]. These categories have been used as a basis for the categories of stakeholders; however, given the described design process and sustainability, the categories have been adapted. For instance, maintainers has been changed to consulting engineering firms (CEFs).

Based on the design process described in the previous section, the proposed categories, and the scope of design of support structures of OCLS, the following stakeholders have been identified and are shown below in the table in relation to the design process and sustainability. Furthermore, it is important to note that ProRail operates under an accreditation scheme [2]. This means the relevant services or products can only be provided by companies which have been accredited by ProRail. The list of these accredited companies can be found in the overview of accredited companies [49]. Similarly, the list of companies allowed to provide certified products for an OCLS is stated in the overview of product certifications [52]. Only a limited number of companies are allowed in principle to participate in the design, manufacture, or supply of the required products.

Table 3.1: Overview of identified stakeholders

Governmental	**Infrastructure manager**	**Railway undertakings**
European Commission: - European Railway Agency *Dutch Government:* - Ministry of Finance - Ministry of Infrastructure and Water Management	*ProRail:* - Asset management department - System/Installation manager	*Main network rail operator:* - NS *Local Rail Operators:* - Connexion - Arriva - Keolis *Cargo Rail Operators*
Safety authorities	**Consulting engineering firms**	**Railway supply industry**
- Research Council of Safety - Inspection of Environment and Transport	*Firms:* - Arcadis - Movares - Dutch Rail Control - Royal HaskoningDHV - Dura Vermeer Railinfra - Sweco - Strukton Rail - VolkerRail	*Contractors:* - Bam Infra Rail - De Wilde - Dura Vermeer - Swietelsky Rail Benelux - VolkerRail *Suppliers:* - VDL Metal - Armada Mobility B.V

Each phase of the OCLS design process involves specific stakeholders, each with distinct roles and responsibilities; therefore, every phase of the design process is discussed. If a stakeholder's role cannot be directly allocated to one of the identified stakeholders, the main category is used.

Research Phase

In the research phase, ProRail, as the infrastructure manager, plays a central role as it is responsible for defining the project objectives and providing its resources. Furthermore, the stated objectives must comply with regulations and be verified during the project. Research, on the other hand, is conducted by one of the consulting firms and can be seen as a key stakeholder. They are responsible for exploring design variants and conducting feasibility studies during this phase of the project. Governmental and safety authorities can be involved in the oversight of transportation infrastructure and have an interest in ensuring that the OCLS design aligns with broader transportation policies and objectives. Consulting firms conducting the research should take these factors into account in design variants and feasibility studies.

Preliminary Design Phase

In this phase, ProRail is one of the key stakeholders, having an overseeing role regarding the development of detailed design variants and ensuring they are in line with project objectives and relevant regulations. During this phase, the perspective of stakeholders which have interfaces with OCLS is also analysed, such as the railway operators. For example, the NS would like to know which type of OCLS is placed as this affects the rolling stock they could use, which could also be formulated reversed as a requirement. As in the previous phase, one of the consulting firms is responsible for further elaborating the design variants and producing preliminary design drawings, thus becoming another key stakeholder in this phase.

Final Design Phase

As a client of the design project, ProRail remains involved as stakeholder; during this phase, it mainly has a monitoring role. Their main task is to review and approve the finalised design drawings and ensure compliance with regulations and standards. The final design variant is further elaborated by one of the consulting firms, developing amongst other products the final drawings of the structure and the design to check with the disciplines involved, such as train safety and track construction. The review of these designs is crucial during this phase.

Design Specifications Phase

In the final phase, ProRail plays a key role as a stakeholder, particularly in ensuring the finalised design documents meet regulatory requirements and are of sufficient quality to serve as contract documents for the tendering and pricing of the project. One of the consulting firms is also a key stakeholder during this phase, responsible for formulating the final design and ensuring compliance with regulations. During this phase, it is also responsible for the formulation of the required documentation on which the contracting or tendering can be based. This documentation includes, amongst other things, final design drawings, calculations, and technical reports. Contractors and suppliers are also involved as stakeholders during this phase as the contractor is responsible for purchasing specified products for the construction of the design, and these materials should ideally be bought from a certified supplier. The contractor relies on the formulated design specifications of the final design for this.

General

In addition to the design process and phases, the design of the support structure for the OCLS is also examined from a general perspective. To identify potential indirect stakeholders involved, it is important to understand the broader aspect of the design process as well. Safety is also considered, with ProRail being the main stakeholder and already having a clear focus on this aspect. Safety authorities such as the Ministry of Infrastructure and Water Management are also involved as a stakeholder in their role in overseeing this. In addition, the Ministry is involved as a client in the development and management of rail infrastructure, but it is also responsible for the location of the funding for ProRail, being the main financier.

It should be noted that the Dutch government, through the Ministry of Finance, is 100% the owner of ProRail. In a similar construction, it is also an owner of the NS and main network rail operator, creating a triangular relationship amongst ProRail, NS, and the Dutch government [53]. This relationship could lead to interesting cases regarding sustainability, rolling stock, and the choice of OCLS design. For example, the Dutch government requires increased sustainability as a stakeholder, and NS aims to achieve this by extending the technical life of its rolling-stock fleet, but ProRail's decision is to implement a more sustainable OCLS which may not be compatible with NS's fleet in the long term. This example highlights the complexity and potential conflicts which may arise during the design of an OCLS.

3.3 Conclusion

The design process for the OCLS is structured into seven phases and follows an SE approach. ProRail oversees the design process according to its regulations and accreditation policies to ensure compliance with standards and legislation. The stakeholder analysis underscores the critical role of collaborative efforts in achieving successful design outcomes. Stakeholders—categorised into distinct groups including governmental bodies, infrastructure managers, and CEFs—contribute diverse perspectives and expertise to the design process. The ProRail accreditation scheme and commitment to safety regulations highlight the importance of regulatory compliance. In essence, the OCLS design process prioritises the satisfaction of design requirements, regulatory compliance, and stakeholder collaboration to deliver safe, efficient, and sustainable railway infrastructure solutions. The design process is an integral process, focussing on collaboration with and amongst stakeholders.

Chapter 4

Design Requirements and Specifications for OCLS

This chapter provides an overview and a review of the design requirements and specifications for an OCLS, specifically those applicable to the main Dutch railway network. The aim is to identify the essential requirements and specifications for the design of a new superstructure which complies with the relevant regulations and standards. The chosen documents have different legal, technical, or policy backgrounds. They were selected based on the conclusions presented in chapter 3 and are relevant to the scope of this research. The first sections of the chapter present the regulations and standards regarding support structures for the OCLS.

Technical specifications for interoperability are covered in section 4.1, whilst section 4.2 discusses related European and national regulations and standards. These regulations and standards are analysed in section 4.4 using methods and tools from SE, which are explained further. The results of the analysis are then discussed, and the findings on the essential requirements and specifications for designing a support structure for the OCLS on the main rail network in the Netherlands are presented in section 4.5.

4.1 Technical Specifications for Interoperability

The European Union has formulated technical specifications for interoperability (TSI) for the rail sector aimed at ensuring interoperability within the EU railway system. These specifications define technical and operational standards for each subsystem or component of these systems which must meet the essential requirements. The European Union Agency for Railways is responsible for the formulation and development of TSIs as outlined in Directive 2016/797 [54], providing the legal basis for TSI and defining the subsystems integral to the EU railway system. An overview of these subsystems is given in Table 4.1.

Table 4.1: Overview of the TSI subsystems, according to EU Directive 2016/797[54]

TSI subsystems	
- Energy	- Rolling Stock - Locomotives and Passengers
- Infrastructure	- Rolling Stock - Freight Wagons
- Noise	- People with Disabilities and Reduced Mobility
- Safety in Railway Tunnels	- Telematics Applications for Passenger Service
- Control Command and Signalling	- Telematics Applications for Freight Service
- Operation and Traffic Management	

Directive 2016/797 defines essential requirements for subsystems, covering aspects such as safety, reliability, availability, health, and environmental protection. These requirements are further categorised into general ones applicable to all subsystems and those specific to each subsystem.

For the OCLS support structure, the most pertinent TSIs are those of the energy and infrastructure subsystems. The energy subsystem includes specifications for the electrification system, including overhead contact lines and trackside electrical consumption measured by the charging system [55], whilst infrastructure refers to track elements, points, engineering structures, and safety equipment [56].

The general essential requirements, along with those specific to related subsystems as formulated in EU Directive 2016/797, form the basis of TSIs for the identified subsystems. In addition, the European Railway Agency has issued a guide to apply each TSI.

In particular, while the TSI for energy [55] clarifies that components such as cantilevers, masts, foundations, and insulators are not part of the overhead contact line of the interoperability components, it also emphasises the role of OCLS in improving interoperability within the European Railway Network. This involves harmonising different types of OCLSs and reducing their variations with the possibility of offering OCLSs as a market product.

The TSI for infrastructure and the associated guide do not introduce additional special requirements. Instead, it mainly focusses on geometric aspects of overhead contact lines, especially in respect to compliance of the contact wire height with NEN-EN50119:2009 [6] and the maximum lateral deviation.

4.2 European and National Standards

An important source of information in the design process is standards, or agreements for and by the market regarding aspects like safety, reliability, and corporate social responsibility. One of the main goals of standards is to improve products. A standard specifies, amongst other things, design requirements and/or how to test and determine these regarding the design. In the European Union, standards (EN) have been developed to harmonise the technical specifications for a product. The standards are issued by the European Committee for Standardisation (CEN) or by European Committee for Electrotechnical Standardisation (CENELEX), in the case of specific electrical standards. These standards are developed alongside the various national standards within the EU. However, the standards define the basis of national standards for the members of CEN. In the Netherlands, the national standards are developed and issued by an organisation named Stichting Koninklijk Nederlands Normalisatie Instituut (NEN). Given the scope of the support structure of the OCLS, the standards stated below are important in designing such a structure.

4.2.1 NEN-EN 50119 - Railway Applications - Fixed Installations, Electric Traction Overhead Contact Lines

The NEN-EN 50119 is the main national and European standard for OCLSs, which encompasses both flexible overhead contact line (FOCL) and rigid overhead contact line (ROCL) systems. In a FOCL configuration, automatic tensioning equipment is used to maintain tension in the catenary and contact wires. This is achieved through the use of fixed anchor points or other devices at the other end of the line of the tension device. The configuration of a FOCL could be when it is automatically tensioned at both ends.

Similarly, fixed points should be used on a ROCL to prevent the conductor rail from migrating. This can be done using rigid profiles or an anchorage system. In case of the latter, anchorage should be installed at approximately the midpoint of the tension length or at a point which will balance the forces along the line at the midpoint to provide mechanical midpoints.

These systems have application in various contexts, including heavy rails, light rails, trolley buses, and industrial rails operated by public or private entities. Whilst the standard primarily addresses contact line aspects of the system, such as wires, system configuration, and electrical aspects, it also outlines requirements and specifications for the support structure. It defines several types of support structure to be used for the OCLS, which are defined on the basis of the type of forces and loads they should withstand. Definitions of these types are as follow:

- **Pole or structure for head span or rigid cross span structures**, designed to withstand forces from cross-supporting structures.
- **Rigid cross span structures** consist of connections that resist bending moments or connections attached to structures by hinges or bending-resistant joints.
- **Suspension structures** to carry cantilevers which support the overhead contact line.
- **Curved cantilever structures** to carry radial forces from overhead contact lines or vertical loads, especially in curved or sloping areas.
- **Tensioning structures**, designed for the termination of the overhead contact line and other conductors, either for an automatically tensioned or rigidly fixed system.
- **Anchor structures**, designed to resist tensile forces from terminating wires in OCLS.
- **Horizontal catenary wire arrangements** are structures which support the wires mainly in a horizontal position, typically used in urban areas.
- **Midpoint support structures**, designed to resist the radial forces of the midpoint anchors and to perform other functions such as supporting cantilevers.
- **OCL support structures with additional conductors** additionally carry the loads from overhead lines and may serve various functions within the OCLS.

The main focus of these requirements is to achieve an acceptable level of reliability in an economically viable manner, ensuring a robust design to improve safety and minimise the risk of human injury. To meet these requirements, the standard places considerable emphasis on the structural design of the support structure. It uses the structural limit stated method, which defines two main types of limit states: ultimate and serviceability. The ultimate limit states are related to structural failure due to excessive deformation, loss of stability, and fracture. The state mainly affects the level of reliability, safety, and security, whereas serviceability limit states relate to conditions beyond which specified service requirements are not met, such as mechanical function and energy transfer.

Design models include relevant design variables, such as the structural model, which are intended to predict the structural behaviour, serviceability, and ultimate limit states. They should be based on established engineering theory and practise so that they can be used to determine in different design conditions and load cases to verify the integrity and performance of the design.

4.2.2 NEN-EN 15273 Railway Applications - Gauges

This standard covers the specifications and regulations regarding gauges within the European Union. The standard consists of three parts: Part 1 describes the general principles, the interface between infrastructure and rolling stock as the reference profiles, and associated rules; part 2 focusses on the rolling stock aspect [57], regarding dimensioning of the vehicles and calculation method given the characteristics of a specified gauge. Part 3 focusses on the infrastructure aspect regarding dimensioning it given a specified gauge and related constraints to operate within [58].

The gauge is defined in the standard as an agreement between the infrastructure and the rolling stock, and it defines the spatial layout between these two and how it should be calculated and verified for both. Furthermore, the standard describes a number of railway gauges in use in Europe—amongst others, the gauges of the infrastructure TSI [59] to ensure interoperability with the European Union.

4.2.3 NEN-EN 199X Eurocode - Structural design

To achieve balance and consistency between technical specifications within the European Union, the Structural Eurocode programme was initiated in 1975 and resulted in a series of standards in 1989. It provides a common set of rules for the design of structures, regardless of their size. The series consists of 10 Eurocodes (standards) and is in principle differentiated by material; an overview of all structural Eurocodes is presented in Table 4.2.

The first two Eurocodes define the basis where the Eurocode (NEN-EN 1990) specifies the applied principles and requirements regarding safety, serviceability, and durability of structures. As mentioned in subsection 4.2.1, the main method and basis of structural design is the concept of a limit state, which is used in combination with the method of partial factors, further specified in NEN-EN 1990 [60]. The standard should be applied for the general case, but depending on the material used in a design, the relevant standard should be employed if specified for the material.

Table 4.2: Overview of the standards part of the Structural Eurocode

Eurocode	**Standard**	**Title**
Eurocode	NEN-EN 1990	Basis of Structural Design
Eurocode 1	NEN-EN 1991	Actions on structures
Eurocode 2	NEN-EN 1992	Design of concrete structures
Eurocode 3	NEN-EN 1993	Design of steel structures
Eurocode 4	NEN-EN 1994	Design of composite steel structures and concrete structures
Eurocode 5	NEN-EN 1995	Design of timber structures
Eurocode 6	NEN-EN 1996	Design of masonry structures
Eurocode 7	NEN-EN 1997	Geo-technical design
Eurocode 8	NEN-EN 1998	Design of structures for earthquake resistance
Eurocode 9	NEN-EN 1999	Design of aluminium structures

4.3 Regulations of ProRail

As the infrastructure manager of the Dutch railway network, ProRail has formulated an extensive collection of company regulations, in addition on the those at national and European level. As a result, the rail branch in the Netherlands is highly regulated. This is due to several reasons, for example, to ensure safety within the network. Another main reason is to ensure uniformity in use of materials and conducting processes.

The company regulations are differentiated based on the phase in lifecycle of the infrastructure and document type conforming to RAMS [51], [61]. Furthermore, the differentiation of the documents can be related to the SE approach which ProRail uses as it took is as a guideline whilst implementing this methodology in its organisation. Moreover, this methodology is widely used in the civil engineering branch in the Netherlands [46]. The company regulations can be consulted via Rail Infra Catalogues. An overview of the various ProRail company regulations is presented in Table 4.3. The Dutch abbreviation of the document type is also stated in parentheses.

Table 4.3: Overview of ProRail's Company Regulations

Phase:	**Document type:**		**Phase:**	**Document type:**	
Design	- Design regulation	(OVS)	*Other*	- Business information document	(BID)
Procurement	- Order and intake form	(BEA)			
	- Product specification	(SPC)		- Directive	(RLN)
Construction	- Installation regulation	(ISV)		- Procedure	(PRC)
Acceptance	- Acceptation protocol	(ACP)		- Product documentation	(PRD)
Usage	- Usage regulation	(GVS)		- Drawing	(TKG)
	- Conservation Risk Analysis	(IRA)		- AKI contractdocument	(ACD)
	- Maintenance document	(OHD)			
Demolition	- Demolition regulation	(SLV)			

Regarding the support structures for the OCLS and its design, the most relevant types are the design regulations, directives, product specification, installation regulation, and maintenance documents. In the following sections, the related documents are discussed concerning the type of regulation.

4.3.1 Design Regulations (OVS)

The design regulations of ProRail describe and specify the whole process of the design phase, as well the requirements and regulations related to the design of a product or system. For the OCLS, focussing on the support structure, the main regulation regarding this topic is *OVS00024—Traction energy supply system, Overhead contact line*. The design regulation consists of nine parts, each one emphasizing a different aspect or part of the system. Other design regulations of relevance are those regarding the traction energy supply (*OVS00012—Traction energy supply 1500V DC* and *OVS00050—25kV/50Hz Traction energy supply*) and those regarding spatial profile and layout (*OVS00026—Gauges* and '*red*' measuring area and *OVS00056—Track*). An overview of the relevant parts regarding the support structure for each of those mentioned above is shown in Table 4.4.

Table 4.4: Overview of relevant Design Regulations (OVS)

OVS	**Title**
OVS00012	- OVS00012-1 General - OVS00012-2 System requirements - OVS00012-3 Design rules
OVS00024	- OVS00024-3 System requirements - OVS00024-4 Generic design regulations - OVS00024-5.1 Generic system requirements - OVS00024-8.2 Poles - OVS00024-8.3 Beams and arms - OVS00024-9 Wind displacements en incoming wires
OVS00026	- OVS00026 Gauges and ”red” measuring area
OVS00050	- OVS00050-2 Functional programme of requirements - OVS00050-3 System specifications - OVS00050-4 Design manual
OVS00056	- OVS00056-4.2 Rail cross-sections

4.3.2 Directives (RLN)

In the directives, ProRail specifies, amongst others things, guidelines for processes and reports, such as how and which calculations should be conducted given a process or product and further requirements for a product or systems in general. As such, it fills the gaps between the regulations. In Table 4.5 below, an overview is given of the related directives regarding the support structure of the OCLS. RLN0009 is the most relevant one as it specifies the calculation method and principles for the support structure of OCLSs.

Table 4.5: Overview of relevant parts of the related design regulations (*RLN)*

RLN	**Title**
RLN00003	Environmental conditions for EV installations
RLN00004	Overview of conservation's
RLN00009	Calculation method and principles for OCLS support structures
RLN00124	Abbreviations and terms - Energy supply
RLN00133	Requirements for materials and fastening materials
RLN00160	RAM-management for 25kV traction-energy supply

4.3.3 Product Specifications (SPC)

As the title of the document indicates, it lists the product specifications and requirements for a given product. For each part of a system in use, ProRail has formulated a product specification to ensure the quality and standardisation of the parts. Table 4.6 provides an overview of the related product specifications regarding the support structure. In these specifications, the different dimensions of the beams or poles are stated, which may be used for the design of a support structure, as are the requirements regarding the quality of the material and the RAMS.

Table 4.6: Overview of relevant Product Specifications (SPC)

SPC	**Title**
SPC00016	Engineered poles for OCLS support structure, Types ‘DLO’ and ‘SLO’
SPC00017	Welded arms for OCLS support structure
SPC00018	Suspension support for beams
SPC00035	Machined strips and profile elements
SPC00036	Steel pipes and pipe elements for OCLS support structure
SPC00051	Curved tube profiles for OCLS support structure
SPC00052	Straight tube profiles for OCLS support structure
SPC00058	RHS beams
SPC00060	Tension struts
SPC00063	Columns for RHS beams
SPC00223	Engineered beams
SPC00226	HE-beams

4.3.4 Installation Regulations (IVS)

In the installation regulations, ProRail specifies the conditions and requirements for assembly of the different elements/parts of a system in a correct manner. As incorrect assembly would most likely have a negative influence on the performance of the system, safety, or technical lifetime. For the OCLS, the main document is *IVS00026 Traction-energy supply system, Overhead contact line system*. In this document, the installation specifications are stated for all the different subsystems and elements related to the OCLS, such as the support structure, type of catenary system, and system voltage. Further, a distinction is made in requirements in regards to different system levels, between the system top level and generic level.

4.3.5 Maintenance Documents (OHD)

In the maintenance document, the procedures and methods are specified by ProRail which should be used for the maintenance of a certain product or element. Examples of this are the maintenance scheme of the product or which type of conservation methods could be used. Furthermore, the decision-making process is described for the maintenance procedure. Regarding the OCLS support structure for the conservation of the structure and maintenance, this can be found in *OHD00029—Conservation of OCLS support structures*.

4.4 Analysis of Design Requirements

This section discusses the analysis to determine the essential requirements for designing the support structure for the OCLS on the Dutch railway network. These essential requirements could be used to formulate a multi-objective optimisation model to quantify the design space for sustainable design. An SE methodology approach is employed, which is known for its systematic analysis of designs or systems. The application of this approach is advantageous in this case as ProRail has incorporated SE into its organisation and also uses it in the development of its requirements [46].

The asset requirements were derived from the documents reviewed in the previous sections. The methodology used to identify, analyse, and prioritise the requirements is discussed in the following sections, along with the results of the analysis.

4.4.1 Requirement Identification

Requirement identification is initiated through context analysis, focussing on the specific needs and functionalities of the support structure for an OCLS. Using a multi-directional approach, such as the middle-out strategy, and employing the snowball search method ensures comprehensive coverage of potential requirements within the selected documents. As the support structure is a subsystem of the OCLS, using the middle-out strategy, both the lower- and higher-in-rank systems are taken into account in the search. Whilst reviewing the documents, their unique contexts are taken into account regarding the OCLS system. The snowball technique is used to do an extensive source check and review them as well so that relevant requirements are systematically identified. This ensures comprehensive coverage of potential requirements within the selected document, resulting in a total of 148 identified requirements which could be related to or affect the support structure of the OCLS; these are listed Table C.1.

4.4.2 Requirement Analysis

Once the potential requirements are identified, they are analysed assessing their relevance to the support structure. Each requirement is critically evaluated, considering its formulation in an unambiguous, verifiable, or prioritising manner. The requirements are then categorised into functional, nonfunctional, and constraint types, providing further insight into their purpose and how they impact the design of the support structure.

4.4.3 Priority Analysis

In addition to the requirement analysis, the identifying requirements are prioritised. The requirements are first categorised by the main topic they address. They are then prioritised based on their importance and impact on the design of the support structure, distinguishing amongst must-have, should-have, and nice-to-have levels This prioritisation allows an allocation of requirements in an efficient manner. This is achieved by addressing critical requirements first, whilst considering trade-offs and dependencies of the requirements within the topic, thus resulting in a selection of potential essential requirements. Within the identified requirements, 18 different categories have been identified, which are listed in Table 4.7. The number of requirements allocated to the category can also be found.

4.4.4 Design Constraint Analysis

After ranking and categorising the requirements, they are further evaluated to determine if they constrain the design and how they do so, resulting in further understanding of their implications on potential designs of the support structure. This is achieved by examining the rationale behind these constraints. Additionally, this allows valuable insights into the limitations and opportunities for designing a support structure which is both feasible and compliant with regulatory standards. As a result, 43 requirements are identified as objectives and 105 as constraints, with their numbers within each category listed in Table 4.7. The five categories with the highest number of requirements are marked in green.

Table 4.7: Number of Requirements per Category: Objectives and Constraints

Category	Total	Objective	Constraint
Adjustability	7	0	7
Complete	1	0	1
Constructive safety	18	3	15
Dimensioning	9	2	7
Electrical	19	6	13
Environmental impact	1	0	1
Legal regulations	11	0	11
Material	7	2	5
Noise	3	0	3
Options	1	1	0
Positioning	31	14	17
Performance	1	1	0
Safety level	13	8	5
Safety measures	7	1	6
System compatibility	2	2	0
Technical lifetime	6	2	4
Visual	3	2	1
Weather	8	1	7

4.5 Conclusion

Based on the analysis of the requirements for the OCLS support structure on the main Dutch rail network, it is evident that safety considerations are considered essential. Although this conclusion may seem obvious, it underscores the importance of ensuring the safety and reliability of the rail infrastructure. This can be achieved, for example, by verifying the structural design through structural analysis with the defined load cases and constraints with respect to the deflection, as specified in RLN0009 [62].

Furthermore, each identified requirement plays a crucial role in the overall system or design as they are all formulated with the purpose of fulfilling specific functions or constraints. From an SE perspective, it is valuable to differentiate amongst requirements as such a distinction helps in prioritising and addressing critical aspects of the design—in this case, in terms of safety.

However, this slightly differs from the guidance ProRail provides in OVS00024-2.1 on the design process [48]. In this document, the focus is primarily on the aspect of feasibility and optimisation of the overhead line design, which should be assessed based on lifecycle costs. Design decision-making must focus on achieving a technically and financially optimal solution whilst adhering to the requirements outlined in OVS00024. In the cases of conflicting requirements, particularly between those of part 4 and the following parts of OVS00024, it may be necessary to deviate from generic requirements depending on the complexity of the design. However, such deviations must still meet the overarching requirements specified in OVS00024-3. Valid deviations are those which lead to lower lifecycle costs or require adaptations to the generic solution, ensuring that safety and efficiency considerations remain essential throughout the design process.

The guidance presented shows that safety is an essential part of the design process, as indicated in the requirement analyses. However, economic factors also play a significant role in decision-taking. Designers must navigate the trade-offs between safety and cost-efficiency as deviations from generic requirements may impact both aspects, indicating that the design should be balanced between safety and economic considerations. The design process would thus benefit from a multi-objective approach to achieve an optimal solution. An overview of the methodology used to determine the essential requirements is given in Figure 4.1.

In conclusion, the answer to the sub-question on the essential requirements and specification for the design of the OCLS support structure involves balancing safety imperatives with economic considerations. Designers can achieve an optimal solution which prioritises both safety and cost-efficiency by carefully assessing trade-offs so that, in addition to safety requirements, economic ones could also be identified as essential.

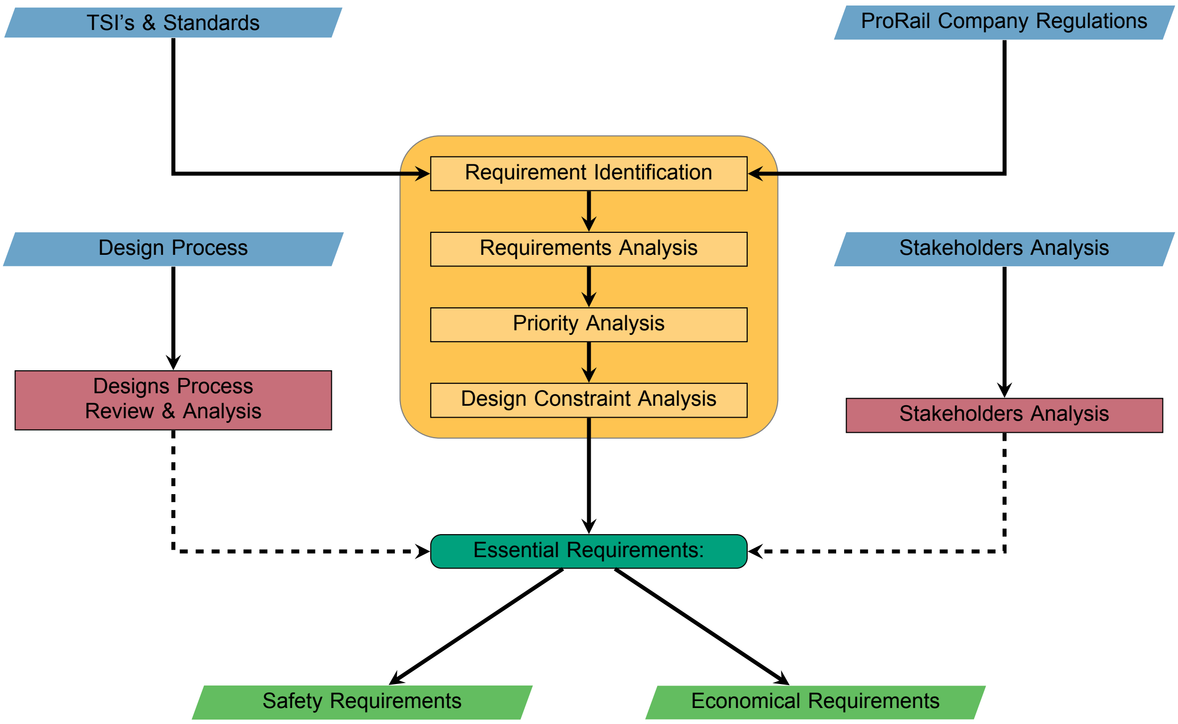


Figure 4.1: Methodology to determine essential requirements

Chapter 5

Sustainability within the Dutch Railway Branch

In this chapter, the concept of sustainability within the Dutch railway branch is explored. The chapter begins with a discussion of the definition of sustainability and reviews various policy documents on sustainability and climate agreements. In section 5.2, the sustainability ambitions of ProRail are presented. The methods used to determine and quantify sustainability in rail projects are examined in section 5.3. Finally, the chapter concludes by summarising the key aspects of sustainability in the Dutch railway branch and answering the sub-question: *Which methods can be used to determine the sustainability of the design of a supporting structure for an OCLS?*

5.1 Definition of Sustainability

This section explores the complex concept of sustainability, drawing on insights from climate and policy documents such as the Brundtland report, the Paris Climate Agreement, the European Green Deal, the Dutch Climate Agreement, and the National Circular Economy Programme. Through an analysis of these documents, the aim is to clarify the fundamental principles and dimensions of sustainability whilst also identifying shared themes and distinctions amongst different initiatives.

5.1.1 Brundtland Report

The Brundtland Report, also known as Our Common Future [63], is a fundamental document to define sustainable development. It emphasises the imperative to meet the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable development, as articulated in the report, encompasses three interrelated dimensions: environmental, social, and economic. At its core, sustainable development aims to achieve a balance amongst human well-being, environmental integrity, and economic prosperity.

The report highlights the principle of equity and inclusion, ensuring that all segments of society have access to resources and opportunities for meaningful participation in decision-making processes. The pursuit of sustainable development goals requires poverty alleviation, equitable resource distribution, and social justice. Furthermore, given the finite carrying capacity of the planet, responsible management of natural resources and ecosystems is essential. Sustainable development involves managing and improving environmental quality whilst promoting sustainable patterns of production and consumption.

In summary, the Brundtland Report presents a comprehensive framework for sustainable development, highlighting the interconnections amongst environmental, social, and economic dimensions. It emphasises the importance of equity, environmental stewardship, and intergenerational equity in shaping a sustainable future.

5.1.2 Paris Climate Agreement

The Paris Climate Agreement is a major global effort to combat climate change and promote sustainability [64]. The agreement was reached at COP21 in December 2015. The agreement's central objective is to limit the increase in global average temperature to below 2°C above preindustrial levels, with an ambitious aim to cap the temperature increase at 1.5°C. The Paris Agreement highlights the urgency to address climate change.

In addition, it emphasises the need to improve adaptive capacity and resilience to impacts of climate change by implementing measures to protect vulnerable communities, ecosystems, and economic sectors from the adverse effects of climate variability and extreme weather events. Furthermore, the transition to renewable energy sources and the improvement of energy efficiency are crucial components of the agreement's strategy to reduce greenhouse gas emissions and advance towards a carbon-neutral economy.

The Paris Agreement reflects an unprecedented global consensus and cooperation in addressing climate change, underscoring the collective responsibility of nations to safeguard the future of the planet. To fulfil their obligations under the agreement, it is essential that the countries continue to collaborate, innovate, and demonstrate political will. This is necessary to achieve a sustainable and climate-resilient world.

5.1.3 European Green Deal

The European Green Deal is a comprehensive EU strategy for the transition to a sustainable low-carbon economy [65]. It is based on the objectives of the Paris Agreement and sets ambitious targets for reducing greenhouse gas emissions, increasing the use of renewable energy, and improving energy efficiency in all EU member states.

The European Green Deal prioritises key initiatives such as promoting renewable energy sources, improving energy efficiency in buildings and transportation, and fostering sustainable agriculture and land use practises. It also prioritises investments in research, innovation, and infrastructure to support the transition to a circular economy and reduce dependence on fossil fuels.

The European Green Deal aims to promote economic prosperity, social equity, and environmental resilience in the EU and beyond by aligning policies and investments with sustainability goals. It represents a bold vision for a sustainable future and underscores the EU's commitment to leading the global transition to a carbon-neutral economy.

5.1.4 Dutch Climate Agreement and National Circular Economy Programme

The Dutch Climate Agreement [66] and the National Circular Economy Programme [67] are two of these national initiatives which address climate change and promote sustainability in the Netherlands. They reflect a collaborative approach involving government, industry, academia, and civil society to achieve ambitious sustainability goals.

The Dutch Climate Agreement establishes objectives for reducing greenhouse gas emissions, deploying renewable energy, and improving energy efficiency, demonstrating a commitment to addressing climate change and transitioning to a low-carbon economy. Similarly, measures to encourage sustainable resource management, promote circularity, and reduce waste in the Netherlands are outlined in the National Circular Economy Programme.

By implementing these initiatives, the Dutch government aims to promote innovation, create sustainable jobs, and increase the resilience of the Dutch society and economy to climate change and environmental challenges. In addition, these initiatives will contribute to the global effort to achieve the goals of sustainability and build a more resilient and fairer world for present and future generations.

The Brundtland Report, the Paris Climate Agreement, the European Green Deal, the Dutch Climate Agreement, and the National Circular Economy Programme all provide valuable insights into the multidisciplinary nature of sustainability and the interaction of environmental, social, and economic dimensions. Although each of these initiatives has different objectives and strategies, they share a common commitment to promote sustainability, resilience, and equity.

5.1.5 Conclusion

This section discusses the concept of sustainability by reviewing the Brundtland Report, the Paris Climate Agreement, the European Green Deal, the Dutch Climate Agreement, and the National Circular Economy Programme to gain insight into the fundamental principles and dimensions of sustainability provided by these documents.

The The Brundtland Report laid the groundwork for sustainable development, focussing on the interconnections of environmental, social, and economic well-being. In addition, the importance of equity, inclusivity, and responsible stewardship of natural resources in shaping a sustainable future is highlighted.

The Paris Climate Agreement shows, on the other hand, global solidarity and commitment to combating climate change. The urgency of transitioning to a low-carbon economy and the resilience to climate impacts are highlighted. In line with this are the European Green Deal and the Dutch national initiatives. All emphasise the importance of aligning policies, investments, and actions with sustainability goals

Reflecting on these policy documents shows that sustainability is not a simple ambition. However, it should be taken seriously to preserve the planet and ensure the well-being of current and future generations. Thus, the transition to a sustainable future requires collective action, innovation, and transformations across all sectors of society.

Putting it in the context of the Dutch rail branch, the principles and commitments in these policy documents formulate the context of sustainability for the branch. In addition, they show the importance of sustainability in decision-making, policy formulation, and project implementation, especially given the challenges and opportunities within the branch in regards to transformation towards sustainability and the circular rail branch.

5.2 Ambitions of the Rail Branch: ProRail

This section explores the sustainability goals and climate policies of ProRail, in addition to reviewing international climate and policy documents. It presents insights into the sector's sustainability efforts by examining ProRail's commitments and initiatives, including its alignment with European rail climate intentions and national CO_2 reduction strategies.

5.2.1 ProRail Sustainability Goals

As the manager of the Dutch rail network, ProRail plays an important role in shaping the sustainable development of rail transport in the Netherlands. The strategic ambitions of the organisation include connectivity, reliability, and sustainability [68]. With a strong focus on integrating sustainable practises throughout the supply chain, sustainability is at the core of ProRail's operations. To minimise environmental impact and promote responsible resource management, this commitment includes the promotion of sustainable use of materials in rail infrastructure projects [69], [70]. ProRail has taken the following steps to achieve these goals.

Roadmap to Sustainability

It has developed a comprehensive roadmap to address the challenges of sustainability in the rail sector. The roadmap focusses on mobility, energy, materials, and nature, with explicit goals set for each path. It aims to make significant progress towards sustainability by 2030. These goals serve as focal points for organisational dialogue, fostering commitment and accountability within the company [71].

Railway Climate Responsibility Pledge

ProRail is committed to sustainability efforts in line with broader industry initiatives, such as the Railway Climate Responsibility Pledge based on the Paris Climate Agreement [72]. By committing to this pledge, ProRail aims to achieve carbon neutrality in rail sector operations by 2050. This is achieved through the reduction of emissions from energy consumption and material use throughout the rail network [50].

5.2.2 CO_2 and Energy Savings Strategy

To reduce CO2 emissions and energy consumption, ProRail has developed the 'CO_2 and Energy Savings Strategy 2021–2025'[66]. The strategy embodies the organisation's ongoing commitment to sustainability by outlining concrete strategies and goals for reducing carbon emissions and conserving energy resources. It serves as a strategic roadmap, providing clarity on ProRail's path to achieving its 2030 sustainability goals whilst also identifying areas for potential intervention. It sets ambitious goals, including a 30% reduction in energy consumption and a 55% reduction in CO_2 emissions by 2030, as well as midterm targets for 2025. These targets are complemented by a comprehensive set of 49 measures designed to address various aspects of energy consumption and emissions across ProRail's operations.

In pursuit of these goals, ProRail's strategy takes a multidisciplinary approach, with initiatives such as improving energy efficiency, promoting renewable energy sources, and fostering collaboration across the supply chain. Through the use of renewable energy technologies, particularly solar and wind power, ProRail aims to achieve self-sufficiency in energy for its facilities by 2030. The strategy also focusses on transparency and accountability, providing a framework for monitoring progress and ensuring alignment with broader industry initiatives. Through these concerted efforts, ProRail aims to be at the forefront of sustainable rail transport, driving meaningful change within the branch and contributing to a greener and more resilient future.

5.2.3 CO_2 Performance Ladder

The CO_2 Performance Ladder, initiated by ProRail, stimulates CO_2 reduction efforts within organisations involved in infrastructure projects. Since 2011, the Foundation for Climate-Friendly Procurement and Business (SKAO) has overseen all matters related to the ladder [73]. The ladder encourages organisations to reduce their CO_2 emissions by improving their energy efficiency, reducing their emissions, and improving cooperation within the whole supply chain.

Certification to the CO_2 Performance Ladder signifies an organisation's commitment to sustainability and its ability to meet the rigorous criteria of understanding, emissions reduction, transparency, and participation. It allows organisations to promote a culture of sustainability in their operations and project delivery and to drive innovation and accountability in their efforts to reduce CO_2 emissions.

5.2.4 Circular Economy Initiatives

ProRail's sustainability agenda focusses on adopting the principles of circular economy. The aim of the company is to create a more sustainable and resource-efficient rail infrastructure by maximising the reuse of materials and minimising waste. Key initiatives include recycling waste materials and promoting efficient use of materials. ProRail's commitment to the circular economy extends beyond rhetoric, with concrete actions aimed at reducing the environmental footprint of rail infrastructure projects [74].

5.2.5 Future Outlook

ProRail aims to play a central role in advancing the sustainability agenda within the rail sector. It does this by embedding sustainability into its core business and working with industry partners. Through strategic investment, innovative solutions, and transparency, the company is committed to creating a greener and more resilient rail network for future generations.

5.3 Methods for Determining Sustainability

In the pursuit of sustainable development, various methodologies are used to comprehensively assess and quantify the environmental, social, and economic impacts of a project or design. Below are the details of three general methodologies used to determine sustainability in the Netherlands.

5.3.1 Lifecycle Assessment

Lifecycle Assessment (LCA) provides a systematic approach to evaluate the environmental performance of products, processes, or systems throughout their lifecycles [75]. According to the EN 15804 standard, LCA offers a comprehensive assessment of environmental impacts, including energy consumption, greenhouse gas emissions, resource depletion, and waste generation from the extraction of raw materials to construction, operation, and ultimately disposal [76]. The lifecycle is further divided into several standard stages; an overview of these stages is provided in Table 5.1

To determine the total environmental impact of a product throughout its lifecycle, LCA uses quantitative methods. Software tools facilitate the implementation of LCA, thereby using databases such as the Dutch National Milieu Database (NMD) or global repositories such as Ecoinvent. These databases offer comprehensive environmental data on production processes, energy generation, and transportation. Conducting an LCA requires a careful assessment of all stages of a product's lifecycle. This ensures a detailed evaluation of the environmental impact and provides a basis for sustainable decision-making [63]. ProRail initiated several LCA analyses included in the NMD. Among these, one study focused on the OCLS, where the LCA was conducted for various components of the system [77].

Table 5.1: Overview of the different system boundaries in a lifecycle according to EN 15804 [76]

Production Stage			Process Stage		Use Stage						
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7
Raw material supply	Transport	Manufacturing	Transport	Construction/Manufacture Installation Process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational Energy use	Operational water use

End of Life Stage				Benefits and Loads beyond the System Boundary
C1	C2	C3	C4	D
Deconstruction demolition	Transport	Waste processing	Disposal	Reuse, Recovery, Recycling potential

5.3.2 Environmental Cost Indicator

The environmental cost indicator (ECI) methodology is used to integrate environmental considerations into procurement processes in the civil engineering sector. As part of the calculation to determine the best price-quality ratio, the ECI serves as a pivotal factor [63].

The ECI is a single-score indicator which combines all relevant environmental impacts into a single cost factor. It represents the shadow environmental price of a product or structure, taking into account factors such as energy consumption, greenhouse gas emissions, resource depletion, and waste generation. This unified score facilitates the assessment of environmental performance, whether per unit of product or per product using a reference unit.

According to the EN15804 standard, the lifecycle of a product is divided into five phases and 17 modules [76]. This framework serves as the foundation for calculating the ECI assessment method. First, the environmental impacts are determined for each module, both at the product level and structural levels. The modules within each phase are summed, and then all phases are aggregated based on the specified phases defined for the ECI.

For the ECI assessment, environmental information per component or product of the product is used in one or more sets of profiles of NMD [78]. The environmental impact of the component or product always involves the cumulative environmental impact on the linked set of profiles. The total environmental impact per unit of product can be calculated by summarising the overall phases. Beforehand, the calculation is performed in the same way as for the product components in subproducts. This means the calculation is based on one or more profile sets, which are directly related to the total product, not to the product components [79].

Furthermore, the calculation process involves several intermediate steps, including the assessment of the environmental impact per module. These intermediate results offer valuable information to aid decision-making processes. The units assigned to NMD products correspond to the way in which they are traded on the market. One disadvantage is that in the case of different units, it is difficult to compare products.

However, understanding which products perform better or worse is useful to optimising the design. To address this issue, the ECI can be expressed per reference unit'of the component, alongside the market unit. Presenting in both the market unit'and the reference unit is, in most cases, a functionality offered by calculation tools. The validated calculation tool used for the civil engineering branch is Dubo Calc [80], [81].

In general, integration of ECI into the design phase, project planning, and execution enables stakeholders to systematically manage environmental impacts, monitor progress, and drive continuous improvement towards sustainability goals in railway construction projects.

5.3.3 Circularity Indicator

The Netherlands is actively transitioning towards a circular economy; with this increase in the importance of circularity, the circularity indicator has been developed to assess the circularity of construction projects, including developments in the rail infrastructure [82]. The circularity indicator is based on existing sustainability and circularity measurement methodologies and combines selected methodologies to provide a robust basis for its development. This results in a standardised set of indicators which are consistently calculated for each project evaluation.

The underlying principle of the indicator methodology is that it allows for the comparison of different circular strategies through the assessment of their impact on circular objectives rather than the assessment of circular strategies in isolation. This allows different circular strategies to be compared, taking into account the entire lifecycle of the building or object under evaluation, including all input and output flows. At the same time, anticipating future developments by considering multiple lifecycles allows for a broader understanding of circular strategies. The indicators used for the protection of material stocks are closely related to the material balance assessments of environmental LCAs, with some adjustments for the measurement of circularity. Similarly, environmental impact categories derived from established methodologies such as the European LCA methodology for construction, NEN-EN 15804 [76], are used as the basis for the environmental protection indicators. Specific indicators were also developed to preserve existing value. These indicators divide the value into technical-functional and economic aspects, including the quantity of the initial value, the value available for the next cycle, and the lost existing value, thus ensuring a thorough evaluation of circularity across various dimensions of infrastructure projects.

The circularity indicator evaluates various aspects crucial to circularity, including the protection of material stocks, environmental impact, and preservation of existing value. The indicator quantifies these elements and provides insight into a project's contribution to circular objectives throughout the lifecycle of infrastructure assets, from initial design and construction to end-of-life scenarios. These objectives are not combined into a single total score, allowing flexibility to incorporate additional indicators as needed. Furthermore, indicators can be seamlessly integrated into existing tools for the calculation of circularity.

By integrating circularity assessments into project evaluations, stakeholders are able to prioritise strategies such as resource efficiency, waste reduction, and value retention, thereby promoting sustainable practises in railway development and aligning with the broader goals of the circular economy.

5.4 Conclusion

This chapter explored the multidimensional concept of sustainability in the Dutch rail branch, including its definition, objectives, and measurement methods. Through an examination of various policy documents and initiatives, including the Brundtland Report, the Paris Climate Agreement, the European Green Deal, the Dutch Climate Agreement, and the National Circular Economy Programme, valuable insights are gained into the fundamental principles and dimensions of sustainability.

ProRail's sustainability goals and initiatives provide an example within the rail sector of a proactive approach to integrating sustainability into core business practises. The company's strategic commitments aim to reduce carbon, improve energy efficiency, and promote circularity in rail infrastructure projects.

Furthermore, methodologies such as LCA, the ECI, and the circularity indicator provide systematic approaches to assess and quantify the environmental impacts of railway projects and offer a standardised framework for evaluating the protection of material stocks, environmental impact, and preservation of existing value throughout the project lifecycle. By integrating sustainability assessment methodologies into project evaluations, stakeholders can prioritise strategies such as resource efficiency, waste reduction, and value retention. This promotes sustainable practises in the development of the railways and contributes to the broader goals of the circular economy.

Together, these findings indicate the importance of sustainability. The methodologies provided in section 5.3 are used to determine the sustainability of a design for a support structure. However, the LCA is the main basis for these different methods and is also used in many policy documents as the primary indicator of environmental impact. Based on the assessment, the effect of the support structure can be expressed in CO_2 emissions. On the other hand, the circularity indicator is also an indicator of environmental impact as it focusses on the potential reuse of the structure. Therefore, both indicators are suitable to show the degree of sustainability of the design of the support structure. Based on this, Figure 5.1 provides a comprehensive summary of the findings of the chapter and the interaction to obtain a sustainable design. Nonetheless, to achieve sustainability on the Dutch rail branch and create a greener and more resilient future for future generations, continued collaboration, innovation, and commitment from all stakeholders are required.

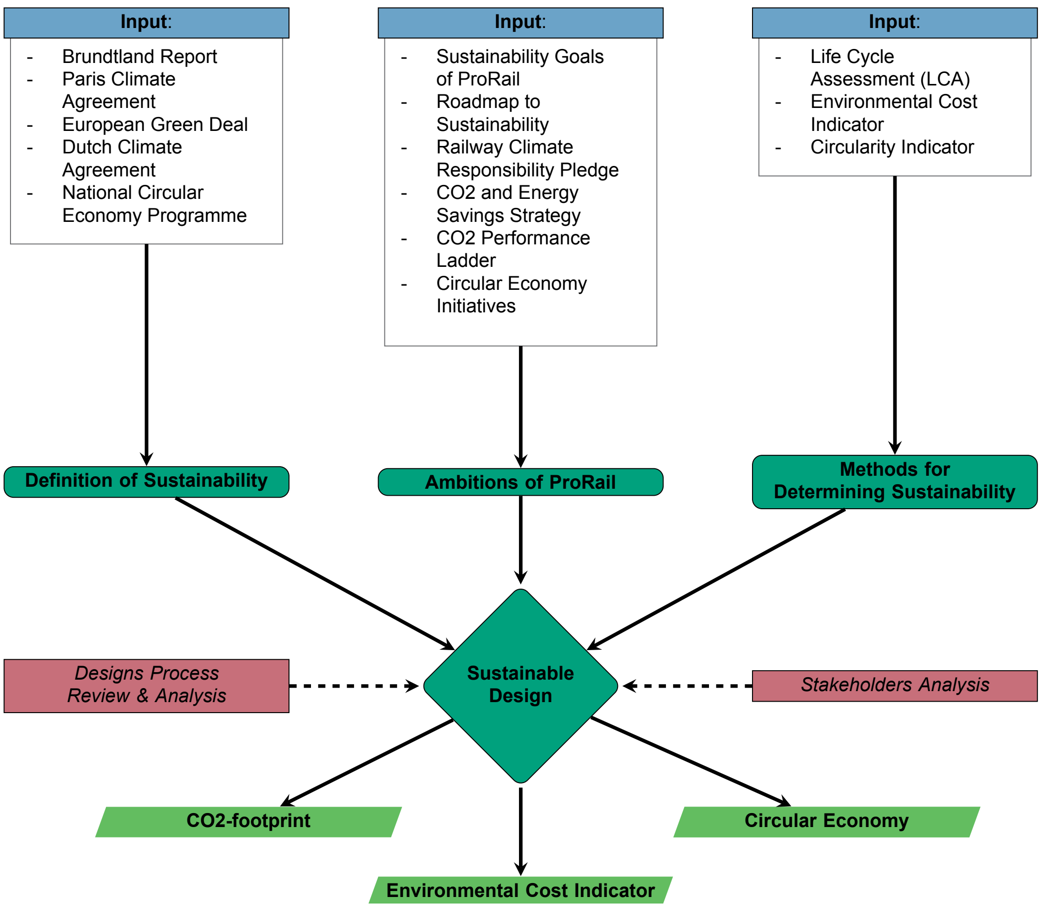


Figure 5.1: Interactions within the chapter regarding to Sustainable design

Chapter 6

Theoretical Foundations of Multi-Objective Optimisation Model

In this chapter, the theoretical foundations of the model are discussed. The multi-objective optimisation model has been formulated to determine the potentially sustainable design space for OCLS. The model has been formulated building on the insights from previous chapters.

Initially, the problem formulation for the multi-objective design problem is introduced, which is optimised to explore the sustainable design space. This is outlined in section 6.1. Subsequently, the assumptions for the further formulation of the model are stated in section 6.2. Section 6.3 discusses the model objectives, and its constraints are described in section 6.4, followed by the optimisation algorithm in section 6.5. The formulated model uses the NSGA-II genetic algorithm for optimisation to explore the sustainable design space. Details concerning the algorithm's standard framework and the implementation of crossover and mutation elements are also discussed in this section. The chapter ends with an exposition of the structural analysis employed to evaluate the structural integrity of the designs within the model.

6.1 Multi-Objective Problem Formulation

The insights and knowledge gained from the preceding chapters form the foundation for the formulation of the design problem—the multifaceted nature and inherent complexity of the design process, the importance of structural requirements in terms of the safety and integrity of the support structure, economic implications, and sustainability considerations—which shows the multi-objective nature of the design problem. Therefore, for the exploration of a sustainable design space for a support structure, the design has been formulated as a multi-objective optimisation problem taking these aspects into account to find a design space with optimal solutions and indicate the trade-offs. The definition for designs within this sustainable space is formulated as follows: designs of a support structure within the sustainable design space are those which ensure safety whilst minimising environmental and economic impact. Given this definition, the objectives for the design of the support structures are as follow: decreasing the environmental impact by minimising carbon emissions and embodied energy and maximising circular efficiency and lowering economic impact by reducing costs. The derived design objectives are described further in section 6.3.

6.2 Assumptions

This section outlines the main assumptions employed in the development of the model. As described in the scope of the research (section 1.4). The support structure is situated along the main Dutch rail network. To further simplify the model, the model is focused on designing the support pole. This is based on the assumption that the pole forms a fundamental element in the design of different configurations of support structures.

To simply the model, the support structure is assumed to be located along a straight segment of the track. In the context of the catenary system. The support structure is positioned within a normal section of the catenary system. As majority of the support structures is located at such as section. The span length between support structures varies depending on the catenary system of the case study. The span length is set a maximum allowable length specified for the catenary system.

The model includes the production (A1-A3) and end-of-life (C1-C3) stages of the LCA life cycle. These stages are significant stages for the emissions of the structure. In contrast, incorporating the entire life cycle would require one to make numerous assumptions. Thereby reducing the general applicability of the model and increasing uncertainties. These assumptions might not reflect reality accurately or could be too restrictive, limiting the reliability of the model's solutions or insights to specific conditions.

6.2.1 Structural Analysis

In the model the proposed design for the pole is structural evaluated. In order to determine the structural integrity of support structure. The assessment is carried out according to RLN0009 [62]. Building on RLN0009's assumptions, the structural analysis is further simplified by neglecting loads insulators due to their minimal impact on the structure. Wind load is considered to act perpendicularly on the support structure in the positive x-direction. Dimensional and dynamic factors, as well as pressure coefficients for the structure, are assumed constant.

The deformation of the structure are modeled use elastic bending. Meaning that the stress-strain relationship is considered linear across all stress levels. According to Hooke Law, a material will return to its original shape after the removal of stress. Using the elastic approach allows to determine internal forces and moments. Even if the actual resistance of a material section is based on its ability to undergo plastic (permanent) deformation [83].

Further details are provided in section 8.1 for the case study.

6.2.2 Orientation of the Model Coordinate System

As the structural analysis of support structure is modelled in 3D, the definition of the coordinate system is stated. As coordinate system a Cartesian coordinate system is used. The orientation of the x-axis is in the direction perpendicular on the rail track. The y-axis is direction along of the rail track and the z-axis is in the direction of the height of the structure. The origin is located at the centre of the pole. On the z-axis, the origin is located at the height of the top of track. This orientation is illustrated in Figure 6.1. For the purpose of displacing the orientation of the axis, the origin has been displaced on the x-axis.

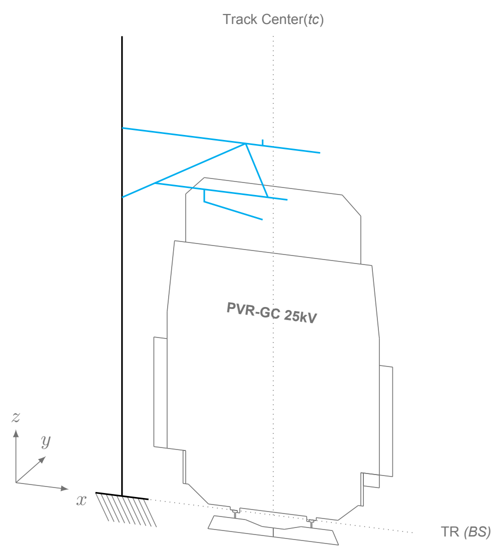


Figure 6.1: Orientation of the Cartesian coordinate system

6.3 Objective Functions

For each of the objective functions, the formulation and motivation are given.

6.3.1 Minimise Carbon Emissions

Carbon emissions are a key determinant in assessing the environmental footprint of a design. As seen in chapter 5, carbon emissions serve as a critical and widely used metric of environmental impact. Given the impracticality of quantifying total carbon emissions for all designs options within the model, as it would require making a significant number of assumptions for all the different stages within the lifecycle. The assumption has been made that the primary contribution originates from the selected material for the pole and its associated production process. Consequently, the carbon emissions of the pole design are determined considering the CO_2 equivalent of the selected material.

In this context, the equivalent denotes the kilogrammes of CO_2 generated and discharged into the atmosphere per kilogramme of material used in the design. The CO_2 equivalent of the material is then multiplied by the mass of the proposed pole design. This mass is computed on the basis of the density of the chosen material, the cross-sectional area, and the length of the pole, culminating in the subsequent objective function:

$$\begin{aligned} \text{Minimise } & f_{CO_2 \text{ footprint}}(x) \\ & f_{CO_2 \text{ footprint}}(x) = C_{CO_2\, m} \cdot \rho_m \cdot A \cdot L_{\text{Pole}} \end{aligned} \tag{6.1}$$

Where:

- $C_{\text{CO}_2,m}$: CO_2-equivalent of material m
- ρ_m: density of material m
- A: cross-sectional area of the pole design
- L_{Pole}: length of the pole

6.3.2 Minimise Embodied Energy

Embodied energy has been chosen as the secondary objective, serving as the second indicator of environmental impact. This embodied energy encapsulates the energy required for the manufacture of the pole design. Here, a similar line of reasoning is used as for carbon emissions. Consequently, the embodied energy of the selected material is considered, representing the energy required for the production of a kilogramme of the material. In the context of pole design, the embodied energy is computed by multiplying the embodied energy of the chosen material with the volume of the pole, culminating in the subsequent objective function:

$$\begin{aligned} \text{Minimise } & f_{\text{Embodied Energy}}(x) \\ & f_{\text{Embodied Energy}}(x) = C_{EE\, m} \cdot A \cdot L_{\text{Pole}} \end{aligned} \tag{6.2}$$

Where:

- $C_{EE\, m}$: embodied energy of material m
- A: cross-sectional area of the pole design
- L_{Pole}: length of the pole

6.3.3 Maximise Circular Efficiency

Circularity emerges as a key indicator, as seen in chapter 5. To incorporate this aspect, the concept of circular efficiency, as defined by the NMD [81], is used. This indicator is based on the correlation between future environmental benefits and the direct environmental cost incurred during production. This is achieved by dividing the environmental benefits (Module D of LCA) by the environmental costs in production (Module A1–3 of LCA). High circular efficiency implies low environmental costs in production and high environmental benefits.

$$\text{Circular Efficiency} = \frac{C_{\text{Module D}}}{C_{\text{Module A1-A3}}}$$

Calculating circular efficiency requires determining the environmental benefits associated with each pole design. These benefits are primarily determined by the proportion of material that can be recycled from the total material used for the design. This should be determined for each material incorporated in the model. However, it is challenging to establish a correct assumption for this proportion as well as the influence it would have on the choice of material. Thus, it was decided to formulate a new indicator of circularity based on the concept of circular efficiency, assuming that the proportion of material which can be recycled is uniform across all materials.

In the data set of materials used for the model derived from the Granta Edupack software [84], a distinction is made with respect to embodied energy and carbon emissions in the categories of virgin, recycling, and typical. The virgin value represents the environmental impact induced by the production of one kilogramme of material from virgin resources. The recycled value represents the impact of recycling a kilogramme of material so that it could be reused as a resource for production. The typical category represents the impact of producing a kilogramme of material from a combination of virgin and recycled resources. This is computed using the subsequent formulation, which incorporates the predefined recycling factor RF:

$$X_{\text{Typical}} = (1 - RF) \cdot X_{\text{Virgin}} + RF \cdot X_{\text{Recycling}}$$

The recycling factor (RF) is defined as the representative proportion of recycled material used in the production of material derived from both virgin and recycled sources.

Integrating the concept of circular efficiency with the respective values of virgin and recycled material, an index of the potential for circularity can be formulated by calculating the ratio obtained by dividing the recycling value by the virgin value. The concept of circular efficiency uses the correlation between future environmental benefits and the direct environmental cost incurred during production. The proportion between the recycling value and the virgin value offers an understanding of the correlation between the future environmental impact when using only recycled material as a resource and the environmental impact when using only virgin resources. This proportion points to the potential environmental benefits of circularity in contrast to the use of only virgin resources. A low value of this ratio implies that the environmental impact of recycling the material is minimal compared to that of producing a kilogramme of material from virgin resources. As a result, this indicates that the material has a high potential for circularity. Recycling and reuse of the material would be beneficial and indirectly promote circularity.

In the context of this research, this ratio is referred to as circular efficiency and has been formulated as an objective function for both carbon emissions and embodied energy. As a lower ratio signifies a higher potential, the functions are also minimised, culminating in the subsequent objective functions:

$$\text{Minimise } f_{\text{Circular Efficiency},CO_2}(x)$$
$$f_{\text{Circular Efficiency},CO_2}(x) = \frac{C_{CO_2,\text{recycling } m}}{C_{CO_2,\text{virgin } m}} \tag{6.3}$$

Where:

- $C_{CO_2,\text{recycling m}}$: CO_2-equivalent to recycle kilogram of material m
- $C_{CO_2,\text{virgin } m}$: CO_2-equivalent to produce kilogram of material m from virgin resources

$$\text{Minimise } f_{\text{Circular Efficiency, EE}}(x)$$
$$f_{\text{Circular Energy, EE}}(x) = \frac{C_{\text{EE,recycling } m}}{C_{\text{EE, virgin } m}} \tag{6.4}$$

Where:

- $C_{\text{EE,recycling}}$: embodied energy required to recycle kilogram of material m
- $C_{\text{EE, virgin } m}$: embodied energy required to produce kilogram of material m from virgin resources

6.3.4 Minimise Cost

In addition to considering the environmental impact, the economic impact is also taken into account by minimising the cost of the design. In determining the cost, the material price is used as an indicative measure following a line of reasoning similar to that of the preceding objective functions, resulting in the cost being simplified to only the material price on the basis that maintenance costs for a pole are negligible and the installation costs would be uniform, in principle, across all pole designs. However, the cost of a material fluctuates for each material used in the model; this topic is further elaborated in section 7.3. The cost of the design is subsequently computed by multiplying the price of the chosen material by the total mass of the pole design, resulting in the ensuing objective function:

$$\begin{aligned} &\text{Minimise } f_{\text{Cost}}(x) \\ &f_{\text{Cost}}(x) = C_m \cdot \rho_m \cdot A \cdot L_{\text{Pole}} \end{aligned} \tag{6.5}$$

Where:

- C_m: the price of material m per kilogram
- ρ_m: density of material m
- A: cross-sectional area of the pole design
- L_{Pole}: length of the pole

Parallels can be drawn between the formulation of objective functions, particularly with regard to carbon emissions (Eq.6.1), embodied energy (Eq.6.2), and cost (Eq.6.5). These three variables are interconnected by the cross-sectional area of the pole, complicating the process of establishing a distinct trade-off amongst these objectives for a given material and pole design. This requires the algorithm to execute the trade-off by selecting the material or shape of the pole. The cross-sectional area is determined by the type of pole shape or the dimensions of the shape. Similarly to carbon emissions, the embodied energy and cost of the material vary amongst the materials in the dataset.

6.4 Constraints

In order to constrain the model, the following constraints are implemented in the model. These constraints are applied in the fitness function of the model. The formulated fitness function can be found in section 7.2.

The structural constraints incorporated within the model are based on the specifications stated in RLN0009. Within RLN0009, constraints are defined for the purpose of constraining the displacement of the top pole, as well as the displacement of the contact line. Furthermore, the structure must be able to withstand a variety of load combinations, ensuring safety through the application of design resistance and shear stress constraints.

The shape factor defined by Ashby and the thickness and width ratio requirements set out in Eurocode 3 for steel structures are employed as constraints to guarantee the model's feasibility and to restrict the fitness values of the objective functions. These constraints are set out in the subsequent subsections and integrated into the model's fitness function.

6.4.1 Displacement Constraints

As mention above the two displacement constraints have been established for the support structure, both originating from RLN0009 [62]. In the case of permanent loads, the maximum displacement of a pole is related to the length of the pole of the structure. The maximum allowed displacement of the top pole should be less than 1% of the length of the pole in the x-direction. This can be expressed mathematically as follows. This constraint has also been applied in the y-direction for permanent loads and wind loads acting in the y-direction along the track. In order to constrain the model regarding the design of the pole shape and increase the validity of the design, it is necessary to minimise the thickness of the pole to a minimum. This is because there are no constraints on the deflection in this direction.

$$\delta_{\text{Top Pole},x} \leq 1\% \cdot L_{\text{Pole}}$$

Where:

- $\delta_{\text{Top Pole},x}$: displacement of the top of the pole in x-direction.
- L_{Pole}: total length of the pole.

In the case of wind loads on the support structure, the maximum allowed displacement of the contact wire is related to the maximum allowed displacement in the horizontal and vertical planes. These displacements are observed when the wind loads are perpendicular to the direction of the rail track. However, the maximum allowed displacement of the contact wire depends on the specified speed limit for that section and is identical in the horizontal and vertical directions. An overview of the maximum displacement allowed given the specified speed limit can be found in Table 6.1.

Table 6.1: Maximum Displacements of Contact Wire Due to Wind Load

Speed limit *[km/h]*	**Maximum Displacement** *[mm]*
$v_{max} \leq 160$	$\delta_y, \delta_z \leq 60$
$160 > v_{max} \leq 200$	$\delta_y, \delta_z \leq 40$
$200 > v_{max} \leq 300$	$\delta_y, \delta_z \leq 20$

For the constraint on the deflection of the contact wire within the model. Its chosen to use the deflection constraints of a speed limit of 160 km/h. The speed limit on the vast majority of the main Dutch rail network is less than 160 km/h.

6.4.2 Design Resistance and Stability Verification of Ground Support

The verification of the resistance and stability of the ground support design assesses compliance with the material boundaries. The method employed involves the linearly summing of the specified ratios for each type of stress result, which is a conservative approach to ensure resistance and stability [83].

$$\frac{F_z}{N_{z_{rd}}} + \frac{M_y}{My_{rd}} + \frac{M_x}{M_{x_{rd}}} <= 1$$

$$N_{z_{rd}} = \frac{Y \cdot A}{Y_m}$$

$$M_{y_{rd}} = \frac{Y \cdot (\frac{I_y}{Y_c})}{Y_m}$$

$$M_{x_{rd}} = \frac{Y \cdot (\frac{I_z}{Z_c})}{Y_m}$$

Where:

- F_z: force along the z-axis
- $N_{z_{rd}}$: design resistance along the z-axis
- M_y: bending moment about the y-axis
- $M_{y_{rd}}$: design bending resistance about the y-axis
- M_x: bending moment about the x-axis
- $M_{x_{rd}}$: design bending resistance about the x-axis
- Y: yield strength of the material
- A: cross-sectional area
- Y_m: partial safety factor for material strength
- I_y: second moment of area about the y-axis
- Y_c: distance from the neutral axis to the extreme compression fibre along the y-axis
- I_z: second moment of area about the z-axis
- Z_c: distance from the neutral axis to the extreme compression fibre along the z-axis

6.4.3 Shear Stress

The shear stress constraint, based on plastic resistance, is of critical importance in ensuring structural integrity under loading conditions. This constraint dictates that the stress distribution must be managed in such a way as to prevent the material from exceeding its yield strength, while accommodating plastic deformations [83].

The formulation of the constraint is based on the flexural formula. The formula enables the calculation of the maximum shear stress experienced at the outer edge of the material. This is achieved by multiplying the bending moment about the axis by the distance to the outer edge and then dividing by the moment of inertia of the axis. The constraint ensures that the shear stress remains within the limits of the yield strength of the material. The formulation of the constraint is as follows:

$$\sigma_m \leq \frac{M_y Y_y}{I_y}$$

Where:

- σ: yield strength of material m
- M_y: total bending moment around the y-axis of the pole
- Y_y: distance from the neutral-axis to the outer fibre of the cross-section of the pole
- I_y: moment of inertia around the y-axis

6.4.4 Shape Factor for Elastic Bending

The shape factor, as defined by Asby, is a dimensionless index that allows for the evaluation of the effectiveness of structural shapes [85]. In particular, the geometry of the section plays a significant role in bending situations. The factor is related to the cross-sectional area and the moment of inertia (I) along the bending axis. By adjusting the cross-sectional shape, the beam stiffness can be enhanced. This is due to both the modulus of elasticity and the second moment of area. Furthermore, it enables the reduction of the quantity of material employed, while maintaining the requisite stiffness. This is accomplished by reallocating material away from the neutral axis [86].

Although slender shapes tend to exhibit higher shape factors, an excessive degree of thinness can precipitate buckling in flanges or tube walls, thereby imposing an upper limit on the shape factor dictated by material characteristics. Practical shape factors often fall below this maximum threshold, mainly due to constraints imposed by manufacturing capabilities or conservative design approaches. The limit of the practical shape factor is related to the ratio of Young's modulus to the yield strength of the material [83].

The derivation of the shape factor employed in the model is presented below. As with the derived constraint based on it, a square beam serves as a reference shape and is assigned a shape factor of 1. The moment of inertia for the reference shape is determined by the following equation:

$$\begin{aligned} I_0 &= \frac{b^4}{12} \\ &= \frac{A^2}{12} \end{aligned}$$

Where:

- I_0: moment of inertia of strong axis of square reference beam
- b: width and height of the square reference beam
- A: cross-sectional area of the square reference beam

The constraint ensures that the shape of the pole design in the solution is feasible. This is achieved by ensuring that it is less than or equal to the limit of the shape factor for the selected material in the solution. The shape factor of the pole design is determined using the relation between cross-sectional area.

Shape Factor:

$$\phi_B^e = \frac{S}{S_0} = \frac{E \cdot I}{E \cdot I_0} = 12 \cdot \frac{I}{A^2}$$

Constraint:

$$\frac{12 \cdot I}{A^2} \leq \phi_{B,\text{Max}}^e$$

Where:

- I_0: moment of inertia of strong axis of square reference beam
- A: cross-sectional area of the design beam
- ϕ_B^e: shape factor of the beam for elastic bending
- $\phi_{B,\text{Max}}^e$: maximal shape factor of the beam for elastic bending
- E: Youngs modulus of the material
- I: moment of inertia of strong axis of design of beam

6.4.5 Ratio of Width-To-Thickness of Shape Design

This constraint is based on the ratio of width-to-thickness of a shape from Eurocode 3 for Steel Structures [83]. A conservative approach has been adopted with the objective of constraining the shape of the pole design and enhancing its reliability. This is intended to improve the feasibility of the pole shape design.

The classification of the cross-sections is used to assess their force resistance and rotational capacity without failure. Furthermore, in order to gain an understanding of the behaviour of cross-sections under stress, it is necessary to consider the phenomenon of local buckling. Local buckling is the bending or warping of components under compression and has a significant impact on the structural integrity and performance of the structure.

The cross-sections are classified into four classes, each indicating a different level of performance in terms of bending and force resistance. Prior to any compromise in structural capabilities due to the effect of buckling, the cross-sections in Class 1 are capable of establishing a plastic hinge. This allows for the necessary rotational capacity for plastic analysis without any loss of resistance. Class 2 comprises those cross-sections that are capable of achieving their plastic moment resistance. However, their rotational capacity is restricted due to local buckling. Class 3 comprises cross-sections that can achieve yield strength when subjected to an elastic stress distribution at the extreme compression fibre of the steel member, despite local buckling.

The constraints of Class 3 are employed to define the limits of this class. These limits allow for the widest range of values for the ratio of the width to thickness, thereby increasing the feasibility of the shape for design. Both the limits for compression and bending have been utilised in the model. The formulation of these limits can be found in Appendix E.

6.4.6 Constraints on the Objective Functions

In addition, constraints have been incorporated into the objective function with regard to their maximum possible values. These constraints relate to the maximum cost and the largest support pole currently in use by ProRail, the HEA300. The maximum cost information was sourced from Sweco's cost analysis for OCLS works and materials [87].

Furthermore, data on CO_2 emissions for the HEA300, used as a support pole, were obtained from the NMD environmental chart [77]. This data is presented per metre/length of the pole and was commissioned by ProRail. The energy data was derived from the Granta Edupack dataset for Steel S235, also used for the HEB300 support pole.

$$
\begin{aligned}
C_{\text{Cost, max}} &= €\,2750 \\
C_{\text{CO}_2\text{ Footprint, max}} &= C_{\text{HEB300}} \cdot L_{\text{Pole}} \\
C_{\text{CO}_2\text{ Footprint, max}} &= 2906.6\text{Kg } CO_2 \text{ eq.} \\
C_{\text{Embodied Energy, max}} &= C_{\text{S235}} \cdot A_{\text{HEA300}} \cdot L_{\text{Pole}} \\
C_{\text{Embodied Energy, max}} &= 2.495\text{MJ}
\end{aligned}
$$

Where:

- C_{Cost}: maximum cost constraint
- $C_{\text{CO}_2\text{ Footprint}}$: CO_2 footprint constraint
- C_{HEB300}: CO_2 emission factor for HEB300 steel support pole
- L_{Pole}: length of the pole
- $C_{\text{Embodied energy}}$: embodied energy constraint
- C_{S235}: embodied Energy data for Steel S235
- A_{HEA300}: cross-sectional area of HEA300

6.5 Optimisation Algorithm - NSGA-II

This section discusses the optimisation algorithm, NSGA-II, used for the multi-objective optimisation (MOO) model to define the Pareto frontier. This frontier exists due to those solutions which cannot be further optimised at the expense of one of the other objectives. Therefore, the trade-offs which should be made are also identified. The Pareto frontier also forms the boundary of the design space of a given design problem as all solutions above or below it, depending on the type of optimisation (minimisation/maximisation), are feasible.

6.5.1 Genetic Algorithm

Genetic algorithms (GAs), also known as evolutionary algorithms, have emerged as a method for addressing multi-objective problems in recent decades. One of the key features of GAs is their ability to find a uniform Pareto frontier, which is a state where no objective can be improved without sacrificing another. The advantage of these algorithms is that they evaluate a diverse range of solutions, which allows them to explore a large solution space. This enables them to quickly identify the optimal solutions in the solution space once they have converged.

The standard GA algorithm process consists of four main elements: fitness function, selection, crossover, and mutation. In addition, individual solutions represent chromosomes. The design variables represent the genes of the chromosomes. In the fitness function, individual solutions are evaluated based on the so-called fitness within the population. The fitness is determined by the fitness score, determined by the objective functions of the problem. The fitness score indicates how well the individual solutions solve the problem.

The fittest solutions are selected to form a new population, which is done in the selection process, where the selection is made based on the fitness score determined in the fitness function. The selected solutions can then be further adapted in the crossover and mutation elements.

In the crossover, the selected solutions are used as parents to generate new solutions. The chromosomes of these parent solutions are used to formulate an offspring of the current population. The crossover thus represents the reproduction process. The mutation element has the main purpose of ensuring diversity within the population and preventing premature convergence. To ensure this diversity amongst the solutions, the values of one or more genes in the solutions are altered.

Over the years, various methods have been developed for this reproduction process. However, the described process of a standard GA is stated in pseudocode below, as shown in the flow diagram in Figure 6.2.

Algorithm 1:
Standard Genetic Algorithm

input : Initial population $R_{initial}$
output: Final population R_{final}

Initialisation;
while *Stop Criteria is not met* **do**
  Fitness Function;
  *Compute fitness for each individual in R_t
  Parent Selection;
  *Select parents from P based on their fitness
  Crossover;
  *Perform crossover on the parents to form new population
  Mutation;
  *Apply mutation on the new population
  New population R_{final};
end

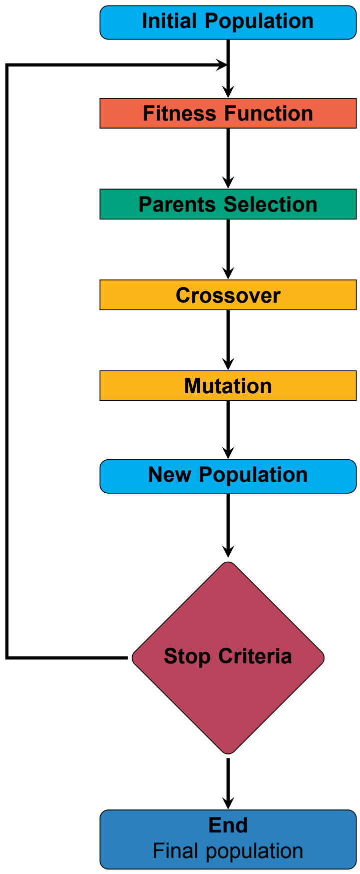


Figure 6.2: Overview of the standard Genetic Algorithm model

6.5.2 Non-Dominate Sorting Genetic Algorithm II

As MOO involves optimising multiple conflicting objectives simultaneously, this presents a significant challenge in traditional optimisation techniques. A widely used genetic algorithm to solve these MOO problems is the NSGA-II, proposed by Deb et al. It is a prominent solution in this domain due to its ability to efficiently provide Pareto optimal solutions [88]. Numerous comparative studies, covering the application of the NSGA-II algorithm to MOO, have been carried out [89] [90] [91].

NSGA-II operates by iteratively evolving a population of candidate solutions towards Pareto optimally. The primary mechanism involves non-dominated sorting, which ranks solutions within the population based on Pareto dominance. This sorting procedure establishes Pareto frontiers (F) which represent optimal trade-offs between conflicting objectives. Furthermore, NSGA-II employs binary tournament mating selection to enable selection pressure amongst the solutions, then using the rank of solution given its front and then its crowding distance. This also allows for maintaining the diversity amongst solutions, thus improving the exploration of feasible solutions within the search space [88].

In each generation, NSGA-II generates a new population by selecting parents (P) from the current population (R_t) through the described elitist mechanisms above. The offspring (Q) of the population can be produced by applying crossover and mutation operators. This procedure is illustrated in Figure 6.3. The algorithm procedure is described in pseudocode in algorithm 2.

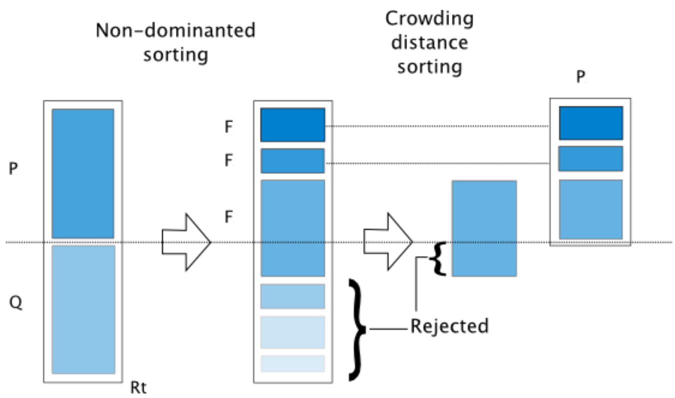


Figure 6.3: Overview of the parent selection of NSGA-II [88]

Algorithm 2: Non-Dominated Sorting Genetic Algorithm II (NSGA-II)

input : Population R_{gent},
Number of generations G,
Number of parents N_P
output: New Population R_{gen+1}

Function Non-Dominated Sorting(R_{gen});
Function Crowding Distance Assignment(F_i);
Function Binary Tournament Selection(R_{gen});

Evaluate each solution in R_{gen};
while $gen < G$ **do**
    Non-Dominated Sorting(R_{gen});
    *Perform non-dominated sorting to divide solutions into fronts $F_1, F_2, \ldots, F_k$
    Crowding Distance Assignment(F_i);
    *Sort solutions in F_i by crowding distance.
    *Add solutions from F_i to P until $|P| = N_P$.
    Binary Tournament Selection(R_{gen}**)**;
    *Select two parents from P using binary tournament selection
    Perform crossover and mutation;
    *Apply crossover and mutation to create the offspring population R_{gen} from P
    Combine parents and offspring;
    $R_{gen+1} \leftarrow Q \cup P$;
end

The population size is typically configured to be twice that of the offspring (Q), ensuring a robust and diverse pool of new solutions for the next generation [88]. As previously stated, the Pareto frontiers within the NSGA-II are established through non-dominated sorting. This process divides the population into separate frontiers, each containing solutions which are not dominated by any other within the solution space. This is illustrated in Figure 6.4 across three frontiers for a bi-objective problem.

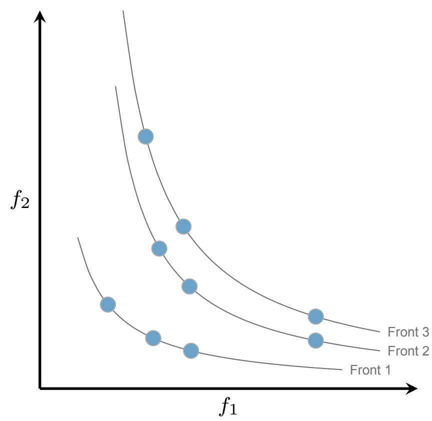


Figure 6.4: Illustration of Non-Dominated Fronts

The crowding distance is subsequently used to hierarchically rank the solutions within each frontier, serving as an indicator of each solution's relative position within its frontier. It is derived from the distances to the nearest neighbouring solutions across each objective. In Figure 6.5, this is illustrated for the case of two objectives. Within the NSGA-II algorithm, the crowding distance is used in selecting solutions from a frontier to serve as parents for the next generation. This is the case where the number of solutions that must be selected as a parent is less than the total available within a frontier. Then those solutions with a larger crowding distance are preferred, as they promote diversity and minimise the risk of premature convergence. Detailed pseudocodes for the non-dominated sorting and crowding distance functions can be found in Appendix D.

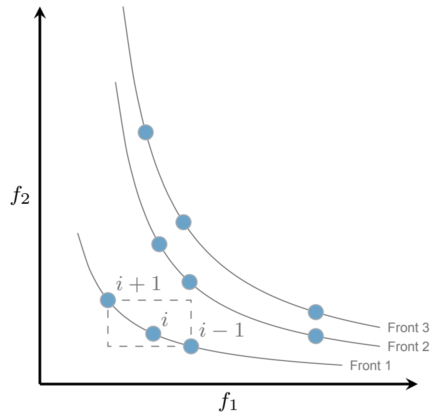


Figure 6.5: Illustration of Crowding Distance

6.5.3 Crossover - Uniform Crossover

In the developed model an uniform crossover to combine genetic information from parent solutions is incorporated. This method randomly exchanges genetic material between parents, maintaining diversity and exploration within the population [90]. Uniform crossover is a genetic operator used in evolutionary algorithms, particularly in GAs, to generate new offspring by combining genetic material (chromosomes) from two parent individuals. Unlike traditional crossover methods, which operate at specific crossover points, uniform crossover randomly selects genes from both parents with a predefined probability (typically 0.5) to create a new offspring [92] [93].

Each gene (or bit) in the offspring is independently inherited from one of the parents based on a coin toss. A randomly generated binary mask determines which genes are inherited from which parent. This method promotes genetic diversity and exploration of the solution space as genes from both parents have an equal chance of being included in the offspring. Uniform crossover is particularly effective in problems where the interaction between genes is complex and non-linear, allowing for a more flexible exploration of genetic combinations [90] [92]. The pseudo code in algorithm 3 outlines the implementation of uniform crossover.

Algorithm 3: Uniform Crossover

input : parents p_1 and p_2,
crossover rate p_c
output: child c

if *random* > p_c **then**
    return; *not crossovered
end
for $i = 1$ **to** D **do**
    *D is length of c
    if $random \leq 0.5$ **then**
        $c_i = p_{1,i}$
    else
        $c_i = p_{2,i}$
    end
    if $random < 0.0001$ **then**
        $c_i = 1 - c_i$
    end
end

6.5.4 Mutation - Adaptive Mutation

In the developed model an adaptive mutation strategy is incorporated. This strategy modulates mutation rates dependent on the fitness attributes of the population, in order to produce changes in offspring solutions. Hence, increasing both exploratory and convergent capacities [93]. The mutation rate is dynamically recalibrated during the optimisation cycle. Re-calibration is performed by measuring the performance of the solutions as fitness values, diversity indices, or convergence rates between successive generations [94].

The mutation rates is tailored in accordance with these metrics observed in the solutions. In the early phases of the optimisation, increased mutation rates boost exploration through the introduction of more frequent random changes. Conversely, reduced mutation rates in later stages concentrate on exploitation by refining promising solutions. Adaptive mutation enables genetic algorithms to adeptly balance exploration and exploitation, dynamically modifying the search paradigm to enhance both the speed of convergence and the calibre of solutions [94] [95]. The details of this algorithm are also presented in algorithm 4.

Algorithm 4: Adaptive Mutation in Genetic Algorithm

```
input  : Population
output: Mutated Population
f_avg ← Calculate Average Fitness(Population);
*Calculate the average fitness value of the population
foreach Solution in Population do
    f ← Calculate Fitness(solution);
    *Calculate the fitness value of the Solution
    if f < f_avg then
        *This solution is regarded as a low-quality solution
        MutationRate ← High Mutation Rate;
        *Keep the mutation rate high
    end
    else if f > f_avg then
        *This solution is regarded as a high-quality solution
        MutationRate ← Low Mutation Rate;
        *Keep the mutation rate low
    end
end
return Mutated Population;
```

6.6 Structural Model

In this section the structural analysis is further discussed in depth, as the different formulas used for the calculation are stated below. The structural analysis on the designs is conducted module used in the model is discussed in section 7.2

In relation to the structural design two limit states are defined. The ultimate limit state, the limit state in case of a structural failure, and the serviceability limit state, the limit of failure given defined conditions. To test these states, the design is validated by formulating a structural and load model taking into account the design conditions and load cases as specified in the RLN0009 and NEN-EN 50119 for support structures.

To test the ultimate limit state of the structure, different load combinations are defined based on the various forces acting on the structure. These load combinations are stated in Table 6.2.

6.6.1 Load Combinations

In *NEN-EN 50119* as in *RLN0009* a number of load combinations are defined for the structural assessment. The load combinations are different combination of loads specified in standards. A main distinction is made between permanent and variable loads, these loads are further described in the sub-sections below. In Table 6.2 the definitions of the load combinations are stated, for the *RLN0009* the discrepancies are stated in the table.

Table 6.2: Specification of the load combinations of *"NEN-EN 50119"* and *RLN0009*"

Load case	**Description**	
	NEN-EN 50119	*RLN0009*
A	Permanent loads conductor tensile forces at the minimum temperature.	Case of the temperature -20°C.
B	Permanent loads conductor tensile forces increased by the wind action and loads on each element, acting most unfavourable direction.	Case of the temperature +10°C with maximum wind load.
C	Permanent loads conductor forces increased by the ice loads.	Case of the temperature -5°C with ice load.
D	Permanent loads conductor tensile forces increased by the combined effects of the ice and wind loads, as the acting ice and wind loads acting on the structure.	Case of the temperature -5°C with ice load and 50% wind load.
E	Permanent loads increased with the loads due to construction and maintenance, with the reduced wind and ice loads.	Case of construction of maintenance.
F	Permanent loads together with the unintentional reduction of one or several conductor forces.	Case of contact wire break.

Moreover, the partial factors are defined for various load combinations, serving as safety factors. Pertinent partial factors for loads are listed in Table 6.3.

Table 6.3: Partial factors for load combinations

		Load combinations					
Type of Loads		**Ultimate limit state**				**Usability limit state**	
Loadcase		**A**	**B**	**C**	**D**	**E**	**F**
Permanent loads	γ_G	1.3	1.3	1.3	1.3	1.3	1.0
Wind loads	γ_W		1.3		0.5		1.0
Ice loads	γ_I			1.3	1.3		
Contact wire break	γ_A						1.0
Construction & maintenance loads	γ_P					1.5	

6.6.2 Permanent Loads

The permanent loads are defined as the loads that act on the structure due to dead weight of the structure itself and all other elements with the structure and the tensile forces of the OCL acting on the structure.

$$F_G = \sum_{i \in M} m_i \cdot g$$

Where:

- F_G: permanent loads working on the structure. [N]
- m_i: mass of component i of the support structure. [kg]
- M: set containing all the mass of each element of the supporting structure.
- g: gravitational acceleration 9.81 [m/s^2]

To determine the permanent load due to the wires of the OCL on the support structure, the length of the wire for a span that must be considered. The effective wire length is delineated by the following function:

For normal section: $$L_{F_{\text{OCL}}} = \frac{1}{2} \cdot L_{\text{Span,Left}} + \frac{1}{2} \cdot L_{\text{Span,Right}}$$

For tensioning section: $$L_{F_{\text{OCL}}} = \frac{1}{2} \cdot L_{\text{Tensioning}}$$

Where:

- $L_{F_{\text{OCL}}}$: effective wire length for force magnitude calculation.
- $L_{\text{Span,i}}$: length of the span located at i side of support structure.

6.6.3 Variable Loads: Wind Loads

The different wind loads that acting on the support structure are discussed below, first the various factors and parameters are discussed. In Table 6.6 an overview of the general value of the various parameters and factors are stated.

Correction for Wind Loads

The correction for the wind loads depends on the specified technical life time, discussed below. The formulation that is defines the correction factor is as follows:

$$\Psi_w = \left(\frac{1 - K \cdot ln(-ln(1-\rho))}{1 - K \cdot ln(-ln(0.98))} \right)^n$$

Where:

- Ψ_w: correction factor for wind loads
- K: shape parameter, depended on the variation coefficient of the extreme value distribution of the wind region.
- ρ: specified technical lifetime [years]
- n: exponent depended on the variation coefficient of the extreme value distribution of the wind region.

The Netherlands is divided into three wind regions. The shape parameter and the corresponding exponent are stated in Table 6.4 for each region. The geographical location of each of the wind regions is illustrated in Figure 6.6.

Table 6.4: Shape parameter (K) and exponent (n) for each wind region in The Netherlands.

Wind region	**I**	**II**	**III**
K	0.2	0.234	0.281
n	0.5	0.5	0.5

The extreme value for the wind pressure for each region has been defined for an undeveloped area at the specified height. An overview of these extreme values is given in Table 6.5.

Table 6.5: Wind pressure by wind region for overhead line height h_{ocl}.

H_{ocl}	**Wind pressure** q_p**[**N/m^2**]**		
	I	**II**	**III**
< 10	1020	850	700
≤ 15	1160	980	800
≤ 20	1270	1070	888
≤ 25	1360	1140	940
≤ 30	1430	1200	990

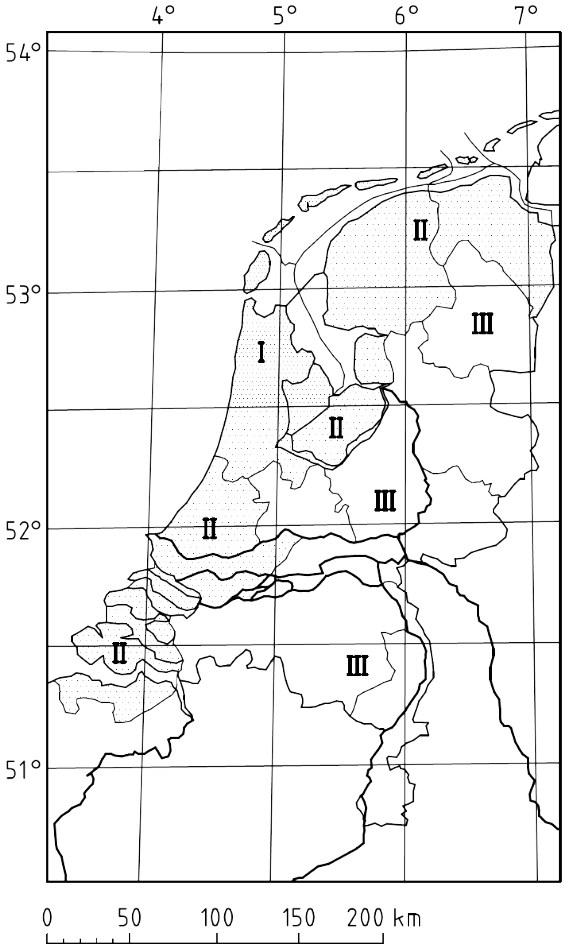


Figure 6.6: Overview of the wind regions in The Netherlands

Table 6.6: Overview of Wind Load Parameters.

Description	**General Value**
Wind correction factor given technical life time of 80 years:	$\Psi_w = 1.03$
Dimensional and dynamic factor for conductors:	$G_c = 0.75$
Dimensional and dynamic factor for insulators:	$G_{ins} = 1.05$
Dimensional and dynamic factor for the support structure:	$G_{ins} = 1.05$
Diameter of 2 contact wires:	$d = 1.8 \cdot d_{Contactwire}$
In case of load combination D	
Ice region A :	$d = 2.99 \cdot d_{Conductor}$
Ice region B :	$d = 2.11 \cdot d_{Conductor}$
Pressure coefficient for contact wire:	$C_c = 1.2$
Pressure coefficient for other conductors:	$C_c = 1$
Pressure coefficient for support structure:	$C_{structure} = 2.8$
Pressure coefficient for single HE or circular pole:	$C_{structure} = 1.82$

OCL Height

The height of the OCL (h_{ocl}) required to ascertain the extreme value acting on the support structure is determined through the following formulation:

$$h_{ocl} = h_{cw} + \frac{1}{3} \cdot h_{cs}$$

Where:

- h_{ocl}: height of the overhead contact line system/support structure. [m]
- h_{cw}: height of the contact wire of the catenary system, measured with respect to ground level. [m]
- h_{cs}: height of the catenary system. [m]

Wind Load on OCL ($Q_{W,c}$)

The resultant force due to the wind pressure on a wire of the OCLs can be calculated with the following formula;

$$Q_{W,c} = \Psi_w \cdot q_p \cdot G_c \cdot d \cdot C_c \cdot \frac{L_1 + L_2}{2}$$

Where:

- $Q_{W,c}$: resultant force due to wind pressure on OCL. [N]
- Ψ_w: correction factor of the wind given the technical lifetime.
- q_p: ultimate wind pressure, predefined for area's in Netherlands. [N/m^2]
- G_c: dimensional and dynamic factor.
- d: diameter of the conductor wire. [m], For double contact wires, $d = 1.5 \cdot d_{contactwire}$
- C_c: pressure coefficient
- L_1, L_2: length of adjacent OCL sections. [m]

Wind Load on Single Element of the Support Structure $Q_{W,structure}$

The resultant force due to the wind pressure on a single pole or beam of the support structure can be calculated with the following formula;

$$Q_{W,structure} = \Psi_w \cdot q_p \cdot G_{structure} \cdot C_{structure} \cdot A_{structure}$$

Where:

- $Q_{W,structure}$: resultant force due to wind pressure on single pole or beam of the support structure. [N]
- Ψ_w: correction factor of the wind given the technical lifetime.
- q_p: ultimate wind pressure, predefined for area's in Netherlands. [N/m^2]
- $G_{structure}$: dimensional and dynamic factor for the structure.
- $C_{structure}$: pressure coefficient for the support structure, depending on the shape.
- $A_{structure}$: effective surface area of the pole or beam of the support structure. [m^2]

6.6.4 Variable Loads: Ice loads

For The Netherlands, the extreme value of the ice load (q_{ice}) has been specified based on the location. The effect due to ice load on the insulators and support structure can be neglected in the case of The Netherlands. Extreme ice load values have been determined for two specific regions, identified as follows:

- Region A, the region east of 6° E.L. in the province of Friesland, Groningen and Drenthe. The extreme ice load value for this region is 7 [N/m].
- Region B, the rest of The Netherlands, and the extreme ice load value for this region is 3.5 [N/m].

The resultant force due to icing on the OCL can be calculated with the following formula;

Conductors: $$Q_I = q_{ice} \cdot \frac{L_1 + L_2}{2}$$

OCL: $$q_{ice} = \Psi_{ice} \cdot C_{ice} \cdot \sqrt{d} \cdot \frac{L_1 + L_2}{2}$$

Where:

- Q_I: resultant force due to the ice load. [N]
- q_{ice}: ice load on the OCL due to icing. [N]
- Ψ_w: correction factor for the icing, depending on the location of support structure.
- d: diameter of the wire. [mm]
- L_1, L_2: length of adjacent OCL sections. [m]

6.6.5 Variable Loads: Temperature Variance Loads

Due to the temperature differentiation, the various loads acting on the support structure will differ in the case of a fixed catenary system. In this case, the following temperatures should be used for the calculating of the effects on the loads;

Table 6.7: Overview of temperature used load calculations and temperature effects.

Temperature	**Value**
Nominal temperature	+10 °C
Minimal temperature	-20 °C
Minimal temperature, case of a tunnel	-10 °C
Temperature in case of ice loads	-5 °C

6.6.6 Technical Life Time

In addition, it specifies the minimal technical life time of the support structure which should be used during the analysis. These are stated in Table 6.8. The formulas stated for the different loads are based on the assumption of a technical lifetime of 50 years, the loads are therefore multiplied by a correction factor based on the specified/required technical lifetime.

Table 6.8: Technical lifetimes for support structures.

Description	**Technical Lifetime**
New support structure	80 years
New support structure during construction phase	1 year < t < construction time
Existing support structure being being modified	15 years < t < 80 years

Chapter 7

Implementation and Validation of the MOO Model

In this chapter, further details of the implementation of the model designed for the optimisation problem are presented. This chapter describes the framework of the developed model, highlighting the differences implemented relative to the conventional NSGA-II framework. Subsequently, the fitness function tailored for the design problem is discussed along with the dataset used in optimising the model and the software implementation of the model in Python. The chapter ends with a discussion on the validation of the developed model.

7.1 Model Framework

This section presents outlines the developed model framework to explore the design space. The framework is based on the standard GA framework. The crossover and mutation methods discussed in the previous chapter are used in the model. Two filtering elements have been integrated into the framework. One element filters the population before the fitness function. The other filters the parents before the crossover. The filtering operations, initial population and constraint score used in fitness function are further discussed in the following. The methods used for the parent selection, crossover and mutation are similar as those discussed in previous chapter. A diagram of the model framework is stated in Figure 7.1. As illustrated in the diagram, for each generation, the selected parents, feasible solutions within the population, are preserved.

Algorithm 5: NSGA-II Adaptation

input : Initial population P_{Initial}, Stop criteria
output: Final population P_{Final}

Initialisation;
Initialise population randomly from design variable ranges;
while *Stop criteria not met* **do**
  Population Filtering;
  Filter the Population P for feasibility.;
  Infeasible solution are replaced with feasible non-dominated solution in current population P ;
  Fitness Function;
  for *each individual ind in P* **do**
    Compute fitness of ind;
  end
  Parent Selection;
  Perform non-dominated sorting and crowding distance determination on P;
  Select parents based on non-dominated fronts and crowding distance;
  Export selected parents and all feasible solutions in P;
  Parents Filtering;
  Filter the selected parents for feasibility.;
  Crossover;
  Perform crossover on the selected parents to create offspring;
  Mutation;
  Apply adaptive mutation on the offspring;
  New Population Update;
  Update P with the new offspring population;
end
Output:;
Final population P_{Final} after meeting stop criteria.

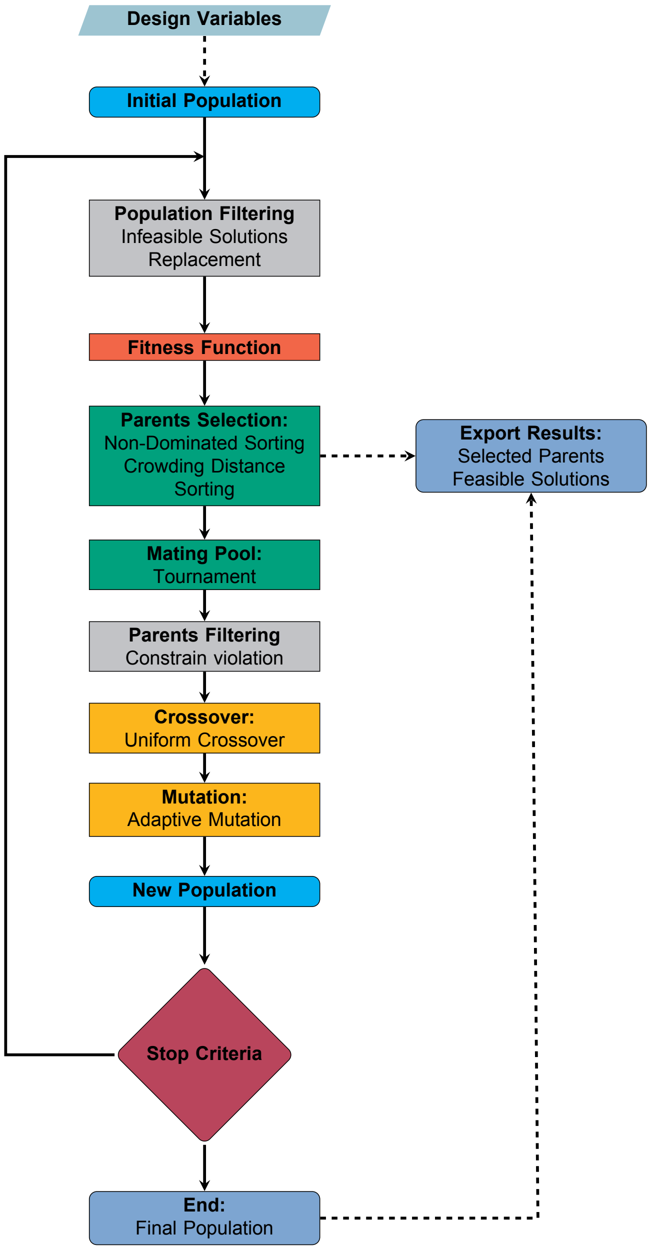


Figure 7.1: Overview of the model framework

7.1.1 Design Variables

The solutions are derived from the design variables, which collectively constitute the gene space. The following design variables have been selected to define the design of the pole: the material from which the pole is constructed; the shape of the pole, which encompasses a range of commonly used steel beam shapes; and the specific dimensions of the pole, including width, height, and the thickness of different flanges in the selected pole shapes. The design variables ranges and data is further discussed in section 7.3.

7.1.2 Initial Population

At the initiation of the model, an initial population (P_{Initial}) established, derived from the gene space. The gene space is constituted by the design variables. The genes for each solution are selected at random from this gene space. Upon the determination of all requisite genes for a solution, it incorporated into the initial population. This process is repeated until the initial population reaches the predetermined size. The selection of genes for each solution is executed independently of the other solutions within the population.

7.1.3 Population Filtering

The implementation of population filtering is designed to enhance the quality of the solutions within the population. The population is filtered on the basis of the feasibility of the solutions. Solutions that are considered infeasible are filtered from the population and replaced with feasible solutions. A solution is considered infeasible if it violates both the deflection constraints and the shape design constraints.

The most viable options for replacement are selected from the current population using the Pareto front and crowding distance metrics. These metrics are then applied to the feasible solutions in the population, after which the most suitable replacements are selected based on their rankings.In the event that the number of infeasible solutions exceeds the aggregate count of feasible solutions, the feasible solutions are reused to replace the infeasible solutions. The pseudo-code of the filter is presented below.

Algorithm 6: Population Filtering

input : Population P,
output: Filtered population P_{Filtered}

Evaluate feasibility

foreach *Solution in Population* P **do**
  if *Solution violates Deflection Constraints* ***AND*** *Shape Design Constraints* **then**
    Solution is Infeasible: ;
    $X_{\text{Feasibility}} == 0$;
  else
    Solution is Feasible: ;
    $X_{\text{Feasibility}} == 1$;
  end
end

Determine ranking of feasible solutions;
if $X_{Feasibility} == 1$ **then**
  Determine Pareto front $F \leftarrow$ Preform Non-Dominated Sorting;
  foreach *Solution in Pareto Front* F **do**
    Ranking of Solution $\leftarrow$ Determine Crowding Distance;
  end
end

Replace all infeasible solutions from Population P;

foreach *Solution in Population* P **do**
  if $X_{Feasibility} == 0$ **then**
    Replace solution $\leftarrow$ Feasible Solution;
  end
end

if $\sum$ *Infeasible Solutions* > $\sum$ *Feasible Solutions* **then**
  Reuse Feasible solutions to replace Infeasible Solutions;
end

7.1.4 Fitness Function and Constrain Score

Within the fitness function, the evaluation of each solution's fitness within the population is computed. The fitness function itsself is discussed in more detail in section 7.2. The constraints within the model are integrated into the fitness function. Consequently, the solutions are assessed based on their compliance with the constraints in the fitness function. A constraint score has been incorporated into the fitness function, allowing to monitor the violations of these constraints.

The constrain score is derived from the methodology that evaluates whether a solution satisfies a given constraint. The formulation is based on the constraint function utilised by Milatz, Winter, Ridder, *et al.* All the constraints are assumed to have equal significance [96]. This is realised through the use of percentile constraint violation by the solution. Should the solution fulfil the constraints, the maximum score is awarded.

The maximal score, predetermined at a value of 10, is multiplied by the percentile constraint violation of a violating solution. Before, multiplying the constrain violating is rounded to decimal. This yields an integer value of constraint violating score. The score is subsequently being deducted from the current constraint score of the solution. Consequently, this mechanism ensures that the feasible solutions attain the maximum scores, whereas infeasible solutions incur significantly negative scores. Within this model, the maximum for the constraint score that a solution can achieve is 1260. The formulation for computing the constraint score is delineated as follows:

Fulfils the constraint: $$C_{\text{Score}} = C_{\text{Score}} + 10$$

Violates the constraint: $$C_{\text{Score}} = C_{\text{Score}} - (10 \cdot \frac{(x_{\text{Sol}} - x_{\text{Con}})}{x_{\text{Con}}})$$

Where:

- C_{Score}: constrain score of a solution
- x_{Sol}: value of the solution for the constrain
- x_{Con}: constrain value

7.1.5 Parents Filtering

The filtration process has been implemented with the objective of guaranteeing that only feasible or least infeasible solutions within specified boundaries are utilised as parents for the subsequent generation. The aim of the filtering process is to maintain the reliability and feasibility of the solutions selected as parents within the model. By filtering out solutions that violate the constraints, the algorithm continuously enhances and refines its approach to generate effective solutions in future generations.

The solutions selected as parents are thus subjected to a filtration process based on their constraint scores. As previously stated, the scores in question reflect any violations of the constraints. Consequently, solutions that do not satisfy the constraints are identified by the maximum constraint score. The selection of new parents for crossover involves the removal of infeasible solutions.

In the event that all initially selected solutions contravene the constraints, alternative solutions are sought. The parents are selected based on their constraint scores, with the objective of identifying those solutions that exhibit the minimal violations.

Algorithm 7: Constraint Score-based Parent Selection Filtering

```
input  : Selected Parents, Constrain Score
output: Filtered Parents
Evaluate constraint score of Selected Parents;
Violating Parents ← Set of solutions with constraint scores < 1260;
Evaluate constraint score of solutions in the Population;
Violating Solutions ← Set of solutions with constraint scores < 1260;
Select new parents based on constraint scores;
if Total number of Violating Parents > 0 then
    if Total number of Violating Solutions == Population Size / 2 then
        Not enough non-violated solutions, least violated are also select as parents;
        Non-Violated Parents ← Set of solutions selected as Parents with constraint score == 1260;
        if Total number of Non-Violated Parents <= 2 then
            Non-Violated Solutions ← Set of solutions with constraint score = 1260;
        end
        else
            Ensure even number of solutions selected as Parents for balanced crossover;
            if Number of selected Parents is odd then
                Remove a solution with the minimum constraint score from selected Parents;
            end
        end
    end
end
New selection of solutions selected as Parent;
```

7.2 Fitness function

This section discusses the fitness function formulated for the model. Initially, a graphical representation of the function is shown in Figure 7.2, which is followed by an explanation of the function flow.

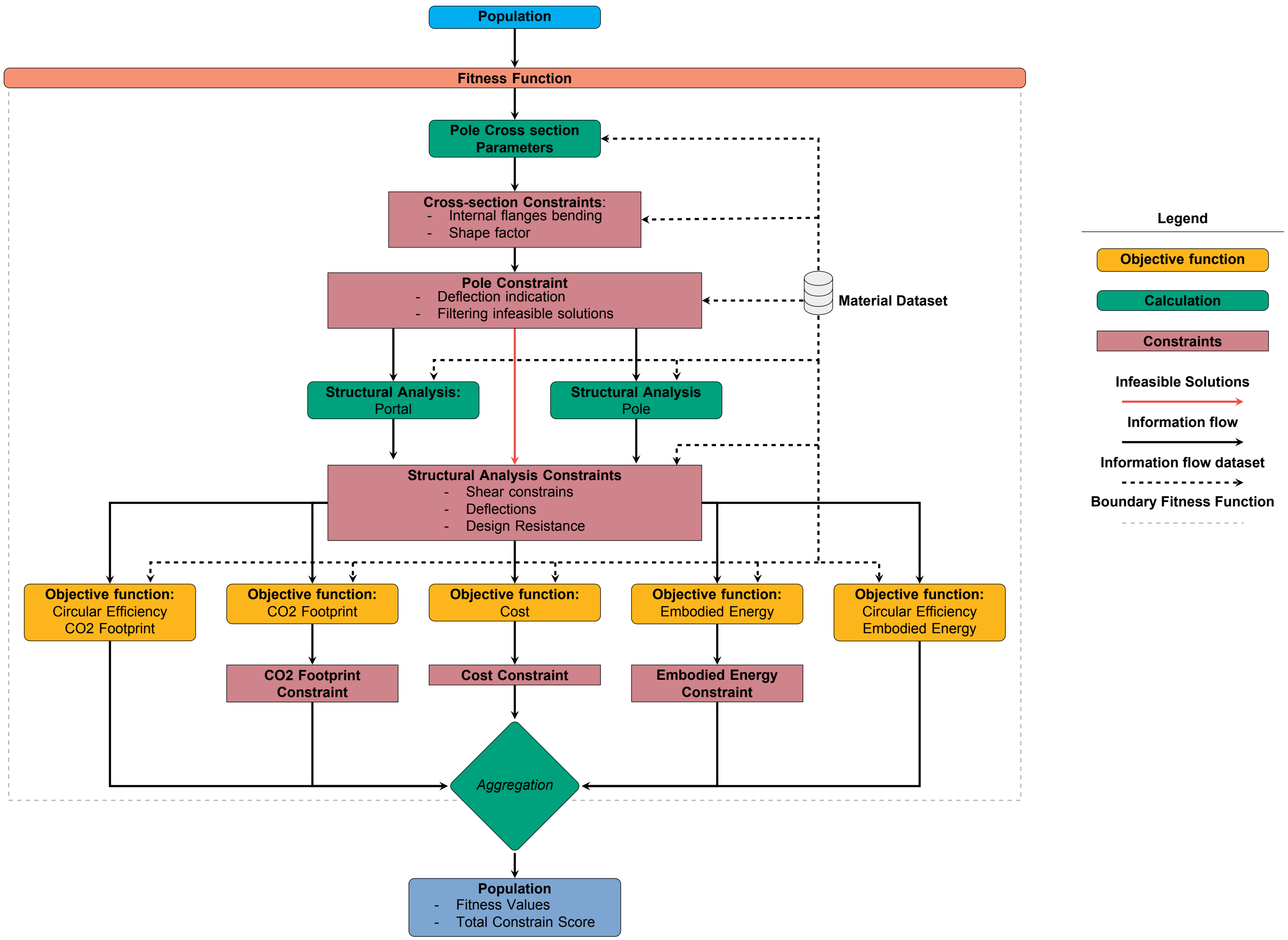


Figure 7.2: Overview of the fitness function used in the optimisation model

The fitness function represents the primary component of the model. Each solution within the population is evaluated, resulting in the determination of the fitness value and the total constraint score. Initially, the design variables are extracted from the solution. This involves the specification of the type of material selected and the shape of the pole, together with the specific dimensions of the pole design. The properties of the material, including Young's modulus, yield strength, Poisson's ratio, and density, were retrieved from the dataset for the chosen material.

Subsequently, the properties of the pole shape, including inertial moments, cross section are determined. These are derived in the Pole Cross Section element, following the determination of all properties for the design. The properties for the Pole Design are evaluated in relation to the Cross-Section Constraints. In this element, the constraints regarding the Width-Thickness Ratio and Shape Factor are evaluated.

Thereafter, the deflections of the pole top are determined using the linear elastic bending formulation. The deflections of the pole top are calculated in the x- and y-directions and evaluated if the maximum displacements constraint is violated. These preliminary calculations of the deflection serve as a filter for the structural analysis. Solutions that violate these constraints are indicated as infeasible.

The feasible solutions are then subjected to further evaluation through a structural analysis of the pole and portal configuration. This analysis is performed for the specified load cases. The results are used to evaluate the structural constraints, namely those for the design resistance, stability of the ground support, displacement constraints, and shear stress.

After structural analysis, the fitness value for the specified objective functions can be determined. Regarding the objectives for CO_2 footprint, embodied energy, and costs, the fitness values are evaluated on the applied constraints. If these constraints are violated, the constraint score is adjusted. The circular efficiency related to the embodied energy and CO_2 footprint are simultaneously calculated.

Following the structural analysis, the fitness value is determined for the specified objective functions. With regard to the objectives for CO_2 footprint, embodied energy and costs, the fitness values are evaluated in light of the applied constraints. In the event that these constraints are violated, the constraint score is adjusted. Finally, the circular efficiency related to the embodied energy and CO_2 footprint is determined.

The output of the fitness function is then formulated, consisting of fitness values for each objective function. Concurrently, the overall constraint score is calculated for the solution. Based on the constraint score for each of the constraints, the solution in the population is then updated by the fitness values and the total constraint score. After that, the fitness of all solutions in the population has been determined. These values are then used to solve the algorithm optimisation.

7.3 Data

In this section, the data used in the optimisation of the model is discussed. The material data used to model different variations of the pole is discussed. Subsequently, the selected pole shape designs are discussed, as well as the ranges for the dimension.

7.3.1 Material Data

Material dataset used in model has been obtained from Granta Edupack 2023 R2 [84]. The data obtained from the software package are from the Level 3 Materials dataset. This data set contains a higher level of detail with respect to the number of properties specified for each material. In Granta EduPack the materials are categorised by material family Table 7.1. An overview of the families can be found in Table 7.1.

Table 7.1: Material Families in Granta Edupack

Material Family - Level 3 Materials Dataset			
-	Ceramic (non-technical)	-	Metal (non-ferrous)
-	Composite (natural)	-	Metal (precious)
-	Composite (metal matrix)	-	Metal (other)
-	Elastomer (thermoplastic, TPE)	-	Plastic (thermoplastic, amorphous)
-	Glass (technical)	-	Plastic (thermoplastic, semi-crystalline)
-	Metal (ferrous)		

The entire set of materials obtained from Granta Edupack has been reviewed. The purpose of the review was to determine whether each material in the dataset had a value for the requisite properties required for use as a model input. In the case that a material did not have value for one of the requisite properties, it was removed from the dataset. An overview of the ranges of the material properties selected materials, designated for model input, is given in Table 7.2

Table 7.2: Material Properties: Level 3 Materials Dataset

Dataset	**Level 3 Materials**	
Total number	166080	
Selection	97293	
Material Property	**Min**	**Max**
CO_2 Footprint Typical [kg/kg]	0.025	45900
CO_2 Footprint Recycling [kg/kg]	0.025	2200
CO_2 Footprint Virgin [kg/kg]	0.025	65100
Density [kg/m^3]	$7.32 \cdot 10^{-6}$	570
Embodied Energy Typical [MJ/m^3]	400000	$1.12 \cdot 10^{12}$
Embodied Energy Recycling [MJ/m^3]	400000	$2.8 \cdot 10^{8}$
Embodied Energy Virgin [MJ/m^3]	400000	$1.37 \cdot 10^{12}$
Poisson Ratio [-]	0.06	0.5
Price [€/kg]	0.0187	603000
Yield Strength [MPa]	1130	$3.6 \cdot 10^{9}$
Young's Modulus [GPa]	7320	$5.7 \cdot 10^{11}$

7.3.2 Pole Shape and Dimensions

In the model, a fixed number of standard shapes have been selected as pole shapes for the design variables. In total, 9 variants of these shapes are used. The shapes are based on the most commonly used shapes for steel beams. These include the following variants for shapes: Solid Rectangular Beam, H-Beam, I-Beam, UNP, T-Beam, Tubular Square Beam, Tubular Rectangular Beam, Tubular Beam, Tubular Solid Beam.

The ranges of dimensional design variables presented in Table 7.3, have been defined based on the minimum and maximum limits for the selected beams in practice. These limits have been obtained from the database of profiles published by Bouwen met Staal for the selected profiles [97]. It has been chosen to use these limits of the range to increase the validity of the model. Initially, broader dimensional intervals were used for the variables. However, these resulted in an increase in the number of infeasible shapes for the pole.

Table 7.3: Range for Dimensions of Design Variables

Dimension	**Min**	**Max**	**Step size**
Height [mm]	100	500	10
Width [mm]	100	400	10
T_w [mm]	2	20	1
T_f [mm]	2	30	1
T_t [mm]	2	40	1

The T_w, T_f, T_t are shape-specific dimensional design variables. T_w, is the web thickness for UNP, H-, I- and T-beams. T_f, is the flange thickness for UNP, H, I and T beams. T_t, on the other hand, represents the thickness of a tubular section. In the case of a round tubular shape, the largest value of width or height is selected as the diameter.

7.4 Software Implementation - Python

The Python multiparadigm programming language [98] has been used to programme the model to solve the optimisation problem. The advantage of using this programme language is due to its open-source nature. Python has a wide library of open-source add-in's to could import as modules, each with specific purpose.

For the optimisation problem, the PyGad package has been used [80]. The package provides several Genetic Algorithms for modelling. The NSGA II genetic algorithm is one of the algorithm options to optimise the problem. The NSGA-II algorithm is implemented in two different versions, one using tournament selection and one without it. For the optimisation problem, tournament versions have been used.

For structural analysis, the PyNite package has been used [99]. This package allows to conduct elastic 3D structural engineering finite element analysis for various load conditions. The load conditions can also be combined, allowing one to perform the structural analysis as stated in the previous section and the constraints described in the related standards and specifications. Hence, determine the deflections of the support structure for the defined load cases.

7.5 Model Validation

The validation of the model, including its sub-modules, and used data are discussed in this section. First, the validation of the structural analysis is discussed, followed by the validation of the environmental data used. Finally, the validation of the model using the Hyper Volume and constraint score.

7.5.1 Structural Analysis - Pynite

The module used for the structural analysis of the design of the pole and the portal is programmed using the Pynite package. This enables 3D modelling of structures, analysis of support structures, and computation of resulting deflections. The first-order analysis used in structural analysis to determine the deflections and the stress distribution. This is in accordance with the requirements stated for these calculations in [6] and [62].

In order to validate the structural analysis module, the models for the pole and portal structure have been validated. In addition, the structural model has been reviewed by expert[1] with regard to the validity of the results and their suitability for use in a practical context. Furthermore, the deflections for the pole design case have been validated using the reference calculation stated in RLN0009.v5 [62]. This comparison yielded results similar to those presented in the example. Note that minor discrepancies may arise due to the handling of a float in Python.

7.5.2 Environmental Data Validation

In order to validate the environmental data used in the model and to verify the applicability of the results, the CO_2 footprints and embodied energy have been recalculated for the H beams evaluated in the LCA study conducted by ProRail for NMD [77]. From the environmental profile of these beams, the related impact category was obtained. With regard to the CO_2 footprint, these are the Global Warming Potential and Climate Change. With respect to Embodied Energy, these are 'Energy, primary, 'renewable', 'Energy, primary, non-renewable' and 'Resource use, fossils'. The environmental data obtained and the results of the calculation can be found in Appendix G.

The typical value from the Granta Edupack dataset is used in the model to calculate the objective functions. The typical values for structural steel S235 in terms of CO_2 footprint are 1.85 kg per kg, while the embodied energy is 17.5 MJ per kg. The results of the comparison for the typical category value are presented in Table 7.4. In the case of the CO_2 footprint, the results demonstrate that the calculated footprint values derived from the impact values are comparable to those of Granta Edupack for S235. This indicates that in the case of the model, the CO_2 footprint values are likely to result in a similar emission value with respect to these impact categories.

However, in the case of embodied energy, such an indication cannot be made. The values derived from the impact categories differ considerably from those of the structural steel S235. It should be noted that the embodied energy results of the model would most closely resemble those of the impact category of Resource Use, Fossil for a material.

[1] Wim Golverdingen, Senior Consultant OCLS, SWECO Nederland

The discrepancy between these factors can be attributed to the fact that they are highly dependent on the type of source use. The values used in the Granta Edupack dataset are derived from published data in the literature and from various life cycle inventory databases. In instances where data are unavailable, the values for the embodied energy and CO_2 footprint are estimated using a model [84]. Consequently, the results of the model should be regarded as indicative of the environmental impact. It should be noted that these values are arbitrary with regard to the determination of the impact.

Table 7.4: Validation for Typical Category for H-Beams by Life Cycle Phase

Virgin Category - Total Pole

A1-A3	**H220**	**H240A**	**HEB240**	**HEB300**	**HEB3004**	**Average**	**Median**	**Std**
Typical approx. - per kg								
GWP	1.874	1.845	1.806	1.769	1.787	1.816	1.806	0.038
CC	1.854	1.823	1.787	1.768	1.775	1.801	1.787	0.032
EP-Ren	3.210	3.218	3.215	3.214	3.244	3.220	3.215	0.012
EP-NRen	38.195	37.978	37.816	37.628	38.010	37.925	37.978	0.191
RU-Fos	35.683	21.164	21.049	20.916	21.186	24.000	21.164	5.843
Typical approx. - Percentage Deviation								
GWP	1.3%	-0.3%	-2.4%	-4.4%	-3.4%	-1.8%	-2.4%	2.071%
CC	0.2%	-1.5%	-3.4%	-4.4%	-4.1%	-2.6%	-3.4%	1.747%
EP-Ren	-81.7%	-81.6%	-81.6%	-81.6%	-81.5%	-81.6%	-81.6%	0.071%
EP-NRen	118.3%	117.0%	116.1%	115.0%	117.2%	116.7%	117.0%	1.092%
RU-Fos	103.9%	20.9%	20.3%	19.5%	21.1%	37.1%	20.9%	33.386%

7.5.3 Optimisation model

In order to validate the optimisation model, several runs have been performed to determine the consistency between the various simulation runs of the model. The simulation runs have been performed for various the number of generations and select materials as input. An overview of these simulation runs and their CPU run time can be found Appendix F. Overall, the model performed consistently between similar runs, as well as between simulation runs with different materials as input. On average, the generation duration was 52.1 seconds. In Table 7.5 run time statistics for the different material families is provided.

Table 7.5: Runtime Statistics per Generation

Material Family	**Mean**	**Standard deviation**	**Standard deviation, unbiased**
Metal (ferrous)	69.2	33.7	38.9
All Materials	49.9	6.5	6.7
All Materials*	48.8	1.7	1.9
Ceramics (non-technical)	45.1	1.4	1.7
Metal (non-ferrous)	47.6	0.8	0.9
Average	52.1	8.8	10.0

Furthermore, for each instance of the exported solution runs, the objective function values were computed independently subsequent to the runs. These calculations, using the gene values of the solution, were then compared with the values exported from the model. In all cases, these values were found to be in congruence with those derived by the model.

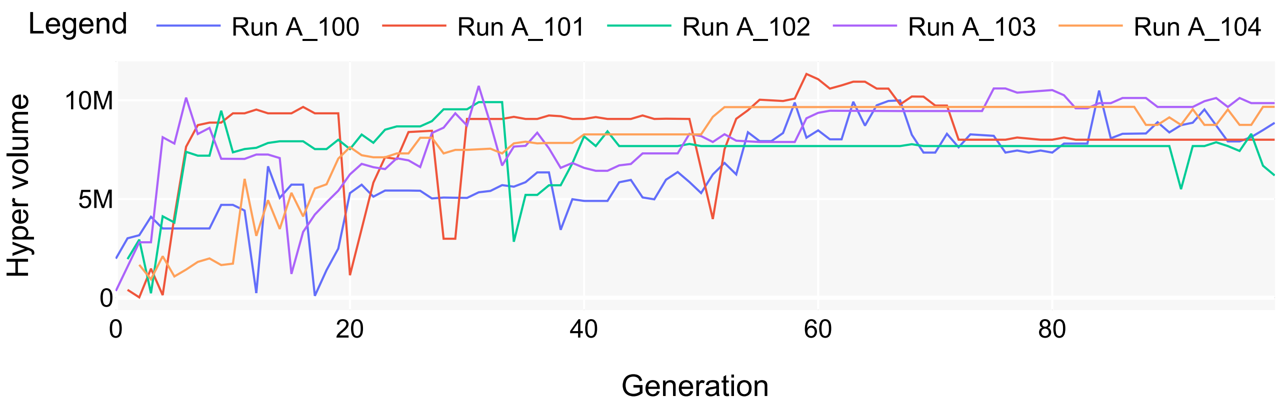
7.5.4 Hyper Volume

The hyper-volume indicator is a metric used to evaluate the performance of multi-objective optimisation algorithms. Measures the volume of the space dominated by a set of non-dominated solutions founded by the algorithm. Therefore, a reference point is used that bounds the volume. The reference point is determined by the maximum values of the objective vectors in each dimension, in the case of a minimisation problem.

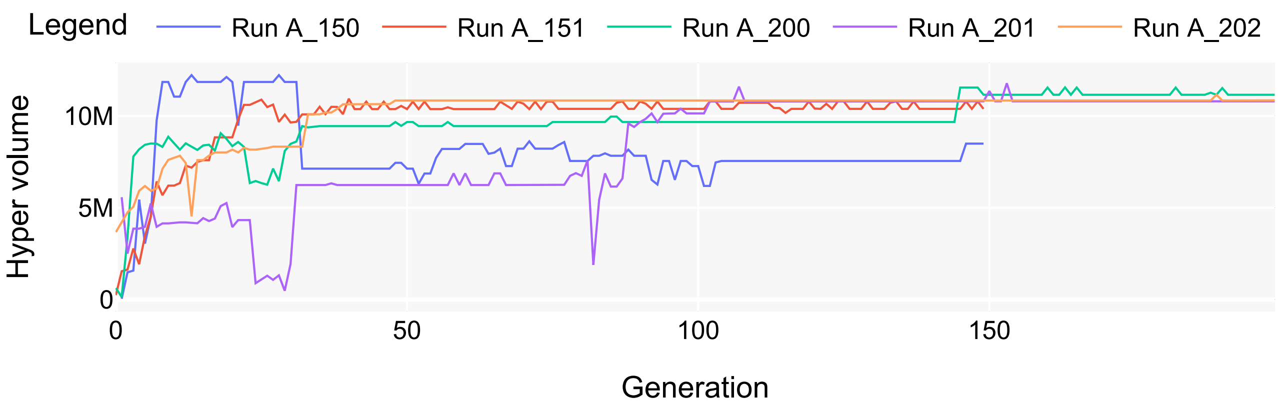
The non-dominated solutions and reference point form a multidimensional shape, based on an orthogonal polytope. The volume is essentially made up of hyper-rectangles, with a common vertex at the reference point. The volume provides a quantitative measure of how good the set of non-dominated solutions is in terms of covering the objective space [100]. The higher hyper volume indicates a better approximation of the true Pareto front by the generated solutions. However, it is essential to consider the computational cost associated with achieving higher hyper-volume values [101]. The hyper volume can also be used to validate NSGA-II models in multi-objective optimisation problems [102], [89].

For the validation of the model, the hyper volume is calculated using the algorithm developed for it by Fonseca, Paquete, and López-Ibáñez [100]. The reference point is the current pole of H300 beam, which also sets the upper limit constraints. The hyper volume calculation considers cost, CO_2 footprint, and embodied energy. The circular efficiency objectives are not used, as the values for these is objectives are not known for the reference point used. Furthermore, for calculation of the hyper volume, only solutions that meet all constraints are used.

In Figure 7.3 the plots are shown of the hyper volume for 100, 150 and 200 generations runs, with material input set 'All Materials'. The input set is described in section 8.2. In the figure it can be seen that the model in general starts to stabilise after 40 generations and in most cases stabilises at similar values of the hyper volume. The stabilisation implies that the model has found similar sets of non-dominated solutions that cover the objective space in the different runs. As the Pareto frontier contains the non-dominated solutions, most likely they will be located on the same Pareto frontier. Furthermore, it can be seen that the behaviour is consistent amongst the runs. Thereby, it can be interpreted as validation of the consistency of the model in regard to finding a set of non-dominated solutions covering the objective space for the same input.



(a) Runs 100 Generations



(b) Runs 150 and 200 Generations

Figure 7.3: Convergence Plots of Hyper Volume

Three runs with 250, 500 and 1000 generations have been conducted to see the behaviour of the model for the increase of generations. The hyper-volume plot is shown in Figure 7.4. Similar behaviour can be observed as the model stabilises when it has found the Pareto frontier. However, some sudden drops in hyper-volume can be observed. These declines suggest that the model has identified a potential novel direction or Pareto frontier, thereby demonstrating its ability to escape from local optima. However, this also reveals a limitation: the model exhibits sensitivity to these local optima, reflecting the randomness in the algorithm's optimisation strategy. This aspect deserves careful consideration, while interpreting the results. However, it can also be seen that the model stabilises relatively quickly in most cases.

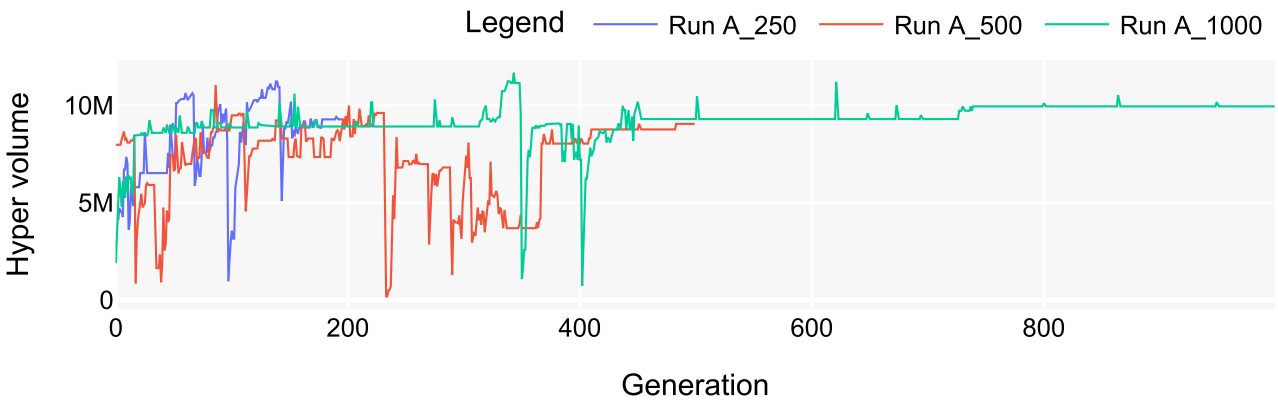
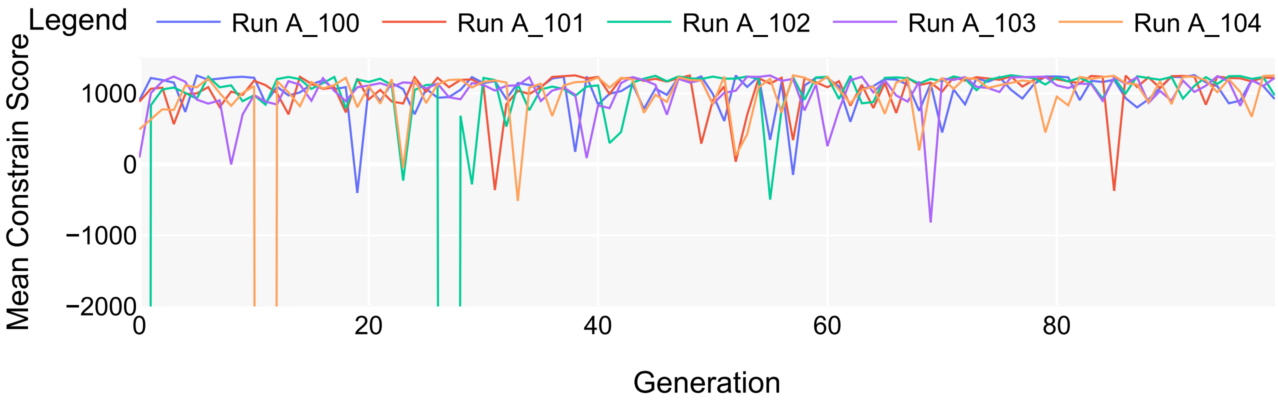


Figure 7.4: Convergence Plots of Hyper Volume of Runs With 250, 500 and 1000 Generations

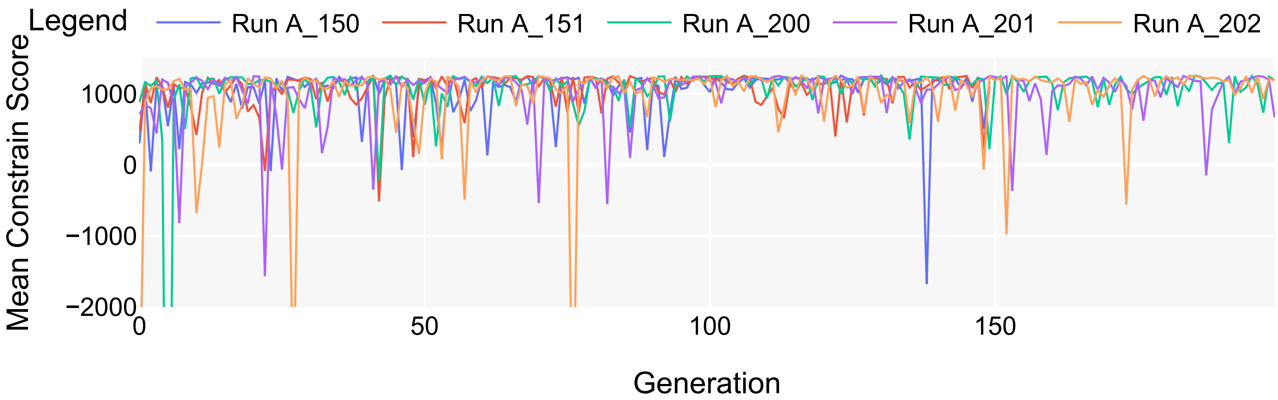
7.5.5 Constrain Score

The constrain score has also been used as an indicator to validate the model. The constraint score of a solution indicates whether it violates any constraint. Thus, the score indicates the ability of the algorithm in finding non-violating solutions. This is based on the ideal scenario wherein all solutions selected as parent do not violate any constraint, thus a new population is formed of solutions that do not violate any constraints.

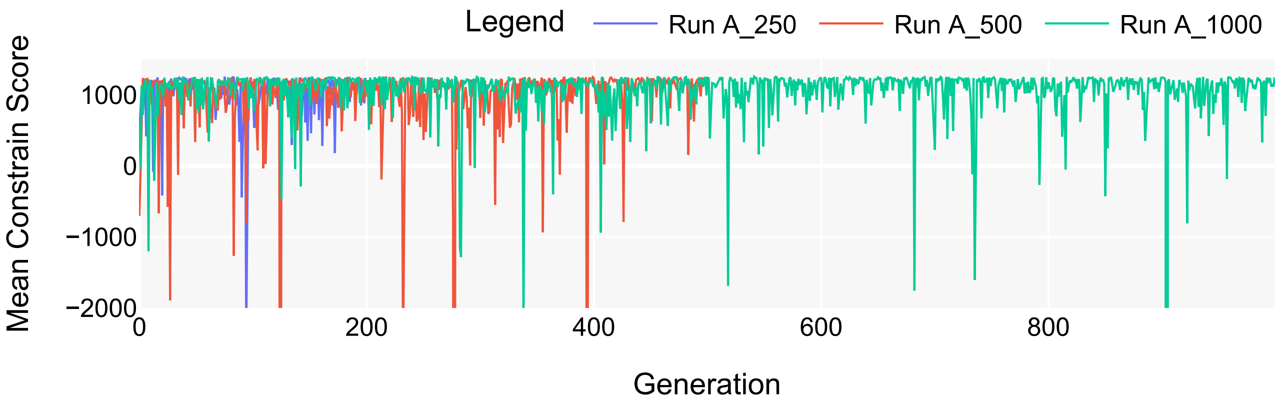
For validation, the aggregated constrain score per generation of the solutions selected as parents has been used. Ideally, this score should increase over generations and stabilise. The stabilisation should occur at the maximum score value, when all the selected solutions as parent do not violate any constraint. In addition, the mean constrain score per generation of the solutions selected as parents has been used as a second indicator. The maximum constrain score for the runs conducted is 37800, given the maximum constrain score per solution stated above in section 7.2 and the number of parents per generation in section 8.2.



(a) Runs 100 Generations

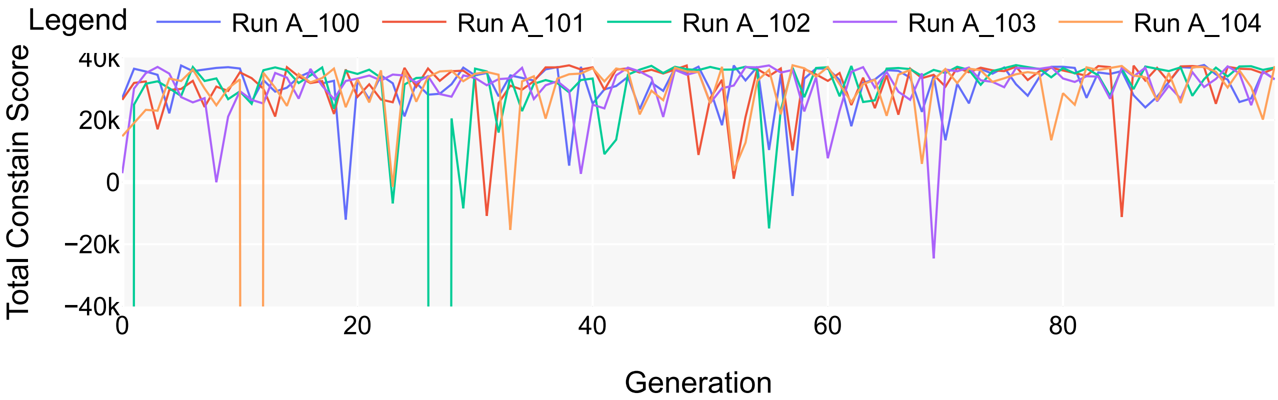


(b) Runs 150 and 200 Generations

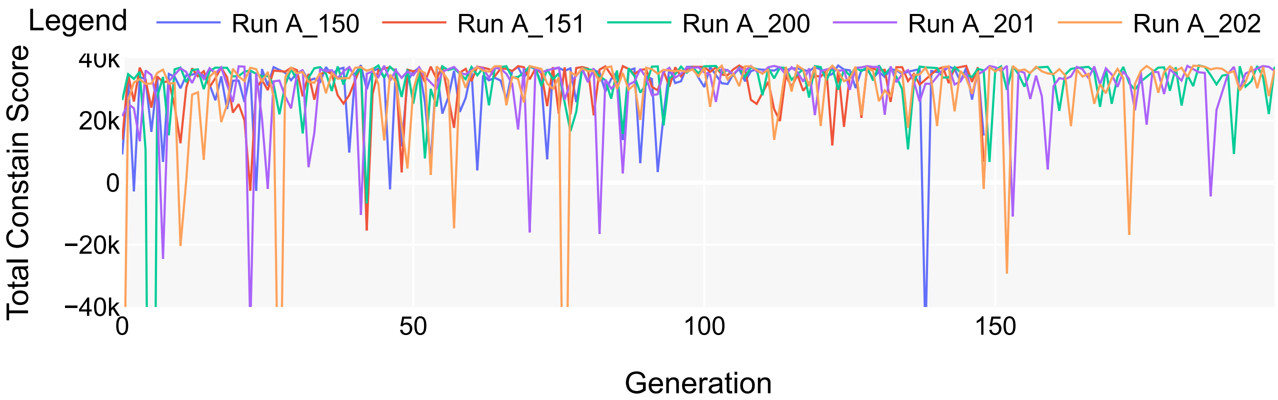


(c) Runs 250, 500 and 1000 Generations

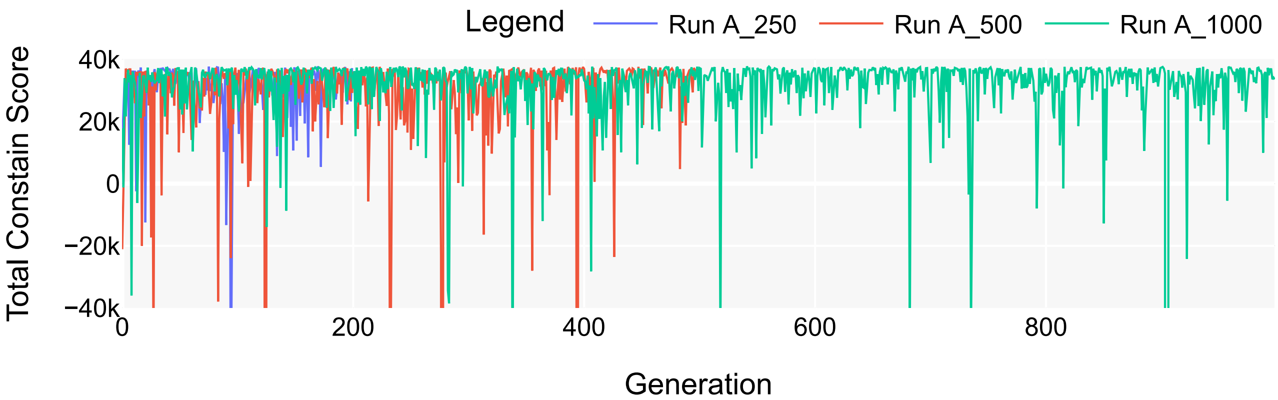
Figure 7.5: Evolution of Mean Constraint Score of Parents per Generation



(a) Runs 100 Generations



(b) Runs 150 and 200 Generations



(c) Runs 250, 500 and 1000 Generations

Figure 7.6: Evolution of the Total Constrain Score of Parents per Generation

On the basis of plots shown in the figures above it can be observed that in general the model has trouble to stabilise, as well preserving the non violating solutions to have a population with only non violating solutions. Consequently, it can be assumed upon these observations that the model identifies potentially viable solutions that violate certain constraints. This should be taken into account with respect to the result and shows that the results of the model are suitable to be interpreted as indication of potential directions. However, the results should not be interpreted as the optimal design for a pole. Both plots show that the model has volatility behaviour, which might be due to the experimental design used or the crossover and mutation methods used.

Chapter 8

Results

This chapter presents the results of the optimisation model developed in this study. The case study used in the simulation is outlined in detail in section 8.1. Following this, the experimental design for the simulations is outlined. Subsequently, the results of the simulations are presented and discussed. The trade involved in designing a sustainable support structure are discussed. Using the Pareto Frontiers to identify them. Finally, using the results of the simulations, the parameters and variables that define the design of the support structure.

8.1 Case Study

For the model, two cases have been formulated. The cases have been formulated within the scope of the research, the Dutch main rail network. The cases differ in the design of the support structure. One case has been formulated with a single-pole configuration. The design of the support structure in the other case is a portal design. In both cases, as stated in section 6.2, only the pole design is optimised. The configurations are illustrated in Figure 8.1. For the portal design, the configuration is based on the standard design of a double-track portal. The beam used in the portal is the standard RHS300 beam, this beam is the standard beam used by ProRail for a portal.

For both cases, the PVR-GC for 25kV gauge is used, a Dutch variant of the European GC gauge, which is suitable for a 25kV catenary system. The Dutch B4 catenary system is chosen as the catenary system. This catenary system operates at 1500 V DC with a maximum speed of 160 km/h. Its chosen to use this system, as it is designed to be able to upgrade to a higher voltage system of up to 25 kV AC.

The requirements and specifications for the system are described in OVS00024-5.4 [103]. The specified wire types for the contact wire, catenary wire, and feeding wire for a voltage of 1500 V DC were used. For the field length, the maximum length of 60 m is applied. As the contact wire zigzags between the support structures, the wire is held at a support structure in the pull-off or push-off position. In the pull-off position, the load caused by it acts unfavourable to the support structure. Therefore, the pull-off position is applied in both cases.

The support arms applied in the cases are the specified arms for the B4-system, described in the product specification SPC00121. The selected arms are selected according to the design and configuration of the contact wire. The length of the pole assumed constant during the optimisation, the standard height of 8.6 m for a pole is used.

An overview of the specifications and further details, as well as the dimension used for the pole and portal design, can be found in Appendix H.

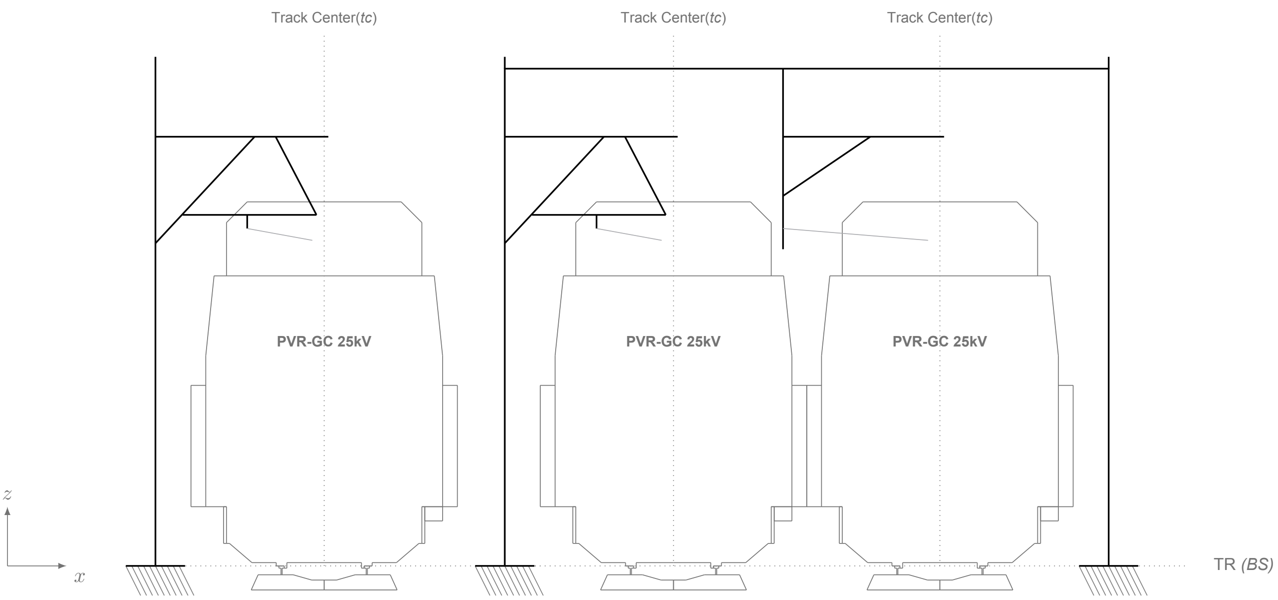


Figure 8.1: Case Study: Pole and Portal Configuration

8.2 Experimental design

In this section, the experimental design is presented, discussing the parameter configurations used for the algorithm and the simulations executed. Furthermore, the operational environment in which these simulations were performed is described.

8.2.1 Parameter Settings and Simulations

The settings that have been used for population size, number of parents, uniform crossover, and adaptive mutation for low-ranking solutions and high-ranking solutions are stated in Table 8.1.

Table 8.1: Parameter Settings used for Simulation Runs

Parameter	**Value**
Population Size	60
Number of Parents	30
Uniform Crossover	Percentage: 0.6
Adaptive Mutation	Low-ranking: 0.8, High-ranking: 0.15

The simulation runs have been conducted for various numbers of generations, primarily for 100 generations and also runs for 150 and 200 generations. In addition, single simulations were performed for 250, 500 and 1000 generations to assess the impact of an increased generational span for the 'All Material' dataset.

Simulations have been conducted for the following input sets for the materials;

- **All Materials**
  This material input dataset contains the following material families; Ceramic (non-technical), Composite (natural), Elastomer (thermoplastic, TPE), Metal (ferrous), Metal (non-ferrous), Plastic (thermoplastic, amorphous). This selection is based on the fact that these material families contain potential materials from which a support structure could be built that comply with constraints. Furthermore, all pole-shaped designs are included in the run. In the plots, these simulations are referred to as: '*A_..RunNumber..*
- **All Materials***
  This dataset contains the same material families as the All Materials input data set, but has been adjusted for the number of pole-shaped designs. The pole-shaped designs of the UNP and T-beam have been excluded, as these shapes dominated the simulations of All Materials and are unlikely to be used as a pole. This is shown in the following section.
  In the plots, these simulations are referred to as: '*Aa_..RunNumber..'*

- **Ceramic (non-technical)**
  This dataset contains only the ceramic (nontechnical) material family, which has been included to strictly evaluate the ceramic material family. All pole-shaped designs are included in the runs. In the plots, these simulations are referred to as: *'C_..RunNumber..'*
- **Metals (non-ferrous**
  This dataset contains only the metal (non-ferrous) material family, which is used for the specific evaluation of the material family. All pole-shaped designs are included in the runs. In the plots, these simulations are referred to as: *'MNF_..RunNumber..'*

In Table 8.2 an overview number of runs for the states numbers of generations stated above, for each of the specified material input data set. In total, a number of 34 simulations have been conducted.

Table 8.2: Simulation Runs by Generation Setting and Material Dataset

Material Input Dataset	**Number of Generations**					
	100	**150**	**200**	**250**	**500**	**1000**
All Material	5	2	3	1	1	1
All Material*	4	-	3	-	-	-
Ceramic (non-technical)	3	-	-	-	-	-
Metal (non-ferrous)	4	-	4	-	-	-

Furthermore, the results from the runs conducted over 100, 150 and 200 generations for each specified material input data set have been consolidated into the total data set. In the case that the model did not find any non-violating solutions, the solutions of the saved parents are used form the consolidated total data set. However, before the data are consolidated. First, the data has been filtered. As the parents are saved for each generation, from each set of the non-dominated parents are taken. Further, the solutions have a positive constrain score and are potential 'feasible'. This process had been applied for the simulation runs of metal (nonferrous) and ceramics (nontechnical). All the runs did not provide any non-violating solutions.

8.2.2 Operating environment

The results generated by the proposed model in the previous chapter were obtained within an operating environment of Windows 10 Home 64-bits with an Intel(R) Core(TM) i7-7700HQ CPU @ 2.80GHz processor and 16,0 GB random access memory. The Python Integrated Development Environment used for the model is PyCharm Community Edition 2024.1 x64, with Python version 3.12.

8.3 Results: Objectives and Deflections

In this section, the results of the runs performed on the optimisation model are presented. First, an overview of the distribution of objectives is discussed. The Subsequently, the results for objectives are discussed. The results on the deflection are discussed, followed by results regarding the parameter related in pole design. Finally, conclusions are drawn on the basis of the results.

8.3.1 Objective Distribution

The distribution of the Pareto frontier for All Material runs is shown below. In plot for the current poles are plotted for the cost, CO_2 footprint and embodied energy. For each of the objectives, it can be seen that the Pareto fronts are shaped by the results. However, for the cost, it can be observed that is one of the main trade-off factors within the objectives, as well between the current poles used. On the other hand, for the CO_2 footprint and the embodied energy, the Pareto frontiers can be observed within the results. The frontiers show that there is potential to minimise these factors. This would be possible to achieve, without which the cost would increase. Interestingly is the difference between two circular efficiency's, where the embodied energy is highly clustered and for the CO_2 footprint is wider distributed.

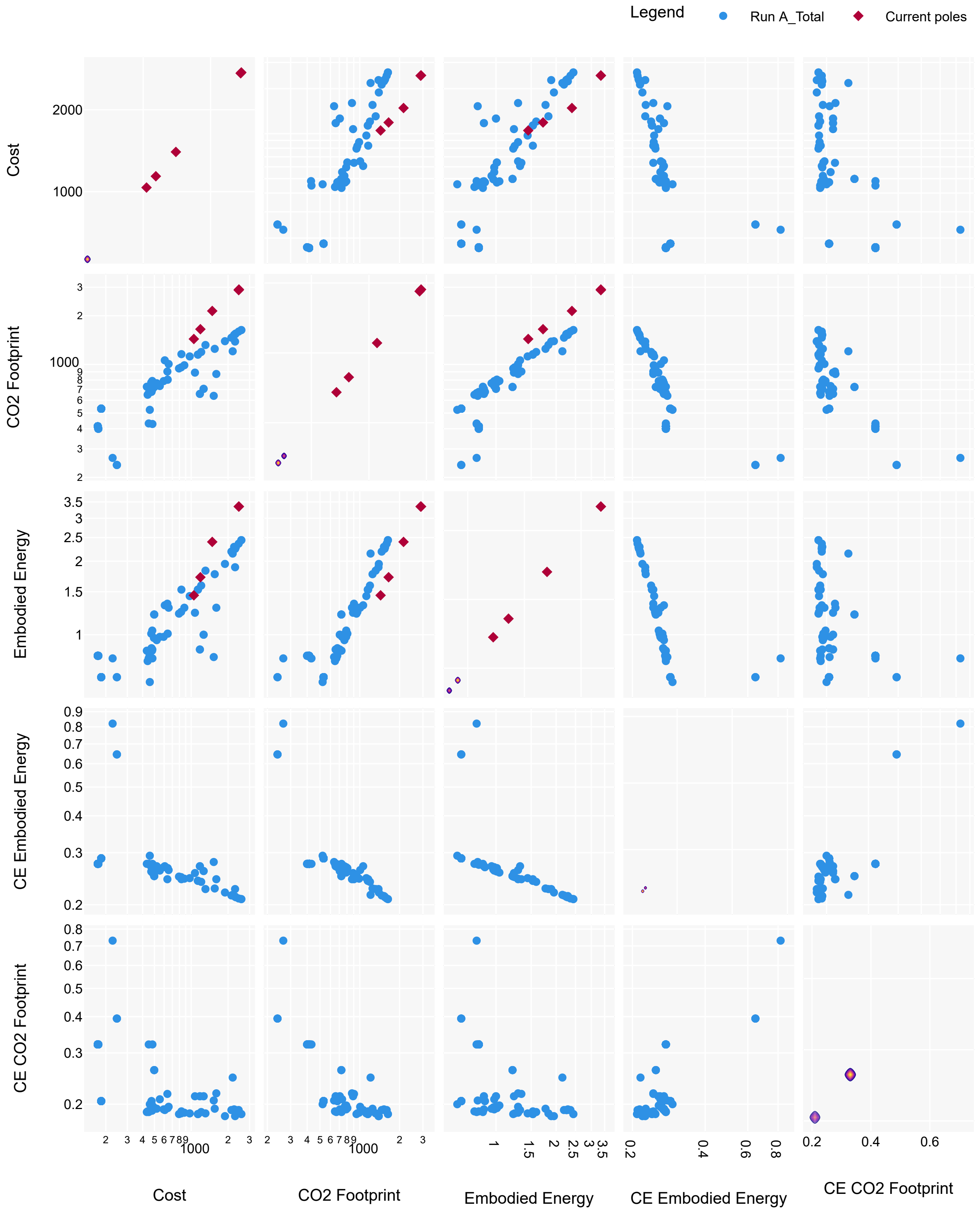


Figure 8.2: Scatter Matrix Representation of Objectives Distributions

To see what is the main selected material in All Material, the distribution of the pole shape type, material family and material are show below. It can be seen that for the pole shape type T-Beam dominates the solutions. Similarly, metal (ferrous) dominates in the case of the material family. In terms of materials, cast iron alloys dominate within the solutions. The domination of T-Beam can be explained by that this shape minimises the cross section and so the footprint and embodied energy, Furthermore, this type of beam is able to carry high loads on its strong axis, as the main forces acting on the pole structure are acting this favourable way for the beam.

Given the absolute dominance in the case of the material family and the type of pole shape, the other data set of input of materials has been used to expand the scope of the results. The distribution graphs for these datasets of the parameters presented can be found in Appendix I.
For the All Materials* set the dominant material family and material are similar to the All Materials set. However, without the T-beam and UNP as pole shape design, the round tubular pole shape design is the dominant variant. In the case of the ceramic (non technical) the dominant material is concrete (high performance), as for the pole shape design also round tubular is the dominant variant. For the metal (non ferrous) input dataset the dominant material is the cobalt-base super alloy. The pole shape design is dominated by the round tubular variant.

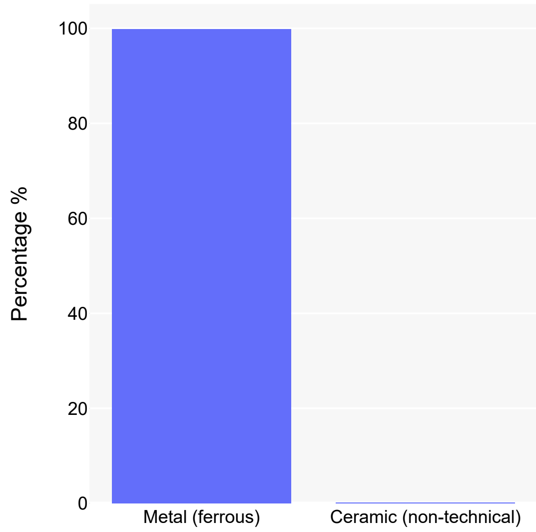
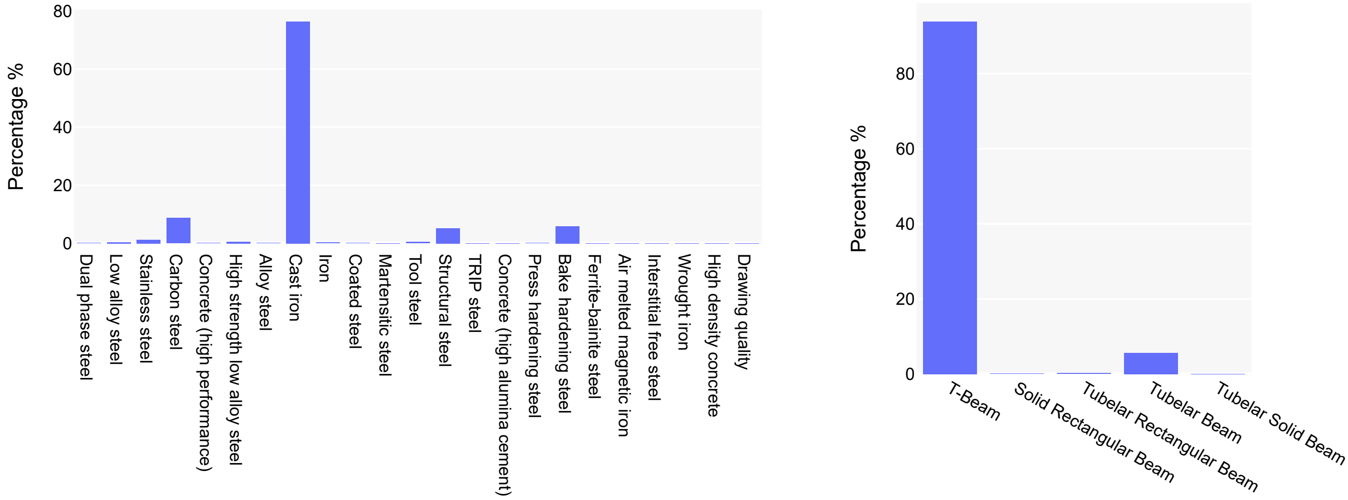


Figure 8.3: Material Family



(a) Selected Materials

(b) Pole Shape Design

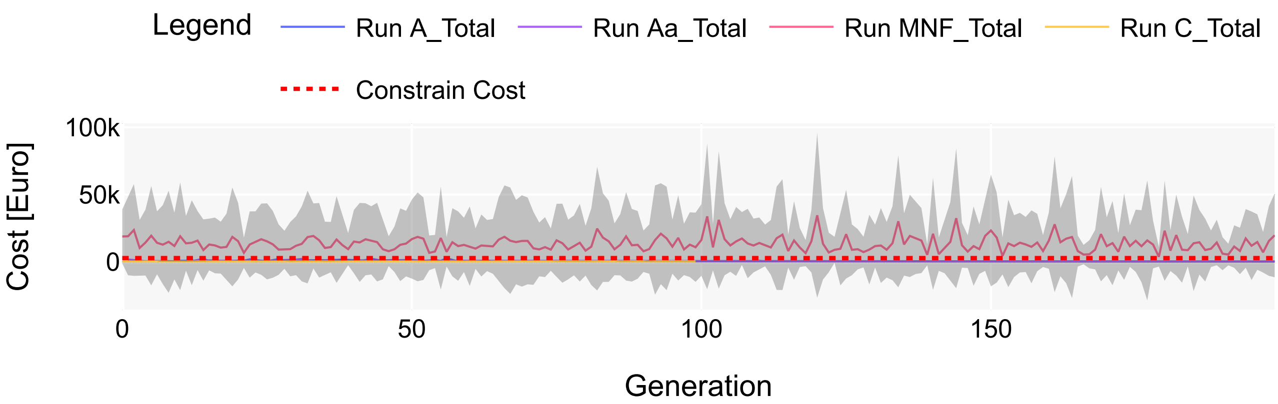
Figure 8.4: Distribution of and Pole Shape Design and Selected Materials

In the subsequent subsection, the results on formulated objectives are discussed in more detail, and the various simulation runs are compared with each other. For each material dataset, the mean value per generation is plotted for each of the objectives in the graphs, accompanied by the standard deviation in both directions represented as a grey fill.

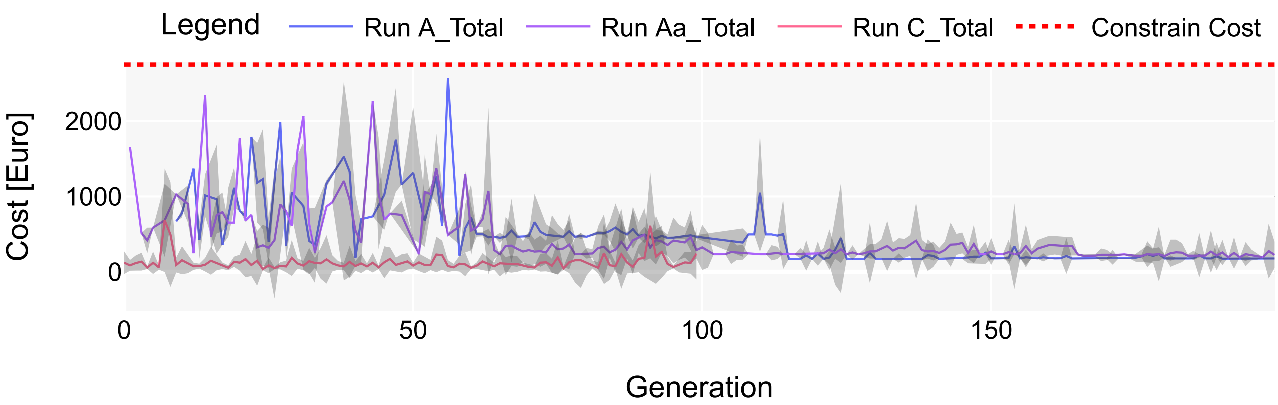
8.3.2 Objective: Cost

In Figure 8.5a, the results of all complete datasets are shown. It is evident that metal (non-ferrous) pole designs solutions have a markedly higher cost relative to the other material input datasets. In Figure 8.5b, it can be seen that the ceramic (non-technical) converges relative fast to a reduced cost than the input datasets for all materials. Eventually, these datasets converge to a similar value cost value after the 150th generation.

To recall, the term cost refers specifically to material costs, while the integrated constraint represents the purchase cost. The absolute difference between these on, as can be seen in the figures, suggests a significant potential for cost reduction. However, it is important to note that the costs associated with manufacturing and transportation are not included in these calculations. These omitted costs are likely to exert a significant influence on the overall potential for cost reduction. Consequently, from this difference it can be deduced that the decrease in material costs associated with the design will exert a minimal influence. However, on the network scale, these marginal differences could have a comprehensive impact, considering the required number of poles.



(a) All Total Runs

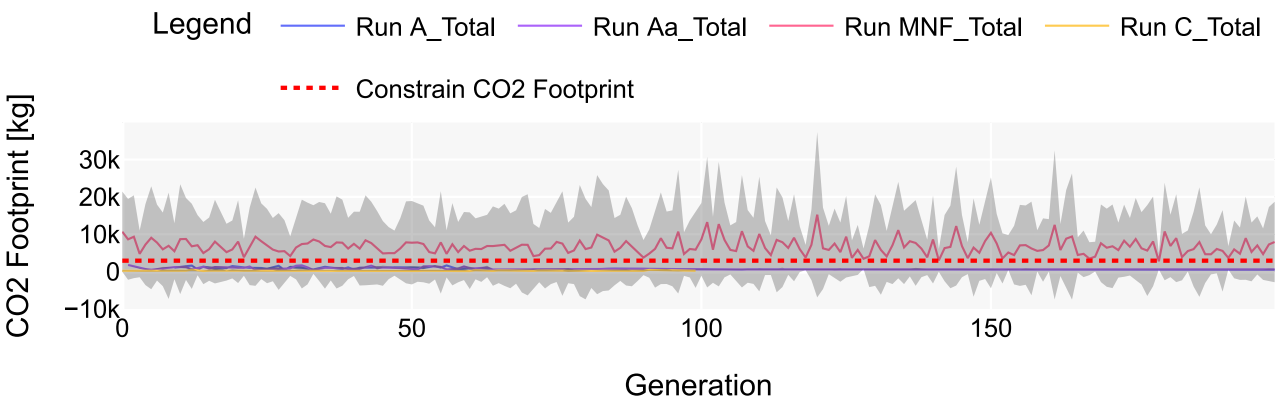


(b) All Materials and Ceramics (non-technical)

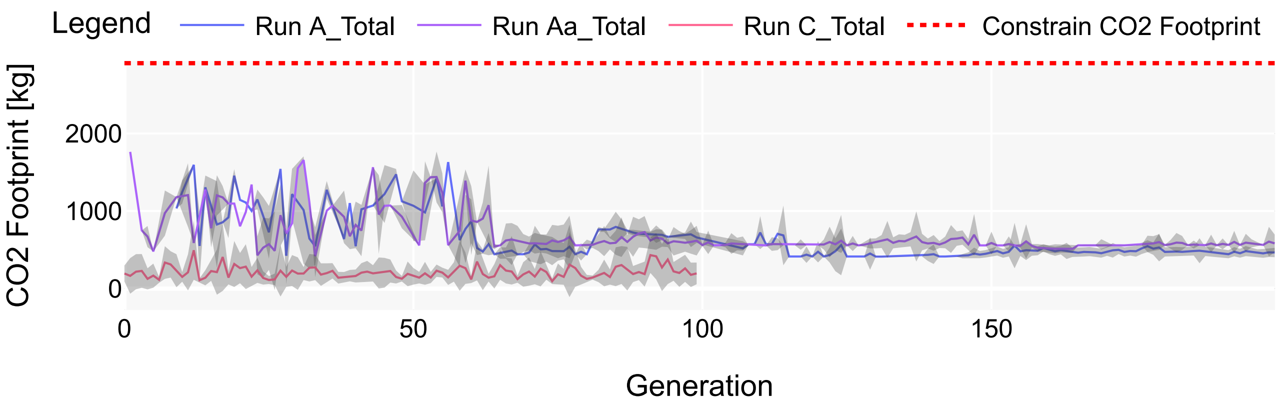
Figure 8.5: Evolution of Cost Objective

8.3.3 Objective: CO_2 Footprint

For the objective of CO_2 footprint, a parallel observation can be made with respect to cost. The metal (non-ferrous) dataset has similar performance in case of the cost objective, namely significantly lower performance compared to other material datasets. The emission value of CO_2 is significantly high for this material dataset compared to the other input datasets, violating the maximum constraint for all generations. In all datasets of materials, a significant reduction in CO_2 footprint can be observed in Figure 8.6b. Both datasets are converging towards comparable emission values. The ceramic (non-technical) dataset performs even better, and these materials would allow further reduction of the footprint of a new pole design for the support structure. These results indicate the potency of ceramic materials, such as concrete, in reducing emission values. However, within the all-material datasets the results show that this is also possible within the metal (ferrous) material set.



(a) All Total Runs

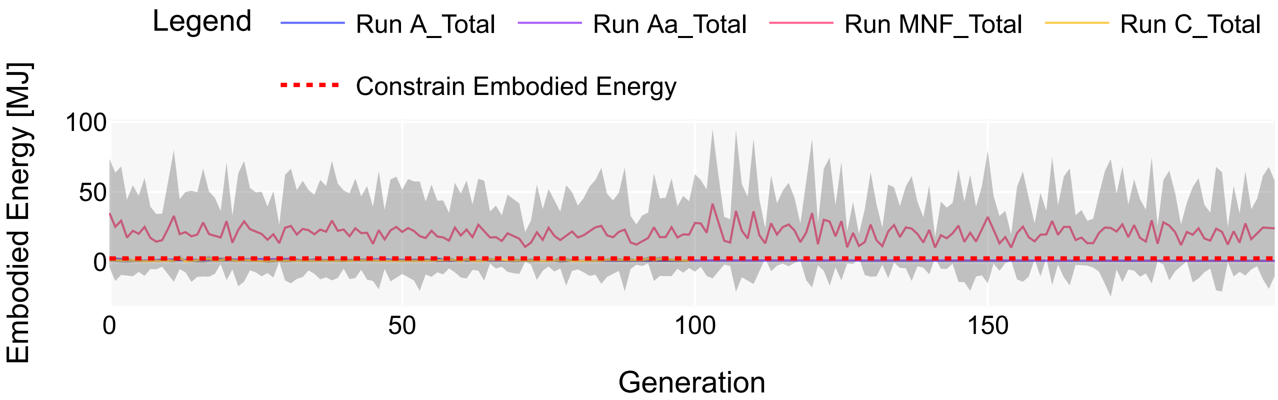


(b) All Materials and Ceramics (non-technical)

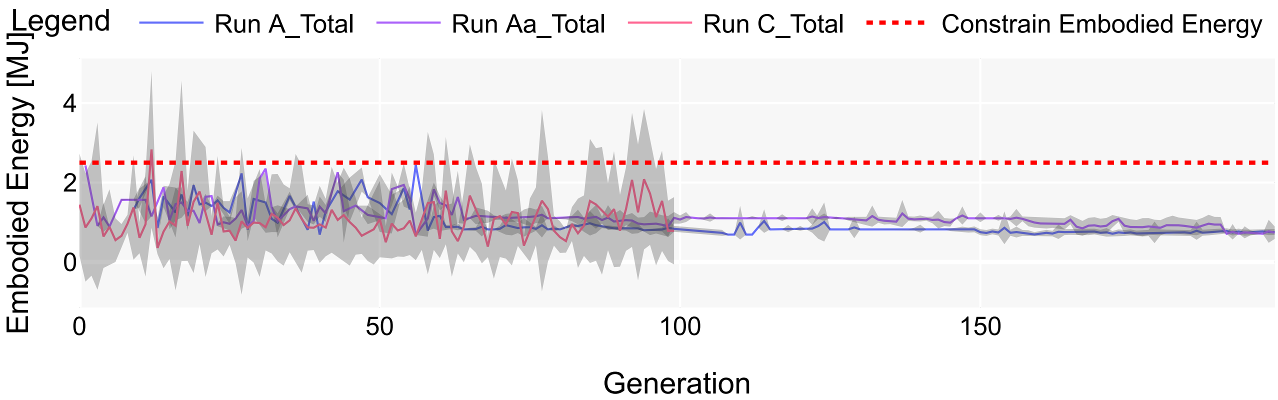
Figure 8.6: Evolution of CO_2 Footprint

8.3.4 Objective: Embodied Energy

As similar to the previous objectives, the metal (non-ferrous) design solutions have a significantly higher value for the embodied energy. Compared to those of the other input datasets, in this case the values violate the maximum value constraint for the energy embodied in the design solution. In Figure 8.7b, the results for the other datasets are shown. It can be seen that, for the value of energy embodied, there is no significant difference between these datasets. It converges to similar values despite the difference in material for the design solutions. However, a slowly developing downward trend can be observed for the energy of the energy. However, for the cost and Co_2 the convergence stabilisation could be observed to a maximum in the minimal value for these objectives. The result indicates in this case similar to that of CO_2 the potential to reduce the embodied energy.



(a) All Total Runs

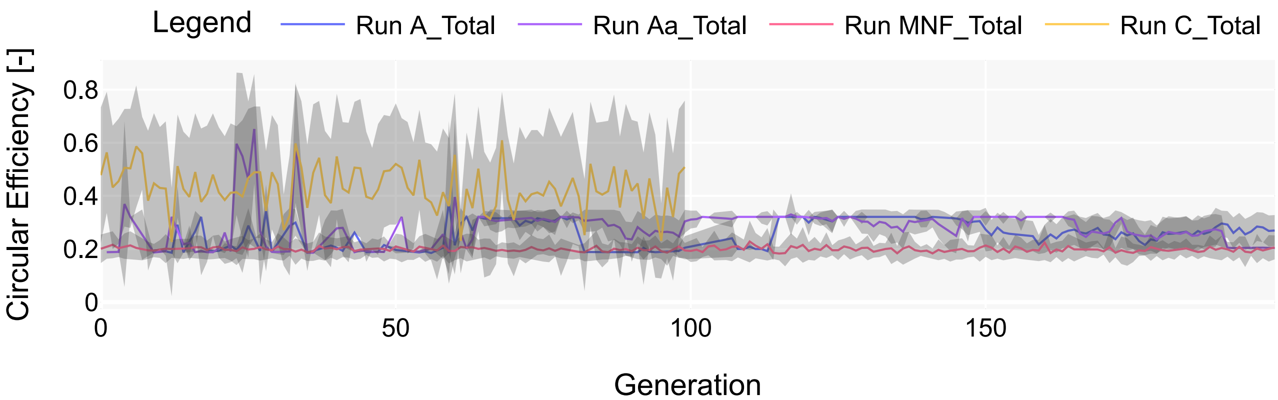


(b) All Materials and Ceramics (non-technical)

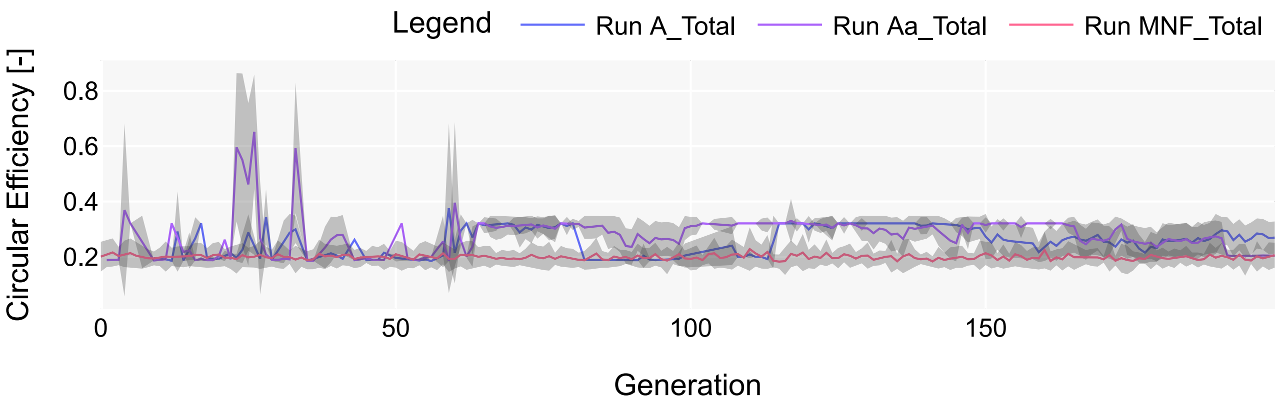
Figure 8.7: Evolution of Embodied Energy

8.3.5 Objective: Circular Efficiency

As defined in section 6.3, the minimal value of circular efficiency in this context means the solutions with the highest potential for improved circular use. From Figure 8.8a it can be seen that ceramic (non technical) has the poorest performance among the sets. Interestingly, the metal (non ferrous) previously demonstrated the least performance in the objectives mentioned above. In this case, it has the best performance for circular efficiency for the embodied energy. This suggests that the recycling processes for these materials most likely require a significantly lower energy composition compared to the virgin production of those materials. However, the ceramic recycling process has significantly higher energy consumption compared to the others.



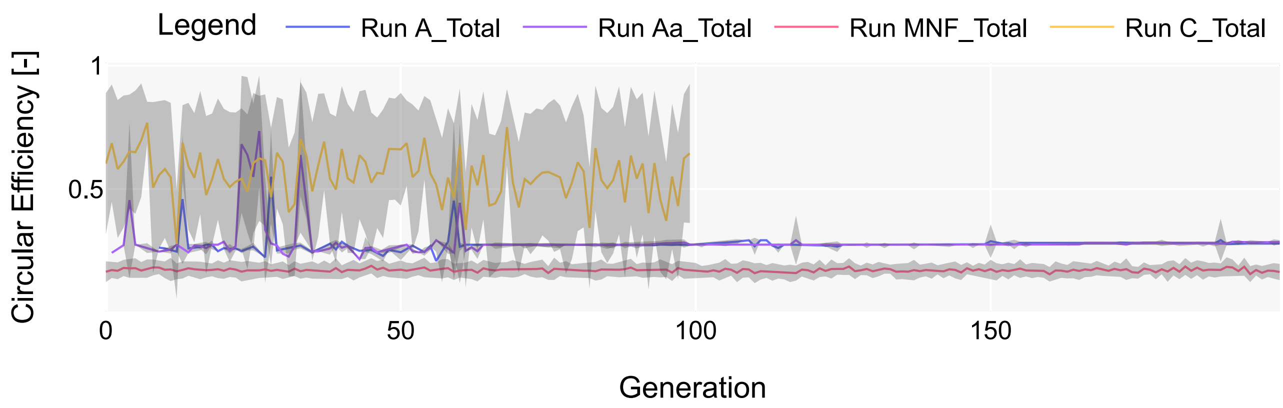
(a) All Total Runs



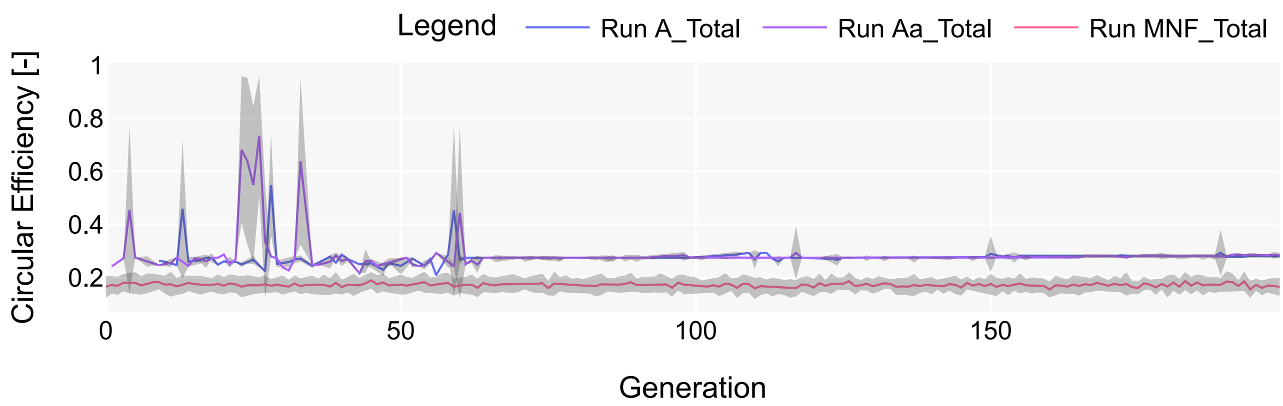
(b) All Materials and Metal (non ferrous)

Figure 8.8: Evolution of Circular Efficiency: Embodied Energy

Comparable results can be observed for circular efficiency concerning the CO_2 footprint. In particular, non-ferrous metals exhibit superior performance, as seen in Figure 8.9. A clear distinction between these goals becomes evident when reviewing convergence, specifically in the case of the CO_2 footprint. The result demonstrates significantly improved effectiveness across the all materials dataset. Furthermore, nonferrous metals consistently exceed the circular efficiency performance in comparison to other datasets.



(a) All Total Runs



(b) All Materials and Metal (non ferrous)

Figure 8.9: Evolution of CO_2 Footprint

8.3.6 Deflection of Pole

The deflection results for pole design for different input datasets are presented below. As illustrated in Figure 8.10, all design solutions in the datasets adhere to the specified constraints on the deflection at the pole top. In addition, the findings suggest that this particular constraint is not the most limiting. The designs formulated deflect significantly less than the constraint, indicating as well the stiffness of the pole designs.

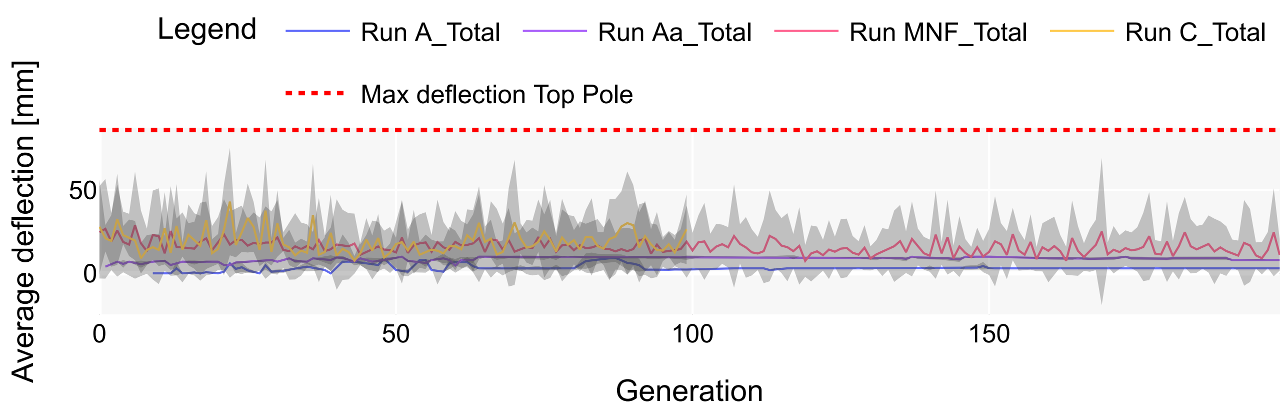
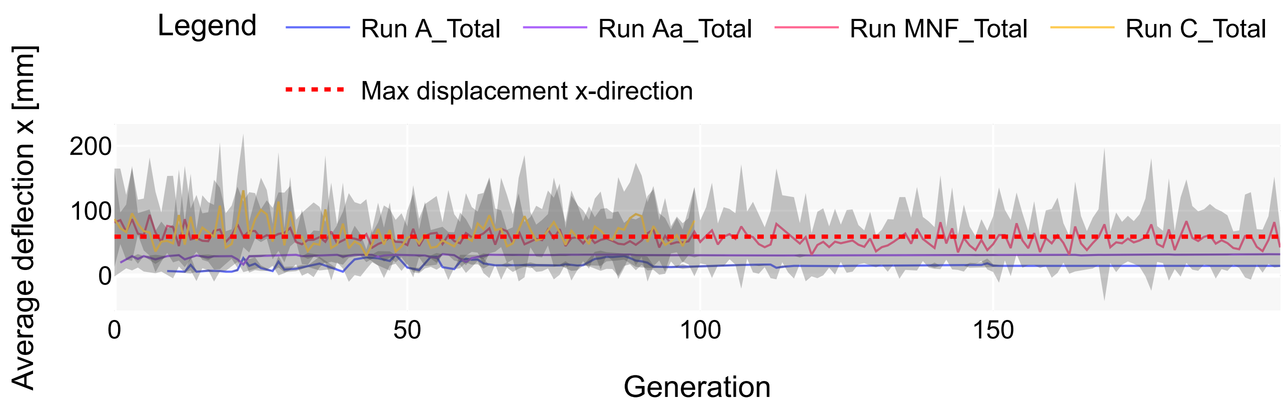
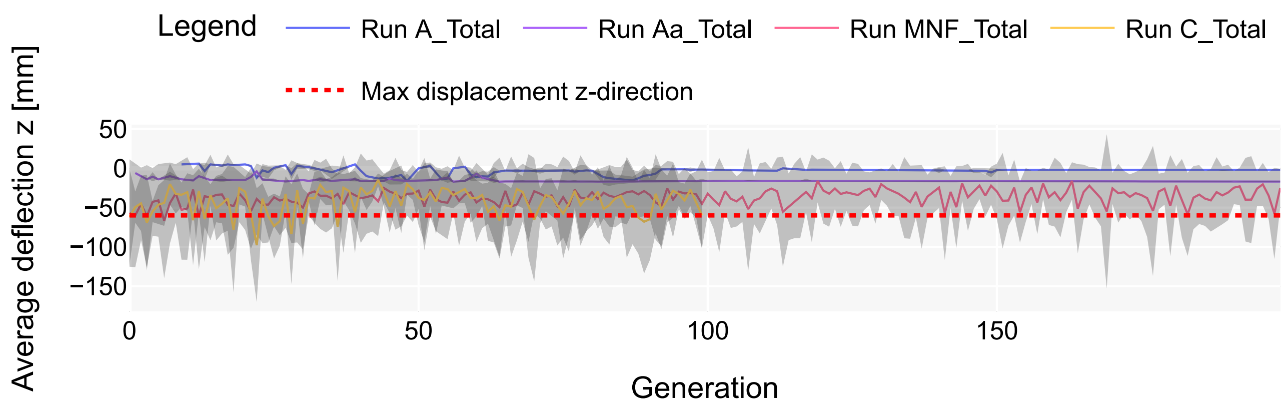


Figure 8.10: Evolution of Deflection at Pole Top in x-Direction

The deflection results relating to the constraints for the deflection of the contact wire are illustrated in Figure 8.11. It can be seen that in both directions x and z, metal (non-ferrous) and ceramic (non-technical) design solutions encounter difficulties in complying with the maximum deflection constraints. In contrast, designs that include all material datasets conform to these constraints. In particular, the all material configuration has the best performance across all datasets, manifesting minimal deflections in both directions. This can be explained by the dominant T-beam pole shape variant within this dataset, which offers enhanced bending resistance on its strong axis compared to the tubular pole shape variants. Which are dominant in the all material* dataset. Furthermore, it is evident that the all material dataset achieves convergence relatively quickly.



(a) x-Direction



(b) z-Direction

Figure 8.11: Evolution of Contact Wire displacement

8.4 Results: Pole Shape Design

In this section, a comprehensive analysis of the findings related to the Pole Shape Design is provided. The graphs illustrate the results for the input datasets of all materials and ceramics. This selection was made based on the results in previous subsections. These datasets indicated the potential for sustainable pole design. Initially, the material properties relevant to the design are discussed. Subsequently, the key properties and principal parameters of the pole design are discussed.

For model calculations, the pole shapes are numbered and referenced accordingly in the following figures. An index table of the pole shapes with the corresponding numbers is shown in Table 8.3.

Table 8.3: Index Table Pole Shapes

#	**Pole Shape**	#	**Pole Shape**	#	**Pole Shape**
1	Solid Rectangular Beam	4	UNP	7	Tubelar Rectangular Beam
2	H-Beam	5	T-Beam	8	Tubelar Beam
3	I-Beam	6	Tubelar Square Beam	9	Tubelar Solid Beam

8.4.1 Material Properties

The distinction among the materials used in the runs is further clarified in Figure 8.12. As material for the current poles, the properties of structural steel, S235J, have been plotted. The datasets for all materials families are aggregated, while ceramics show a broader distribution for the properties of the presented material. Notably, the datasets for all material datasets primarily consist of metal (ferrous) materials. Observations reveal that these materials consistently have higher property values compared to ceramics for each of the properties shown. This underscores the critical role of pole shape design within the framework of support structure design. Consequently, it highlights that the optimal design strategy involves balancing between material selection and pole shape selection. Thus, the trade-offs within the design process on material properties are shown in Figure 8.12.

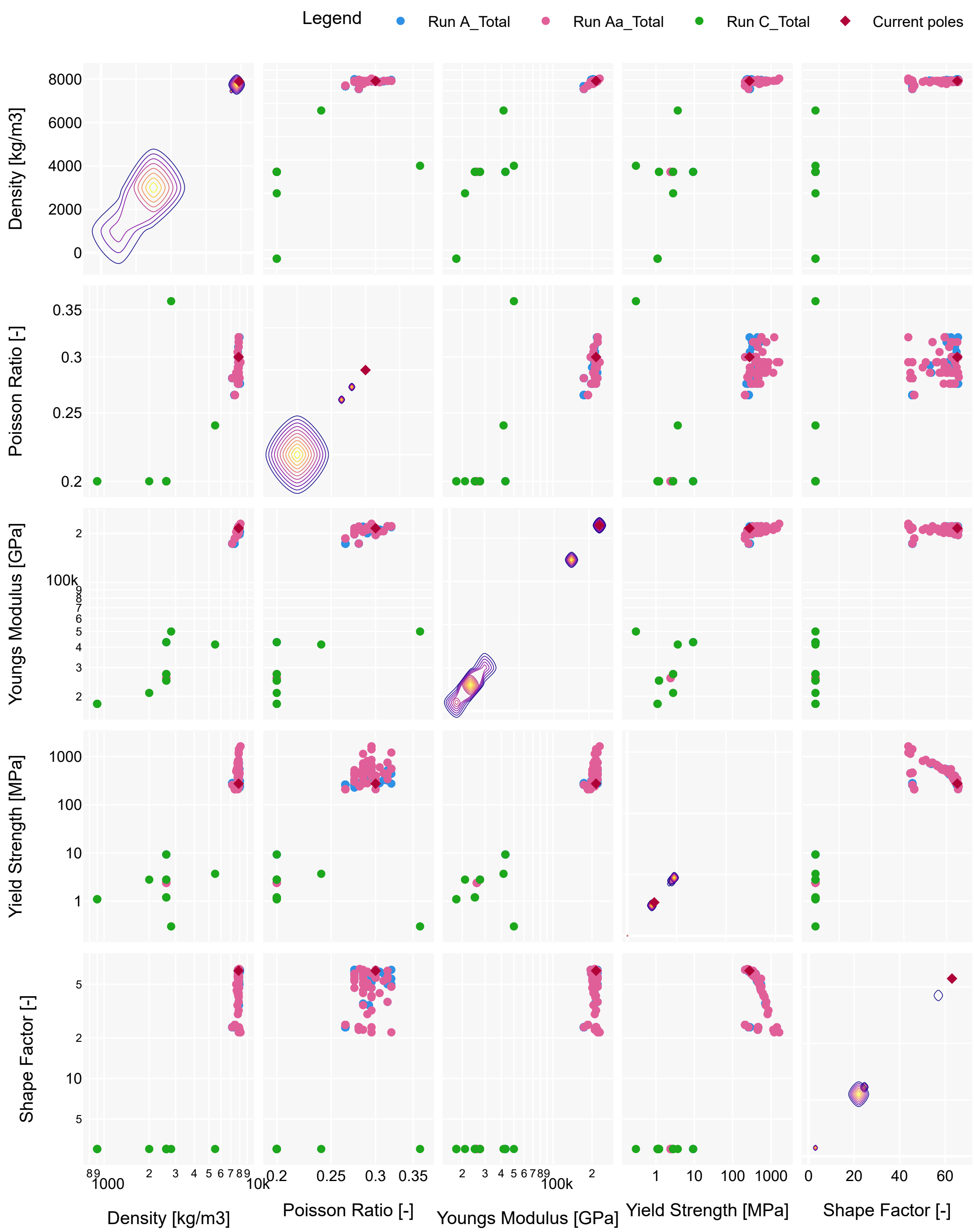


Figure 8.12: Scatter Matrix Representation of Material Properties Distributions

8.4.2 Pole Shape Properties

The pole shape properties illustrated in Figure 8.13, show the trade-offs and design orientations defined by established Pareto frontiers. Moreover, clustering was observed across all material input datasets. It is particularly notable for moments of inertia, a critical parameter that influences deflection. This distinct clustering is clear regardless of the material input dataset. Having said that, with respect to the moment of inertia around the z-axis, two design orientations are observed, as dictated by the formulated Pareto frontiers. In contrast, for the moment of inertia around the y-axis, a singular direction is apparent. Additionally, it is observable that ceramic solutions straddle between the extremes of solution designs and the clustered solutions encompassing by all material datasets.

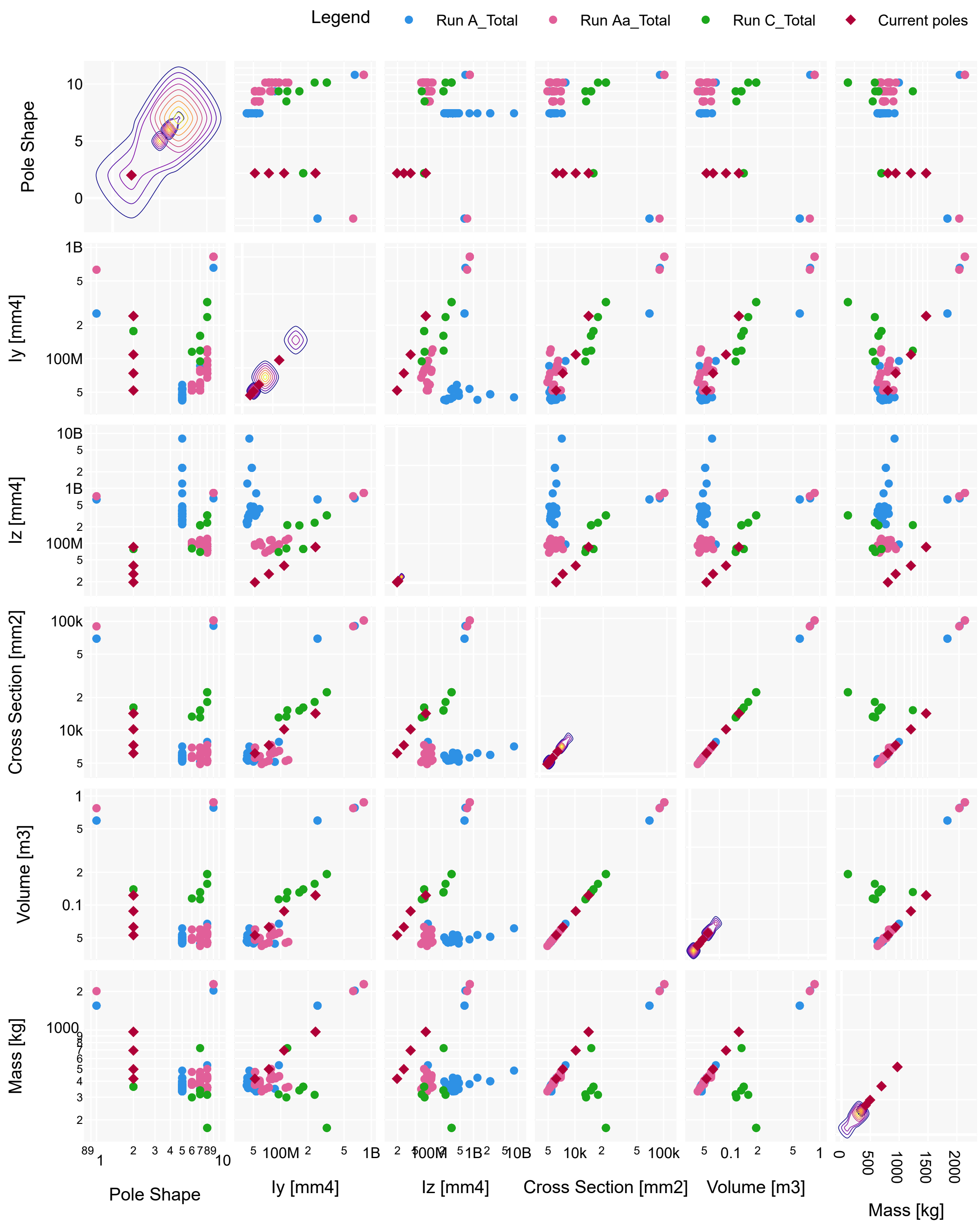


Figure 8.13: Scatter Matrix Representation of Pole Shape Properties Distributions

8.4.3 Pole Shape Parameters

Regarding the Pole Shape Parameters shown in Figure 8.14, for each solution the parameter value that does not correspond to the selected pole shape variant has been assigned a value of zero. This event is visually represented in the figure by the horizontal and vertical lines at the zero value mark for these parameters. In the graph, further recurring clustering patterns can be observed. In particular, for the height, width and T_f of the pole shape, these values tend to aggregate around the current pole values. Moreover, particularly with respect to the width and T_f, a Pareto frontier is observable surrounding the largest current pole variant. The height parameter shows a relatively high degree of clustering compared to the width, which is more dispersed. The aggregation of data points could be explained by the significant impact that height has on the moment of inertia.

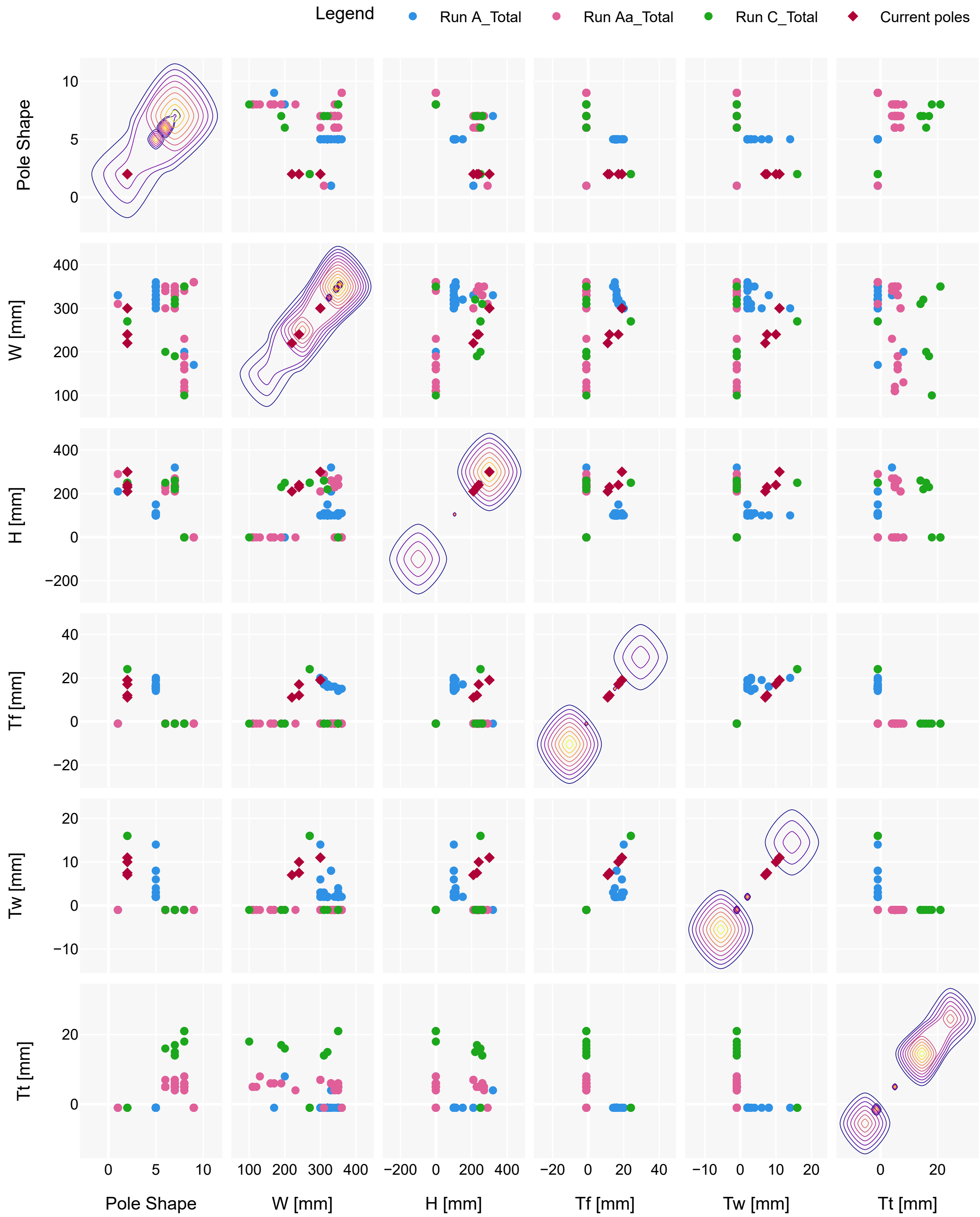


Figure 8.14: Scatter Matrix Representation of Pole Shape Parameter Distributions

8.5 Conclusion

The analysis of results from the presented material input datasets and the design configurations of support structures has provided insights into the interaction between material properties, structural designs, and sustainability objectives. The dominance of T-Beam and ferrous materials in the All Materials dataset, along with the performance of non-ferrous metals in terms of circular efficiency, highlights the critical role of material selection in optimising design taking into account structural aspect and sustainability. The results of the simulation runs emphasise the necessity of a balanced approach in material and shape selection to meet specific requirements and environmental impact.

Challenges such as the deflection of the contact wire underscore the need for ongoing assessment. In addition, the dynamic nature of the performance of the material over generations requires an iterative design process. The results underscore the effectiveness of certain materials and designs in meeting deflection constraints and achieving optimal performance. The balanced and dynamic approach will be crucial to advancing sustainable design in the face of evolving environmental and economic contexts. Hence, demonstrating that the model performs proficiently in indicating potential design directions. However, to achieve the optimal design of a pole, the model should be further refined and detailed.

In conclusion, the results indicated that ferrous metals and ceramics are in general the most fruitful options to improve sustainability. The main trade-off between these materials can be seen in circular efficiency. In results, the ferrous metals perform better than the ceramics. It is important to note that this conclusion regarding performance depends on the particular dataset used. However, in regards to sustainable design, the aspect of circularity emerges as an aspect of interest. This aspect may prove decisive in identifying the most sustainable design approach, particularly due to its significant impact on material use and emissions within a LCA.

Furthermore, the results indicate that for the pole shape, a shape as tubular pole shape is structurally feasible and enhances the sustainability of the design. In instances involving ceramics, employing a solid pole configuration would also be beneficial. In general, the findings show the implications of the trade-off between structural integrity and the environmental footprint of a design, along with its relationship with the choice of materials.

Chapter 9

Discussion

In this chapter, the results and findings obtained in the research are further discussed. By evaluating and connecting them to the research questions, the purpose of this chapter is to gain insight into the implications of the research findings and provide a better understanding of the significance of the study.

Placing it in the broader context of the Dutch rail branch and the interdisciplinary approach of the research, the findings involve current policies and infrastructure development, particularly in relation to the OCLS support structures. Situating the results within the broader landscape of rail infrastructure elucidates impact and consequences on the various stakeholders within the rail industry, as it does with governmental bodies and society in general.

The research started by identifying the essential requirements for OCLS support structures. Therefore, the design process and stakeholders were reviewed. In addition, a detailed analysis of the relevant standards and design specifications was performed. As a result, the essential requirements were identified. The essential requirements identified are a balance between safety and economic considerations. Although these aspects are well defined in numerous regulations. They both allow some flexibility due to how the importance of each can be interpreted.

This can also be seen in the need to connect safety standards with cost efficiency. As policymakers and engineers do during the design process. It emphasises improving structural integrity while remaining profitable, although this often proves challenging. These insights allow for a better understanding of the regulatory frameworks in place. Furthermore, in understanding the application of the standard within the design process. As discussed, the Dutch rail network is highly regulated. Increasing the complexity of implementing new designs in rail infrastructure projects.

In light of the Dutch Rail branch's ambitions and the latest sustainability regulations from the government. Illustrating an interesting dynamic between these ambitions and practise. Sustainability is an increasing factor of importance within projects and design. ProRail and the Dutch Rail branch are using an environmental cost indicator. To indicate sustainability of project or design, additional circularity principles are also factors of importance. However, within most policies, the main focus is on the aspect of carbon footprint as the main indicator.

Controversy emerges regarding the complexity of LCA and how certain emissions can cancel each other out. However, the implementation of these indicators allows the assessment of environmental impact. Facilitating stakeholders and other parties involved to take the impact into account. These indicators are needed to measure the contribution to national and international policies. In order to progress towards a more durable world.

Implementing various aspects into the design of the support structure necessitates a multi-objective approach. This research highlights that issues which may initially seem simple can become complex as the design process unfolds. It underscores the importance of using eco-friendly materials and construction methods. Consequently, making trade-offs between cost and safety might be essential to achieve sustainable design.

Furthermore, re-evaluating current design requirements in light of sustainability might be unavoidable. This is also a social question, as society must collectively agree to accept certain consequences which will follow from it. Despite expectations regarding technology and environmental ambitions. At some point, there will be friction between these ambitions resulting in a dilemma. On how to accommodate innovations and emerging technologies versus economic concerns and sustainability. This will require a collective approach to address these problems. Governments, rail branches, and other stakeholders will have to address them collectively.

Similar results can be seen from the model, showing the importance of material selection to achieve a sustainable design. However, ferrous metals and ceramics showed the most promising results. These materials are also widely used for supporting structures. The results indicated furthermore the importance of circularity as an aspect regarding the sustainability of the design. Thus, environmental data on the production and recycling process have a significant influence on this aspect. A material that could be produced with minimal emissions and could also be efficiently recycled in terms of material yield and emission would be optimal.

Reflecting upon the model developed during this research to explore sustainable design space. The developed model is suitable to use for indicative purposes, to evaluate the potential sustainable design space. However, the current configuration model is not suitable for being used to identify a single optimal design for the pole. Therefore, the model should be adjusted. With a focus on further improving the validity of the assessment of structural integrity and environmental impact. In addition, the parameters and configuration of the model and algorithm could be adjusted to the design problem. This would improve the results and performance of the model. For example, the choice of population size can significantly influence the performance of NSGA-II. Although larger populations offer a broader exploration of the search space. It will also lead to higher computational costs. This results in a longer iterative process due to the increased number of Pareto fronts. The same holds for the parameters set for the uniform crossover and adaptive mutation. These could be further specified to the design problem.

Another aspect to consider is the data used in the model. As the well-known aphorism by George Box states, ”All models are wrong, but some are useful”, its important to keep this in mind. Similarly, to it is crucial to remember that poor quality input data will invariably yield poor quality output. The data used for the model are adequate for its purpose to be indicative. However, the model would benefit if to some extent one if the environmental data would be similar to those used in LCA for NMD. Furthermore, it may be useful to express certain parameters as unit of function. An example of this is the cost of the material that is expressed as €/kg. In the case of a space filling role for concrete, it is the price per unit volume €/m3, not per unit weight, €/kg, that is relevant. More generally, still, it is the price per unit of function that is the proper measure.

The results show the potential to reduce the impact of the support structure. However, the solutions on the Pareto front show that there will always be an environmental impact. ProRail would have to compensate for this minimal impact, in order to be completely neutral in the case of CO_2 emissions. An implication of the result could be that one could conclude that the most sustainable option is to remove the OCLS. Therefore, all the infrastructure needed for the system is no longer needed and will further reduce the impact of ProRail. This raises the question whether this would truly be the most sustainable option. However, such a choice for this is a political choice. Considering that it will have a significant impact on the entire rail sector. For example, operators would have to adapt their train fleet to it.

This research highlights the significant roles of sustainability and circulation in rail infrastructure. Furthermore, the study identified the potential to integrate these aspects into the design. Taking into account the current designs and requirements. In addition to environmental considerations, safety standards, and economic efficiency of the design. The integration of these aspects contributes to an efficient and environmentally sustainable rail network. To achieve this, a flexible and collective approach will be required, aimed at fostering a sustainable and circular future.

Chapter 10

Conclusion and Recommendations

The main objective of this research was to develop an MOO model to explore and quantify the design space and key design variables for a sustainable support structure for an OCLS. In this way, it contributes to filling one of the knowledge gaps identified from the literature review. It specifically provided insight into potential design directions for a sustainable support structure for the main Dutch rail network. Identifying the current design process and involved stakeholders also allowed a deeper understanding of the context for the design of the support structure and helped to answer the research questions by accounting for the different aspects involved.

The research sub-questions and main question are answered below. From this, recommendations are given in section 4.5.

10.1 Conclusions

In this section, the conclusions of the research are summarised and further structured into separate passages by first answering the sub-research questions. Each paragraph ends with a key conclusion for this research, from which is the main research question is answered and final conclusions are drawn.

What are the essential requirements and design specifications to be met when designing a supporting structure for an OCLS on the main rail network in the Netherlands?

The extensive analysis of related requirements and specifications showed that the essential requirements and specifications for the design of the OCLS support structure involve balancing safety imperatives with economic considerations. The safety aspects are primarily guaranteed by the structural safety of the design, and economics are affected by the material choice and pole design. However, the trade-offs between safety and cost-efficiency should be clearly considered to find an optimal design.

Which methods can be used to determine the sustainability of the design of a supporting structure for an OCLS?
The concept of sustainability in the context of the Dutch Rail branch, as well as how to apply it to the design of the support structure, indicates the importance of incorporating sustainable design. Whilst all of the methods mentioned in this research are suitable to determine the sustainability of the design, LCA is the main foundation for all of them. The impact of the design can be determined on the basis of the assessment. The aspect of circularity, which focusses on the potential reuse of the structure, is another important factor, and both are suitable to indicate the degree of sustainability of the design of the support structure.

Which parameters and variables define the design of the OCLS supporting structure?
The design of the supporting structure of the OCLS is defined by several key parameters and variables. These include the material properties and the shape properties of the pole, which are crucial to optimising the design and achieving sustainability objectives. The interaction and constraints between these properties play a significant role. Additionally, the dimensions of the structure are influenced by the gauge and the catenary system, which determine the minimum length necessary for the pole to support the overhead contact lines. The design is also limited by the constraints on the displacement of the contact wire, stiffness, and maximum deflection of the pole. A tubular pole shape, which minimises the cross-section, is shown to be beneficial. To conclude, material selection and the pole shape are the variables that define the supporting structure. Along with properties and the balance between them.

How can the degree of sustainability be influenced when designing the OCLS supporting structure?
The sustainability of the OCLS supporting structure's design is influenced by several factors, with material selection being a key component. Selecting materials that improve sustainability involves considering their CO_2 footprint and embodied energy. Balancing the shape of the pole with the material choices is crucial to achieving sustainability goals effectively. An iterative design process is employed, allowing for continuous assessment and modification of the design to ensure it remains effective and adaptable to changing environmental and economic conditions. The trade-off between cost, structural integrity, and environmental impact is vital for sustainable design. Furthermore, the concept of circularity is becoming increasingly important in sustainable design, particularly due to its significant influence on material usage and emissions within a LCA.

What are the implications of sustainability on the current design of the OCLS supporting structure?
There are two main implications which sustainability has for the current design. To further reduce the C02 footprint of a pole, there is a trade-off between cost and CO2 footprint (e.g., a choice must be made to reduce the CO2 footprint by increasing the cost of the pole). Another implication is that allowing for other materials or cross-sections of poles, the current requirements must be re-evaluated, hence, balancing the trade-off between safety and cost, for example.

Based on the sub-questions above, the main research question—What are the key design variables for the sustainable design of a support structure for an OCLS?—can be answered. The key design variables are, first, the material choice, where the trade-off between cost and CO2 footprint and the circularity of the material play the primary roles in the aspect of sustainable design of a support structure given the current requirements. The greatest step towards a sustainable design can be made by optimising the material choice. However, in most cases, reducing the CO2 footprint leads to increased cost, as shown in the dataset of materials used.

10.2 Recommendations

The findings presented in this study serve as a basis for more in-depth research on the discussion surrounding existing regulations and specifications for sustainability within the rail branch. From these, the following recommendations are made for the design of a sustainable support structure design, along with suggestions for future research exploration and enhancement of the developed model.

Design of a Sustainable Support Structure

- **Requirements and sustainability**
  Based on the insights gained from this study, there is a clear need for research to improve the sustainability of the rail branch to fulfil the current specifications and requirements. Further analyses would allow for an understanding of effects and nuances which can inform future developments in the field as well as how current requirements and specifications should be adapted to improve the sustainability of rail infrastructure in a safe manner.

Further Research

- **Comparative sustainability study between OCLS and alternative train drive system**
  Conducting a comparative study on the sustainability of the OCLS as a system, particularly in contrast to alternative train-driven systems such as hydrogen trains, is a highly relevant research direction. Such an analysis would provide valuable information on the environmental, social, and economic dimensions of both systems. This would allow for more informed decision-making and policy development regarding system choice and infrastructure in the broader context of the transportation sector.
- **Circular design for the OCLS support structure**
  Embracing circular design principles presents an opportunity to achieve net-zero carbon emissions in the design of the support structure. Investigating circularity strategies, such as material reuse and recycling, can lead to more sustainable infrastructure solutions and is one way to reduce the environmental impact of the support structure.

Multi-Objective Model

- **Implementation of the environmental cost indicator in the model**
  The ECI is the main indicator to be used in practise. Implementing it or other LCA modules into the developed model would provide additional practical insights to improve sustainability. It would also provide a more robust framework for evaluating the environmental impacts of the support structure, therefore contributing to informed decision-making in order to apply sustainability in industry practises.
- **Adoption of specific standards for material types**
  To assess various designs, relevant standards for structural analysis could be applied. This would enhance the validity of the results for the specified materials and ensure an fair handling of these materials. Consequently, it might enhance the performance of certain materials that are currently under performing in the results. The consideration here is the extent to which the results might vary from existing ones, as this would add to the model's complexity and detail.
- **Parameter and variables ranges testing**
  To effectively outline the design space and key parameters and variables, additional tests on the boundaries of these parameters and variables would be beneficial. Often, the algorithm quickly converges to an 'optimal' value for a parameter. Thus, it would be valuable to explore the extent to which these parameters can be extended to better define the limits of the design space or support structure.
- **Material properties per functional unit**
  It might be beneficial to express the material properties used in objective functions by the functional unit for the pole. For example, the price of material property is expressed in euros per kilogram, which is also used for cost calculation in the model. However, for materials that serve a space filling function, the relevant metric is price per unit of volume, not weight. This might have revelevant effect the materials used in the case of the solid pole shape design. Therefore, it might be useful to consider pricing per unit of function, similar to the approach in the NMD.
- **Hyper Volume and Constrain Score as objective**
  Implementing both the Hyper Volume and Constrain Score as objective in model, that has to be maximise. Will force the algorithm to select feasible solutions that improve the current Pareto front. Futhermore, it will increase the number of feasible solutions within the solutions.

By addressing these recommendations, future research will contribute to understanding sustainable rail infrastructure development. In addition, more research and insights into environmentally responsible transportation systems are needed from a system and operation perspective as the impact of sustainability and its implementation into the rail branch is not yet well known.

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Appendix A

Scientific Article

This appendix encompasses the scientific article formulated from the research undertaken throughout the graduate study. The article summarises the key findings of the study; moreover, the research methodology described therein allows reproducibility by the comprehensive explanation given in the article.

Sustainability of the Overhead Contact Line Support Structure

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14th May, 2024

Abstract

The Overhead Catenary Line System (OCLS) is crucial for continuous electrical supply to trains in electrified railway networks. This article outlines the research conducted on the exploration of the sustainable design space of the Overhead Contact Line support structure on the main Dutch rail network. The research began with a comprehensive review of the literature on OCLS support structures, covering publications from 2013 to 2022. A multi-objective optimisation model is developed to explore sustainable design possibilities. Further result analyses elucidate the defining parameters and variables of the support structure design. The findings presented in this research serve as a basis for more in-depth research on the discussion surrounding existing regulations and specifications and sustainability within the rail branch.

Keywords - Overhead Contact Lines, Catenary, Dutch main rail network, Sustainability, Muli-objective Optimisation, NSGA-II

1 Introduction

This article outlines the research conducted on the exploration of the sustainable design space of the Overhead Contact Line support structure. The research has been conducted part of the graduate research.

The overhead contact line system (OCLS) is crucial for continuous electrical supply to trains in electrified railway networks. This system, which requires regular maintenance and reliable operation, faces challenges due to ageing infrastructure, particularly in the Netherlands, where about 500 km of OCLS are due for replacement to prevent network failures. Current replacement methods are inadequate due to high time and delay costs, prompting the exploration of new methods and innovations to improve reliability, sustainability, and affordability. In addition, sustainability considerations are emerging in the design of OCLS support structures, highlighting a knowledge gap in the current literature. This research addresses this by proposing a multi-objective optimisation model to explore sustainable design options for these structures [1].

1.1 Research Context

This study began with a comprehensive review of the literature on OCLS support structures, covering publications from 2013 to 2022. The classification of this literature was based on the taxonomy of Sedghi, Kauppila, Bergquist, *et al.* [2], focussing on structural characteristics, maintenance management, monitoring, and decision-making frameworks.

The literature review reveals a well-established knowledge base on OCLS support structures, but identifies four key knowledge gaps:

- Further understanding and development of methods on the structural condition of the structures
- Use of condition-based maintenance using structural models and new monitoring methods
- Further development of multi-objective decision-making models, as well as the implementation of more complex algorithms
- Impact and influence of sustainability on the design and maintenance of support structures

The summary of literature review can found in section 2.

1.2 Problem Definition

ProRail is tasked with replacing the overhead contact line system (OCLS) and improving its sustainability. Studies by Ecofys in 2010 and TNO in 2011 evaluated the carbon footprint and potential sustainable designs of OCLS support structures, respectively. The Ecofys study highlighted that the production phase emissions are significant, with concrete as a preferable material for reducing CO2 emissions. The research of TNO suggested that concrete structures could be most beneficial for the reduction of emissions, although other materials like steel or wood could also be viable depending on the design. Despite these findings, recent years have not seen significant changes in the support structures used in ProRail's main rail network. The present obstacles include compliance with more rigorous environmental laws and addressing the lack of understanding about the effects of sustainability on the design of support structures. This leads to several critical inquiries:

- How can the support structure be made in a sustainable manner?
- What are the potential design directions to increase the sustainability of the support structure?
- What is the potential design space for designing a sustainable support structure?

1.3 Research Objective and Scope

The purpose of this research is to develop a multi-objective optimisation model which can be used to explore and quantify the design space and key design variables for a sustainable support structure for OCLS. The scope of the research is limited to the support structure because of its importance within the OCLS and its unique characteristics as a structure.

To define and quantify the design space, an optimisation model is developed, for which it is important to accurately define and formulate the different objectives, related constraints, and decision variables considering the various aspects and disciplines involved in designing a support structure. Therefore, design variables are identified that impact and influence the sustainability of the design of the support structure.

The research scope is defined contextually and geographically by focussing on the case of the Dutch main railway network. Physically, the scope is demarcated in the context of OCLS by analysing only the structural elements of the support structure, namely the poles above the foundation and the beams in the case of a portal structure. The structural elements of catenary systems are not taken into account in this research as they depend on the installed catenary system.

1.4 Research Questions

Given the identified knowledge gaps and the defined objectives of this study,the following main research question is posed:

What are the key design variables for the sustainable design of a support structure for an OCLS?

To answer this question, the following sub-questions have been formulated:

1. What are the essential requirements and design specifications to be met when designing a supporting structure for an OCLS on the main rail network in the Netherlands?
2. What are the methods which can be used to determine the sustainability of the design of a supporting structure for an OCLS?
3. Which parameters and variables define the design of the OCLS supporting structure?
4. How can the degree of sustainability be influenced when designing the OCLS supporting structure?
5. What are the implications of sustainability on the current design of the OCLS supporting structure?

1.5 Outline

As stated above, the aim of this research is to explore the design space for sustainable OCLS structures on the main Dutch rail network. To do so, the article is structured as follows.

Section 2 reviews the state of the art in support structures for OCLS, categorised into structural characteristics, maintenance management, decision support systems, and prevalent frameworks. Section 3 discusses the design process for OCLSs at ProRail, including a stakeholder analysis to identify varying interests and perspectives affecting the design.

Design requirements and specifications for OCLS structures are detailed in section 4, focusing on technical specifications, European and national standards, and governing regulations. Essential requirements are derived from an analysis of these specifications. This chapter outlines the necessary requirements and specifications for designing support structures within the main Dutch rail network.

Sustainability in OCLS structures is discussed in section 5, defining it in line with rail industry and ProRail goals. The chapter reviews assessment methodologies and criteria for evaluating sustainability in support structure designs, addressing which methods effectively determine sustainability.

Building on previous insights, a multi-objective optimisation model for OCLS structures is developed to explore sustainable design possibilities. Section 6 covers the model's theoretical basis, including problem statement, assumptions, objectives, and constraints. It employs the NSGA-II genetic algorithm for optimisation, with detailed discussions on its framework and the implementation of crossover and mutation elements.

Detailed model implementation and optimisation are discussed in **??**, including modifications to the NSGA-II framework, the custom fitness function, and Python implementation and validation. The results and trade-offs for a sustainable support structure design, based on the Pareto frontier, are presented in section 10. Further result analyses elucidate the defining parameters and variables of the support structure design. Section 8 explores the results' interpretations and broader implications, including their impact on sustainability and the design of the OCLS support structure, addressing the final subquestions.

Based on the discussion, the conclusion of the research on the key design variables for the sustainable design of a support structure for an OCLS is drawn and presented in section 12. Finally, recommendations are given for future research.

2 State of the Art of Support structures for Overhead Contact Line System

The Overhead Contact Line System (OCLS) is defined as a support system and contact line that supplies electric energy to vehicles, with its main components being the support structures. These structures are crucial for the safe and reliable operation of rail networks and are subject to various standards such as NEN-EN 50119. The literature and standards emphasise the importance of reliability, safety, and security in their design and maintenance. Significant literature, including standard reference works such as those by Kiessling, Puschmann, Schmieder, *et al.* and Keenor, provides practical insights into the design and analysis of OCLS, particularly in the context of European and British railways. Research indicates that while these structures are structurally simple, they require substantial investment due to their large numbers and the costs associated with their lifecycle. Standardisation of these structures, as discussed by Perera, Nagarur, and Tabucanon and Rechena, Infante, Sousa, *et al.*, generally reduces costs and is beneficial, especially for smaller networks. The visual aspect of these structures also plays a critical role in public acceptance, particularly in urban settings. Designed structurally, these support structures are designed to withstand various environmental and operational stresses, including extreme weather events and operational vibrations, which could potentially compromise their integrity and safety. The choice of materials, such as prestressed concrete, has evolved to enhance the durability and reliability of these structures. In general, the design, standardisation and maintenance of OCLS support structures are vital to the efficient and safe operation of electrified railways.

Maintenance management & monitoring and evaluations

Challenges and innovations in maintenance and performance evaluation of the railway infrastructure due to ageing systems and increased safety demands. Key studies focus on the heterogeneity of designs and the complexity it introduces, advocating a systems thinking approach that combines mechanistic and data-driven methods for asset management ([7]). Various methodologies such as the Markov Estimator and Bayesian inference are used to assess the reliability of structures such as prestressed concrete poles and steel structures, with particular attention to the effects of corrosion over time ([8]; [9]; [10]). The adoption of digital twins and preventive maintenance strategies is discussed as cost-effective solutions to improve the longevity and reliability of the infrastructure ([11]; [12]; [13]). In addition, the implementation of Prognostics and Health Management (PHM) systems is highlighted to modernise asset management and reduce operational costs, with a call for further standardisation and research to optimise monitoring techniques ([14]; [15]; [16]).

Decision support system & Decision-making framework

Recent advances in decision support systems (DDS) for railway infrastructure focus on improving maintenance and design processes. Key studies, such as those of Sedghi, Kauppila, Bergquist, *et al.*, Jamshidi, and Xu, Lai, and Huang, highlight the adoption of predictive maintenance strategies that significantly reduce costs and improve efficiency compared to traditional methods. DDSs are integral in the management of complex design requirements and standards, as noted by Berthold and Garcia, Gomez, Saa, *et al.*, who also emphasise the reduction of design times and errors through automated solutions such as the EL-BAS OLACAD tool. Furthermore, the shift towards multiobjective DDS approaches, as discussed by Peralta, Bergmeir, Krone, *et al.* and Chen, Zhang, Liu, *et al.*, incorporates various performance metrics such as cost, serviceability, and passenger comfort, often outperforming expert-developed schedules. These systems utilise advanced algorithms such as Pareto-based methods and particle swarm optimisation to optimise maintenance and design decisions, reflecting a trend toward more integrated and efficient infrastructure management.

Identified knowledge gaps highlight the need for in-depth research, particularly in maintenance and asset management, crucial throughout the technical lifetime of support structures. Research aims to improve understanding of structural conditions, optimising maintenance timing and efficiency. This includes improving the accuracy of the assessment of structural conditions, supporting condition-based maintenance, which is performed only as needed, and enhancing process efficiency. In addition, the growing use of monitoring and data collection informs maintenance decisions and supports the development of models capable of handling increasing data volumes and complexity. These models are essential for optimising multiple objectives in environments such as expanding rail networks with limited maintenance opportunities. Advanced algorithms are crucial to leverage these models in decision-making. A significant gap remains in understanding sustainability's role in the design and lifecycle of structures, with current research focussing on integrating sustainability into the design process.

OCLS support structures are crucial to railway infrastructure, with substantial knowledge developed over time. Recent literature indicates a trend towards standardised designs, though diverse designs and methods persist across networks. The researchers focus on in-depth structural studies, including extreme load effects and assessing structural conditions. Recently, there is heightened interest in maintenance planning and scheduling from a multicomponent and network perspective, alongside condition-based maintenance policies. Monitoring methods and systematic maintenance planning using decision-making frameworks are also gaining attention. In addition, the use of complex models to support decision making is increasing. Despite the growing importance of sustainability, research in this area remains limited. These observations highlight several significant knowledge gaps.

- Further understanding and development of methods on the structural condition of the structures.
- Use of condition-based maintenance using structural models and new monitoring methods.
- Further development of multi-objective decision-making models, as well as the implementation of more complex algorithms
- Impact and influence of sustainability on the design and maintenance of support structures

3 Design Process & Stakeholders

3.1 Design Process for Overhead Contact Line Systems

the design process for Overhead Catenary Line Systems (OCLS) on the Dutch railway network, governed by ProRail's regulations and based on the System Engineering (SE) approach as detailed in the Handbook [23]. This approach optimizes the system's lifecycle and has been adopted across the Dutch civil engineering sector, with guidelines published by ProRail to ensure national uniformity [24]. The design process incorporates a model distinguishing three main phases: modeling, functional design, and physical design, with a looping interaction between the last two phases. The process is structured into seven development phases: Needs Analysis, Concept Exploration, Concept Definition, Working Draft Definition, Detailed Elaboration, Realisation, and Management & Operation, each crucial for the system's lifecycle and described in the design specification OVS00024 and RVOI [25]. The design must adhere to ProRail's standards and regulations, using only approved products [25], and is carried out by accredited consulting engineering firms [26].

3.2 Stakeholder Analysis for Overhead Catenary Line Systems

The identified stakeholders involved in the design process of Overhead Catenary Line Systems (OCLS) are discussed. Adapting the stakeholder categories defined by the NEN-EN50126 standard, which includes railway companies, infrastructure managers, maintenance companies, rail supply industry, and safety authorities. The maintenance category is replaced by Consulting Engineering Firms (CEF), and a government category is added. Key stakeholders include ProRail, which plays a central role in all design phases, and various consulting firms that contribute to research, design variants, and feasibility studies. The design process is segmented into phases, each involving specific stakeholders with distinct roles, ensuring compliance with regulations and alignment with transportation policies. The table provided lists stakeholders classified by their roles, emphasising the limited number of companies allowed to participate in the design, manufacture, or supply of OCLS due to ProRail's accreditation scheme. References include citations to relevant standards and lists of accredited companies and certified products.

To conclude, the OCLS design process is structured into seven phases and adheres to a system engineering approach. ProRail manages this process under strict regulations and accreditation to ensure standard compliance. The importance of collaborative efforts among stakeholders, including government bodies, infrastructure managers, and engineering firms. These collaborations, along with ProRail's commitment to safety and regulatory compliance, are crucial to achieving safe, efficient, and sustainable rail infrastructure.

4 Design Requirements and Specifications for OCLS

This section outlines the design requirements and specifications for Overhead Catenary Line Systems (OCLS) on the Dutch railway network, focusing on the development of a new superstructure. It integrates various regulations and standards from legal, technical, and policy frameworks, as detailed in earlier sections and analysed using system engineering techniques. Key sources include Technical Specifications for Interoperability and European and national regulations, discussed in respective sections. Concludes by summarising essential findings for the design of OCLS support structures, providing a comprehensive overview of the necessary compliance and design considerations.

The European Union has established Technical Specifications for Interoperability (TSI) to ensure the interoperability of the railway system across the EU.

These specifications, managed by the European Union Agency for Railways and outlined in Directive 2016/797 [27], set the technical and operational standards for subsystems and components. Essential requirements such as safety, reliability, and environmental protection are defined for these subsystems, which include Energy, Infrastructure, Noise. Specific TSIs, like those for Energy [28] and Infrastructure [29], address detailed aspects such as the electrification system and track elements. The European Railway Agency also provides guides for applying these TSIs, aiming to harmonise components like the overhead contact lines to enhance interoperability within the European Railway Network. Additionally, compliance with European and National Standards, such as NEN-EN50119:2009 [30], is crucial in the design process for these systems.

The NEN-EN 50119 standard addresses the design and implementation of overhead contact line systems for electric traction, including flexible overhead contact line (FOCL) and rigid overhead contact line (ROCL) systems. It outlines the use of automatic tensioning and fixed anchor points to maintain tension in FOCL systems, and rigid profiles or anchorage systems to stabilise ROCL systems. The standard is applicable to various rail systems, including heavy and light rails, and covers both the electrical and structural aspects of these systems. Specifies different types of support structures based on the forces they need to withstand, such as pole structures, rigid cross-section structures, suspension structures, and tension structures. The standard emphasises robust design to enhance safety and reliability, using the structural limit states method to define the ultimate and serviceability limit states for evaluating structural integrity and performance.

The NEN-EN 15273 standard details specifications and regulations for railway gauges within the European Union, divided into three parts. Part 1 outlines general principles and the interface between infrastructure and rolling stock, including reference profiles and rules[31]. Part 2 focusses on rolling stock, discussing dimensioning and calculation methods based on gauge characteristics[32]. Part 3 addresses infrastructure dimensioning and operational constraints related to specified gauges[33]. The gauge is defined as a spatial agreement between infrastructure and rolling stock, essential for ensuring interoperability across European railways, including those defined in the Infrastructure TSI[34].

The Structural Eurocode programme, initiated in 1975 and formalised in 1989, aims to harmonise technical specifications across the European Union. It introduces a series of 10 standards known as 'Eurocodes' which provide a unified approach to structural design applicable to various materials. The foundational standards, particularly NEN-EN 1990, outline essential principles and requirements for safety, serviceability, and durability of structures. These are based on the limit state concept combined with partial factors method, elaborated in NEN-EN 1990 [35]. While NEN-EN 1990 serves as a general guideline, material-specific standards should be applied as necessary.

ProRail, as the infrastructure manager of the Dutch railway network, has developed a comprehensive set of company regulations, supplementing national and European standards. These regulations are crucial to ensure safety and uniformity in material usage and process execution within the network, as highlighted in **??**. The regulations vary according to the infrastructure's lifecycle phase and document type, in accordance with RAMS standards ([36][37]). This differentiation also aligns with the Systems Engineering approach adopted by ProRail, a common methodology in the Dutch civil engineering sector ([23]). Details on these regulations are available in the Rail Infra Catalogues.

The analysis of design requirements for the support structure of the Overhead Contact Line System (OCLS) on the Dutch railway network is carried out employing a system engineering methodology. The Systems Engineering is well integrated with ProRail's practices, as noted in [23]. The analysis begins with the identification of 148 potential requirements through a middle-of-the-way strategy and a snowball search method, ensuring a comprehensive review of relevant documents. Following identification, the relevance of the requirements is analysed and categorised into functional, non-functional, and constraints, which are then prioritised according to their impact on the design. This prioritisation helps to efficiently address critical requirements first, considering trade-offs and dependencies. Prioritised requirements are classified into 18 different groups. Finally, the constraints are analysed to understand their implications on design feasibility and compliance, identifying 43 as objectives and 105 as constraints, with detailed categorisation also in **??**.

In conclusion, the analysis of the requirements of the OCLS support structure in the Dutch rail network highlights safety as a fundamental requirement, as detailed in RLN0009[38]. This is crucial to ensure the reliability of rail infrastructure through rigorous structural analysis. The requirements are crucial for the overall functionality and safety of the system, which is a primary focus in the design process according to OVS00024-2.1[25]. However, economic considerations also play an important role, necessitating a balance between cost-efficiency and safety. Designers are encouraged to achieve a technically and financially optimal solution that adheres to safety standards while considering life-cycle costs and potential deviations that meet overarching requirements. This approach ensures that both safety and economic factors are taken into account to achieve an optimal design solution.

5 Sustainability within the Dutch Railway Branch

5.1 Definition of Sustainability

First to definition of sustainability has been defined by analysing key documents such as the Brundtland Report (Our Common Future) [39], the Paris Climate Agreement [40], the European Green Deal [41], the Dutch Climate Agreement [42] and the National Circular Economy Programme [43]. It aims to elucidate the core principles and dimensions of sustainability, highlighting the interplay of environmental, social, and economic factors. The Brundtland Report emphasises sustainable development without compromising future generations, focussing on equity and resource management. The Paris agreement seeks to limit global temperature increases, improving resilience to climate change through renewable energy and efficiency improvements. The European Green Deal aligns with these goals, setting ambitious targets for the EU. Similarly, the Dutch initiatives aim to reduce emissions and promote circular economy practices. Collectively, these documents underscore the need for global cooperation, innovation, and policy alignment to foster a sustainable and resilient future.

5.2 Ambitions of the Rail Branch: ProRail

The sustainability ambitions and strategies of ProRail are reviewed. ProRail is committed to sustainability, focusing on reducing CO2 emissions, energy consumption, and promoting a circular economy. Key initiatives include a comprehensive roadmap to sustainability, adherence to the Railway Climate Responsibility Pledge, and the implementation of the 'CO2 and Energy Savings Strategy 2021-2025'. ProRail also supports the CO2 Performance Ladder to encourage CO2 reduction in infrastructure projects and is actively following the principles of circular economy to minimise environmental impact. These efforts are part of ProRail's broader goal of achieving carbon neutrality by 2050 and improving the sustainability of rail transport in the Netherlands. References include [44], [45], [46], [47], [48], [26], [49], and [50].

5.3 Methods for Determining Sustainability

Various methodologies for assessing sustainability in the Netherlands have been reviewed, focusing on the Life Cycle Assessment (LCA). LCA evaluates the environmental performance of products or systems from creation to disposal, as per the EN 15804 standard. Consider factors like energy use, emissions, resource depletion, and waste generation. Quantitative methods and software tools, supported by databases such as the Dutch National Milieu Database or Ecoinvent, are used to ensure comprehensive environmental data analysis and sustainable decision making [39], [51], [52].

In conclusion, sustainability has been explored in the Dutch rail sector, focusing on its definition, objectives, and measurement methods. Key documents such as the Brundtland Report, the Paris Climate Agreement, and the European Green Deal, along with national initiatives like the Dutch Climate Agreement and the National Circular Economy Programme, have been reviewed to understand the core principles of sustainability. ProRail's initiatives, including the Railway Climate Responsibility Pledge and CO2 Performance Ladder, exemplify the integration of sustainability in rail operations. Methodologies such as Life Cycle Assessment (LCA) and the Circularity Indicator are highlighted as effective tools for assessing environmental impacts and promoting circularity in projects. The chapter concludes that achieving sustainability in the rail sector requires ongoing collaboration and innovation.

6 Theoretical Foundations of Multi-Objective Optimisation Model

Building upon the insights of the research discussed in the previous sections, a multi-objective optimisation model has been formulated to determine the potentially sustainable design space for OCLS. In this section, the theoretical foundations of the model are discussed.

6.1 Multi-objective problem formulation

The complex and multi-faceted nature of the design problem based on insights from; the complexity and stakeholder considerations, the critical structural requirements, and the sustainability indicators. The design problem is defined as a multi-objective optimisation challenge aimed at balancing safety, environmental, and economic factors within a sustainable design space. The main objectives include minimising environmental impact through reduced emissions and energy use and enhancing circular efficiency, alongside reducing economic costs.

6.2 Assumptions

The model assumes that the support structure is on the Dutch rail network, focussing on the pole's cross-sectional design. Consider only the production and end-of-life stages of the life cycle assessment (LCA) as key stages. The structural assessment adheres to RLN0009 [38], assuming elastic bending of the materials and linear stress-strain relationships across all stress levels, following Hooke's law [53]. The support structure is located on a straight track segment within a normal section of the catenary system, with the maximum allowed span length.

6.3 Objective functions

Objective functions of the objectives stated above are specified below. For each of the functions, in addition to the formulation, the motivation for the formulation of the function is given.

The focus is on reducing the carbon footprint of a pole design. Carbon emissions are identified as a crucial indicator for assessing environmental impact. Due to the complexity of calculating total emissions in all design stages, the analysis is narrowed down to the emissions of the material used for the pole. The objective function formulated calculates the carbon footprint based on the CO_2 equivalent per kilogramme of the selected material, the density of the material, the cross-sectional area of the pole and its length. The formula is:

$$\text{Minimise } f_{CO_2 \text{ footprint}}(x) \tag{1}$$

$$f_{CO_2 \text{ footprint}}(x) = C_{CO_2\ m} \cdot \rho_m \cdot A \cdot L_{\text{Pole}} \tag{2}$$

Minimising embodied energy in pole design, which is considered a secondary objective to evaluate environmental impact. The energy embodied represents the total energy required to produce the material used in the pole. The objective function to minimise the embodied energy, labelled $f_{\text{Embodied Energy}}(x)$, is defined as the product of the embodied energy per unit mass of the material ($C_{EE\ m}$), the cross-sectional area (A) and the length of the pole (L_{Pole}). This function is crucial for evaluating the environmental footprint of the pole design.

$$\begin{aligned} &\text{Minimise } f_{\text{Embodied Energy}}(x) \\ &f_{\text{Embodied Energy}}(x) = C_{EE\ m} \cdot A \cdot L_{\text{Pole}} \end{aligned} \tag{3}$$

Circularity, particularly Circular Efficiency, is a crucial indicator in assessing sustainability, as discussed in section 5 and defined by the NMD [54]. The formula for Circular Efficiency, which measures the ratio of environmental benefits to production costs, is given by:

$$\text{Circular Efficiency} = \frac{C_{\text{Module D}}}{C_{\text{Module A1-A3}}} \tag{4}$$

This efficiency is calculated by considering the proportion of recyclable material in a product's design, influencing material selection due to its significant environmental impact. The environmental impact of materials, categorised into virgin, recycled and typical based on embodied energy and carbon emissions, is computed using the following.

$$X_{\text{Typical}} = (1 - RF) \cdot X_{\text{Virgin}} + RF \cdot X_{\text{Recycling}} \tag{5}$$

The recycling factor (RF) represents the proportion of recycled material in production. Circular efficiency also considers the ratio of recycling to the values of virgin material, indicating the potential environmental benefits of recycling. Lower values of this ratio suggest a higher circularity potential, which promotes material reuse. The objective functions for minimising carbon emissions and embodied energy in terms of circular efficiency are:

$$\text{Minimise } f_{\text{Circular Efficiency},CO_2}(x) \tag{6}$$

$$f_{\text{Circular Efficiency},CO_2}(x) = \frac{C_{CO_2,\text{recycling m}}}{C_{CO_2,\text{virgin } m}} \tag{7}$$

$$\text{Minimise } f_{\text{Circular Efficiency, EE}}(x) \tag{8}$$

$$f_{\text{Circular Energy, EE}}(x) = \frac{C_{\text{EE,recycling } m}}{C_{\text{EE, virgin } m}} \tag{9}$$

The economic impact of a pole design is considered by minimising costs, focussing on the material price as a key factor. Maintenance and installation costs are generally negligible and uniform, respectively. The fluctuation in materials costs over time is noted and further details are provided in **??**. The cost function is defined as:

$$\text{Minimise } f_{\text{Cost}}(x) \tag{10}$$

$$f_{\text{Cost}}(x) = C_m \cdot \rho_m \cdot A \cdot L_{\text{Pole}} \tag{11}$$

This cost function is interconnected with the carbon emissions (Eq.2) and embodied energy (Eq.3) through the cross-sectional area, complicating the trade-off among these objectives. The selection of material or pole shape by the algorithm is crucial in managing these trade-offs.

6.4 Constraints

The model incorporates several constraints applied to the fitness function. Key constraints include deflection limits based on RLN0009 standards, ensuring that the structure withstands various load combinations safely, as verified by design resistance and shear stress constraints. Additionally, shape feasibility is checked using Ashby's shape factor, and Eurocode 3's thickness and width ratio requirements. Specific displacement constraints for the pole under permanent loads dictate that the top pole displacement in the x-direction must not exceed 1% of the pole's length, as shown in the equation:

$$\delta_{\text{Top Pole},x} \leq 1\% \cdot L_{\text{Pole}}$$

Similar constraints apply for wind loads affecting the contact wire's displacement in both horizontal and vertical directions, related to the track's speed limit. These constraints are crucial for the model's design and operational validity.

An additional constraint within the model focusses on shear stress, emphasising the importance of not exceeding the yield strength in the design of materials. at the outer edges of a pole under bending stress. The maximum shear stress is calculated using the formula:

$$\sigma_m \leq \frac{M_y Y_y}{I_y}$$

Where σ_m is the yield strength, M_y is the bending moment, Y_y is the distance from the neutral axis, and I_y is the moment of inertia. This ensures that the material does not undergo plastic deformations that exceed its elastic limit. The constraint on shape factors explains how the geometry of a section affects its bending efficiency and stiffness, emphasising the need to optimise shape to minimise material use while avoiding structural weaknesses like buckling. The shape factor for a square beam is used as a reference to set constraints on the design of other shapes, ensuring that they remain within practical limits of stiffness and material properties.

The shape factor ϕ_B^e must not exceed the maximum allowed shape factor $\phi_{B,\text{Max}}^e$. Shape factor is calculated by:

$$\phi_B^e \leq \phi_{B,\text{Max}}^e$$
$$\phi_B^e = 12\frac{I}{A^2}$$

The constraints based on the width-to-thickness ratio of shapes in steel structures as specified in Eurocode 3[53]. A conservative approach is adopted to improve the reliability and feasibility of pole-shaped design. The section explains the classification of cross-sections into four classes based on their force resistance and rotational capacity, which are crucial for assessing the structural integrity and performance under stress, particularly local buckling. Class 3 limits are specifically used for this constraint, allowing for a wide range of values for the width-to-thickness ratio to increase design feasibility. The mathematical constraints for Class 3 are:

Class 3 formulas:

Bending

$$\frac{c}{t} \leq 124 \cdot \epsilon$$

Compression

$$\frac{c}{t} \leq 42 \cdot \epsilon,$$

Outer, Rolled section

$$\frac{c}{t} \leq 14 \cdot \epsilon,$$

Tubelar, Bending and compression

$$\frac{d}{t} \leq 90 \cdot \epsilon^2$$

$$\epsilon = \sqrt{\frac{235}{f_y}},$$

The constraints on the objective functions cover several aspects related to cost, CO2 emissions, and embodied energy, incorporating maximum values pertinent to ProRail's operations. The maximum cost parameter is based on Sweco's cost analysis for Overhead Contact Line System (OCLS) works and materials (Sweco, [55]). Furthermore, CO2 emissions data for the HEA300 support pole, sourced from the ProRail-commissioned NMD environmental chart [56], are considered per metre of pole length. The energy data, derived from the CES Edupack dataset for Steel S235, pertain to the HEB300 support pole.

The constraints are represented as follows:

$$C_{\text{Cost, max}} = 2750$$
$$C_{\text{CO2 Footprint, max}} = C_{\text{HEB300}} \cdot L_{\text{Pole}}$$
$$C_{\text{CO2 Footprint, max}} = 2906.6\text{Kg } CO_2 \text{ eq.}$$
$$C_{\text{Embodied Energy, max}} = C_{\text{S235}} \cdot A_{\text{HEA300}} \cdot L_{\text{Pole}}$$
$$C_{\text{Embodied Energy, max}} = 2.495\text{MJ}$$

6.5 Structural Analysis

The proposed pole design is structurally evaluated to assess its integrity, following the RLN0009 guidelines [38]. The following assumptions are made for simplifications. Insulator loads are neglected, as they have minimal impact. Wind load is considered to act perpendicularly in the positive x-direction. All dimensional, dynamic factors, and pressure coefficients are constant. The structure's deformation is modelled using elastic bending, assuming a linear stress-strain relationship at all stress levels. According to Hooke's Law, materials return to their original shape post-stress. This elastic model helps determine internal forces and moments, despite material resistance being based on the capacity for plastic deformation [53].

7 Implementation and Validation of the Multi-Objective Optimisation Model

7.1 Model Framework

The model framework designed to explore the design space, is based on the standard NSGA-II framework. A widely used genetic algorithm to solve these MOO problems is the NSGA-II, proposed by Deb et al. It is a prominent solution in this domain due to its ability to efficiently provide Pareto optimal solutions [57]. Numerous comparative studies, covering the application of the NSGA-II algorithm to MOO, have been carried out [58] [59] [60]. The model incorporates a uniform crossover to merge genetic information from parent solutions, enhancing diversity and exploration within the population [59]. As mutation, an adaptive mutation strategy is incorporated. This strategy adjusts mutation rates based on the fitness attributes of the population to alter the solutions of the offspring, improving the exploratory and convergent capacities [61]. Mutation rates are dynamically reconfigured throughout the optimisation cycle by assessing solution performance through fitness values, diversity indices, or convergence rates [62]. The gene space for this model is formed by following design variables. The following design variables are used to define the pole's design through its material, commonly used steel beam shapes, and specific dimensions such as width, height, and flange thickness.

The framework includes two filters: one pre-fitness function for the population and another pre-crossover for the parents. Pre-fitness function filtering of the population aims to improve solution quality by removing infeasible solutions, defined as those violating deflection or shape design constraints, and replacing them with feasible ones. Replacement candidates are chosen from the existing population using the Pareto front and crowding distance metrics. These metrics help identify the top replacements. If infeasible solutions outnumber feasible ones, the latter are recycled.

The precrossover filtering ensures that only feasible or minimally infeasible solutions within defined boundaries are used as parents for the next generation. This process aims to maintain the reliability and feasibility of the selected parent solutions. By excluding solutions that violate constraints, the algorithm improves and refines its strategy for future generations. Parent solutions undergo a filtration process based on their constraint scores, which indicate any constraint violations. Solutions that do not meet the constraints are identified by the highest constraint score, and infeasible solutions are removed for cross-selection. If all initially chosen solutions violate the constraints, alternative solutions are considered. Parents are chosen based on their constraint scores to find those with the least violations. The framework of the model configuration is illustrated in Figure 1, along with the pseudo code of the model is provided.

Algorithm 1: NSGA-II Adaptation

input : Initial population P_{Initial}, Stop criteria
output: Final population P_{Final}

Initialisation;
Initialise population randomly from design variable ranges;
while *Stop criteria not met* **do**
  Population Filtering;
  Filter the Population P for feasibility.;
  Infeasible solution are replaced with feasible non-dominated solution in current population P ;
  Fitness Function;
  for *each individual ind in P* **do**
    Compute fitness of ind;
  end
  Parent Selection;
  Perform non-dominated sorting and crowding distance determination on P;
  Select parents based on non-dominated fronts and crowding distance;
  Export selected parents and all feasible solutions in P;
  Parents Filtering;
  Filter the selected parents for feasibility.;
  Crossover;
  Perform crossover on the selected parents to create offspring;
  Mutation;
  Apply adaptive mutation on the offspring;
  New Population Update;
  Update P with the new offspring population;
end
Output:;
Final population P_{Final} after meeting stop criteria.

7.2 Fitness function

Within the fitness function, each solution's fitness is evaluated and integrated with model constraints. The fitness function includes a constraint score to track violations, based on a methodology that checks the compliance of the solution with constraints using the function of Milatz, Winter, Ridder, *et al.* All constraints are equally significant [63], and compliance is measured by percentile violation. Full compliance awards a maximum score of 10, which is adjusted by rounding the percentile violation to a decimal, then multiplying. This integer score is deducted from the solution's current constraint score, ensuring that feasible solutions receive high scores while infeasible ones get negative scores. The maximum achievable constraint score is 1260.

Fulfils the constraint:

$$C_{\text{Score}} = C_{\text{Score}} + 10$$

Violates the constraint:

$$C_{\text{Score}} = C_{\text{Score}} - (10 \cdot \frac{(x_{\text{Sol}} - x_{\text{Con}})}{x_{\text{Con}}})$$

Where C_{Score} is the constrain score of a solution, x_{Sol} is the value of the solution for the constrain and x_{Con} is the constrain value. The fitness function, a central component of the model, evaluates each population solution to determine its fitness value and total constraint score. Initially, design variables such as material type, pole shape, and dimensions are extracted, with material properties like Young's modulus, yield strength, Poisson's ratio, and density sourced from the dataset. Next, pole shape properties like inertial moments and cross-section are derived in the pole cross-section element, assessing them against Cross-Section Constraints including Width-Thickness Ratio and Shape Factor. Deflections at the pole top are calculated in the x- and y-directions using linear elastic bending, filtering out infeasible solutions that exceed displacement constraints. Feasible solutions undergo further structural analysis for specified load cases, evaluating structural constraints such as design resistance, ground support stability, displacement, and shear stress. After the analysis, the fitness values for objectives such as CO_2 footprint, embodied energy, and the costs are determined on the basis of these constraints. If constraints are violated, the constraint score is adjusted and the circular efficiency is calculated for the footprint of embodied energy and CO_2. Finally, the fitness function outputs fitness values for each objective, calculating the overall constraint score, updating solutions in the population based on these scores, and using these values for algorithm optimisation.

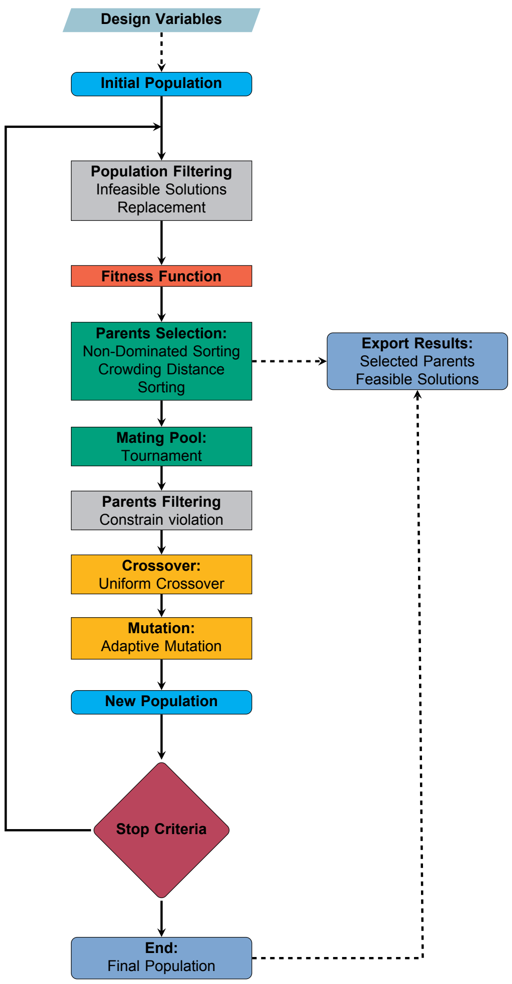


Figure 1: Overview of the model framework

7.3 Data

This section presents the data used for model optimisation, including material data for various pole variations and the selected pole shape designs with their dimensional ranges. The material dataset for the model is sourced from Granta Edupack 2023 R2, specifically the Level 3 Materials dataset. This dataset provides detailed properties for each material, categorised by family in Granta EduPack. All materials from Granta Edupack were reviewed to ensure that they possessed the requisite properties for model input. Any materials that lacked any required property were excluded from the dataset. An overview of the ranges of the material properties selected for model input is provided in Table 1

Table 1: Material Properties: Level 3 Materials Dataset

Dataset	Level 3 Materials	
Total number	166080	
Selection	97293	
Material Property	**Min**	**Max**
CO_2 Footprint Typical [kg/kg]	0.025	45900
CO_2 Footprint Recycling [kg/kg]	0.025	2200
CO_2 Footprint Virgin [kg/kg]	0.025	65100
Density [kg/m^3]	$7.32 \cdot 10^{-6}$	570
Embodied Energy Typical [MJ/m^3]	400000	$1.12 \cdot 10^{12}$
Embodied Energy Recycling [MJ/m^3]	400000	$2.8 \cdot 10^{8}$
Embodied Energy Virgin [MJ/m^3]	400000	$1.37 \cdot 10^{12}$
Poisson Ratio [-]	0.06	0.5
Price [€/kg]	0.0187	603000
Yield Strength [MPa]	1130	$3.6 \cdot 10^{9}$
Young's Modulus [GPa]	7320	$5.7 \cdot 10^{11}$

The model employs nine standard pole shapes as design variables, including Solid Rectangular Beam, H-Beam, I-Beam, UNP, T-Beam, and various Tubular Beams. The dimensional design variable ranges, detailed in autoreftab:DimensionDesignVariables, adhere to practical minimum and maximum limits from the Bouwen met Staal profile database [64]. Initially, the use of broader intervals led to the generation of shapes that were not feasible, prompting the introduction of these specific limits in order to enhance the validity of the model.

Table 2: Range for Dimensions of Design Variables

Dimension	Min	Max	Step size
Height [mm]	100	500	10
Width [mm]	100	400	10
T_w [mm]	2	20	1
T_f [mm]	2	30	1
T_t [mm]	2	40	1

T_w, T_f, and T_t denote the web, flange, and tubular thicknesses, respectively, for UNP, H-, I-, and T-beams. For round tubular sections, the diameter is the maximum of width or height.

7.4 Software Implementation - Python

The Python programming language [65], known for its open-source nature and extensive library of modules, was utilised to develop the model for the optimisation problem. For this, the PyGad package [66] was used, which offers various genetic algorithms including NSGA II, which was used in its tournament selection version to enhance optimisation. Furthermore, the PyNite package [67] facilitated the analysis of finite elements of elastic 3D structural engineering under combined load conditions, allowing the evaluation of deflections in the support structures according to the specified standards and constraints.

This section discusses the fitness function formulated for the model. Initially, a graphical representation of the function is shown in Figure 14, which is followed by an explanation of the function flow.

8 Model Validation

This section discusses the validation of the model, its sub-modules, and the data used. It begins with the structural analysis, followed by the environmental data, and concludes with the model's validation using Hyper Volume and constraint score.

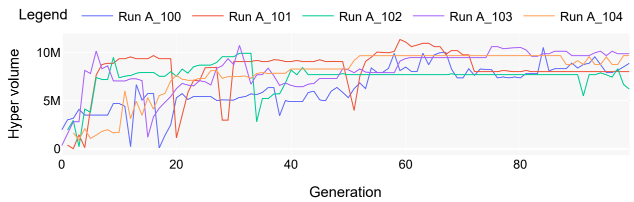
The Pynite package, used for the structural analysis of the pole and portal designs, facilitates 3D modeling, support structure analysis, and deflection computations. First-order analysis determines deflections and stress distribution, complying with [30] and [38]. To validate the module, both pole and portal models were confirmed. Additionally, an expert[1] reviewed the structural model for result accuracy and practical applicability. Deflections in the pole design were validated against RLN0009.v5 [38], showing similarities to example results. Note, minor discrepancies may occur due to Python's float handling.

To validate the environmental data in the model and ensure result applicability, CO_2 footprints and embodied energy for H beams were recalculated based on the LCA by ProRail for NMD [56]. The environmental profile yielded impact categories such as Global Warming Potential and Climate Change for CO_2 footprint, and 'Energy, primary, renewable', 'Energy, primary, non-renewable', and 'Resource use, fossils' for Embodied Energy. The model uses typical values from the Granta Edupack dataset, with CO_2 footprint for structural steel S235 at 1.85 kg/kg and embodied energy at 17.5 MJ/kg. The CO_2 footprint values align with Granta Edupack, suggesting similar emissions. However, embodied energy values differ significantly from S235, resembling the impact category of Resource Use, Fossil. These discrepancies arise from source type dependencies. The Granta Edupack val-

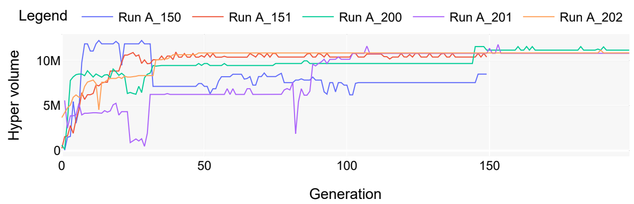
[1] Wim Golverdingen, Senior Consultant OCLS, SWECO Nederland

ues, based on literature and life cycle inventories, are estimated when data is lacking [68]. Thus, model results are indicative and should be considered arbitrary in impact determination.

The hyper-volume indicator evaluates multi-objective optimisation algorithms by measuring the volume dominated by non-dominated solutions. A reference point, defined by the maximum values in each dimension for minimisation problems, bounds this volume. The volume, composed of hyper-rectangles with a common vertex at the reference point, quantifies the coverage of the objective space by these solutions [69]. Higher hyper-volume values suggest a closer approximation to the true Pareto front, though computational costs must be considered [70]. Hyper-volume also validates NSGA-II models in these problems [71], [58]. For model validation, hyper-volume is calculated using the algorithm from Fonseca, Paquete, and López-Ibáñez [69], considering cost, CO_2 footprint, and embodied energy, but excluding circular efficiency objectives due to unknown reference values. Only solutions that meet all constraints are considered. Plots in Figure 2 show hyper-volume over 100, 150, and 200 generation runs, indicating model stabilisation and consistent coverage of the objective space, validating the model's consistency [69].



(a) Runs 100 Generations



(b) Runs 150 and 200 Generations

Figure 2: Convergence Plots of Hyper Volume

Three runs with 250, 500, and 1000 generations were conducted to examine the model's behavior with increasing generations. The hyper-volume plot is shown in Figure 3. The model stabilizes upon reaching the Pareto frontier, though occasional hyper-volume drops indicate the detection of new potential Pareto frontiers, highlighting the model's ability to escape local optima. These drops also show the model's sensitivity to local optima, a result of the algorithm's inherent randomness. This sensitivity is an important consideration when interpreting results, despite the model's generally quick stabilization.

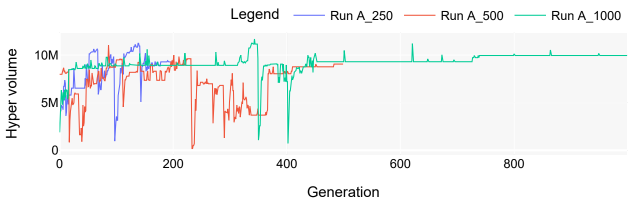
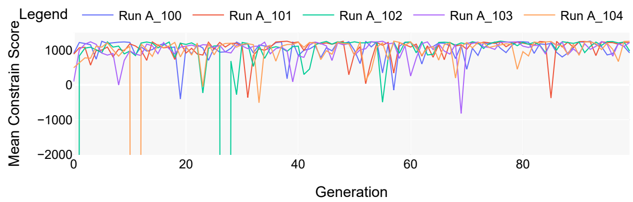
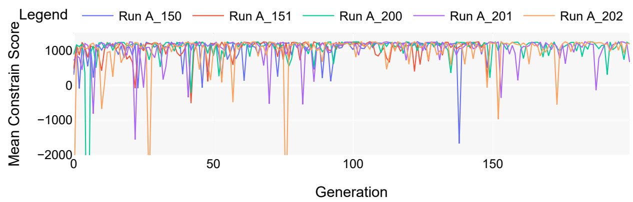


Figure 3: Convergence Plots of Hyper Volume of Runs With 250, 500 and 1000 Generations

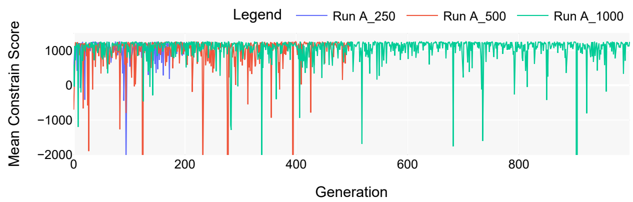
The constraint score validates the model by indicating if a solution violates any constraints. It reflects the algorithm's effectiveness in identifying compliant solutions. Ideally, all parent-selected solutions should be compliant, forming a non-violating new population. For validation, both the aggregated and mean constraint scores per generation of parent-selected solutions are monitored. These scores should ideally increase and stabilize at the maximum value of 37800, indicating full compliance across generations.



(a) Runs 100 Generations

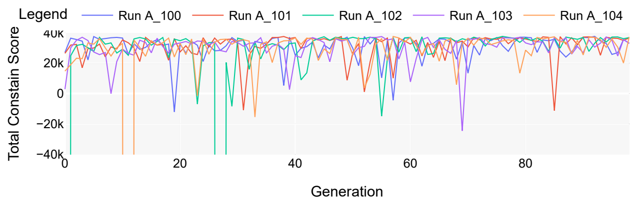


(b) Runs 150 and 200 Generations

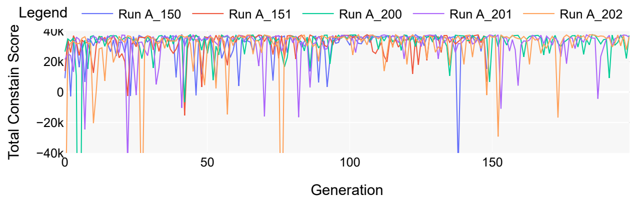


(c) Runs 250, 500 and 1000 Generations

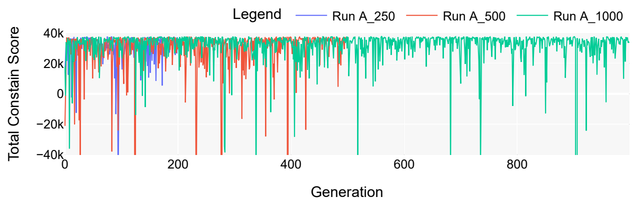
Figure 4: Evolution of Mean Constraint Score of Parents per Generation



(a) Runs 100 Generations



(b) Runs 150 and 200 Generations



(c) Runs 250, 500 and 1000 Generations

Figure 5: Evolution of the Total Constrain Score of Parents per Generation

The plots indicate that the model struggles to stabilise and maintain non-violating solutions, suggesting a tendency to identify viable but constraint-violating solutions. These results should be seen as indicative of potential directions rather than optimal solutions. The observed volatility in the model may stem from the experimental design or the employed crossover and mutation methods.

9 Case Study and Experimental Setup

This section presents the results of the optimisation model and outlines the case study and experimental design used in the simulations.

9.1 Case Study

Two cases are developed within the main Dutch rail network, differing in the design of the support structure: a single pole and a portal design. Only the pole design is optimised, as detailed in **??**. The portal configuration employs the standard double-track design using ProRail's RHS300 beam. Both cases utilise the PVR-GC for the 25kV gauge, a Dutch adaptation of the European GC gauge, compatible with a 25kV catenary system. The Dutch B4 catenary system, operating at 1500 V DC and capable of 160 km/h, is selected for its ability to be upgraded to 25 kV AC. The system specifications are described in OVS00024-5.4 [72], using specified wire types for 1500 V DC and a maximum field length of 60 m. The contact wire, supported in the pull-off position to manage the impact of the load, zigzags between structures. Support arms for the B4 system are detailed in SPC00121, chosen based on the contact wire design and configuration. The pole height is standardised at 8.6 m throughout the optimisation.

9.2 Experimental design

The experimental design, including the parameter configurations for the algorithm and the simulations conducted, is outlined below. It also describes the operational environment for these simulations.

The settings for population size, number of parents, uniform crossover, and adaptive mutation for both low-ranking and high-ranking solutions are detailed in Table 3.

Table 3: Parameter Settings used for Simulation Runs

Parameter	**Value**
Population Size	60
Number of Parents	30
Uniform Crossover	Percentage: 0.6
Adaptive Mutation	Low-ranking: 0.8, High-ranking: 0.15

Simulations were conducted for 100, 150, and 200 generations, with additional single runs for 250, 500, and 1000 generations to evaluate the effects of longer generational spans on the 'All Material' dataset.

The following input sets were used for the materials in the All Materials dataset: ceramic (non-technical), composite (natural), elastomer (thermoplastic, TPE), metal (ferrous), metal (non-ferrous), plastic (thermoplastic, amorphous). The materials families were chosen for their potential to build compliant support structures. All pole-shaped designs were considered in the simulations. The plots are denoted as follows: '*A_..RunNumber..*'. The All Materials* dataset includes the same material families as the All Materials dataset, but excludes pole-shaped designs from UNP and T-beam, which were prevalent in previous simulations but impractical for poles. In the plots, these simulations are labelled as '*Aa_..RunNumber..*'. The Ceramic (non-technical) dataset exclusively features the ceramic material family for focused evaluation. The dataset includes all pole-shaped designs, which are denoted in plots as '*C_..RunNumber..*'. The Metals (non-ferrous) dataset contains only the metal (non-ferrous) material family, which is used for the specific evaluation of the material family. All pole-shaped designs are included in the runs. In the plots, these simulations are referred to as: '*MNF_..RunNumber..*'.

In Table 4 an overview number of runs for the states numbers of generations stated above, for each of the specified material input data set. In total, a number of 34 simulations have been conducted.

Table 4: Runs per number of generation for each material dataset

Material Input Dataset	Number of Generations					
	100	150	200	250	500	1000
All Material	5	2	3	1	1	1
All Material*	4	-	3	-	-	-
Ceramic (non-technical)	3	-	-	-	-	-
Metal (non-ferrous)	4	-	4	-	-	-

The results of the simulations conducted over 100, 150, and 200 generations for each material dataset were consolidated. In the event that no non-violating solutions were identified, the saved parent solutions were utilised. The data were initially filtered, with the non-dominated parents from each generation with positive constraint scores, deemed 'feasible', selected. This method was applied to the nonferrous metals and nontechnical ceramics simulations, with the result that no non-violating solutions were yielded.

9.3 Operating environment

The results generated by the proposed model in the previous chapter were obtained within an operating environment of Windows 10 Home 64-bits with an Intel(R) Core(TM) i7-7700HQ CPU @ 2.80GHz processor and 16,0 GB random access memory. The Python Integrated Development Environment used for the model is PyCharm Community Edition 2024.1 x64, with Python version 3.12.

10 Results

The results of the optimisation model runs are presented. First, an overview of the distribution of objectives is discussed. Subsequently, the results for objectives are discussed. Finally, conclusions are drawn on the basis of the results.

10.1 Objective Distribution

The Pareto frontier distribution for all material runs is illustrated below, plotting the current poles for cost, CO_2 footprint, and embodied energy. The Pareto fronts, shaped by the results, highlight cost as a primary trade-off factor among the objectives. The frontiers for CO_2 footprint and embodied energy demonstrate the potential for minimisation without increasing costs. In particular, the distribution of embodied energy is highly clustered, whereas the distribution of CO_2 footprint is more widely dispersed.

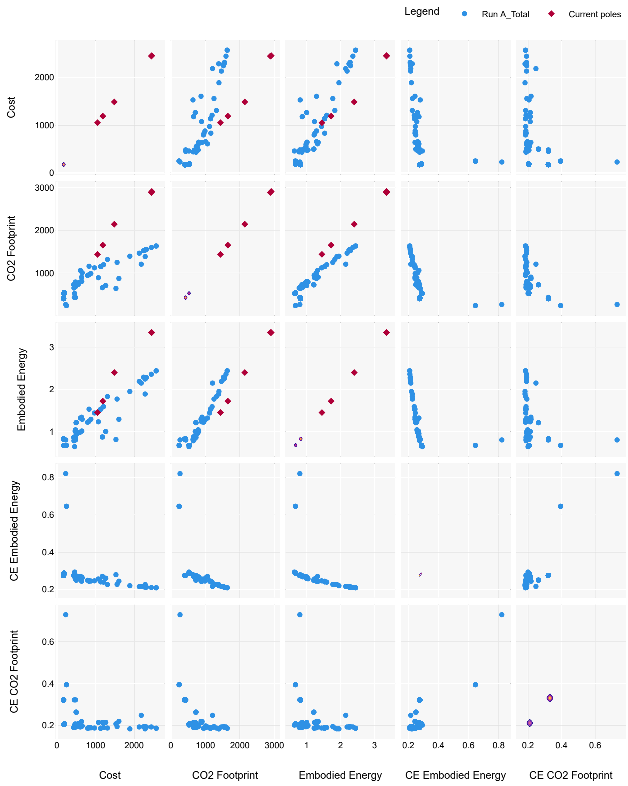


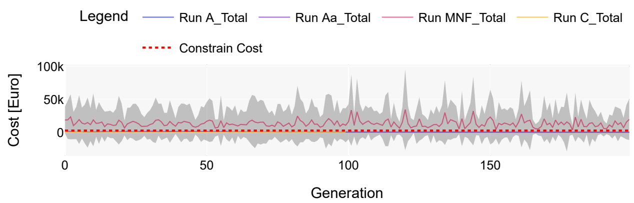
Figure 6: Scatter Matrix Representation of Objectives Distributions

The analysis of the principal material in the All Material set reveals that the T-beam is the primary pole shape, with ferrous metals representing the leading material family, and cast iron alloys being the most prevalent materials. The T-beam is favoured for its reduced cross-section, footprint, and embodied energy, while efficiently bearing high loads along its strong axis, which suits the main forces on the pole structure. In order to obtain a more comprehensive understanding of the data, additional datasets were examined. In the All Materials* set, the material family and materials remain consistent with the All Materials set, but the round tubular shape becomes predominant without the T-beam and UNP. In the case of the ceramic (non-technical) and metal (non-ferrous) datasets, high-performance concrete and cobalt-base super alloy are the dominant materials, respectively. The round tubular shape remains the favoured pole shape design.

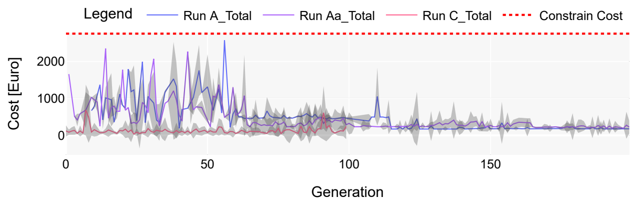
The results for the formulated objectives are detailed below, comparing different runs. Each material dataset's mean value per generation is shown in graphs with the standard deviation indicated by a grey fill.

10.2 Objective: Cost

Figure 7a illustrates that non-ferrous metal pole designs are considerably more expensive than other materials. Figure 7b demonstrates that ceramic (non-technical) rapidly reaches a lower cost compared to other materials, with all datasets aligning in cost after the 150th generation. Note that the term ”cost” in this context refers to material costs, whereas ”integrated constraint” refers to purchase cost. The figures reveal a potential for cost reduction, although it should be acknowledged that manufacturing and transportation costs, which are not included here, could significantly impact this potential. The reduction in material costs has minimal effect individually, but could be impactful at a network scale due to the volume of poles required.



(a) All Total Runs

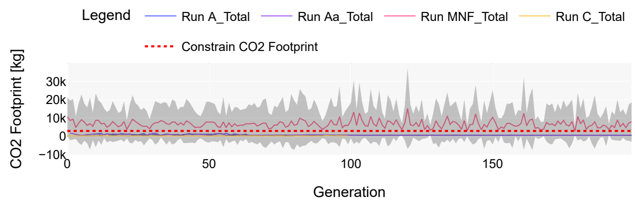


(b) All Materials and Ceramics (non-technical)

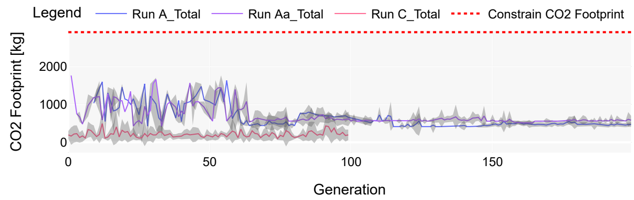
Figure 7: Evolution of Cost Objective

10.3 Objective: CO_2 Footprint

With regard to the objective of CO_2 footprint, it can be observed that a parallel phenomenon occurs with respect to cost. The metal (non-ferrous) dataset exhibits a similar performance in terms of cost, namely significantly lower performance compared to other material datasets. The emission value of CO_2 is significantly high for this material dataset compared to the other input datasets, violating the maximum constraint for all generations. A significant reduction in CO_2 footprint can be observed in all datasets of materials, as shown in Figure 8b. Both datasets are converging towards comparable emission values. The ceramic (non-technical) dataset performs even better, and these materials would allow further reduction of the footprint of a new pole design for the support structure. These results indicate the potency of ceramic materials, such as concrete, in reducing emission values. Nevertheless, the results of the all-material datasets indicate that this is also possible within the metal (ferrous) material set.



(a) All Total Runs

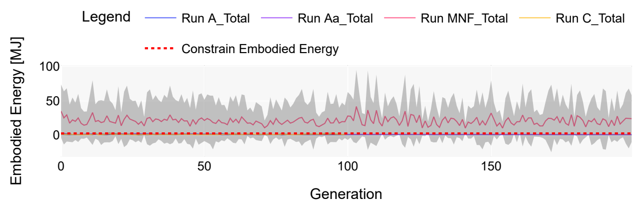


(b) All Materials and Ceramics (non-technical)

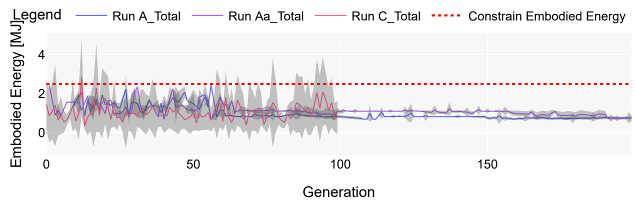
Figure 8: Evolution of CO_2 Footprint

10.4 Objective: Embodied Energy

Similar to previous objectives, non-ferrous metal design solutions exhibit significantly higher embodied energy, exceeding the maximum allowed values. **??** shows the results for other data sets, demonstrating no significant differences in embodied energy values, which tend to converge despite material differences. A gradual downward trend is observed for energy, while the cost and CO_2 values stabilise at minimal levels, indicating the potential to reduce the embodied energy in a manner analogous to CO_2.



(a) All Total Runs

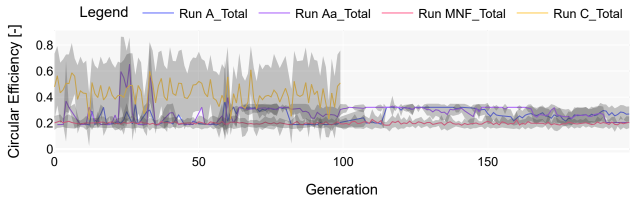


(b) All Materials and Ceramics (non-technical)

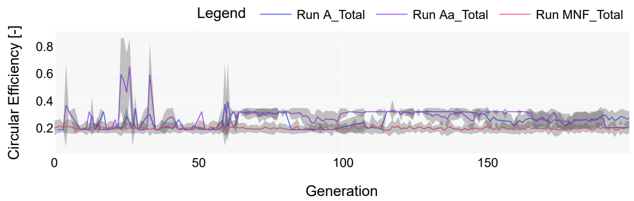
Figure 9: Evolution of Embodied Energy

10.5 Objective: Circular Efficiency

The minimal circular efficiency value indicates solutions with the highest potential for enhanced circular use. Figure 10a illustrates that non-technical ceramics perform the worst, while non-ferrous metals, previously the least effective, now exhibit the best circular efficiency for embodied energy. This suggests that the energy consumption associated with recycling these materials is likely to be less than that required for their production from raw materials. In contrast, the energy expenditure associated with recycling ceramics is likely to be greater than that required for their production from raw materials.



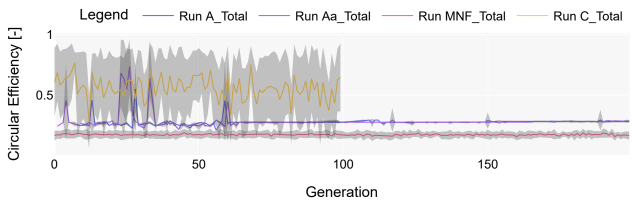
(a) All Total Runs



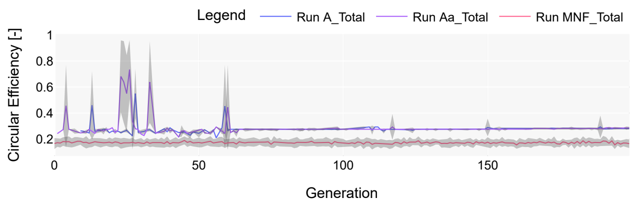
(b) All Materials and Metal (non ferrous)

Figure 10: Evolution of Circular Efficiency: Embodied Energy

The results of the circular efficiency analysis for the CO_2 footprint are comparable. The non-ferrous metals exhibit superior performance, as evidenced by the results presented in Figure 1. There is a clear distinction in the convergence goals, particularly with regard to the CO_2 footprint, with significantly improved effectiveness across all materials. Furthermore, non-ferrous metals consistently demonstrate superior performance compared to other datasets in terms of circular efficiency.



(a) All Total Runs



(b) All Materials and Metal (non ferrous)

Figure 11: Evolution of CO_2 Footprint

10.6 Deflection of Pole

The deflection results for various input data sets are shown below. As shown in Figure 12, all designs meet the deflection constraints at the top of the pole. Furthermore, these constraints are not the most restrictive as the designs have deflections well below the limits, demonstrating their stiffness.

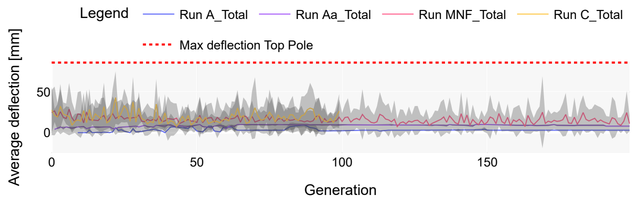
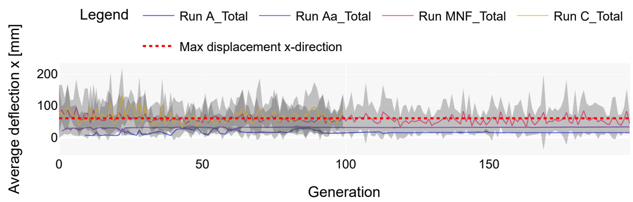
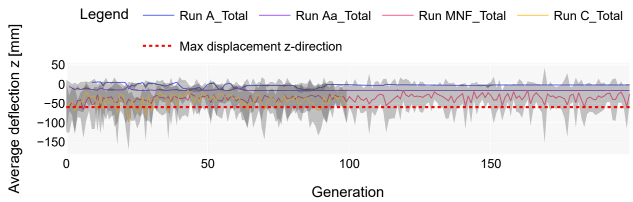


Figure 12: Evolution of Deflection at Pole Top in x-Direction

Figure 13 shows the deflection results for the contact wire. Both metal (non-ferrous) and ceramic (non-technical) designs struggle to meet the maximum deflection limits in x and z directions. However, designs using the all-material data sets meet these limits, with the all-material configuration showing the lowest deflection. This superior performance is due to the dominant T-beam pole shape in this dataset, which provides better bending resistance compared to tubular shapes. In addition, the all-material data set converges quickly.



(a) x-Direction



(b) z-Direction

Figure 13: Evolution of Contact Wire displacement

10.7 Conclusion

Analysis of material input data sets and support structure designs reveals the interplay between material properties, structural designs, and sustainability objectives. Predominantly, T-Beam and ferrous materials are prevalent in the All Materials dataset, whereas non-ferrous metals demonstrate high circular efficiency. This highlights the critical role of material selection in the improvement of sustainable design practices. The simulation results emphasise the necessity for a balanced approach in choosing materials and shapes to achieve both performance and environmental objectives. Challenges such as contact wire deflection and the evolving performance of materials require ongoing design evaluations and modifications. These simulations validate the efficacy of certain materials and designs in adhering to deflection limits and enhancing performance. Therefore, a dynamic and balanced strategy is crucial for progressing sustainable design in the face of shifting environmental and economic landscapes.

11 Discussion

Research started with reviewing the design process and stakeholders, to support determining the essential requirements. Extensive analysis of requirements and design specifications resulted in the finding of essential requirements for the design of OCLS support structures. These are a balance of safety and economic considerations. However, these are well defined via many regulations. They both allow some flexibility, due to the way one could interpate the importance of one of the aspects.

Similar, this can be seen in the need for policymakers and engineers to connect safety standards with cost efficiency. Improving the structural integrity while remaining profitable, which often turns the other way. Given these insights allow to better understand of regulatory frameworks and standards in the design process. As shown in the rail network, it is highly regulated, increasing it to implement new design in rail infrastructure projects throughout the Netherlands.

Given the aspect of sustainability, the commitment of Ducht Rail branch and all new regulations for government, shows an interesting playing field of ambitions versus practice. Certainly given the increasing importance of sustainability within projects and design. Where ProRail and the Dutch Rail branch are using environmental cost indicator. In a manner to indicate sustainability, the circularity principles are also of importance.

However, within most policies, the main focus is on the aspect of carbon footprint as the main indicator. What brings tension is a complex world of life cycle assessment. In the same case, it can be a bit concerning how certain emission can cancel each other out. On the other hand, the introduction of indicators allows stakeholders and other involved parties to take into account their impact on the environment. As stated stated before, we need each other in order to go transgress towards a more durable world. Thereby contributing to national and international policies

Implimenting all these different aspects to the design of the support structure licence confirms the potential of in multi-objective appoarch. This research showed that furtner that appears to be a relative simpele issuce can be increasingly more complex. Given the different factors, especially given the importance of eco-friendly materials and construction methods. As these might allow gain forword towards sustainable world. It should be notice that will result in making trade-offs in either cost or safety to move towards a sustainable future.

Furthermore, the call to re-evaluating current design requirements in light of sustainability might unavoidable. This is also a more social question, as we need to collectively agree to accept certain consequences that will follow from it. Despite our expectations regarding technology and environmental ambitions. At some point there will be friction. Therefore, creating dillema between how to accommodate innovations and emerging technologies versus econmical concerns and sustainability. This requires a collective approach among governments, rail branch, and wider to address these problems.

Similar can be seen in the results of the model. This eventually returns to the current cross section and the materials used for the support structure. So, potently is the current design most optimal design given all the aspects. This would lead to the acceptance of certain exceptions and polution. Despite our need to improve and try to find more innovative solutions as humans. This could lead in a worse case towards an political choice not to use overhead continuous line system, as it is on paper the most sustainable solution.

Taken together, this research showed that sustainability and circulation will play an important role within the rail infrastructure. Additionally, it showed that there is the possibility of consolidating these aspects in the current designs and requirements. However, in the design, environmental considerations, safety standards, and economic efficiency are included. The result would be an efficient and environmentally sustainable rail network. But this will require a flexible and collective approach towards a sustainable and circulair future.

12 Conclusion & Recommendations

12.1 Conclusions

This research concludes that the design of a supporting structure for an Overhead Contact Line System (OCLS) in the Netherlands must balance safety and cost, as detailed in section 4. Sustainability, a crucial aspect, is assessed mainly through life cycle assessment and circularity, as discussed in section 5. The design parameters, including material choice and structural dimensions, are constrained by safety and economic factors, and are critical in defining the sustainability and functionality of the support structure (section 10). To enhance sustainability, reducing CO2 emissions through optimized material selection and design is essential. The trade-off between cost and environmental impact is significant, suggesting that material innovations could lead to more sustainable designs without compromising safety or economic feasibility.

12.2 Recommendations

This research supports the need for further detailed studies on regulations and sustainability in the rail sector. It proposes designing sustainable support structures and suggests future research to refine and expand the developed model. Key areas include enhancing the rail sector's sustainability, comparative sustainability studies between the OCLS system and alternative train systems, and adopting circular design principles for support structures. Additionally, the integration of environmental cost indicators, the adoption of specific standards for material types, and the testing of parameter and variable ranges are recommended to enhance the model's effectiveness and sustainability. These efforts are crucial for advancing sustainable rail infrastructure development and understanding environmentally responsible transportation systems.

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A Fitness Function Configuration

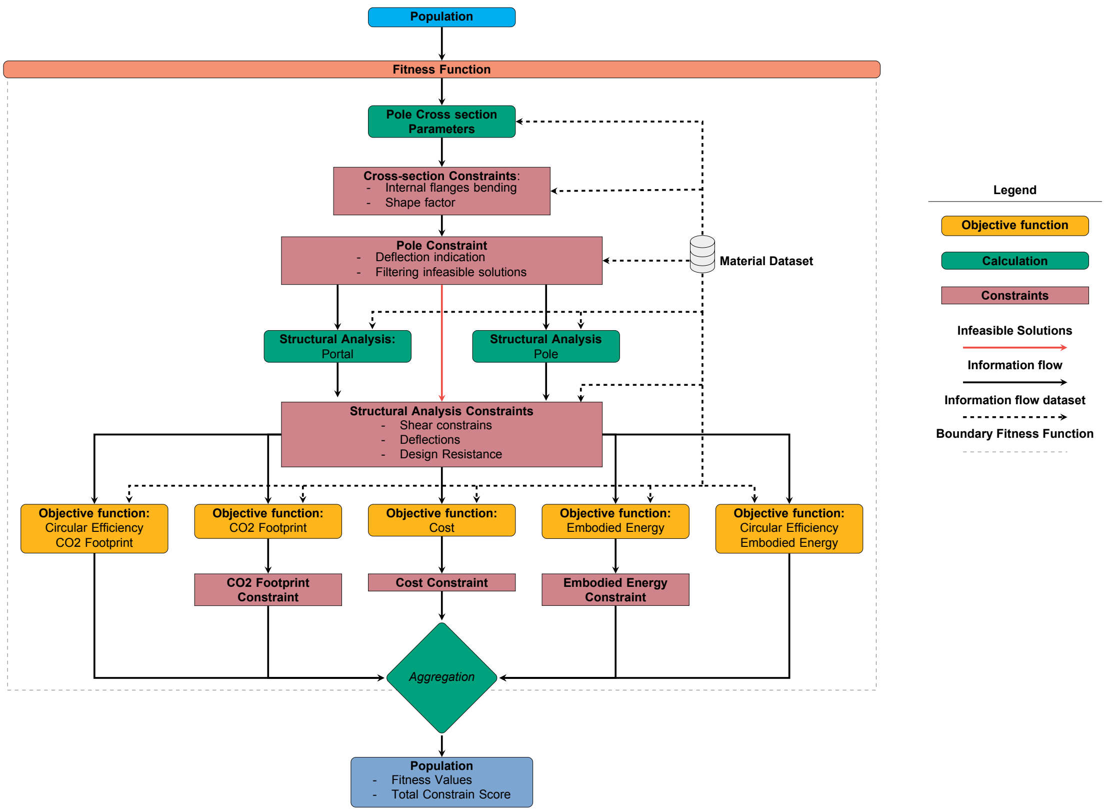


Figure 14: Overview of the fitness function used in the optimisation model

Appendix B

Search method used for literature review

In this appendix describes the used keyword based search method to find relevant and related literature on the topic of support structure for Overhead Contact Lines Systems. The keywords used during the search were formulated based on the general context of the topic and were adapted during search based on the keywords found in the founded literature. An overview of the used keywords used is given in Table B.1. During the search the following search engines were used to find the the academic literature: TU Delft Repository, Scopus and Google Scholar. While searching the following search fields were mainly used: title, abstract and keywords. In addition, a general internet search was carried out using the same keywords. This resulted in a wider range of sources. A number of interesting articles, books and reports were found, for example from government agencies and other institutes and organisations with an interest in the topic. An overview of the founded literature is given in Table B.2.

Table B.1: Overview of the used keywords

Used keywords for the literature review			
TU Delft Repository			
Rail	AND Infrastructure		
Railway	AND Infrastructure		
Catenary			
Catenary system			
ProRail			
Rail	AND Building		
Railway	AND Building		
Building process	AND Optimisation		
Operation management	AND Construction		
Operation management	AND Rail		
Scopus			
Catenary	AND Poles		
Railway	AND Poles		
Catenary	AND Poles	AND Sustainability	
Railway	AND Overhead	AND Structures	
Overhead	AND Line	AND Structure	AND Sustainability
Overhead	AND Line	AND System	AND Sustainability
Overhead	AND Line	AND System	AND Rail
Overhead	AND Line	AND Equipment	AND Rail
Railway	AND Overhead	AND Wiring	AND Structures

Used keywords for the literature review

Google Scholar				
Catenary				
Catenary	AND System			
Catenary	AND Poles			
Track	AND Maintenance			
Catenary	AND System	AND Infrastructure		
Overhead	AND Line	AND Structures		
Overhead	AND Contact	AND Line	AND System	
Overhead	AND Contact	AND Line	AND System	AND Structure

Table B.2: Overview of the reviewed literature

Structural Characteristics

Author	*Year*	*Topic*
Kiessling, Puschmann, Schmieder, *et al.*	2001	Overview
Given	2020	Overview
Keenor	2021	Overview
Hu and Chan	2022	Overview, Structural
Rechena, Infante, Sousa, *et al.*	2020	Standardisation, Structural
Boorse	2005	Design
Ngamkhanong, Kaewunruen, Calçada, *et al.*	2022	Structural
Matsuoka, Tokunaga, and Tsunemoto	2022	Structural
Ngamkhanong and Kaewunruen	2018	Structural
McSaveney	1987	Structural, Concrete
Zheltenkov, Li, Demina, *et al.*	2020	Structural, Concrete, Overview
Tsunemoto, Shimizu, Kudo, *et al.*	2017	Structural, Concrete
Zheltenkov, Li, Demina, *et al.*	2021	Structural, Concrete
Pennings	2014	Design, Construction

Maintenance management & monitoring and evaluations

Author	*Year*	*Topic*
Shang, Nogal, Wang, *et al.*	2021	Maintenance, Asset Management
Alkam and Lahmer	2018	Evaluation, Markov Estimator, Bayesian
Alkam, Pereira, and Lahmer	2020	Evaluation, Bayesian
Ikeda	2020	Maintenance, Asset Management, Digitisation
Budai, Huisman, and Dekker	2017	Maintenance, Model
Oudshoorn, Koppenberg, and Yorke□Smith	2021	Maintenance, Model
Hu and Chan	2019	Monitoring, Asset Management
Efanov, Sedykh, Osadchy, *et al.*	2017	Monitoring
Brahimi, Medjaher, Leouatni, *et al.*	2017	Monitoring
Hofler, Dambacher, Dimopoulos, *et al.*	2004	Monitoring
Alkam and Lahmer	2021	Monitoring
Na, Jung, and Park	2021	Detection, Life-cycle

Decision-making framework/system

Author	*Year*	*Topic*
Jamshidi	2019	KPI's, Single-Objective
Xu, Lai, and Huang	2021	Maintenance, Single-Objective
Bojda, Dziaduch, Nowakowski, *et al.*	2014	Maintenance, Single-Objective
Zoeteman	2001	Design, Evaluation, Life-Cycle, Single-Objective
Garcia, Gomez, Saa, *et al.*	2013	Design, Single-Objective
Berthold	2014	Design, Complexity, Single-Objective
Peralta, Bergmeir, Krone, *et al.*	2018	Maintenance, Multi-Objective, Pareto Based
Liu, Liu, Núñez, *et al.*	2018	Maintenance, Multi-Objective, Neural Networks
Chen, Zhang, Liu, *et al.*	2022	Maintenance, Multi-Objective, Particle Swarm
Stipanovic, Bukhsh, Reale, *et al.*	2021	Maintenance, Multi-Objective, Risk Based

Appendix C

Requirements analysis of support structure

In this appendix the founded requirements related to support structure are listed. In the sections below the results of each steps taken in the analysis of the requirements are stated. In the table below all the founded requirements that could be related to the support structure in the reviewed documents are listed. The requirements are sorted by the source document they originated from.

Table C.1: Overview of the identified potential requirements

Number	Requirement	Source
1.1	The functioning of the electrical or thermal energy-supply systems must not interfere with the environment beyond the specified limits.	Energy TSI
1.2	Operation of the energy-supply systems must not impair the safety either of rains or of persons (users, operating staff, track side dwellers and third parties)	Energy TSI
1.3	The electricity/thermal energy-supply systems used must; enable trains to achieve the specified performance levels, in the case of electricity energy-supply systems, be compatible with the collection devices fitted to the trains.	Energy TSI
2.1	The components used must withstand any normal or exceptional stresses that have been specified during their period in service.	General TSI
2.2	The rolling stock and energy-supply systems must be designed and manufactured in such a way as to be electromagnetically compatible with the installations, equipment and public or private networks with which they might interfere.	General TSI
2.3	The environmental impact of establishment and operation of the rail system must be assessed and taken into account at the design stage of the system in accordance with Union law.	General TSI
2.4	The materials used in the trains and infrastructures must prevent the emission of fumes or gases which are harmful and dangerous to the environment, particularly in the event of fire.	General TSI
2.5	Materials likely, by virtue of the way they are used, to constitute a health hazard to those having access to them must not be used in trains and railway infrastructures.	General TSI
2.6	Those materials must be selected, deployed and used in such a way as to restrict the emission of harmful and dangerous fumes or gases, particularly in the event of fire.	General TSI

Number	Requirement	Source
2.7	The design of fixed installations and rolling stock and the choice of the materials used must be aimed at limiting the generation, propagation and effects of fire and smoke in the event of a fire.	General TSI
2.8	The design and operation of the rail system must not lead to an inadmissible level of noise generated by it; in areas close to railway infrastructure, as defined in point (3) of Article 3 of Directive 2012/34/EU, and in the driver's cab.	General TSI
2.9	The design, construction or assembly, maintenance and monitoring of safety-critical components, and more particularly of the components involved in train movements, must be such as to guarantee safety at the level corresponding to the aims laid down for the network, including those for specific degraded situations.	General TSI
2.10	The safety repercussions of any accidental failures must be limited by appropriate means.	General TSI
2.11	The technical characteristics of the infrastructure and fixed installations must be compatible with each other and with those of the trains to be used on the rail system. This requirement includes the safe integration of the vehicle's subsystem with the infrastructure.	General TSI
2.12	If compliance with these characteristics proves difficult on certain sections of the network, temporary solutions, which ensure compatibility in the future, may be implemented.	General TSI
3.1	Appropriate provisions must be laid down to take account of the particular safety conditions in very long tunnels and viaducts.	Infrastructure TSI
3.2	Appropriate steps must be taken to prevent access to, or undesirable intrusions into, installations.	Infrastructure TSI
3.3	Infrastructure to which the public has access must be designed and made in such a way as to limit any human safety hazards (stability, fire, access, evacuation, platforms, etc.).	Infrastructure TSI
3.4	Steps must be taken to limit the dangers to which persons are exposed, particularly when trains pass through stations.	Infrastructure TSI
4.1	The support for the support wire must be able to be 50 mm horizontal be adjusted in both direction.	IVS00026
4.2	Guying shall be constructed according the specified dimension, contact wire at height of 6,10 m above the track and support wire at height of 8,30m above the track in case of B1 system.	IVS00026
4.3	The height of the track (BS) determines the height on which the beam or side-support should mounted, given specified system height, contact wire height or support wire height.	IVS00026
4.4	The support structure may be displaced within the tolerances specified in IVS00026	IVS00026
5.1	The support structure shall also be designed, constructed and maintained in such a way that due regard is given to safety of the public, durability, robustness, maintainability and environmental considerations.	NEN-EN 50119
5.2	The support structure will perform its purpose under a defined set of conditions with acceptable levels of reliability and in an economic manner.	NEN-EN 50119
5.3	The support structure will not be liable to cause human injuries or loss of life during construction, operation and maintenance.	NEN-EN 50119
5.4	The support structure will not be liable to progressive collapse if a failure is triggered in a defined component.	NEN-EN 50119
6.1	The traction energy supply system shall comply to the Dutch legal requirements in force at the date the system is designed.	OVS00012-2
6.2	The design of the traction energy supply system shall be designed in such a manner that work on the system can be conducted according the therefore applicable regulations.	OVS00012-2
6.3	The traction energy supply system shall be designed for a technical lifetime of 80 years.	OVS00012-2

Number	Requirement	Source
7.1	The products making up the whole overhead contact line system, shall be matched to each other in such a way that the performance is guaranteed, with regard to integration, short-circuit resistance, electrical and mechanical load capacity.	OVS00024-2
8.1	The support structure must have a horizontal adjustable by +/- 100 mm.	OVS00024-3
8.2	The support structure should have vertical adjustable by at least +/- 300 mm in case of independent poles and +/- 100 mm in the case of columns.	OVS00024-3
8.3	The products making up the whole overhead contact line system, shall be matched to each other in such a way that the performance is guaranteed, with regard to integration, short-circuit resistance, electrical and mechanical load capacity.	OVS00024-3
8.4	When projecting and dimension the support structure, pressure waves caused by rail vehicles shall be taken into account.	OVS00024-3
8.5	The support structure must founded so that the vertical settlement does not exceed 100 mm in time period of 10 years.	OVS00024-3
8.6	The support structure must founded so that the skewness after 10 years at wire height does not exceed 50 mm for freestanding poles and 25 mm for gantries.	OVS00024-3
8.7	The overhead contact line system must comply in principal with the following European standards, if not otherwise specified in the ProRail regulations; NEN-EN 50119, NEN-EN 50637 and NEN-EN 50124.	OVS00024-3
8.8	The overhead contact line system must comply with the European standards.	OVS00024-3
8.9	The overhead contact line system must comply with the legal requirements.	OVS00024-3
8.10	The overhead contact line system, part of Trans European Network, must comply with the Energy TSI.	OVS00024-3
8.11	The support structure shall comply to the specified Eurocodes.	OVS00024-3
8.12	Regarding the infrastructure compatibility shall comply with the Dutch Ministerial Railway Vehicle Inspection Regulations(MRKS).	OVS00024-3
8.13	Mechanical maintenance on the track shall not be hindered by the supporting structure.	OVS00024-3
8.14	The support structure should not conflict with the specified gauges and 'red' measuring area. Thereby taking into account construction- and maintenance margins.	OVS00024-3
8.15	The performance of the catenary system shall be guaranteed throughout the entire lifetime of the contact wire.	OVS00024-3
8.16	The performance of the overhead contact line system shall be guaranteed throughout the entire lifetime of the system, including maintenance and renewals.	OVS00024-3
8.17	Regarding to the electrical safety, compliance with EN-50122-1 is required.	OVS00024-3
8.18	Structures part of the the overhead contact line system shall be dimensioned for a lifetime of 50 years.	OVS00024-3
8.19	Technical lifetime of the support structure shall at least 40 years with limited maintenance and minimal 80 years with maintenance.	OVS00024-3
8.20	In the case of open track situation the surrounding conditions of location A and B, as specified in RLN00003, shall be taken into account.	OVS00024-3
8.21	In the case of tunnel situation the surrounding conditions of location I and J, as specified in RLN00003, shall be taken into account.	OVS00024-3
8.22	Overhead contact line system shall operate at the wind conditions of area II and III, as specified in RLN00003, up to a height of 20 meters.	OVS00024-3
8.23	Overhead contact line system and sub-systems shall operate at ambient temperatures in range of -20 Celsius and + 40 Celsius	OVS00024-3
8.24	Overhead contact line system and sub-systems shall operate in tunnels at ambient temperatures in range of -5 Celsius and + 25 Celsius	OVS00024-3
8.25	The overhead contact line system shall comply with the requirements under the climatic conditions in the Netherlands, as they have occurred over the past 20 years.	OVS00024-3

Number	Requirement	Source
8.26	Damage to structures or overhead contact lines due to electrical arcing should be prevented.	OVS00024-3
8.27	Defects due to over-voltage from lightning or switching action on the overhead contact line system and sub-systems should be prevented.	OVS00024-3
8.28	The publicly accessible areas should be free of objects that could lead to human injuries in case of failure of the conductor.	OVS00024-3
8.29	The return- and earth circuit of the overhead contact line system should not be conflicting with the train control- and train safety systems.	OVS00024-3
8.30	The use of the following elements should be avoided; Cadmium (Cd), Chromium (Cr), Lead-Nickel alloy (Pb.Ni) and Mercury (Hg).	OVS00024-3
8.31	Measure should be taken to prevent galvanic corrosion or, if unavoidable, to minimise the galvanic corrosion.	OVS00024-3
8.32	Elements part of the overhead contact line system should not conflict with the specified gauges unless they are functional intended to do so.	OVS00024-3
8.33	The publicly accessible areas should be free of objects that could lead to human injuries or that would seriously impede the flow of the public.	OVS00024-3
8.34	The support structure should be designed in such a way that in the case of derailment of a train would cause minimal damage with minimal functional recovery time.	OVS00024-3
8.35	In case of failure of the conductor in publicly accessible areas the risk of human injury should be minimised.	OVS00024-3
8.36	The overhead contact line system should minimise the risk of injury to persons.	OVS00024-3
8.37	The overhead contact line system should be designed such that the consequences of a malfunction of system is minimised, in terms of affected area as duration.	OVS00024-3
8.38	The overhead contact line system should fit within the boundaries of the whole traction energy supply system.	OVS00024-3
8.39	The overhead contact line system should fit within the whole rail infra system.	OVS00024-3
8.40	The technical lifetime of (composite) components of the overhead contact line system should be logical fit in the chosen life-cycle path	OVS00024-3
9.1	Components with a horizontal and/or vertical adjustment requirement shall be adjustable to both sides of 100 mm.	OVS00024-4
9.2	The support structure shall be dimensioned according the RLN0009.	OVS00024-4
9.3	Regarding the electrical safety the RLN00008 shall be applied.	OVS00024-4
9.4	The support structure shall be connected with electrical return systems according to OVS00085 in case of 1500V or to OVS00053 in the case of 25kV.	OVS00024-4
9.5	The design chose of the support structure should based on OVS00024-8 and its underlying parts.	OVS00024-4
9.6	Determining the location of poles on a platform the obstacle free zone shall be taken into account according to OVS00067	OVS00024-4
9.7	In determination of the location of the support structure and objects attached to it one must take into account the ability to safely inspect, operate and maintain these objects, without that the track should be taken out of service.	OVS00024-4
9.8	The field length difference between two consecutive fields shall be less or equal than maximum of 15 metres.	OVS00024-4
9.9	The maximal field length of contact wire given the maximal wind deflection of contact wire shall be determined according to RLN0009.	OVS00024-4

Number	Requirement	Source
9.10	The nominal field length difference between two consecutive fields shall be less or equal than maximum of 5 metres.	OVS00024-4
9.11	Poles part of support structure shall not be placed on bike- or inspections paths.	OVS00024-4
9.12	Movable guards should be used as standard, where wheel guards should be applied as movable guard.	OVS00024-4
9.13	In determination of the location of support structures existing and any new cable bed and pipes should be taken into account.	OVS00024-4
9.14	In determination of the location of support structures, guying and conductors signalling objects along the track should be taken into account, in regards to the safe working distance, isolation distance and visibility of signals for the train driver.	OVS00024-4
9.15	Contact wire section should be maximised, unless with regard to the availability otherwise is required.	OVS00024-4
9.16	The support structure located at platforms should be avoided within reasonable financial boundaries.	OVS00024-4
9.17	The location of the foundation of the support structure the specified gauges should be taken in account as the required space needed for mechanised track maintenance.	OVS00024-4
9.18	In regards to the public safety wheel guards and braces should be avoided on platforms.	OVS00024-4
9.19	In the chose and placing of the support structure the visual aspect of the support structures should be taken into account.	OVS00024-4
10.1	The minimal contact wire height is in the case 1500 V is 5,10 m and in the case of 25kV is 5,20m.	OVS00024-5
10.2	The nominal contact wire height should be 5,50 metres at an ambient temperature of 10 Celsius.	OVS00024-5
10.3	The ridden contact wire should not be larger 5,75 metre.	OVS00024-5
10.4	The field length shall not be larger than 60 metres.	OVS00024-5
10.5	The nominal distance between the centre of pole of support structure and centre of the track should be equal to 2850 mm.	OVS00024-5
10.6	The nominal field length should not be larger than 60 metres.	OVS00024-5
10.7	The track distance/width for existing track is 3,60m / 4,00m, upgrade track: 4,00m and new track 4,50 m	OVS00024-5
10.8	The distance between the centre of track and front-side towards the track should be minimal 2500 mm curve radius larger than 250m. In the case of curve radius smaller than 250 metre OVS00026 should be applied.	OVS00024-5
11.1	A minimum clearance of 300 mm should be kept above the connection with a beam or arm for maintenance purpose.	OVS00024-8.2
11.2	Poles located on structures that may not transmit a moment should be constructed with a articulated pole base according the SPC0008-005.	OVS00024-8.2
11.3	The total length of the pole depends on the height of the beam or support arm for the contact wire.	OVS00024-8.2
11.4	At least one of the poles of a portal support structure shall be connected with the return circuit.	OVS00024-8.2
11.5	Each detached pole shall be connected to the return via a breakdown safety via pole-rail connection.	OVS00024-8.2
11.6	If a standard length of pole is not sufficient, the required length should be determined by increasing the length by increments of 400 mm from a length of 8600 mm	OVS00024-8.2
12.1	A support arm placed on a beam or pole shall be adjustable in vertical direction of minimal +/- 300mm.	OVS00024-8.3
12.2	A support arm which has an separable connection with a pole from track shall be adjustable vertical direction +/- 0.10 metres minimal.	OVS00024-8.3
12.3	A tubular beam below a support wire shall not be applied by a track speed above 100 km/h.	OVS00024-8.3
12.4	The beam should comply with boundaries for the loads, strength and deformation as specified in the RLN0009	OVS00024-8.3

Number	Requirement	Source
12.5	In case skewness larger than the maximum skewness is expected, the connection between the pole and beam should be hinged.	OVS00024-8.3
12.6	Track distances larger of equal than 7,70 metre should be spanned by a beam.	OVS00024-8.3
12.7	When a beam is applied, as many tracks as possible should be spanned, unless an additional pole is needed for guying or a switch.	OVS00024-8.3
12.8	On a track section a homogeneous design of support structures should be applied.	OVS00024-8.3
12.9	The applied beam type should be determined by the loads occurring on the support structure.	OVS00024-8.3
12.10	RHS-beam should be applied in the case requirements are specified regarding the design of the support structure, for example in a station environment.	OVS00024-8.3
13.1	No single object may be placed within the specified gauges extend by ”red measuring area”, thereby taking into account tolerances related to object.	OVS00026
13.2	PVR-NL gauge may only be applied on track sections, where it all ready is applied and PVR-GC can’t be applied.	OVS00026
13.3	PVR-GC gauge shall be applied in principle in the specified situations, including the ”red measuring area”.	OVS00026
14.1	The Traction Energy Supply (TEV) system and its components shall be designed so that human safety problems related to stepping and contact stresses will be eliminated. will not occur. This requirement applies to a fully intact return and earthing system and earthing system, but should also apply in the event of a break in a single return conductor.	OVS00050-2
14.2	The Traction Energy Supply (TEV) system shall be designed in such a way that direct contact hazard to personnel, passengers or third parties is prevented.	OVS00050-2
14.3	The isolation distances between the Traction Energy Supply (TEV) system and the PVR gauge must be at least 270 mm (static) and 150 mm (dynamic) in accordance with NEN-EN50119.	OVS00050-2
14.4	The 25 kV Traction Energy Supply (TEV) system and its components shall be designed and constructed so that problems of electromagnetic interference in general.	OVS00050-2
14.5	The Traction Energy Supply (TEV) system shall comply with European standards relating to interoperability with equipment to be applied.	OVS00050-2
14.6	The Traction Energy Supply (TEV) system system shall withstand contamination from the track system itself (copper, iron and carbon emissions) or precipitation of sand, salt, coal dust from the environment (if applicable).	OVS00050-2
14.7	The Traction Energy Supply (TEV) system system must meet the statutory noise standards.	OVS00050-2
14.8	System components of the Traction Energy Supply (TEV) system system close to the structure gauge (PVR) shall, at least for at least for two-track sections, be maintainable per track without restriction in the operation of the adjacent track. In the case of more than two parallel tracks an Life Cycle M consideration should be made.	OVS00050-2

Number	Requirement	Source
14.9	The Traction Energy Supply (TEV) system system has a differentiated minimum lifetime. For the support structure a lifetime of 80 years is specified.	OVS00050-2
14.10	The Traction Energy Supply (TEV) system system shall function fully under the prevailing weather conditions in the Netherlands (precipitation, frost, dew).	OVS00050-2
14.11	The Traction Energy Supply (TEV) system system shall be resistant to vibrations caused by the system itself and by train traffic.	OVS00050-2
14.12	The Traction Energy Supply (TEV) system system should be sufficiently protected against the effects of lightning strikes.	OVS00050-2
14.13	Placement of Traction Energy Supply (TEV) system installations near the profile of free space should preferably such that the performance of work does not require a workplace protection class or decommissioning is required.	OVS00050-2
14.14	The anticipated unavailability of the Traction Energy Supply(TEV) system required for maintenance and inspection should be less than 0.04292, assuming a double-track AT track section of up to 42 km.	OVS00050-2
14.15	The Mean Time Between Failure (MTBF) of Traction Energy Supply system should be at least 2621 hours, assuming a double-track AT track section of up to 42 km.	OVS00050-2
14.16	The technical endogenous availability of the Traction Energy Supply (TEV) system for train service should be at least 0.9999271, assuming a double-track AT section of maximum 42 km.	OVS00050-2
15.1	With regard to the vibrations caused by the Traction Energy Supply (TEV) system, it shall comply with the requirements set out in directive RLN00003.	OVS00050-3
15.2	The Traction Energy Supply (TEV) system shall be designed to meet the interoperability requirements in the Energy TSI and the applicable requirements in NEN-EN50388 and NEN-EN50367 for category lines type II and III.	OVS00050-3
15.3	The Traction Energy Supply (TEV) system must meet the statutory noise standards.	OVS00050-3
15.4	The isolation distances between the Traction Energy Supply (TEV) system and the PVR gauge must be at least 270 mm (static) and 150 mm (dynamic) in accordance with NEN-EN50119.	OVS00050-3
15.5	The cantenary system at each main track should have an support structure that is not mechanically connected with the surrounding tracks.	OVS00050-3
15.6	Replacement of components should not be of influence on the lifetime of adjacent components.	OVS00050-3
15.7	The Traction Energy Supply (TEV) system should function fully at the prevailing weather conditions in the Netherlands, in accordance with the requirements set out in directive RLN00003.	OVS00050-3
16.1	The distance between the centre of track and centre of the pole of a support structure should be in principle 2,85 metre.	OVS00056-4.2
16.2	The distance between the centre of track and front side towards the track should be minimal 2500 mm curve radius larger than 250m. In the case of cruve radius smaller than 250 metre OVS00026 should be applied.	OVS00056-4.2
16.3	A reservation of 1 metre should be made in cross-section of a track at the location of a pole for the support structure.	OVS00056-4.2
17.1	The support structure shall be calculated following the methods specified in NEN-EN 50119 to ensure the constructive safety of the structure.	RLN00009
17.2	The support structure shall not exceed the specified ultimate and serviceability limit states during its lifetime.	RLN00009
17.3	The horizontal displacement of the top of a pole in all directions due to permanent loads shall be less than 1% of the total length of a pole.	RLN00009
17.4	The horizontal and vertical displacement of support structure perpendicular to the track shall not lead to exceeding the allowed displacement of the contact wire.	RLN00009
17.5	The level of structural safety shall comply with the required level according the Dutch building regulations (Bouwbesluit).	RLN00009

Appendix D

NSGA-II Functions

In this Appendix the pseudocode can be found of used main algorithm; NSGA-II. For the algorithm, the code for the non-dominated sorting and crowding distance is provided as further background information.

D.1 Pseudocode of Non-Dominated Sorting

Function: Non-Dominated Sorting(R_t)

```
foreach individual $ind_i$ in $R_t$ do
    $S_i \leftarrow \emptyset$ ;
    *Set of solutions dominated by $ind_i$
    $n_i \leftarrow 0$;
    *Number of solutions dominating $ind_i$
    foreach individual $ind_j$ in $R_t$ do
        if $ind_i$ dominates $ind_j$ then
            Add $ind_j$ to $S_i$;
        end
        else if $ind_j$ dominates $ind_i$ then
            Increment $n_i$;
        end
    end
    if $n_i = 0$ then
        Mark $ind_i$ as a member of the first non-dominated frontier ($F_1$);
    end
end
$PF \leftarrow F_1$;
*Initialise list of the Pareto frontiers
$i \leftarrow 1$;
while $PF_i \neq \emptyset$ do
    $f \leftarrow \emptyset$;
    *Where set $f$ contains solutions of frontier $F_i$
    foreach individual $ind_p$ in $F_i$ do
        foreach individual $ind_q$ in $S_p$ do
            Decrement domination count $n_q$ of $ind_q$ by 1;
            if $n_q = 0$ then
                Mark $ind_q$ as a member of the next non-dominated frontier ($F_{i+1}$);
                Add $ind_q$ to $PF$;
            end
        end
    end
    $i \leftarrow i + 1$;
    Add $f$ to $PF$ as the next front;
end
```

D.2 Pseudocode of Crowding Distance Assignment

Function: Crowding Distance Assignment(F_i)

```
foreach front F_i do
    foreach individual ind in F_i do
        ind.crowding Distance ← 0;
    end
    for m ← 1 to number of objectives do
        Sort individuals in F_i based on objective m;
        F_i[1].crowding Distance ← ∞;
        F_i[|F_i|].crowding Distance ← ∞;
        for j ← 2 to |F_i| − 1 do
            F_i[j].crowding Distance ← F_i[j].crowding Distance + (F_i[j + 1].objective[m] -
              F_i[j − 1].objective[m]);
        end
    end
end
```

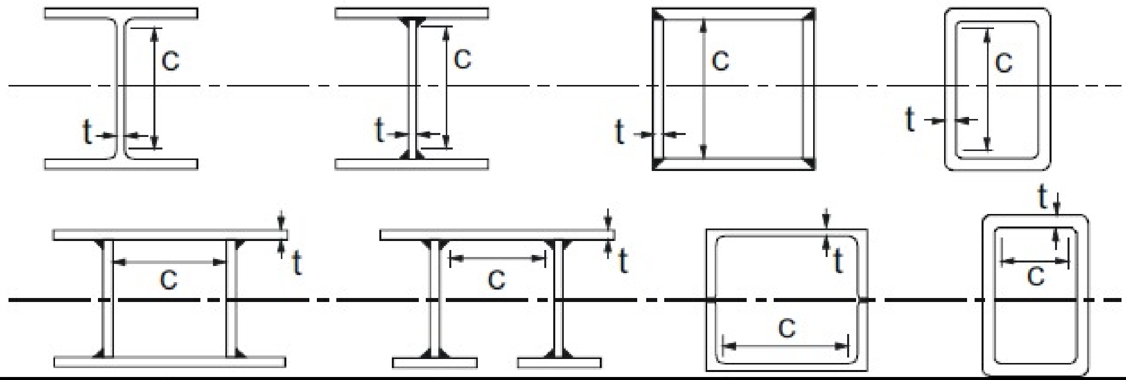
Appendix E

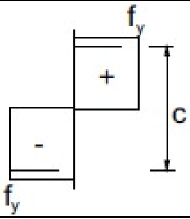
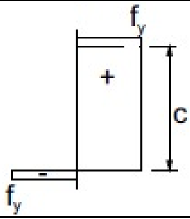
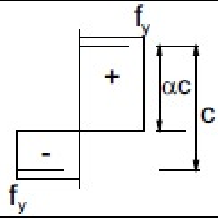
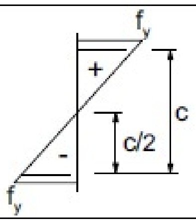
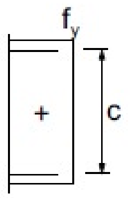
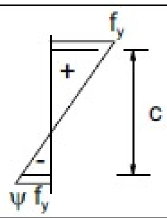
Constraint: Ratio of width-to-thickness of Shape Design - Formulas

The formulas employed for the constraint on the ratio of width-to-thickness in Shape Design, subsection 6.4.5, are illustrated in the following figures. The formulas are taken from Table 5.2 of the standard NEN-EN 1993-1-1[83]. The used parameters in figures are stated below:

- ϵ, Yield Strength reference factor to Steel S235
- f_y, Yield strength
- c, Height or width of the flange/internal part
- t, Thickness of material
- d, Diameter of tubular section

Internal compression parts



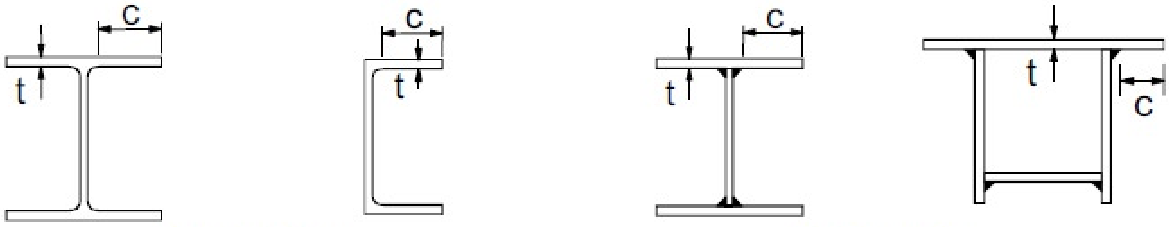
Class	Part subject to bending	Part subject to compression	Part subject to bending and compression
Stress distribution in parts (compression positive)			
1	$c/t \le 72\varepsilon$	$c/t \le 33\varepsilon$	when $\alpha > 0{,}5$: $c/t \le \frac{396\varepsilon}{13\alpha - 1}$ when $\alpha \le 0{,}5$: $c/t \le \frac{36\varepsilon}{\alpha}$
2	$c/t \le 83\varepsilon$	$c/t \le 38\varepsilon$	when $\alpha > 0{,}5$: $c/t \le \frac{456\varepsilon}{13\alpha - 1}$ when $\alpha \le 0{,}5$: $c/t \le \frac{41{,}5\varepsilon}{\alpha}$
Stress distribution in parts (compression positive)			
3	$c/t \le 124\varepsilon$	$c/t \le 42\varepsilon$	when $\psi > -1$: $c/t \le \frac{42\varepsilon}{0{,}67 + 0{,}33\psi}$ when $\psi \le -1^{*)}$: $c/t \le 62\varepsilon(1-\psi)\sqrt{(-\psi)}$

$\varepsilon = \sqrt{235/f_y}$	f_y	235	275	355	420	460
	ε	1,00	0,92	0,81	0,75	0,71

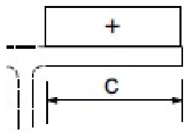
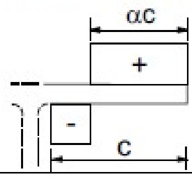
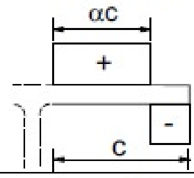
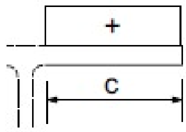
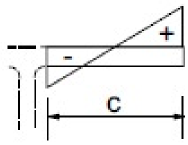
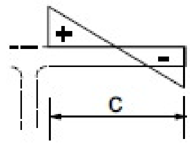
*) $\psi \le -1$ applies where either the compression stress $\sigma \le f_y$ or the tensile strain $\varepsilon_y > f_y/E$

Figure E.1: Maximum Width-To-Thickness Ratios for Internal Compression Parts[83]

Outstand flanges



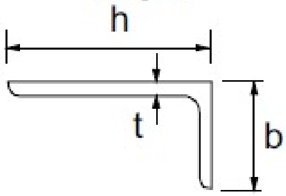
Rolled sections   Welded sections

Class	Part subject to compression	Part subject to bending and compression: Tip in compression	Part subject to bending and compression: Tip in tension
Stress distribution in parts (compression positive)			
1	$c/t \le 9\varepsilon$	$c/t \le \frac{9\varepsilon}{\alpha}$	$c/t \le \frac{9\varepsilon}{\alpha\sqrt{\alpha}}$
2	$c/t \le 10\varepsilon$	$c/t \le \frac{10\varepsilon}{\alpha}$	$c/t \le \frac{10\varepsilon}{\alpha\sqrt{\alpha}}$
Stress distribution in parts (compression positive)			
3	$c/t \le 14\varepsilon$	$c/t \le 21\varepsilon\sqrt{k_\sigma}$ For k_σ see EN 1993-1-5	

$\varepsilon = \sqrt{235/f_y}$	f_y	235	275	355	420	460
	ε	1,00	0,92	0,81	0,75	0,71

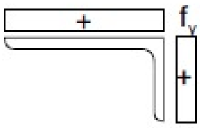
Figure E.2: Maximum Width-To-Thickness Ratios for Outstand Flanges[83]

Angles

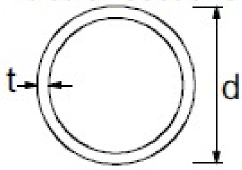


Refer also to "Outstand flanges" (see sheet 2 of 3)

Does not apply to angles in continuous contact with other components

Class	Section in compression
Stress distribution across section (compression positive)	
3	$h/t \leq 15\varepsilon : \dfrac{b+h}{2t} \leq 11{,}5\varepsilon$

Tubular sections



Class	Section in bending and/or compression
1	$d/t \leq 50\varepsilon^2$
2	$d/t \leq 70\varepsilon^2$
3	$d/t \leq 90\varepsilon^2$ NOTE For $d/t > 90\varepsilon^2$ see EN 1993-1-6.

$\varepsilon = \sqrt{235/f_y}$	f_y	235	275	355	420	460
	ε	1,00	0,92	0,81	0,75	0,71
	ε^2	1,00	0,85	0,66	0,56	0,51

Figure E.3: Maximum Width-To-Thickness Ratios for Angles and Tubular Sections[83]

Appendix F

Model Runtime Data

The All materials* are modified runs without the t-beam and UNP-beam pole design shape, as gene during the run.

Table F.1: Overview of Runs - Part 1

Run	Material Family	Number of Generations	Total Duration	Average duration per generation
1	All Materials	100	4683.3	46.8
2	All Materials	100	4741.1	47.4
3	All Materials	100	4832.9	48.3
4	All Materials	100	4646.5	46.5
5	All Materials	100	4740.5	47.4
6	All Materials	150	7333.4	48.9
7	All Materials	150	8955.2	59.7
8	All Materials	200	13828.1	69.1
9	All Materials	200	9506.6	47.5
10	All Materials	200	9279.6	46.4
11	All Materials	200	9372.6	46.9
12	All Materials	500	23664	47.3
13	All Materials	1000	46962.2	47
14	All Materials*	100	4705.7	47.1
15	All Materials*	100	4822.3	48.2
16	All Materials*	100	4757.4	47.6
17	All Materials*	100	4979.8	49.8
18	All Materials*	200	9588.1	47.9
19	All Materials*	200	10415.3	52.1

Table F.2: Overview of Runs - Part 2

Run	Material Family	Number of Generations	Total Duration	Average duration per generation
20	Metal (ferrous)	100	12756.9	127.6
21	Metal (ferrous)	100	4946.9	49.5
22	Metal (ferrous)	200	10099.9	50.5
23	Metal (ferrous)	500	24572.5	49.1
24	Ceramic (non-technical)	100	4664.8	46.6
25	Ceramic (non-technical)	100	4527.8	45.3
26	Ceramic (non-technical)	100	4331.8	43.3
27	Metal (non-ferrous)	100	4793.23	47.93
28	Metal (non-ferrous)	100	4770.47	47.70
29	Metal (non-ferrous)	100	4459.42	44.59
30	Metal (non-ferrous)	100	4763.05	47.63
31	Metal (non-ferrous)	200	9736.05	48.68
32	Metal (non-ferrous)	200	9544.62	47.72
33	Metal (non-ferrous)	200	9134.97	45.67
34	Metal (non-ferrous)	200	9471.87	47.36

Appendix G

Environmental Data: Current H Beam Poles and Validation Results

In this Appendix, the values used for the validation of the environmental data are presented. The environmental data for the reference poles is taken from the LCA Reportage for OCLS in the NMD[77]. The LCA is conducted in cooperation with ProRail and is the base LCA that should be used for environmental calculations. The environmental data used for the model are taken from the Granta Edupack 2023 R2, Level 3 Materials dataset[84].

In the environmental data from the NMD, the poles reviewed in the LCA are assumed to be made from unalloyed steel with a zinc coating. The specific description is: *0233-fab & Staal. staalplaat. verzinkt (o.b.v. 98.6% Steel. unalloyed GLO| market for | Cut-off. U + Sheet rolling; 0.06 m2 Zinc coat. coils)*. For the validation calculation, it is assumed that the pole is made of steel S235J. An overview of the environmental data for the S235J is given in Table G.1.

The data of environmental data from NMD for different indicators of impact categories used are listed below. For the validation of CO_2 footprint the indicators climate change and global warming potential are used. For Embodied Energy the following indicators have been used; 'energy, primary, renewable', 'energy, primary, nonrenewable', and 'resource use, fossils'.

Acronyms for indicators used in validation tables:

- Global warming potential - GWP
- Climate change - CC
- Energy, primary, renewable - EP-Ren
- Energy, primary, non-renewable - EP-NRen
- Resource use, fossils - RU-Fos

Environmental Data: Steel S235J - Granta Edupack R2 2023

Table G.1: Overview of the environmental data of Steel S235J

S235J	**Virgin**	**Recycling**	**Typical**
CO2 footprint [kg CO_2 eq. / kg]	3.13	0.59	1.85
Embodied Energy [MJ / kg]	27.3	7.51	17.5
Recycle Factor [-]	54.6		

G.1 Reference Poles Specification

First, the reference poles specifications are presented, including the environmental data from the LCA conducted for NMD. The amount of material used in the specified life cycle phases is presented. The environmental data from NMD for different indicators are listed below. At the end of each table the values for the whole life cycle of the H beam are given in the row 'Total'.

Table G.2: Overview of H-beam Structural and Environmental Data

Type	**HEA 220**	**HEA 240**	**HEB 240**	**HEB 300**	**HEB 300**
ProRail Type	HE-005	HE-006	HE-007	HE-123	HE-008
Baseplate	3	3	3	3	4
H [mm]	210	230	240	300	300
W [mm]	220	240	240	300	300
T_w [mm]	7	7.5	10	11	11
T_f [mm]	11	12	17	19	19
I_x[mm^4]	$51.84 \cdot 10^6$	$73.97 \cdot 10^6$	$108.93 \cdot 10^6$	$241.87 \cdot 10^6$	$241.87 \cdot 10^6$
I_z [mm4]	$19.53 \cdot 10^6$	$27.66 \cdot 10^6$	$39.19 \cdot 10^6$	$85.53 \cdot 10^6$	$85.53 \cdot 10^6$
A [mm^2]	6156	7305	10220	14282	14282
Cost [€]	1050	1188	1485	2445	2455
CO2 Footprint [kg CO_2 eq.]	1436.2	1651.2	2141.4	2881	2906.8
Embodied Energy [MJ]	1.45	1.72	2.4	3.35	3.35

Table G.3: Assumed Raw Material Use by Life Cycle Phase in NMD

Material used [kg]

	H220	**H240A**	**HEB240**	**HEB300**	**HEB3004**	**Average**	**Median**	**Std**
C	0.615	0.715	0.893	1.293	1.293	0.9618	0.893	0.285
A1	61.5	71.5	94.8	129.3	129.3	97.28	94.8	28.290
A3	61.5	71.5	94.8	129.3	129.3	97.28	94.8	28.290

Table G.4: Overview Climate change for H-Beams by Life Cycle Phase

Climate change [kg CO_2 eq.]

	H220	**H240A**	**HEB240**	**HEB300**	**HEB3004**	**Average**	**Median**	**Std**
A1	162	188	250	341	344	257	250	75.445
A2	8.1	9.42	12.5	17	17.2	12.844	12.5	3.758
A3	58.4	67.9	90.1	123	124	92.68	90.1	27.188
A4	3.38	3.52	3.83	4.3	4.32	3.87	3.83	0.388
A5	12.1	13.2	15.8	19.7	19.8	16.12	15.8	3.198
B	0	0	0	0	0	0	0	0
C1	7.66	7.66	7.66	7.66	7.66	7.66	7.66	0
C2	0.409	0.476	0.631	0.86	0.87	0.6492	0.631	0.1904
C3	0	0	0	0	0	0	0	0
C4	0.00578	0.00672	0.0089	0.0121	0.0123	0.00916	0.0089	0.00268
D	-84.8	-98.6	-131	-178	-180	-134.48	-131	39.329
Total	167.255	191.583	249.53	335.532	337.862	256.352	249.53	149.499

Table G.5: Overview Global warming for H-Beams by Life Cycle Phase

Global warming Potential (GWP) [kg CO_2 eq.]

	H220	H240A	HEB240	HEB300	HEB3004	Average	Median	Std
A1	156	181	240	327	331	247	240	72.308
A2	8.03	9.34	12.4	16.9	17.1	12.754	12.4	3.746
A3	57	66.3	87.9	120	121	90.44	87.9	26.515
A4	3.34	3.48	3.79	4.25	4.27	3.826	3.79	0.383
A5	11.8	12.9	15.4	19.1	19.3	15.7	15.4	3.087
B	0	0	0	0	0	0	0	0
C1	7.57	7.57	7.57	7.57	7.57	7.57	7.57	0
C2	0.406	0.471	0.625	0.853	0.863	0.6436	0.625	0.189
C3	0	0	0	0	0	0	0	0
C4	0.00553	0.00643	0.00852	0.0116	0.0118	0.008776	0.00852	0.002578
D	-79.7	-92.7	-123	-168	-170	-126.68	-123	37.308
Total	164.452	188.367	244.694	327.685	331.115	251.262	244.694	143.538

Table G.6: Overview Energy,Primary, Renewable for H-Beams by Life Cycle Phase

Energy, primary, renewable [MJ]

	H220	H240A	HEB240	HEB300	HEB3004	Average	Median	Std
A1	79.1	91.9	122	166	168	125.4	122	36.717
A2	1.31	1.53	2.03	2.76	2.8	2.086	2.03	0.613
A3	119	139	184	251	253	189.2	184	55.434
A4	0.58	0.639	0.778	0.983	0.992	0.794	0.778	0.170
A5	6.43	7.41	9.68	13	13.2	9.944	9.68	2.785
B	0	0	0	0	0	0	0	0
C1	0.641	0.641	0.641	0.641	0.641	0.641	0.641	0
C2	0.0664	0.0772	0.102	0.14	0.141	0.10532	0.102	0.031
C3	0	0	0	0	0	0	0	0
C4	0.00873	0.0101	0.0135	0.0183	0.0186	0.013846	0.0135	0.004
D	4.22	4.9	6.5	8.87	8.97	6.692	6.5	1.964
Total	211.356	246.107	325.745	443.412	447.763	334.877	325.745	97.719

Table G.7: Overview Energy,Primary, Non-Renewable for H-Beams by Life Cycle Phase

Energy, primary, non-renewable [MJ]

	H220	H240A	HEB240	HEB300	HEB3004	Average	Median	Std
A1	1820	2110	2800	3820	3860	2882	2800	844.616
A2	133	155	206	280	284	211.6	206	62.182
A3	1100	1280	1700	2320	2350	1750	1700	515.907
A4	52.7	54.9	60	67.6	67.9	60.62	60	6.286
A5	172	187	222	273	276	226	222	42.807
B	0	0	0	0	0	0	0	0
C1	118	118	118	118	118	118	118	0.000
C2	6.74	7.83	10.4	14.2	14.3	10.694	10.4	3.137
C3	0	0	0	0	0	0	0	0
C4	0.17	0.198	0.262	0.357	0.361	0.2696	0.262	0.079
D	-656	-763	-1010	-1380	-1400	-1041.8	-1010	306.682
Total	2746.61	3149.928	4106.662	5513.157	5570.561	4217.384	4106.662	1781.696

Table G.8: Overview Resource use, fossils for H-Beams by Life Cycle Phase

Resource use, fossils [MJ]	**H220**	**H240A**	**HEB240**	**HEB300**	**HEB3004**	**Average**	**Median**	**Std**
A1	1710	1990	2640	3600	3640	2716	2640	797.511
A2	126	146	194	264	267	199.4	194	58.329
A3	1040	1210	1610	2190	2220	1654	1610	486.563
A4	49.6	51.7	56.5	63.7	64	57.1	56.5	5.949
A5	162	176	209	258	260	213	209	40.546
B	0	0	0	0	0	0	0	0
C1	111	111	111	111	111	111	111	0
C2	6.34	7.37	9.78	13.3	13.5	10.058	9.78	2.949
C3	0	0	0	0	0	0	0	0
C4	0.161	0.187	0.248	0.338	0.342	0.2552	0.248	0.075
D	-631	-734	-973	-1330	-1340	-1001.6	-973	293.984
Total	2574.101	2958.257	3857.528	5170.338	5235.842	3959.213	3857.528	1685.906

G.2 Environmental Data Validation - Virgin Category Granta Edupack R2 2023

For the virgin category, the phases of the life cycle A1-A3 have been used from the NMD environmental data to validate the data. First, the total emissions are calculated for the whole pole given the H-Beam. These values are divided by the total mass of the pole from the H beam and compared with steel S235J by calculating the percentage deviation.

Table G.9: Validation for Virgin Category for H-Beams by Life Cycle Phases A1-A3

Virgin Category - Total Pole								
A1-A3	**H220**	**H240A**	**HEB240**	**HEB300**	**HEB3004**	**Average**	**Median**	**Std**
GWP	221.030	256.640	340.300	463.900	469.100	350.194	340.300	102.568
CC	228.500	265.320	352.600	481.000	485.200	362.524	352.600	106.391
EP-Ren	199.410	232.430	308.030	419.760	423.800	316.686	308.030	92.763
EP-NRen	3053.000	3545.000	4706.000	6420.000	6494.000	4843.600	4706.000	1422.702
RU-Fos	2876.000	1990.000	2640.000	3600.000	3640.000	2949.200	2876.000	619.963
Virgin approx. - per kg								
GWP	3.594	3.589	3.590	3.588	3.628	3.598	3.590	0.015
CC	3.715	3.711	3.719	3.720	3.753	3.724	3.719	0.015
EP-Ren	3.242	3.251	3.249	3.246	3.278	3.253	3.249	0.012
EP-NRen	49.642	49.580	49.641	49.652	50.224	49.748	49.642	0.239
RU-Fos	46.764	32.358	42.927	58.537	59.187	47.954	46.764	10.081
Virgin approx. - Percentage Deviation								
GWP	14.8%	14.7%	14.7%	14.6%	15.9%	14.9%	14.7%	0.5%
CC	14.8%	14.7%	14.7%	14.6%	15.9%	14.9%	14.7%	0.5%
EP-Ren	-88.1%	-88.1%	-88.1%	-88.1%	-88.0%	-88.1%	-88.1%	0.0%
EP-NRen	81.8%	81.6%	81.8%	81.9%	84.0%	82.2%	81.8%	0.9%
RU-Fos	71.3%	18.5%	57.2%	114.4%	116.8%	75.7%	71.3%	36.9%

G.3 Environmental Data Validation - Recycle Category Granta Edupack R2 2023

For the recycle category, the phases of the life cycle C2-C4 have been used from the NMD environmental data to validate the data. First, the total emissions are calculated for the whole pole given the H-Beam. These values are divided by the total mass of the pole from the H beam and compared with steel S235J by calculating the percentage deviation.

Table G.10: Validation for Recycle Category for H-Beams by Life Cycle Phases C2-C4

Recyle Category - Total Pole								
C2-C4	**H220**	**H240A**	**HEB240**	**HEB300**	**HEB3004**	**Average**	**Median**	**Std**
GWP	0.412	0.477	0.634	0.865	0.875	0.652	0.634	0.192
CC	0.415	0.483	0.640	0.872	0.882	0.658	0.640	0.193
EP-Ren	0.075	0.087	0.116	0.158	0.160	0.119	0.116	0.035
EP-NRen	6.910	8.028	10.662	14.557	14.661	10.964	10.662	3.216
RU-Fos	6.501	7.557	10.028	13.638	13.842	10.313	10.028	3.024
Recycle approx. - per kg								
GWP	0.669	0.668	0.709	0.669	0.677	0.678	0.669	0.016
CC	0.674	0.675	0.717	0.674	0.682	0.685	0.675	0.016
EP-Ren	0.122	0.122	0.129	0.122	0.123	0.124	0.122	0.003
EP-NRen	11.236	11.228	11.940	11.258	11.339	11.400	11.258	0.273
RU-Fos	10.571	10.569	11.230	10.548	10.705	10.724	10.571	0.259
Recycle approx. - Percentage Deviation								
GWP	13.4%	13.2%	20.2%	13.3%	14.7%	15.0%	13.4%	2.7%
CC	14.3%	14.4%	21.5%	14.3%	15.7%	16.0%	14.4%	2.8%
EP-Ren	-98.4%	-98.4%	-98.3%	-98.4%	-98.4%	-98.4%	-98.4%	0.0%
EP-NRen	49.6%	49.5%	59.0%	49.9%	51.0%	51.8%	49.9%	3.6%
RU-Fos	40.8%	40.7%	49.5%	40.4%	42.5%	42.8%	40.8%	3.4%

G.4 Environmental Data Validation - Recycle Factor Granta Edupack R2 2023

For the recycling factor, the value of phase D of the life cycle is divided by the total value of the indicator for the H-Beam. The recycle factor for steel S235J is 54.6 %.

Table G.11: Validation for Recycle Factor for H-Beams by Life Cycle Phase D

Recycle factor								
	H220	**H240A**	**HEB240**	**HEB300**	**HEB3004**	**Average**	**Median**	**Std**
GWP	48.5%	49.2%	50.3%	51.3%	51.3%	50.1%	50.3%	1.1%
CC	50.7%	51.5%	52.5%	53.1%	53.3%	52.2%	52.5%	1.0%
EP-Ren	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	0.0%
EP-NRen	23.9%	24.2%	24.6%	25.0%	25.1%	24.6%	24.6%	0.5%
RU-Fos	24.5%	24.8%	25.2%	25.7%	25.6%	25.2%	25.2%	0.5%

G.5 Environmental Data Validation - Typical Category Granta Edupack R2 2023

The typical category (X_{Typical}) is derived from the virgin (X_{Virgin}), recycling ($X_{\text{Recycling}}$), and recycling factor (RF) values using the formula:

$$X_{\text{Typical}} = (1 - RF) \cdot X_{\text{Virgin}} + RF \cdot X_{\text{Recycling}}$$

Table G.12: Validation for Typical Category for H-Beams by Life Cycle Phase Data

Typical Category - Total Pole								
A1-A3	**H220**	**H240A**	**HEB240**	**HEB300**	**HEB3004**	**Average**	**Median**	**Std**
GWP	114.109	130.576	169.560	226.507	228.705	173.892	169.560	47.417
CC	112.858	129.019	167.825	226.292	227.174	172.634	167.825	47.649
EP-Ren	195.430	227.804	301.886	411.366	415.313	310.360	301.886	90.900
EP-NRen	2325.472	2688.247	3551.220	4816.652	4865.605	3649.439	3551.220	1051.463
RU-Fos	2172.588	1498.118	1976.631	2677.457	2711.964	2207.352	2172.588	454.551
Typical approx. - per kg								
GWP	1.874	1.845	1.806	1.769	1.787	1.816	1.806	0.038
CC	1.854	1.823	1.787	1.768	1.775	1.801	1.787	0.032
EP-Ren	3.210	3.218	3.215	3.214	3.244	3.220	3.215	0.012
EP-NRen	38.195	37.978	37.816	37.628	38.010	37.925	37.978	0.191
RU-Fos	35.683	21.164	21.049	20.916	21.186	24.000	21.164	5.843
Typical approx. - Percentage Deviation								
GWP	1.3%	-0.3%	-2.4%	-4.4%	-3.4%	-1.8%	-2.4%	2.071%
CC	0.2%	-1.5%	-3.4%	-4.4%	-4.1%	-2.6%	-3.4%	1.747%
EP-Ren	-81.7%	-81.6%	-81.6%	-81.6%	-81.5%	-81.6%	-81.6%	0.071%
EP-NRen	118.3%	117.0%	116.1%	115.0%	117.2%	116.7%	117.0%	1.092%
RU-Fos	103.9%	20.9%	20.3%	19.5%	21.1%	37.1%	20.9%	33.386%

Appendix H

Case Study Specifications

In this Appendix an overview of the specifications for the applied case study is given.

The data for Structural Steel S235J have been used for all the other elements in the structural model made of steel. Aluminium EN AW 6082 has been used for all the tubular elements in support arms used of the B4-system.

Table H.1: Material Properties Table

Structural Steel S235J		
Name	**Variable**	**Value**
Density	ρ_{S235}	7850 [kg/m^3]
Poisson Ratio	v_{S235}	0.3
Young's Modulus	E_{S235}	$210 \cdot 10^3$ [MPa]
Aluminium EN AW 6082		
Name	**Variable**	**Value**
Density	$\rho_{\text{EN\_AW\_6082}}$	2700 [kg/m^3]
Poisson Ratio	$v_{\text{EN\_AW\_6082}}$	0.33
Young's Modulus	$E_{\text{EN\_AW\_6082}}$	$70 \cdot 10^3$ [MPa]

Table H.2: Table of Wire Specifications

Contact Wire - CuAg0.1 H AC - 100, 1500V DC		
Name	**Variable**	**Value**
Mass	$M_{\text{contact\_wire}}$	8.72×10^{-3} [N/mm]
Diameter	$d_{\text{contact\_wire}}$	12 [mm]
Tension Force	$T_{\text{contact\_wire}}$	10000 [N]
Number of Wires	$num_{\text{contact\_wires}}$	2
Catenary Wire - BzII 70/19 - 70		
Name	**Variable**	**Value**
Mass	$M_{\text{catenary\_wire}}$	5.85×10^{-3} [N/mm]
Diameter	$d_{\text{catenary\_wire}}$	10.5 [mm]
Tension Force	$T_{\text{catenary\_wire}}$	15000 [N]
Number of Wires	$num_{\text{catenary\_wires}}$	1
Feeding Wire - E-AlMgSi 240		
Name	**Variable**	**Value**
Mass	$M_{\text{feeding\_wire}}$	6.57×10^{-3} [N/mm]
Diameter	$d_{\text{feeding\_wire}}$	20.3 [mm]
Tension Force	$T_{\text{feeding\_wire}}$	9000 [N]
Number of Wires	$num_{\text{feeding\_wires}}$	2

Table H.3: Parameters and Values for Applied Loads

Name	**Variable**	**Value**
Wind Load for Region II	Q_{wind}	850×10^{-6} [N/mm^2]
Wire Safety Factor	G_{wire}	0.75
Pole Safety Factor	G_{pole}	1
Contact Wire Coefficient	$C_{\text{contact\_wire}}$	1.2
Wire Coefficient	C_{wire}	1
Pole Coefficient	C_{pole}	1.82
Number of Contact Wires	$N_{\text{contact\_wires}}$	1.5
Technical Lifetime of Pole	TL_{Pole}	50 [years]
Construction Maintenance Force at Portal	$F_{\text{Construction\_Maintenance\_Portal}}$	1000 [N]
Construction Maintenance Force at Pole	$F_{\text{Construction\_Maintenance\_Pole}}$	1000 [N]

Pole and Portal Configuration

In the figures below the used configuration can be seen used in the structural analysis for the Pole and Portal case, in the figures the dimensions are also shown.

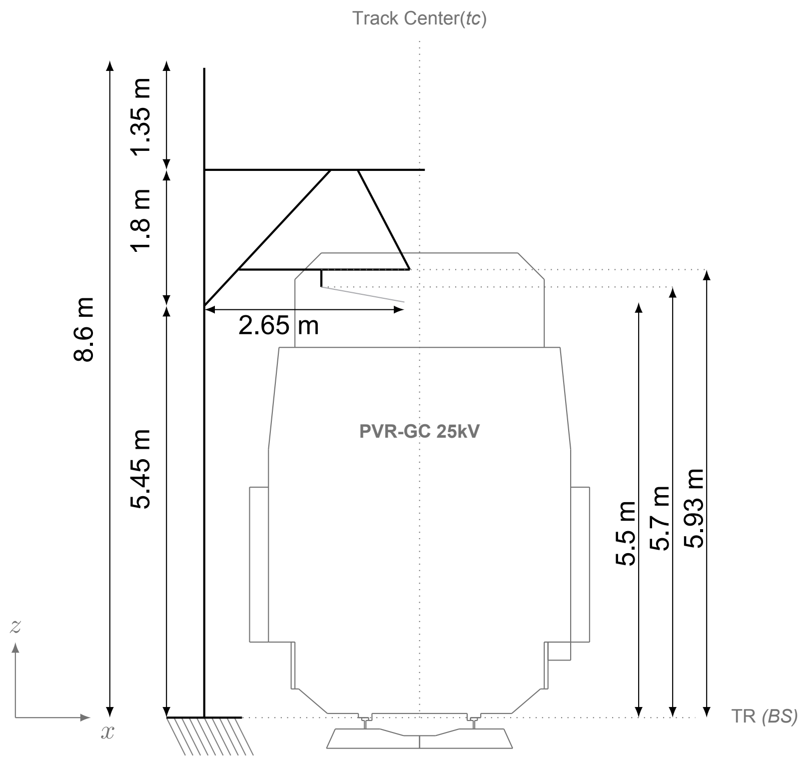


Figure H.1: Pole Design Configuration with Dimensions

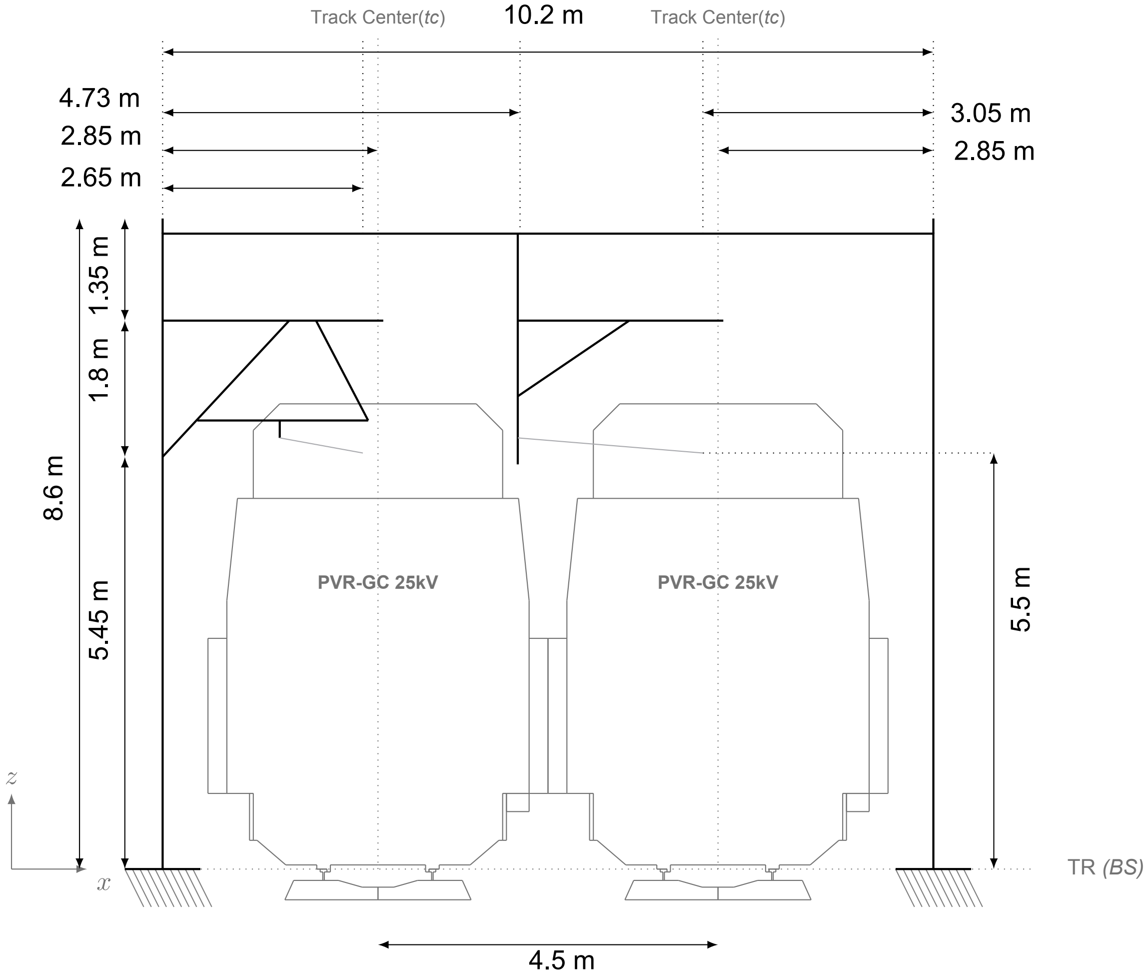


Figure H.2: Portal Design Configuration with Dimensions

Appendix I

Results: Background and Scatter Plots

This appendix provides the graphs of the distribution of the material family, selected materials, and pole shape design for the supplementary material input datasets, accompanied by additional scatter plots of these data sets presented in chapter 8.

I.1 Distribution of Material Family, Material, and Pole Shape

All Materials* Similar to the All Material input data set, the metal (ferrous) is the dominant material family within the set. The same can be seen for the material, where Cast Iron alloys are dominated materials. However, without the T-Beam and UNP as options within the pole shape variants. The tubular variants are the dominant pole shape design variants. The round tubular variant clearly dominates the square and rectangular variants.

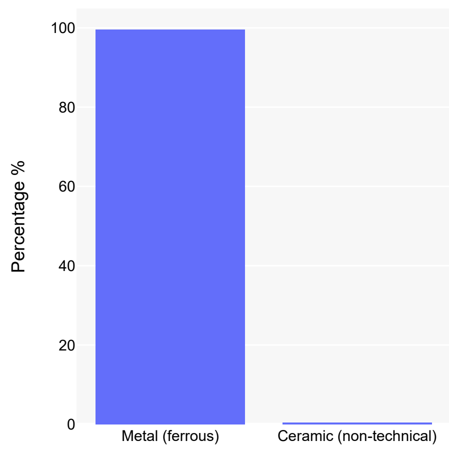
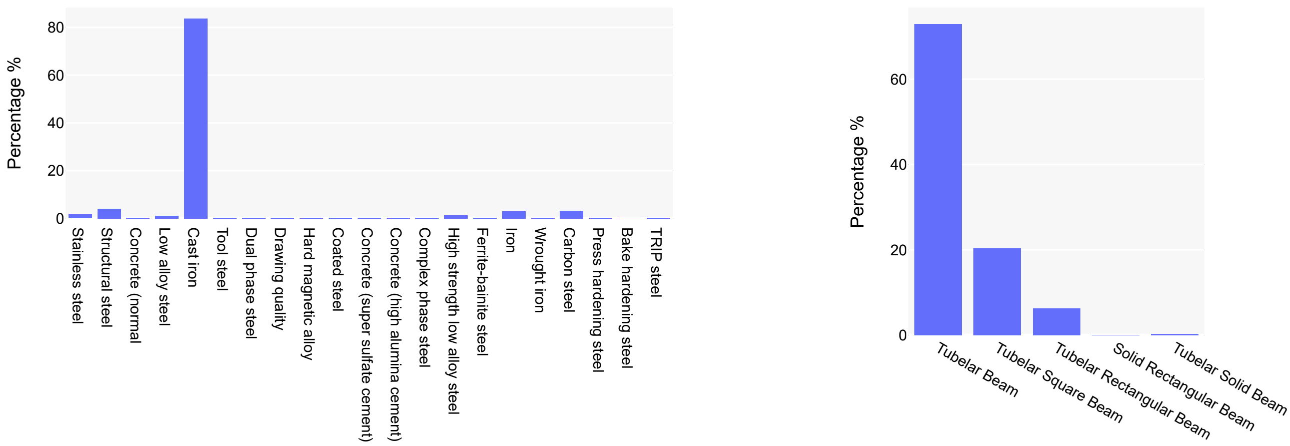


Figure I.1: Selected Material Family Distribution in All Materials* Dataset



(a) Selected Materials

(b) Pole Shape Design

Figure I.2: Selected Pole Shape Design and Materials Distribution in All Materials* Dataset

Ceramic (non-technical)

In the case of the ceramic (non technical), the dominant materials are concrete variants of high performance, structural lightweight and aerated. For the pole shape design, the round tubular and solid tubular pole shape design are the dominant variants, the round tubular variant is the dominant variant of the pole shape design.

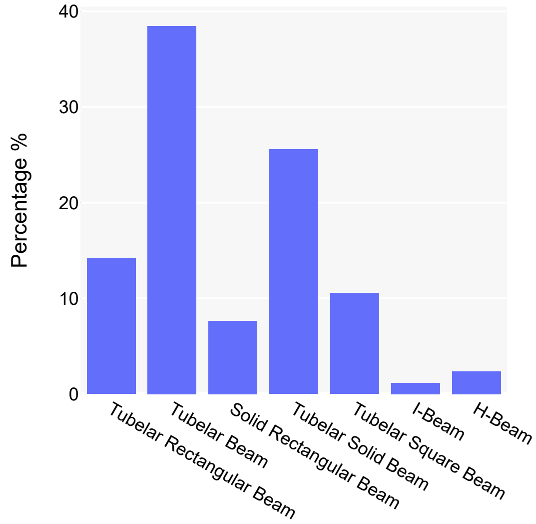


Figure I.3: Selected Pole Shape Design Distribution in Ceramics Dataset

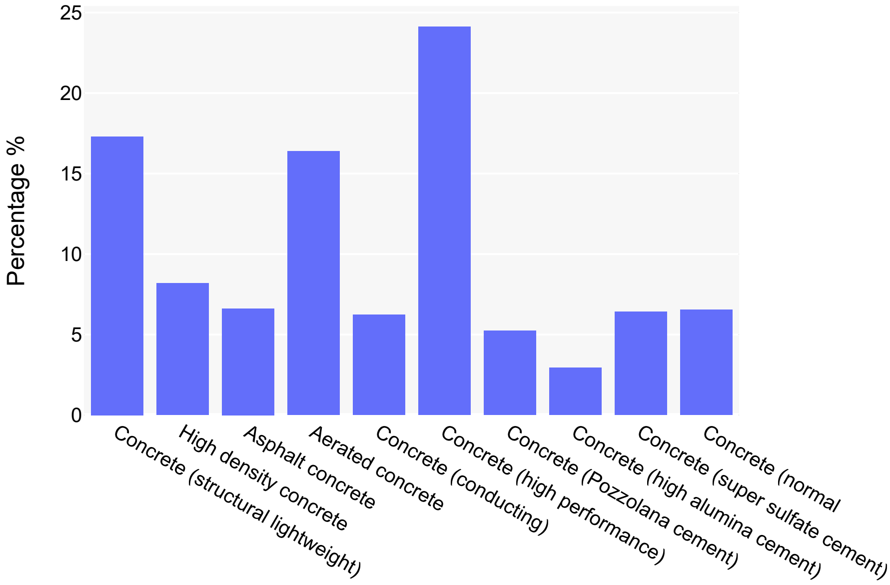


Figure I.4: Selected Materials Distribution in Ceramics Dataset

Metal (non-ferrous)

In the case of the metal (non-ferrous) dominant material is the cobalt-base super alloy. That clearly dominates the other materials within the set. As for the pole shape design the round tubular is the dominant variant within this input date set.

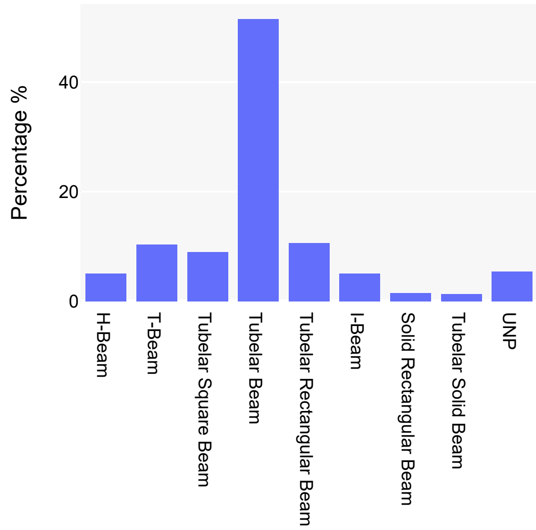


Figure I.5: Selected Pole Shape Design Distribution in Metal (non ferrous) Dataset

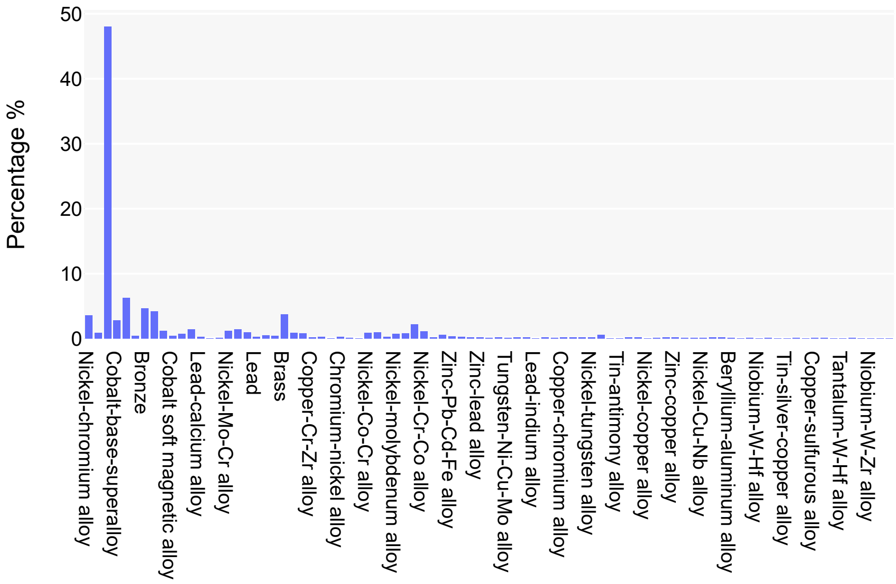


Figure I.6: Selected Materials Distribution in Metal (non ferrous) Dataset

I.2 Objective Distribution Scatter Plots

In this section the objective distribution for the other datasets can be found.

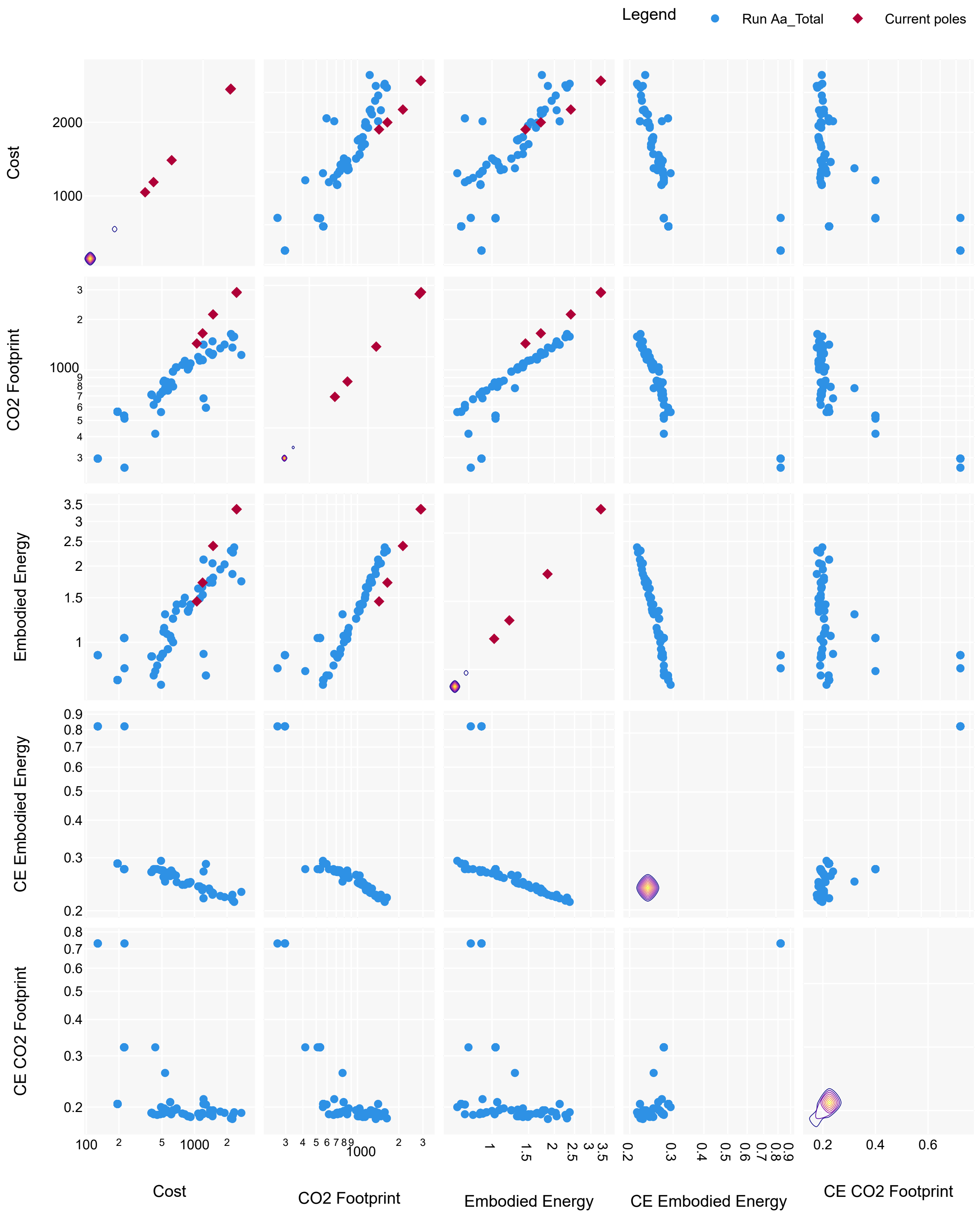


Figure I.7: Scatter Matrix Representation of Objectives Distribution in All Materials* Dataset

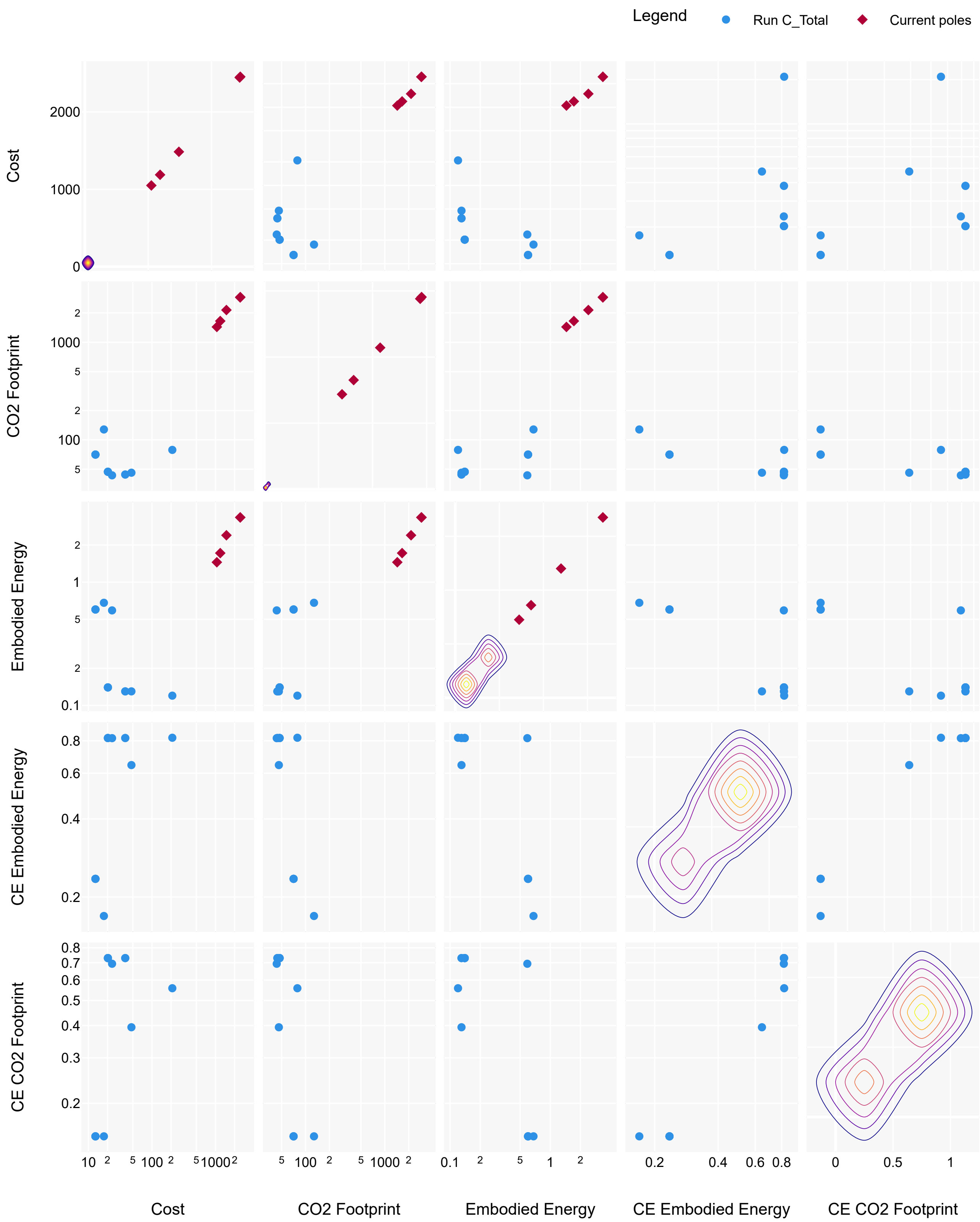


Figure I.8: Scatter Matrix Representation of Objectives Distribution in Ceramics Dataset

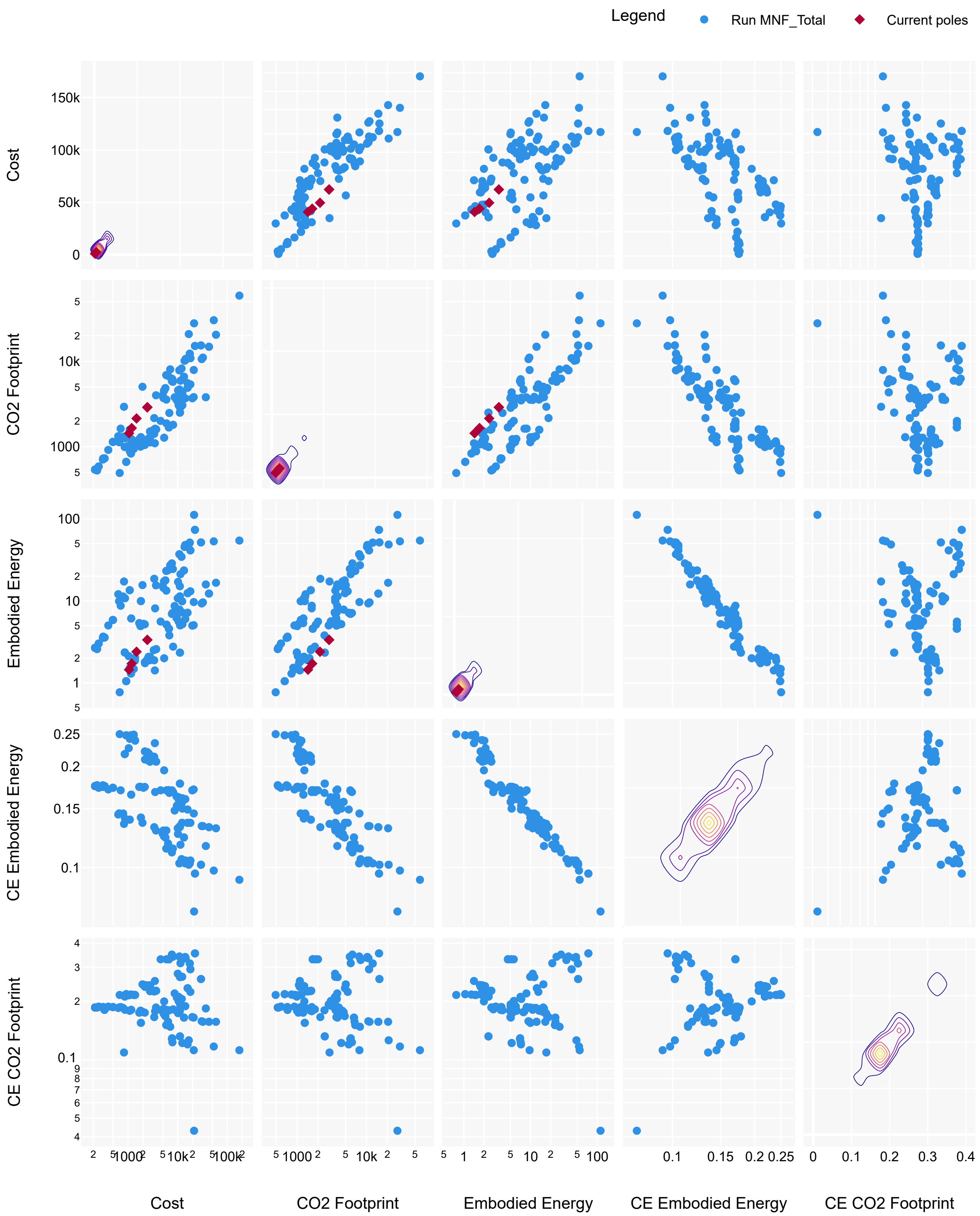


Figure I.9: Scatter Matrix Representation of Objectives Distribution in Metal (non ferrous) Dataset

I.3 Pole Shape Parameters Scatter Plots

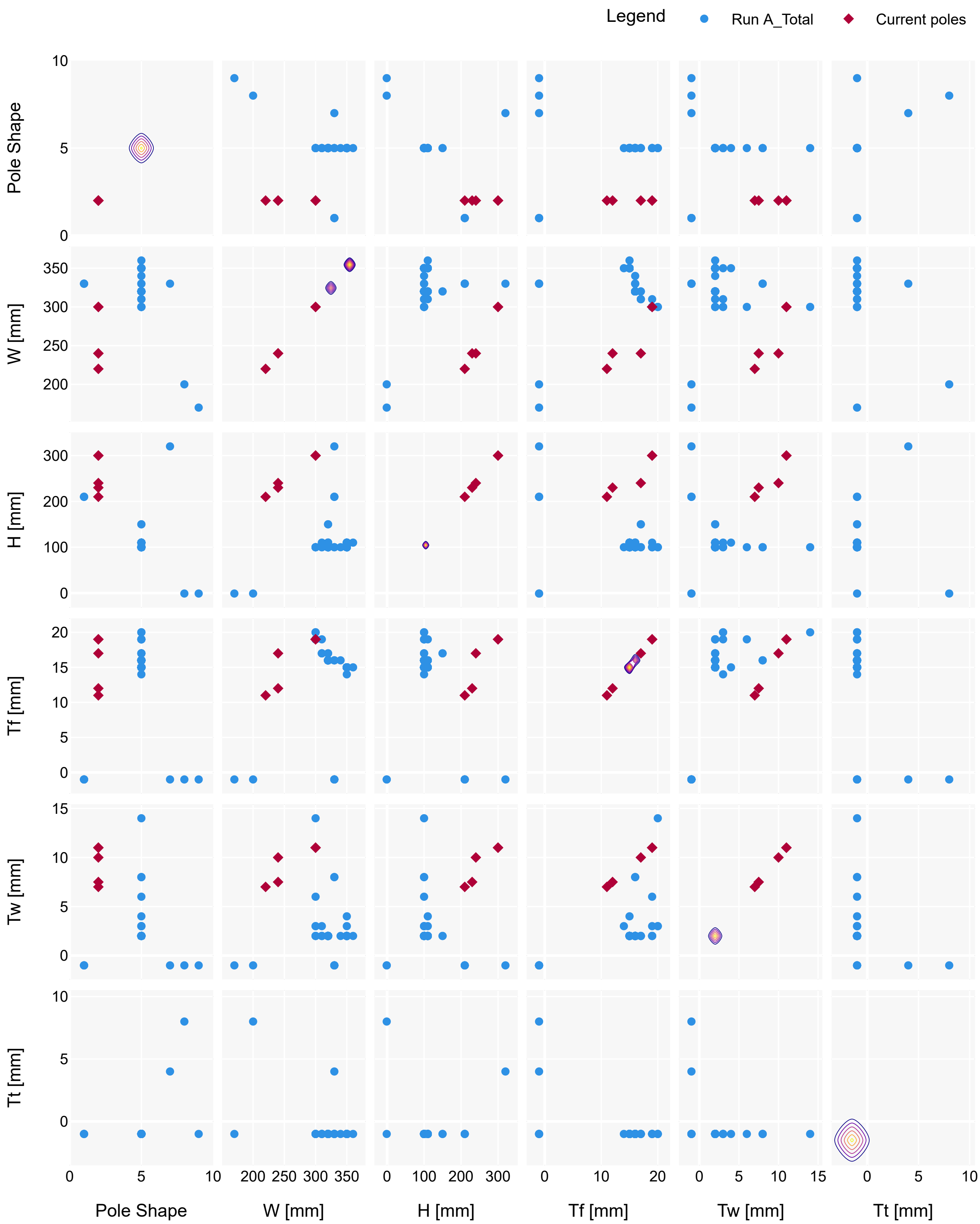


Figure I.10: Scatter Matrix Representation of Pole Shape Parameter Distribution in All Materials Dataset

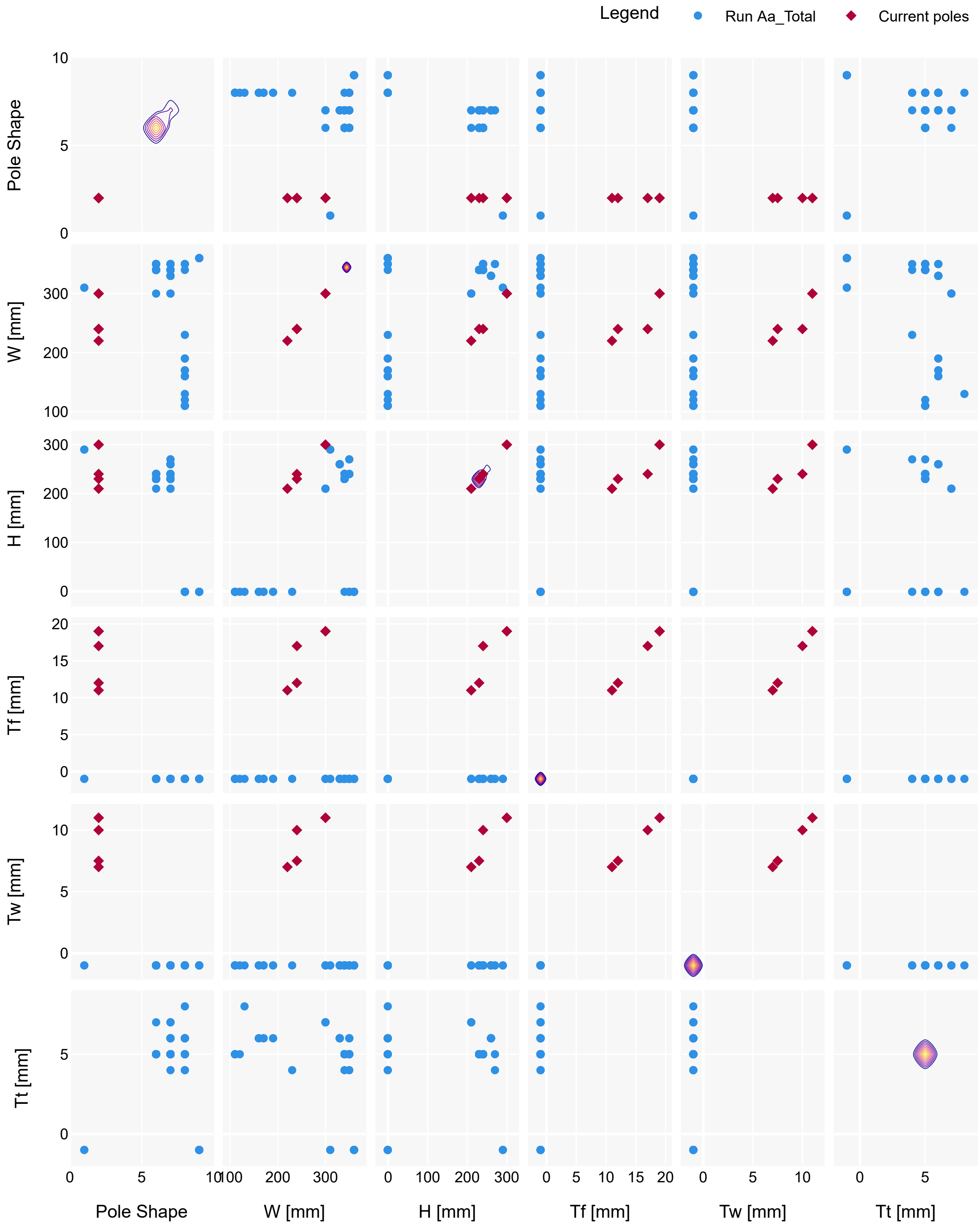


Figure I.11: Scatter Matrix Representation of Pole Shape Parameter Distribution in All Materials* Dataset

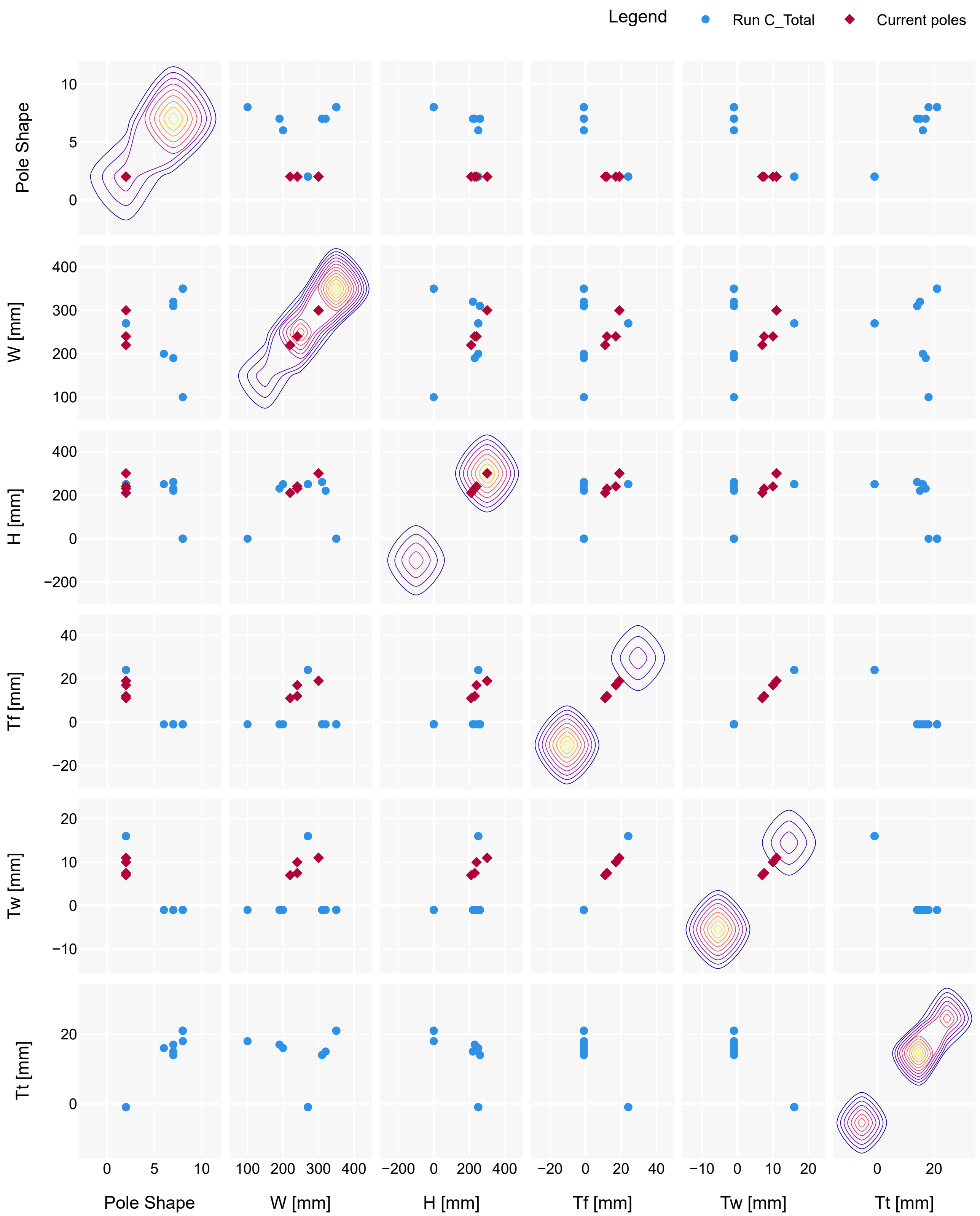


Figure I.12: Scatter Matrix Representation of Pole Shape Parameter Distribution in Ceramics Dataset

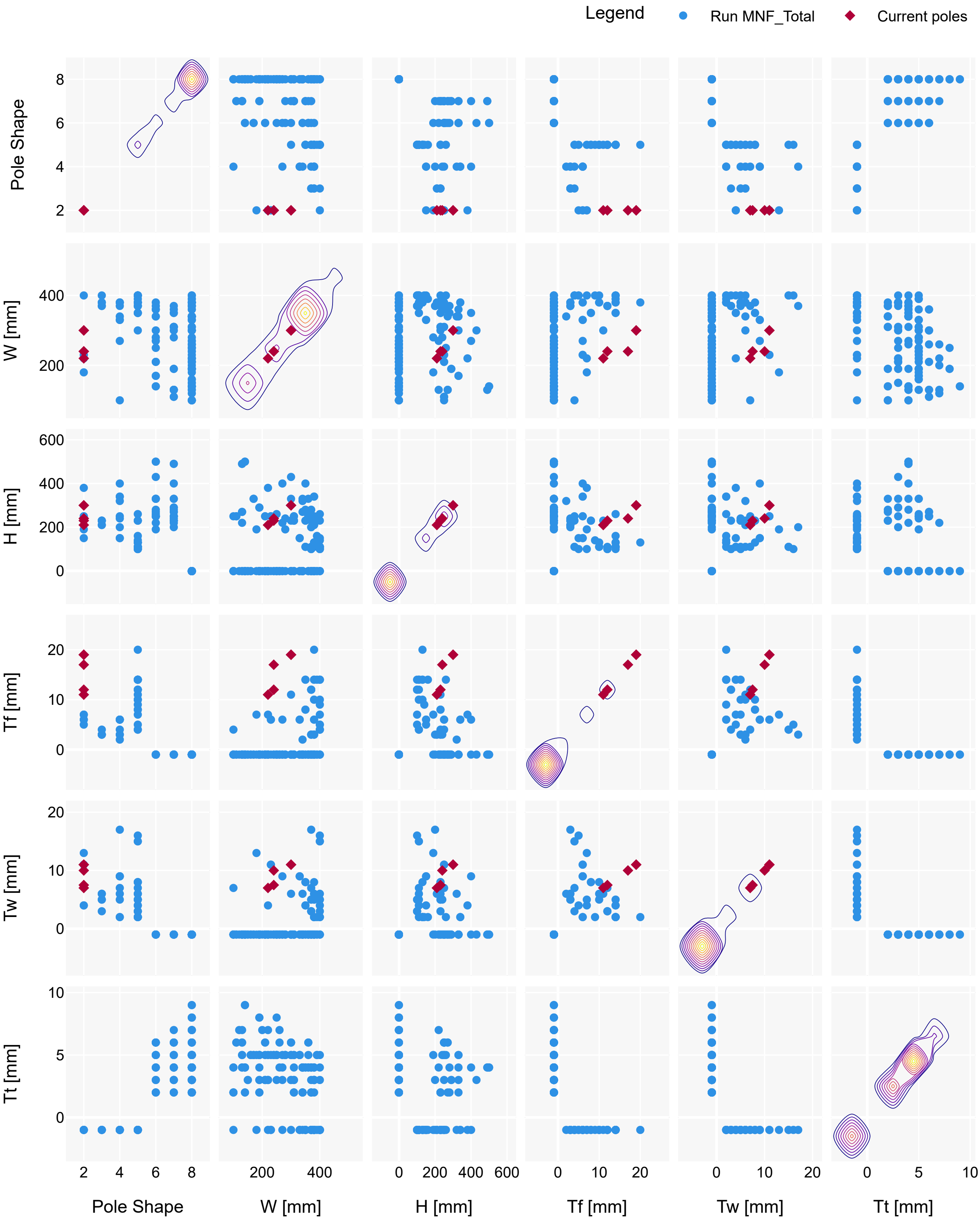


Figure I.13: Scatter Matrix Representation of Pole Shape Parameter Distribution in Metal (non ferrous) Dataset

I.4 Pole Shape Design Properties Scatter Plots

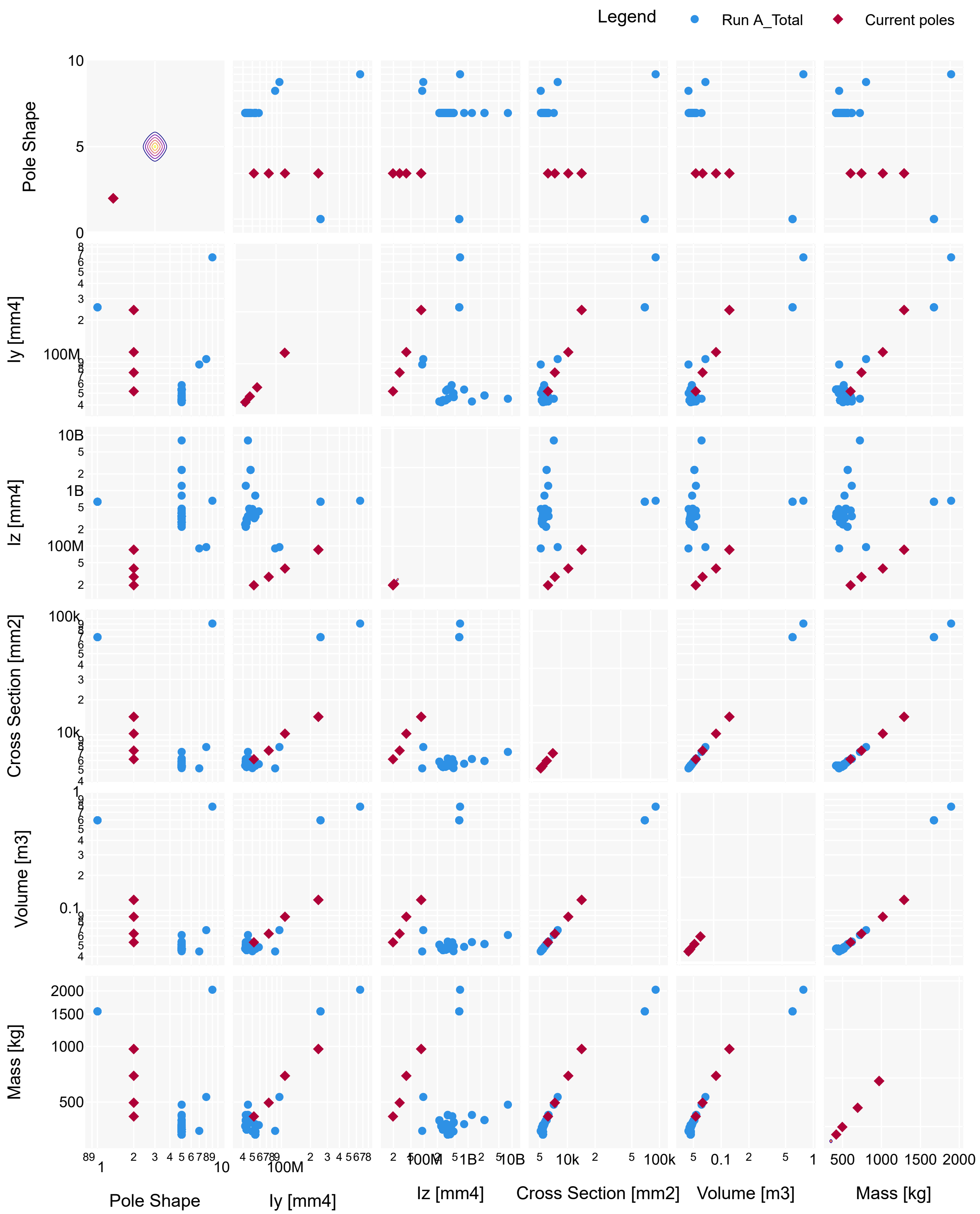


Figure I.14: Scatter Matrix Representation of Pole Shape Properties Distribution in All Materials Dataset

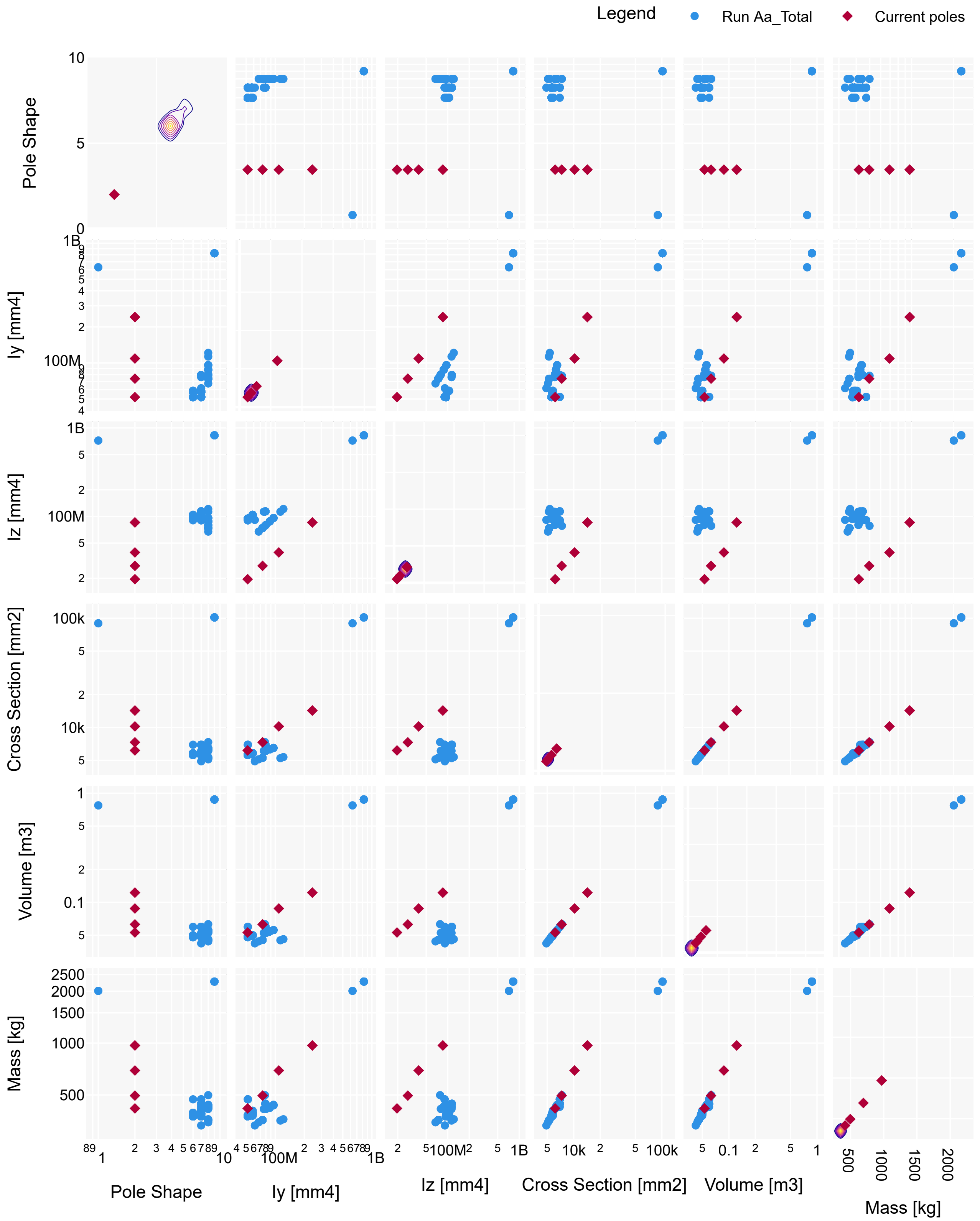


Figure I.15: Scatter Matrix Representation of Pole Shape Properties Distribution in All Materials* Dataset

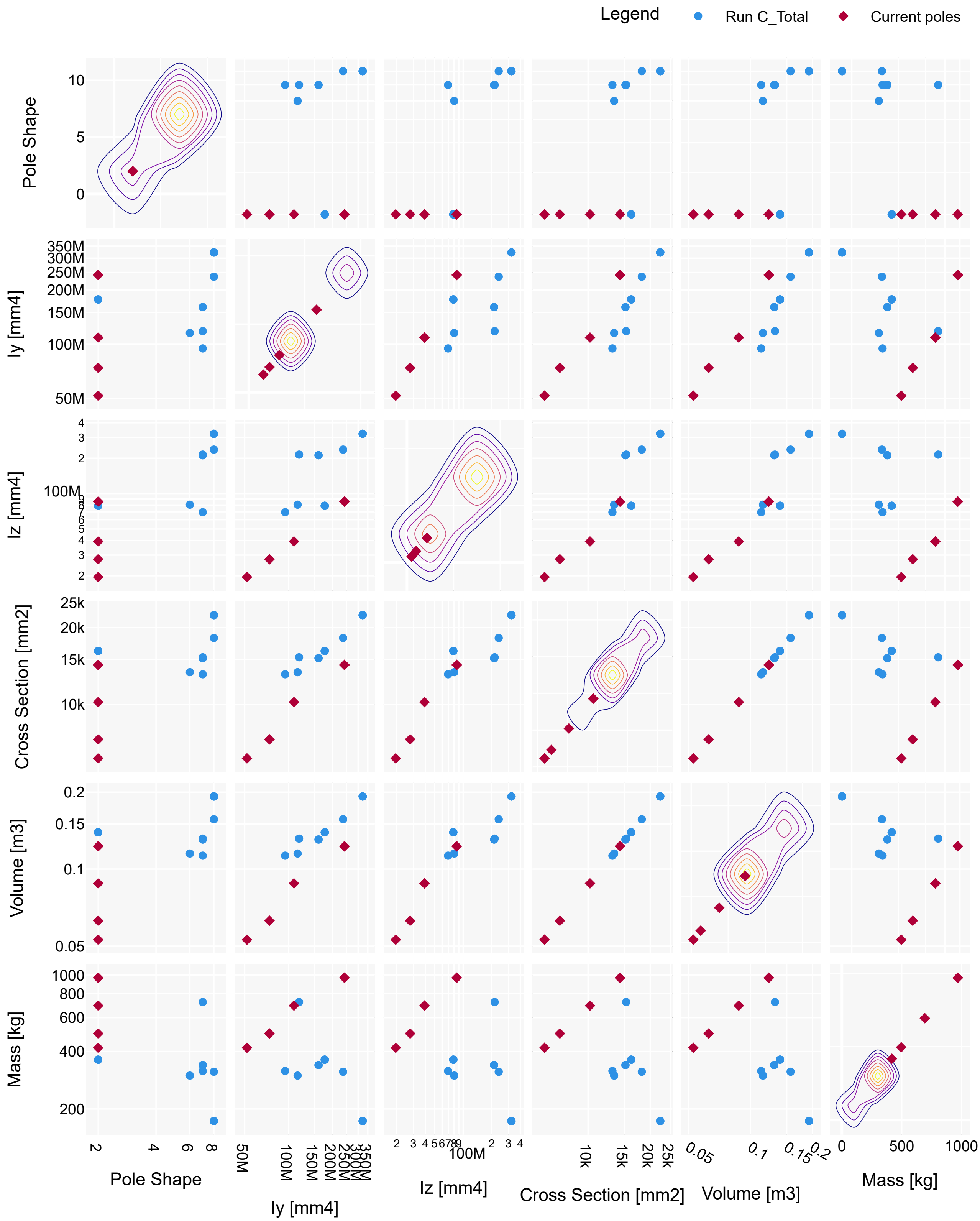


Figure I.16: Scatter Matrix Representation of Pole Shape Properties Distribution in Ceramics Dataset

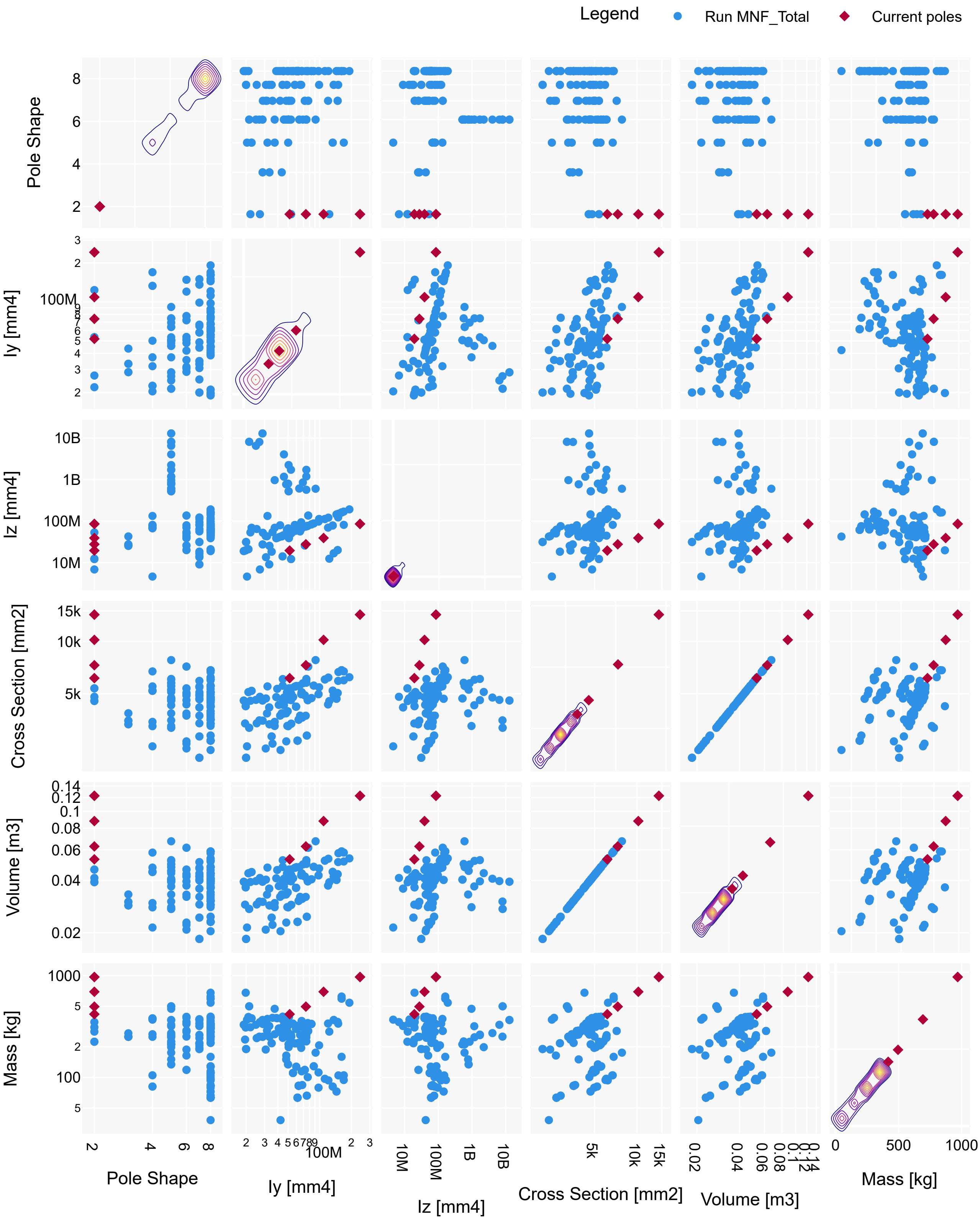


Figure I.17: Scatter Matrix Representation of Pole Shape Properties Distribution in Metal (non ferrous) Dataset

I.5 Material Properties Scatter Plots

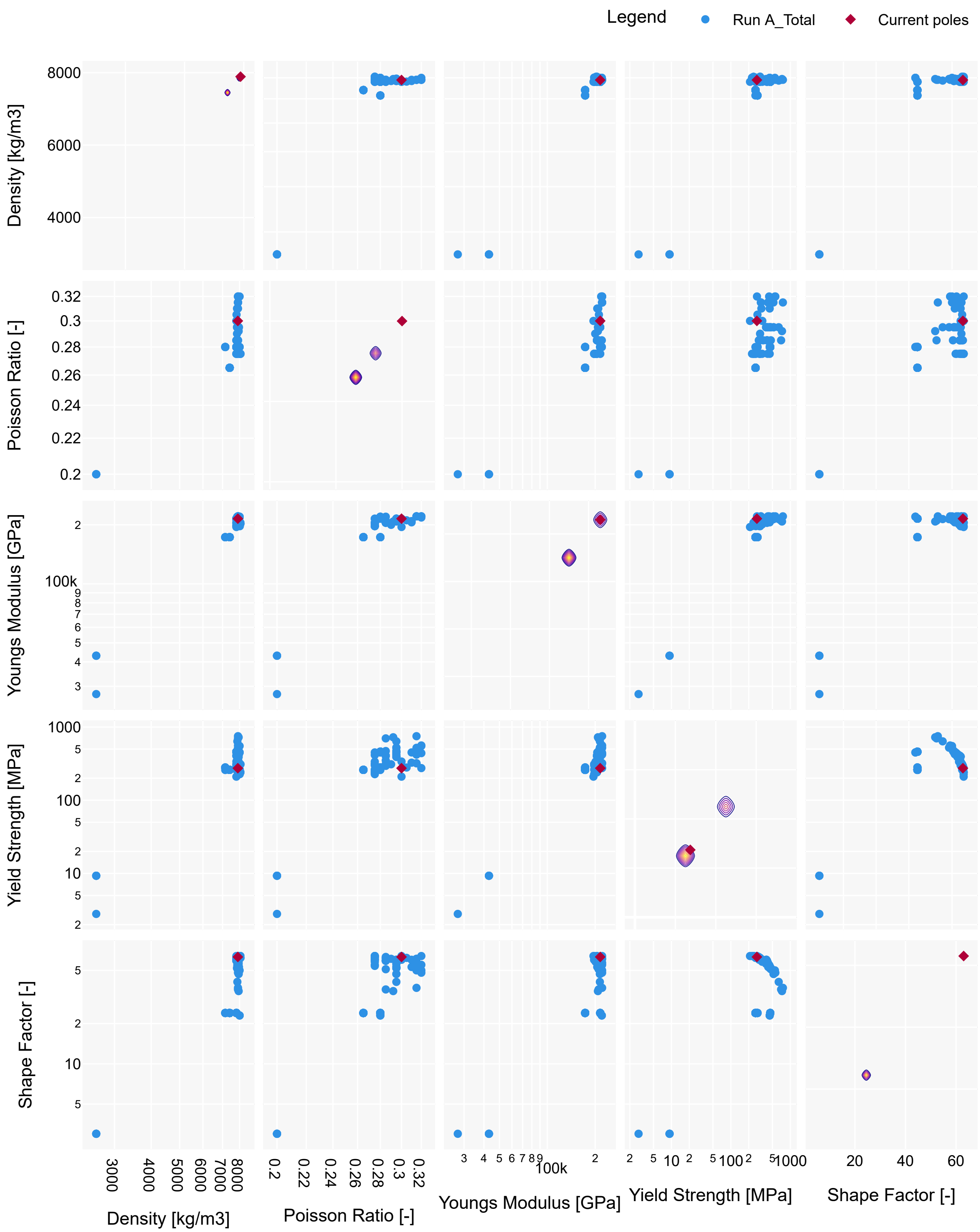


Figure I.18: Scatter Matrix Representation of Material Properties Distribution in All Materials Dataset

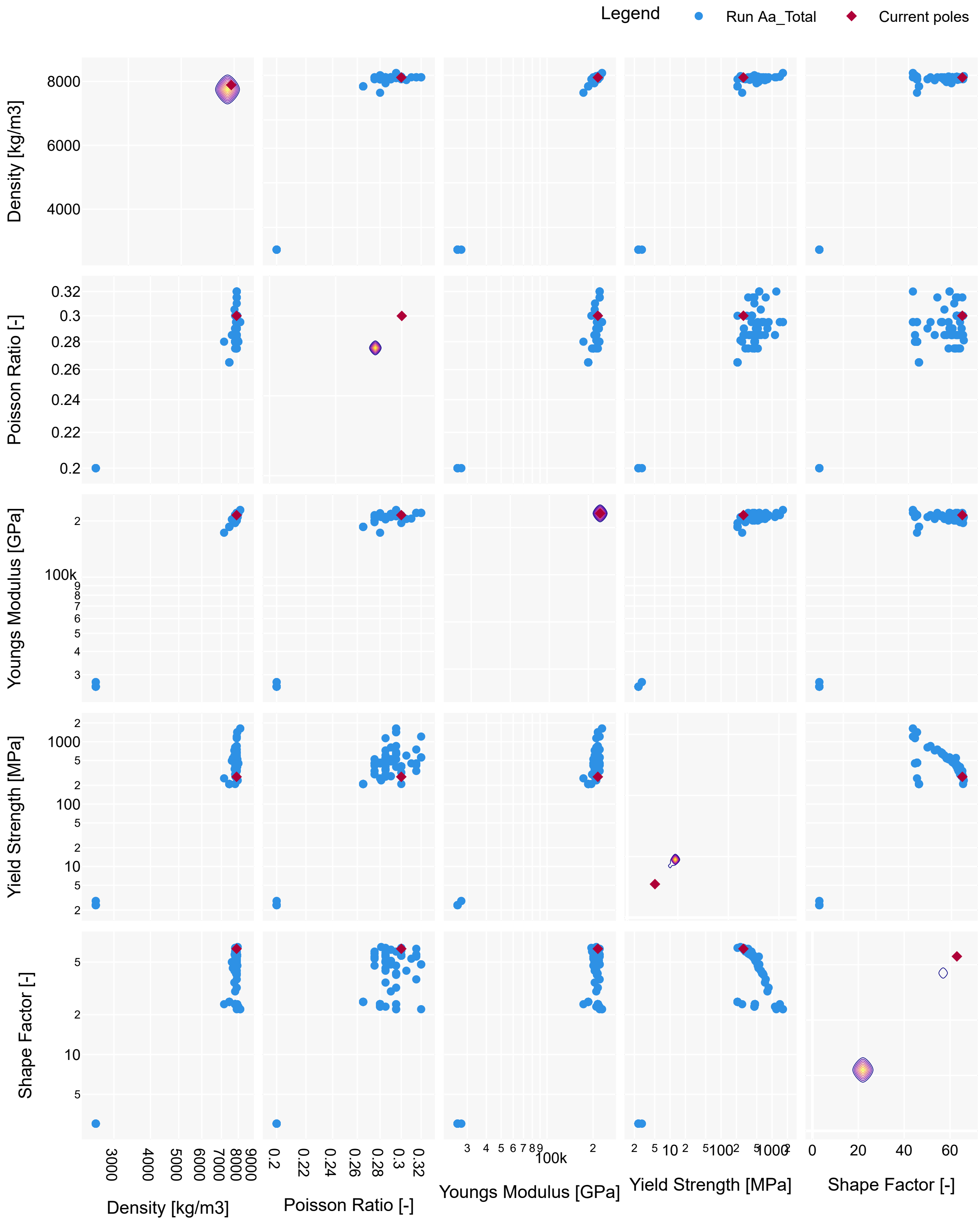


Figure I.19: Scatter Matrix Representation of Material Properties Distribution in All Materials* Dataset

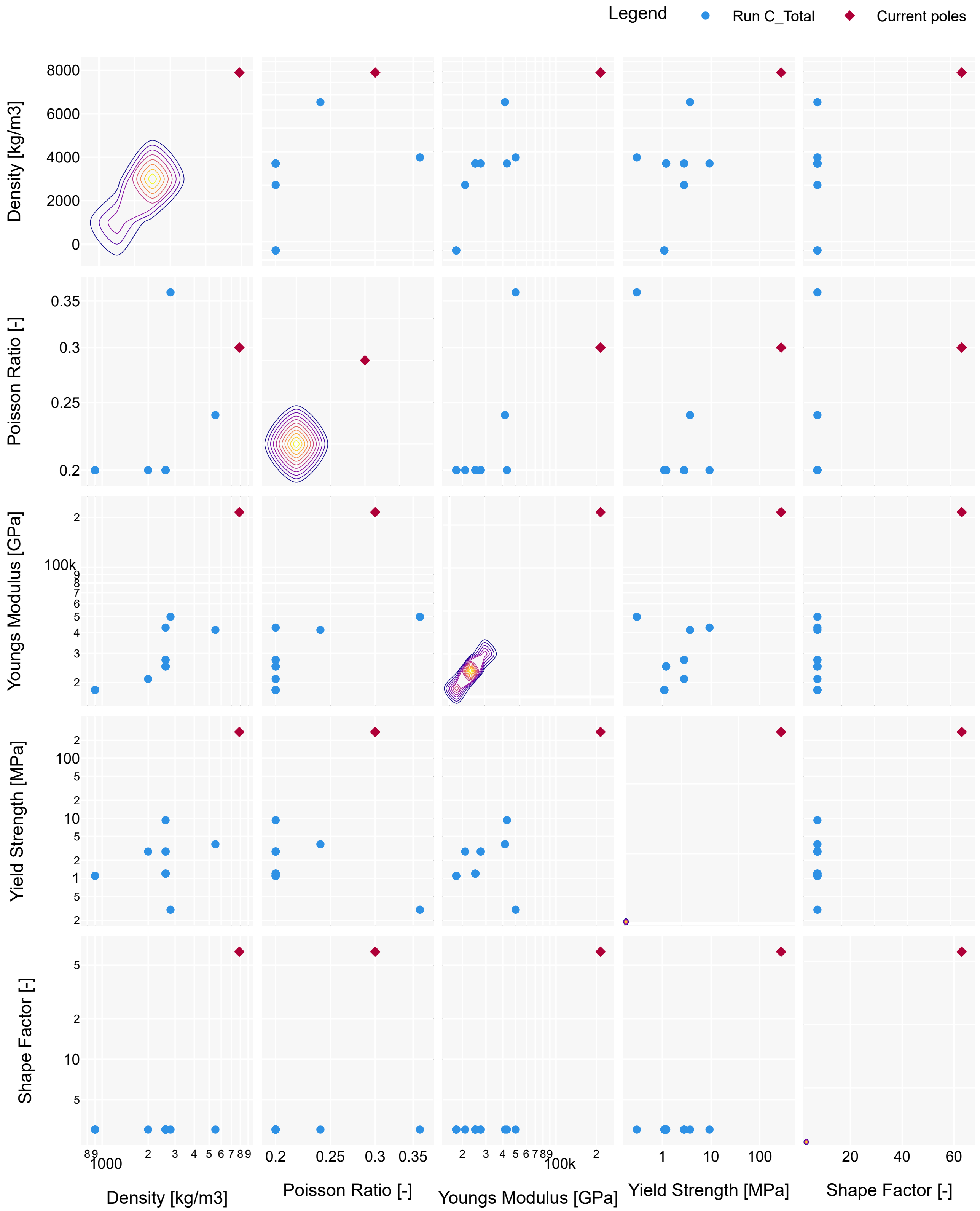


Figure I.20: Scatter Matrix Representation of Material Properties Distribution in Ceramics Dataset

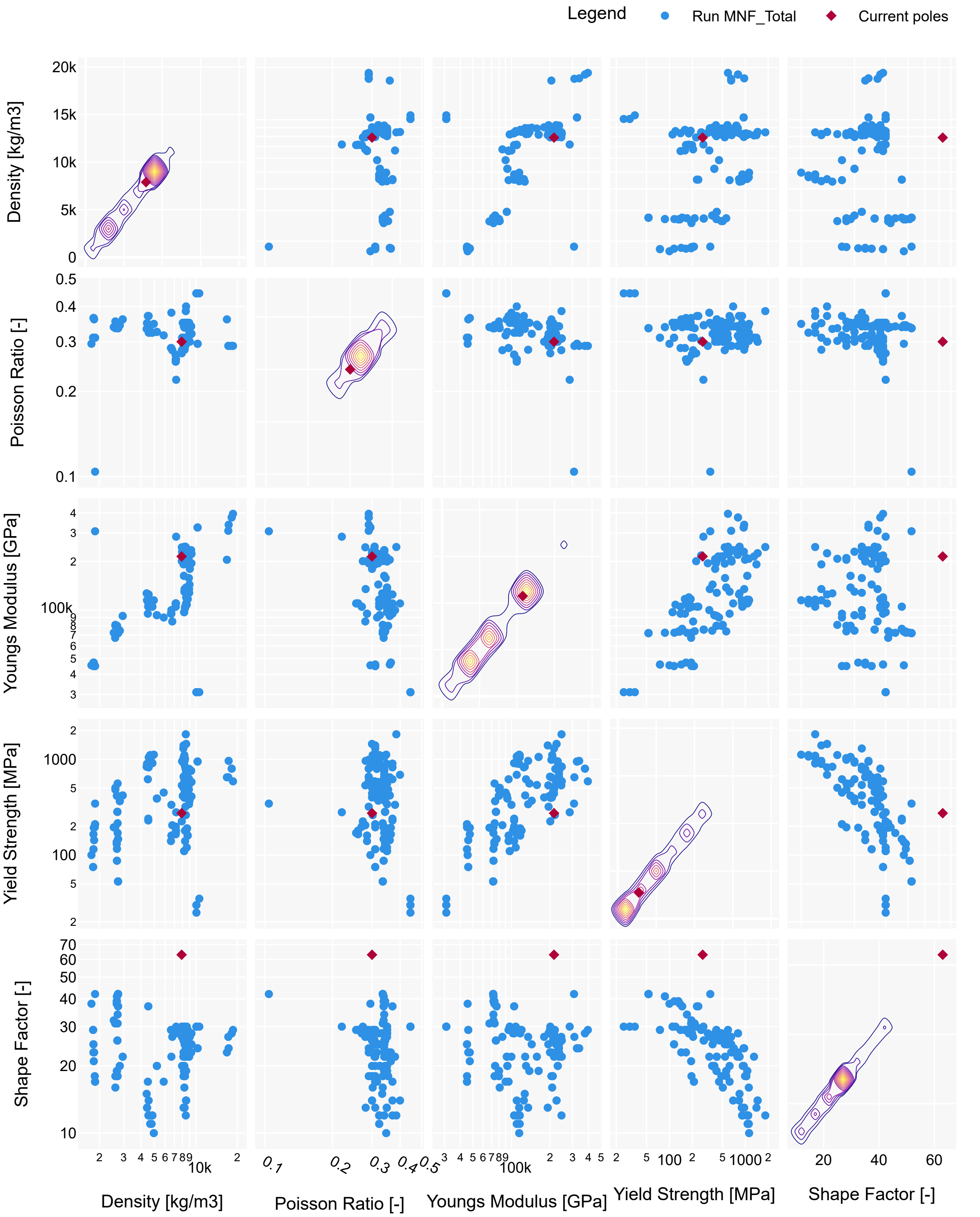


Figure I.21: Scatter Matrix Representation of Material Properties Distribution in Metal (non ferrous) Dataset

Sustainability of the Overhead Contact Line Support Structure

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28th May, 2024

Abstract

The Overhead Catenary Line System (OCLS) is crucial for continuous electrical supply to trains in electrified railway networks. This article outlines the research conducted on the exploration of the sustainable design space of the Overhead Contact Line support structure on the main Dutch rail network. The research began with a comprehensive review of the literature on OCLS support structures, covering publications from 2013 to 2022. A multi-objective optimisation model is developed to explore sustainable design possibilities. Further result analyses elucidate the defining parameters and variables of the support structure design. The findings presented in this research serve as a basis for more in-depth research on the discussion surrounding existing regulations and specifications and sustainability within the rail branch.

Keywords - Overhead Contact Lines, OCLS, Catenary, Dutch main rail network, Sustainability, Multi-objective Optimisation, NSGA-II

1 Introduction

This article outlines the research conducted on the exploration of the sustainable design space of the Overhead Contact Line support structure. The research has been conducted part of the graduate research.

The overhead contact line system (OCLS) is crucial for continuous electrical supply to trains in electrified railway networks. This system, which requires regular maintenance and reliable operation, faces challenges due to ageing infrastructure, particularly in the Netherlands, where about 500 km of OCLS are due for replacement to prevent network failures. Current replacement methods are inadequate due to high time and delay costs, prompting the exploration of new methods and innovations to improve reliability, sustainability, and affordability. In addition, sustainability considerations are emerging in the design of OCLS support structures, highlighting a knowledge gap in the current literature. This research addresses this by proposing a multi-objective optimisation model to explore sustainable design options for these structures [1].

1.1 Research Context

This study began with a comprehensive review of the literature on OCLS support structures, covering publications from 2013 to 2022. The classification of this literature was based on the taxonomy of Sedghi, Kauppila, Bergquist, *et al.* [2], focussing on structural characteristics, maintenance management, monitoring, and decision-making frameworks.

The literature review reveals a well-established knowledge base on OCLS support structures, but identifies four key knowledge gaps:

- Further understanding and development of methods on the structural condition of the structures
- Use of condition-based maintenance using structural models and new monitoring methods
- Further development of multi-objective decision-making models, as well as the implementation of more complex algorithms
- Impact and influence of sustainability on the design and maintenance of support structures

The summary of literature review can found in section 2.

1.2 Problem Definition

ProRail is tasked with replacing the OCLS and improving its sustainability. Studies by Ecofys in 2010 and TNO in 2011 evaluated the carbon footprint and potential sustainable designs of OCLS support structures, respectively. The Ecofys study highlighted that the production phase emissions are significant, with concrete as a preferable material for reducing CO2 emissions. The research of TNO suggested that concrete structures could be most beneficial for the reduction of emissions, although other materials like steel or wood could also be viable depending on the design. Despite these findings, recent years have not seen significant changes in the support structures used in ProRail's main rail network. The present obstacles include compliance with more rigorous environmental laws and addressing the lack of understanding about the effects of sustainability on the design of support structures. This leads to several critical inquiries:

- How can the support structure be made in a sustainable manner?
- What are the potential design directions to increase the sustainability of the support structure?
- What is the potential design space for designing a sustainable support structure?

1.3 Research Objective and Scope

The purpose of this research is to develop a multi-objective optimisation model which can be used to explore and quantify the design space and key design variables for a sustainable support structure for OCLS. The scope of the research is limited to the support structure because of its importance within the OCLS and its unique characteristics as a structure.

To define and quantify the design space, an optimisation model is developed, for which it is important to accurately define and formulate the different objectives, related constraints, and decision variables considering the various aspects and disciplines involved in designing a support structure. Therefore, design variables are identified that impact and influence the sustainability of the design of the support structure.

The research scope is defined contextually and geographically by focussing on the case of the Dutch main railway network. Physically, the scope is demarcated in the context of OCLS by analysing only the structural elements of the support structure, namely the poles above the foundation and the beams in the case of a portal structure. The structural elements of catenary systems are not taken into account in this research as they depend on the installed catenary system.

1.4 Research Questions

Given the identified knowledge gaps and the defined objectives of this study,the following main research question is posed:

What are the key design variables for the sustainable design of a support structure for an OCLS?

To answer this question, the following sub-questions have been formulated:

1. What are the essential requirements and design specifications to be met when designing a supporting structure for an OCLS on the main rail network in the Netherlands?
2. What are the methods which can be used to determine the sustainability of the design of a supporting structure for an OCLS?
3. Which parameters and variables define the design of the OCLS supporting structure?
4. How can the degree of sustainability be influenced when designing the OCLS supporting structure?
5. What are the implications of sustainability on the current design of the OCLS supporting structure?

1.5 Outline

As stated above, the aim of this research is to explore the design space for sustainable OCLS structures on the main Dutch rail network. To do so, the article is structured as follows.

Section 2 reviews the state of the art in support structures for OCLS, categorised into structural characteristics, maintenance management, decision support systems, and prevalent frameworks. Section 3 discusses the design process for OCLSs at ProRail, including a stakeholder analysis to identify varying interests and perspectives affecting the design.

Design requirements and specifications for OCLS structures are detailed in section 4, focusing on technical specifications, European and national standards, and governing regulations. Essential requirements are derived from an analysis of these specifications. This chapter outlines the necessary requirements and specifications for designing support structures within the main Dutch rail network.

Sustainability in OCLS structures is discussed in section 5, defining it in line with rail industry and ProRail goals. The chapter reviews assessment methodologies and criteria for evaluating sustainability in support structure designs, addressing which methods effectively determine sustainability.

Building on previous insights, a multi-objective optimisation model for OCLS structures is developed to explore sustainable design possibilities. Section 6 covers the model's theoretical basis, including problem statement, assumptions, objectives, and constraints. It employs the NSGA-II genetic algorithm for optimisation, with detailed discussions on its framework and the implementation of crossover and mutation elements.

Detailed model implementation and optimisation are discussed in section 7, including modifications to the NSGA-II framework, the custom fitness function, and Python implementation and validation. The results and trade-offs for a sustainable support structure design, based on the Pareto frontier, are presented in section 10. Further result analyses elucidate the defining parameters and variables of the support structure design. Section 8 explores the results' interpretations and broader implications, including their impact on sustainability and the design of the OCLS support structure, addressing the final subquestions.

Based on the discussion, the conclusion of the research on the key design variables for the sustainable design of a support structure for an OCLS is drawn and presented in section 12. Finally, recommendations are given for future research.

2 State of the Art of Support structures for OCLS

The OCLS is defined as a support system and contact line that supplies electric energy to vehicles, with its main components being the support structures. These structures are crucial for the safe and reliable operation of rail networks and are subject to various standards such as NEN-EN 50119. The literature and standards emphasise the importance of reliability, safety, and security in their design and maintenance. Significant literature, including standard reference works such as those by Kiessling, Puschmann, Schmieder, *et al.* and Keenor, provides practical insights into the design and analysis of OCLS, particularly in the context of European and British railways. Research indicates that while these structures are structurally simple, they require substantial investment due to their large numbers and the costs associated with their lifecycle. Standardisation of these structures, as discussed by Perera, Nagarur, and Tabucanon and Rechena, Infante, Sousa, *et al.*, generally reduces costs and is beneficial, especially for smaller networks. The visual aspect of these structures also plays a critical role in public acceptance, particularly in urban settings. Designed structurally, these support structures are designed to withstand various environmental and operational stresses, including extreme weather events and operational vibrations, which could potentially compromise their integrity and safety. The choice of materials, such as prestressed concrete, has evolved to enhance the durability and reliability of these structures. In general, the design, standardisation and maintenance of OCLS support structures are vital to the efficient and safe operation of electrified railways.

Maintenance management and monitoring and evaluations

Challenges and innovations in maintenance and performance evaluation of the railway infrastructure due to ageing systems and increased safety demands. Key studies focus on the heterogeneity of designs and the complexity it introduces, advocating a systems thinking approach that combines mechanistic and data-driven methods for asset management ([7]). Various methodologies such as the Markov Estimator and Bayesian inference are used to assess the reliability of structures such as prestressed concrete poles and steel structures, with particular attention to the effects of corrosion over time ([8]; [9]; [10]). The adoption of digital twins and preventive maintenance strategies is discussed as cost-effective solutions to improve the longevity and reliability of the infrastructure ([11]; [12]; [13]). In addition, the implementation of Prognostics and Health Management (PHM) systems is highlighted to modernise asset management and reduce operational costs, with a call for further standardisation and research to optimise monitoring techniques ([14]; [15]; [16]).

Decision support system and Decision-making framework

Recent advances in decision support systems (DDS) for railway infrastructure focus on improving maintenance and design processes. Key studies, such as those of Sedghi, Kauppila, Bergquist, *et al.*, Jamshidi, and Xu, Lai, and Huang, highlight the adoption of predictive maintenance strategies that significantly reduce costs and improve efficiency compared to traditional methods. DDSs are integral in the management of complex design requirements and standards, as noted by Berthold and Garcia, Gomez, Saa, *et al.*, who also emphasise the reduction of design times and errors through automated solutions such as the EL-BAS OLACAD tool. Furthermore, the shift towards multiobjective DDS approaches, as discussed by Peralta, Bergmeir, Krone, *et al.* and Chen, Zhang, Liu, *et al.*, incorporates various performance metrics such as cost, serviceability, and passenger comfort, often outperforming expert-developed schedules. These systems utilise advanced algorithms such as Pareto-based methods and particle swarm optimisation to optimise maintenance and design decisions, reflecting a trend toward more integrated and efficient infrastructure management.

Identified knowledge gaps highlight the need for in-depth research, particularly in maintenance and asset management, crucial throughout the technical lifetime of support structures. Research aims to improve understanding of structural conditions, optimising maintenance timing and efficiency. This includes improving the accuracy of the assessment of structural conditions, supporting condition-based maintenance, which is performed only as needed, and enhancing process efficiency. In addition, the growing use of monitoring and data collection informs maintenance decisions and supports the development of models capable of handling increasing data volumes and complexity. These models are essential for optimising multiple objectives in environments such as expanding rail networks with limited maintenance opportunities. Advanced algorithms are crucial to leverage these models in decision-making. A significant gap remains in understanding the role of sustainability in the design and life cycle of structures, with current research focussing on integrating sustainability into the design process.

OCLS support structures are crucial to railway infrastructure, with substantial knowledge developed over time. Recent literature indicates a trend towards standardised designs, though diverse designs and methods persist across networks. The researchers focus on in-depth structural studies, including extreme load effects and assessing structural conditions. Recently, there is heightened interest in maintenance planning and scheduling from a multicomponent and network perspective, alongside condition-based maintenance policies. Monitoring methods and systematic maintenance planning using decision-making frameworks are also gaining attention. In addition, the use of complex models to support decision making is increasing. Despite the growing importance of sustainability, research in this area remains limited. These observations highlight several significant knowledge gaps.

- Further understanding and development of methods on the structural condition of the structures.
- Use of condition-based maintenance using structural models and new monitoring methods.
- Further development of multi-objective decision-making models, as well as the implementation of more complex algorithms
- Impact and influence of sustainability on the design and maintenance of support structures

3 Design Process and Stakeholders

3.1 Design Process for OCLS

The design process for OCLS on the Dutch railway network, governed by ProRail's regulations and based on the System Engineering (SE) approach as detailed in the Handbook [23]. This approach optimizes the system's lifecycle and has been adopted across the Dutch civil engineering sector, with guidelines published by ProRail to ensure national uniformity [24]. The design process incorporates a model distinguishing three main phases: modeling, functional design, and physical design, with a looping interaction between the last two phases. The process is structured into seven development phases: Needs Analysis, Concept Exploration, Concept Definition, Working Draft Definition, Detailed Elaboration, Realisation, and Management & Operation, each crucial for the system's lifecycle and described in the design specification OVS00024 and RVOI [25]. The design must adhere to ProRail's standards and regulations, using only approved products [25], and is carried out by accredited consulting engineering firms [26].

3.2 Stakeholder Analysis for OCLS

The identified stakeholders involved in the design process of OCLS are discussed. Adapting the stakeholder categories defined by the NEN-EN50126 standard, which includes railway companies, infrastructure managers, maintenance companies, rail supply industry, and safety authorities. The maintenance category is replaced by Consulting Engineering Firms (CEF), and a government category is added. Key stakeholders include ProRail, which plays a central role in all design phases, and various consulting firms that contribute to research, design variants, and feasibility studies. The design process is segmented into phases, each involving specific stakeholders with distinct roles, ensuring compliance with regulations and alignment with transportation policies. The table provided lists stakeholders classified by their roles, emphasising the limited number of companies allowed to participate in the design, manufacture, or supply of OCLS due to ProRail's accreditation scheme. References include citations to relevant standards and lists of accredited companies and certified products.

To conclude, the OCLS design process is structured into seven phases and adheres to a system engineering approach. ProRail manages this process under strict regulations and accreditation to ensure standard compliance. The importance of collaborative efforts among stakeholders, including government bodies, infrastructure managers, and engineering firms. These collaborations, along with ProRail's commitment to safety and regulatory compliance, are crucial to achieving safe, efficient, and sustainable rail infrastructure.

4 Design Requirements and Specifications for OCLS

This section outlines the design requirements and specifications for OCLS on the Dutch railway network, focusing on the development of a new superstructure. It integrates various regulations and standards from legal, technical, and policy frameworks, as detailed in earlier sections and analysed using system engineering techniques. Key sources include Technical Specifications for Interoperability and European and national regulations, discussed in respective sections. Concludes by summarising essential findings for the design of OCLS support structures, providing a comprehensive overview of the necessary compliance and design considerations.

The European Union has established Technical Specifications for Interoperability (TSI) to ensure the interoperability of the railway system across the EU. These specifications, managed by the European Union Agency for Railways and outlined in Directive 2016/797 [27], set the technical and operational standards for subsystems and components. Essential requirements such as safety, reliability, and environmental protection are defined for these subsystems, which include Energy, Infrastructure, Noise. Specific TSIs, like those for Energy [28] and Infrastructure [29], address detailed aspects such as the electrification system and track elements. The European Railway Agency also provides guides for applying these TSIs, aiming to harmonise components like the overhead contact lines to enhance interoperability within the European Railway Network. Additionally, compliance with European and National Standards, such as NEN-EN50119:2009 [30], is crucial in the design process for these systems.

The NEN-EN 50119 standard addresses the design and implementation of OCLS for electric traction, including flexible overhead contact line (FOCL) and rigid overhead contact line (ROCL) systems. It outlines the use of automatic tensioning and fixed anchor points to maintain tension in FOCL systems, and rigid profiles or anchorage systems to stabilise ROCL systems. The standard is applicable to various rail systems, including heavy and light rails, and covers both the electrical and structural aspects of these systems. Specifies different types of support structures based on the forces they need to withstand, such as pole structures, rigid cross-section structures, suspension structures, and tension structures. The standard emphasises robust design to enhance safety and reliability, using the structural limit states method to define the ultimate and serviceability limit states for evaluating structural integrity and performance.

The NEN-EN 15273 standard details specifications and regulations for railway gauges within the European Union, divided into three parts. Part 1 outlines general principles and the interface between infrastructure and rolling stock, including reference profiles and rules[31]. Part 2 focusses on rolling stock, discussing dimensioning and calculation methods based on gauge characteristics[32]. Part 3 addresses infrastructure dimensioning and operational constraints related to specified gauges[33]. The gauge is defined as a spatial agreement between infrastructure and rolling stock, essential for ensuring interoperability across European railways, including those defined in the Infrastructure TSI[34].

The Structural Eurocode programme, initiated in 1975 and formalised in 1989, aims to harmonise technical specifications across the European Union. It introduces a series of 10 standards known as 'Eurocodes' which provide a unified approach to structural design applicable to various materials. The foundational standards, particularly NEN-EN 1990, outline essential principles and requirements for safety, serviceability, and durability of structures. These are based on the limit state concept combined with partial factors method, elaborated in NEN-EN 1990 [35]. While NEN-EN 1990 serves as a general guideline, material-specific standards should be applied as necessary.

ProRail, as the infrastructure manager of the Dutch railway network, has developed a comprehensive set of company regulations, supplementing national and European standards. These regulations are crucial to ensure safety and uniformity in material usage and process execution within the network, as highlighted in section 3. The regulations vary according to the infrastructure's lifecycle phase and document type, in accordance with RAMS standards [36], [37]. This differentiation also aligns with the Systems Engineering approach adopted by ProRail, a common methodology in the Dutch civil engineering sector [23]. Details on these regulations are available in the Rail Infra Catalogues.

The analysis of design requirements for the support structure of the OCLS on the Dutch railway network is carried out employing a system engineering methodology. The Systems Engineering is well integrated with ProRail's practices, as noted in [23]. The analysis begins with the identification of 148 potential requirements through a middle-of-the-way strategy and a snowball search method, ensuring a comprehensive review of relevant documents. Following identification, the relevance of the requirements is analysed and categorised into functional, non-functional, and constraints, which are then prioritised according to their impact on the design. This prioritisation helps to efficiently address critical requirements first, considering trade-offs and dependencies. Prioritised requirements are classified into 18 different groups. Finally, the constraints are analysed to understand their implications on design feasibility and compliance, identifying 43 as objectives and 105 as constraints.

In conclusion, the analysis of the requirements of the OCLS support structure in the Dutch rail network highlights safety as a fundamental requirement, as detailed in RLN0009[38]. This is crucial to ensure the reliability of rail infrastructure through rigorous structural analysis. The requirements are crucial for the overall functionality and safety of the system, which is a primary focus in the design process according to OVS00024-2.1[25]. However, economic considerations also play an important role, necessitating a balance between cost-efficiency and safety. Designers are encouraged to achieve a technically and financially optimal solution that adheres to safety standards while considering lifecycle costs and potential deviations that meet overarching requirements. This approach ensures that both safety and economic factors are taken into account to achieve an optimal design solution.

5 Sustainability within the Dutch Railway Branch

5.1 Definition of Sustainability

First to definition of sustainability has been defined by analysing key documents such as the Brundtland Report (Our Common Future) [39], the Paris Climate Agreement [40], the European Green Deal [41], the Dutch Climate Agreement [42] and the National Circular Economy Programme [43]. It aims to elucidate the core principles and dimensions of sustainability, highlighting the interplay of environmental, social, and economic factors. The Brundtland Report emphasises sustainable development without compromising future generations, focussing on equity and resource management. The Paris agreement seeks to limit global temperature increases, improving resilience to climate change through renewable energy and efficiency improvements. The European Green Deal aligns with these goals, setting ambitious targets for the EU. Similarly, the Dutch initiatives aim to reduce emissions and promote circular economy practices. Collectively, these documents underscore the need for global co-operation, innovation, and policy alignment to foster a sustainable and resilient future.

5.2 Ambitions of the Rail Branch: ProRail

The sustainability ambitions and strategies of ProRail are reviewed. ProRail is committed to sustainability, focusing on reducing CO2 emissions, energy consumption, and promoting a circular economy. Key initiatives include a comprehensive roadmap to sustainability, adherence to the Railway Climate Responsibility Pledge, and the implementation of the 'CO2 and Energy Savings Strategy 2021-2025'. ProRail also supports the CO2 Performance Ladder to encourage CO2 reduction in infrastructure projects and is actively following the principles of circular economy to minimise environmental impact. These efforts are part of ProRail's broader goal of achieving carbon neutrality by 2050 and improving the sustainability of rail transport in the Netherlands. References include [44], [45], [46], [47], [48], [26], [49], and [50].

5.3 Methods for Determining Sustainability

Various methodologies for assessing sustainability in the Netherlands have been reviewed, focusing on the Life Cycle Assessment (LCA). LCA evaluates the environmental performance of products or systems from creation to disposal, as per the EN 15804 standard. Consider factors like energy use, emissions, resource depletion, and waste generation. Quantitative methods and software tools, supported by databases such as the Dutch National Milieu Database or Ecoinvent, are used to ensure comprehensive environmental data analysis and sustainable decision making [39], [51], [52].

In conclusion, sustainability has been explored in the Dutch rail sector, focusing on its definition, objectives, and measurement methods. Key documents such as the Brundtland Report, the Paris Climate Agreement, and the European Green Deal, along with national initiatives like the Dutch Climate Agreement and the National Circular Economy Programme, have been reviewed to understand the core principles of sustainability. ProRail's initiatives, including the Railway Climate Responsibility Pledge and CO2 Performance Ladder, exemplify the integration of sustainability in rail operations. Methodologies such as Life Cycle Assessment (LCA) and the Circularity Indicator are highlighted as effective tools for assessing environmental impacts and promoting circularity in projects. The chapter concludes that achieving sustainability in the rail sector requires ongoing collaboration and innovation.

6 Theoretical Foundations of Multi-Objective Optimisation Model

Building upon the insights of the research discussed in the previous sections, a multi-objective optimisation model has been formulated to determine the potentially sustainable design space for OCLS. In this section, the theoretical foundations of the model are discussed.

6.1 Multi-objective problem formulation

The complex and multi-faceted nature of the design problem based on insights from; the complexity and stakeholder considerations, the critical structural requirements, and the sustainability indicators. The design problem is defined as a multi-objective optimisation challenge aimed at balancing safety, environmental, and economic factors within a sustainable design space. The main objectives include minimising environmental impact through reduced emissions and energy use and enhancing circular efficiency, alongside reducing economic costs.

6.2 Assumptions

The model assumes that the support structure is on the Dutch rail network, focussing on the pole's cross-sectional design. Consider only the production and end-of-life stages of the life cycle assessment (LCA) as key stages. The structural assessment adheres to RLN0009 [38], assuming elastic bending of the materials and linear stress-strain relationships across all stress levels, following Hooke's law [53]. The support structure is located on a straight track segment within a normal section of the catenary system, with the maximum allowed span length.

6.3 Objective functions

Objective functions of the objectives stated above are specified below. For each of the functions, in addition to the formulation, the motivation for the formulation of the function is given.

The focus is on reducing the carbon footprint of a pole design. Carbon emissions are identified as a crucial indicator for assessing environmental impact. Due to the complexity of calculating total emissions in all design stages, the analysis is narrowed down to the emissions of the material used for the pole. The objective function formulated calculates the carbon footprint based on the CO_2 equivalent per kilogramme of the selected material, the density of the material, the cross-sectional area of the pole and its length. The formula is:

$$\text{Minimise } f_{CO_2 \text{ footprint}}(x) \tag{1}$$

$$f_{CO_2 \text{ footprint}}(x) = C_{CO_2\,m} \cdot \rho_m \cdot A \cdot L_{\text{Pole}} \tag{2}$$

Minimising embodied energy in pole design, which is considered a secondary objective to evaluate environmental impact. The energy embodied represents the total energy required to produce the material used in the pole. The objective function to minimise the embodied energy, labelled $f_{\text{Embodied Energy}}(x)$, is defined as the product of the embodied energy per unit mass of the material ($C_{EE\,m}$), the cross-sectional area (A) and the length of the pole (L_{Pole}). This function is crucial for evaluating the environmental footprint of the pole design.

$$\begin{aligned} &\text{Minimise } f_{\text{Embodied Energy}}(x) \\ &f_{\text{Embodied Energy}}(x) = C_{EE\,m} \cdot A \cdot L_{\text{Pole}} \end{aligned} \tag{3}$$

Circularity, particularly Circular Efficiency, is a crucial indicator in assessing sustainability, as discussed in section 5 and defined by the NMD [54]. The formula for Circular Efficiency, which measures the ratio of environmental benefits to production costs, is given by:

$$\text{Circular Efficiency} = \frac{C_{\text{Module D}}}{C_{\text{Module A1-A3}}} \tag{4}$$

This efficiency is calculated by considering the proportion of recyclable material in a product's design, influencing material selection due to its significant environmental impact. The environmental impact of materials, categorised into virgin, recycled and typical based on embodied energy and carbon emissions, is computed using the following.

$$X_{\text{Typical}} = (1 - RF) \cdot X_{\text{Virgin}} + RF \cdot X_{\text{Recycling}} \tag{5}$$

The recycling factor (RF) represents the proportion of recycled material in production. Circular efficiency also considers the ratio of recycling to the values of virgin material, indicating the potential environmental benefits of recycling. Lower values of this ratio suggest a higher circularity potential, which promotes material reuse. The objective functions for minimising carbon emissions and embodied energy in terms of circular efficiency are:

$$\text{Minimise } f_{\text{Circular Efficiency},CO_2}(x) \tag{6}$$

$$f_{\text{Circular Efficiency},CO_2}(x) = \frac{C_{CO_2,\text{recycling } m}}{C_{CO_2,\text{virgin } m}} \tag{7}$$

$$\text{Minimise } f_{\text{Circular Efficiency, EE}}(x) \tag{8}$$

$$f_{\text{Circular Energy, EE}}(x) = \frac{C_{\text{EE,recycling } m}}{C_{\text{EE, virgin } m}} \tag{9}$$

The economic impact of a pole design is considered by minimising costs, focussing on the material price as a key factor. Maintenance and installation costs are generally negligible and uniform, respectively. The fluctuation in materials costs over time is noted and further details are provided in **??**. The cost function is defined as:

$$\text{Minimise } f_{\text{Cost}}(x) \tag{10}$$

$$f_{\text{Cost}}(x) = C_m \cdot \rho_m \cdot A \cdot L_{\text{Pole}} \tag{11}$$

This cost function is interconnected with the carbon emissions (Eq.2) and embodied energy (Eq.3) through the cross-sectional area, complicating the trade-off among these objectives. The selection of material or pole shape by the algorithm is crucial in managing these trade-offs.

6.4 Constraints

The model incorporates several constraints applied to the fitness function. Key constraints include deflection limits based on RLN0009 standards, ensuring that the structure withstands various load combinations safely, as verified by design resistance and shear stress constraints. Additionally, shape feasibility is checked using Ashby's shape factor, and Eurocode 3's thickness and width ratio requirements. Specific displacement constraints for the pole under permanent loads dictate that the top pole displacement in the x-direction must not exceed 1% of the pole's length, as shown in the equation:

$$\delta_{\text{Top Pole},x} \leq 1\% \cdot L_{\text{Pole}}$$

Similar constraints apply for wind loads affecting the contact wire's displacement in both horizontal and vertical directions, related to the track's speed limit. These constraints are crucial for the model's design and operational validity.

An additional constraint within the model focusses on shear stress, emphasising the importance of not exceeding the yield strength in the design of materials. at the outer edges of a pole under bending stress. The maximum shear stress is calculated using the formula:

$$\sigma_m \leq \frac{M_y Y_y}{I_y}$$

Where σ_m is the yield strength, M_y is the bending moment, Y_y is the distance from the neutral axis, and I_y is the moment of inertia. This ensures that the material does not undergo plastic deformations that exceed its elastic limit. The constraint on shape factors explains how the geometry of a section affects its bending efficiency and stiffness, emphasising the need to optimise shape to minimise material use while avoiding structural weaknesses like buckling. The shape factor for a square beam is used as a reference to set constraints on the design of other shapes, ensuring that they remain within practical limits of stiffness and material properties.

The shape factor ϕ_B^e must not exceed the maximum allowed shape factor $\phi_{B,\text{Max}}^e$. Shape factor is calculated by:

$$\phi_B^e \leq \phi_{B,\text{Max}}^e$$
$$\phi_B^e = 12\frac{I}{A^2}$$

The constraints based on the width-to-thickness ratio of shapes in steel structures as specified in Eurocode 3[53]. A conservative approach is adopted to improve the reliability and feasibility of pole-shaped design. The section explains the classification of cross-sections into four classes based on their force resistance and rotational capacity, which are crucial for assessing the structural integrity and performance under stress, particularly local buckling. Class 3 limits are specifically used for this constraint, allowing for a wide range of values for the width-to-thickness ratio to increase design feasibility. The mathematical constraints for Class 3 are:

Class 3 formulas:

Bending

$$\frac{c}{t} \leq 124 \cdot \epsilon$$

Compression

$$\frac{c}{t} \leq 42 \cdot \epsilon,$$

Outer, Rolled section

$$\frac{c}{t} \leq 14 \cdot \epsilon,$$

Tubelar, Bending and compression

$$\frac{d}{t} \leq 90 \cdot \epsilon^2$$

$$\epsilon = \sqrt{\frac{235}{f_y}},$$

The constraints on the objective functions cover several aspects related to cost, CO2 emissions, and embodied energy, incorporating maximum values pertinent to ProRail's operations. The maximum cost parameter is based on Sweco's cost analysis for OCLS works and materials (Sweco, [55]). Furthermore, CO2 emissions data for the HEA300 support pole, sourced from the ProRail-commissioned NMD environmental chart [56], are considered per metre of pole length. The energy data, derived from the CES Edupack dataset for Steel S235, pertain to the HEB300 support pole.

The constraints are represented as follows:

$$C_{\text{Cost, max}} = 2750$$
$$C_{\text{CO2 Footprint, max}} = C_{\text{HEB300}} \cdot L_{\text{Pole}}$$
$$C_{\text{CO2 Footprint, max}} = 2906.6\text{Kg } CO_2 \text{ eq.}$$
$$C_{\text{Embodied Energy, max}} = C_{\text{S235}} \cdot A_{\text{HEA300}} \cdot L_{\text{Pole}}$$
$$C_{\text{Embodied Energy, max}} = 2.495\text{MJ}$$

6.5 Structural Analysis

The proposed pole design is structurally evaluated to assess its integrity, following the RLN0009 guidelines [38]. The following assumptions are made for simplifications. Insulator loads are neglected, as they have minimal impact. Wind load is considered to act perpendicularly in the positive x-direction. All dimensional, dynamic factors, and pressure coefficients are constant. The structure's deformation is modelled using elastic bending, assuming a linear stress-strain relationship at all stress levels. According to Hooke's Law, materials return to their original shape post-stress. This elastic model helps determine internal forces and moments, despite material resistance being based on the capacity for plastic deformation [53].

7 Implementation and Validation of the Multi-Objective Optimisation Model

7.1 Model Framework

The model framework designed to explore the design space, is based on the standard NSGA-II framework. A widely used genetic algorithm to solve these MOO problems is the NSGA-II, proposed by Deb et al. It is a prominent solution in this domain due to its ability to efficiently provide Pareto optimal solutions [57]. Numerous comparative studies, covering the application of the NSGA-II algorithm to MOO, have been carried out [58] [59] [60].

The model incorporates a uniform crossover to merge genetic information from parent solutions, enhancing diversity and exploration within the population [59]. As mutation, an adaptive mutation strategy is incorporated. This strategy adjusts mutation rates based on the fitness attributes of the population to alter the solutions of the offspring, improving the exploratory and convergent capacities [61]. Mutation rates are dynamically reconfigured throughout the optimisation cycle by assessing solution performance through fitness values, diversity indices, or convergence rates [62]. The gene space for this model is formed by following design variables. The following design variables are used to define the pole's design through its material, commonly used steel beam shapes, and specific dimensions such as width, height, and flange thickness.

The framework includes two filters: one pre-fitness function for the population and another pre-crossover for the parents. Pre-fitness function filtering of the population aims to improve solution quality by removing infeasible solutions, defined as those violating deflection or shape design constraints, and replacing them with feasible ones. Replacement candidates are chosen from the existing population using the Pareto front and crowding distance metrics. These metrics help identify the top replacements. If infeasible solutions outnumber feasible ones, the latter are recycled.

The precrossover filtering ensures that only feasible or minimally infeasible solutions within defined boundaries are used as parents for the next generation. This process aims to maintain the reliability and feasibility of the selected parent solutions. By excluding solutions that violate constraints, the algorithm improves and refines its strategy for future generations. Parent solutions undergo a filtration process based on their constraint scores, which indicate any constraint violations. Solutions that do not meet the constraints are identified by the highest constraint score, and infeasible solutions are removed for cross-selection. If all initially chosen solutions violate the constraints, alternative solutions are considered. Parents are chosen based on their constraint scores to find those with the least violations. The framework of the model configuration is illustrated in Figure 1, along with the pseudo code of the model is provided.

Algorithm 1: NSGA-II Adaptation

input : Initial population P_{Initial}, Stop criteria
output: Final population P_{Final}

Initialisation;
Initialise population randomly from design variable ranges;
while *Stop criteria not met* **do**
  Population Filtering;
  Filter the Population P for feasibility.;
  Infeasible solution are replaced with feasible non-dominated solution in current population P ;
  Fitness Function;
  for *each individual* ind *in* P **do**
    Compute fitness of ind;
  end
  Parent Selection;
  Perform non-dominated sorting and crowding distance determination on P;
  Select parents based on non-dominated fronts and crowding distance;
  Export selected parents and all feasible solutions in P;
  Parents Filtering;
  Filter the selected parents for feasibility.;
  Crossover;
  Perform crossover on the selected parents to create offspring;
  Mutation;
  Apply adaptive mutation on the offspring;
  New Population Update;
  Update P with the new offspring population;
end
Output:;
Final population P_{Final} after meeting stop criteria.

7.2 Fitness function

Within the fitness function, each solution's fitness is evaluated and integrated with model constraints. The fitness function includes a constraint score to track violations, based on a methodology that checks the compliance of the solution with constraints using the function of Milatz, Winter, Ridder, *et al.* All constraints are equally significant [63], and compliance is measured by percentile violation. Full compliance awards a maximum score of 10, which is adjusted by rounding the percentile violation to a decimal, then multiplying. This integer score is deducted from the solution's current constraint score, ensuring that feasible solutions receive high scores while infeasible ones get negative scores. The maximum achievable constraint score is 1260.

Fulfils the constraint:

$$C_{\text{Score}} = C_{\text{Score}} + 10$$

Violates the constraint:

$$C_{\text{Score}} = C_{\text{Score}} - (10 \cdot \frac{(x_{\text{Sol}} - x_{\text{Con}})}{x_{\text{Con}}})$$

Where C_{Score} is the constrain score of a solution, x_{Sol} is the value of the solution for the constrain and x_{Con} is the constrain value. The fitness function, a central component of the model, evaluates each population solution to determine its fitness value and total constraint score. Initially, design variables such as material type, pole shape, and dimensions are extracted, with material properties like Young's modulus, yield strength, Poisson's ratio, and density sourced from the dataset. Next, pole shape properties like inertial moments and cross-section are derived in the pole cross-section element, assessing them against Cross-Section Constraints including Width-Thickness Ratio and Shape Factor. Deflections at the pole top are calculated in the x- and y-directions using linear elastic bending, filtering out infeasible solutions that exceed displacement constraints. Feasible solutions undergo further structural analysis for specified load cases, evaluating structural constraints such as design resistance, ground support stability, displacement, and shear stress. After the analysis, the fitness values for objectives such as CO_2 footprint, embodied energy, and the costs are determined on the basis of these constraints. If constraints are violated, the constraint score is adjusted and the circular efficiency is calculated for the footprint of embodied energy and CO_2. Finally, the fitness function outputs fitness values for each objective, calculating the overall constraint score, updating solutions in the population based on these scores, and using these values for algorithm optimisation.

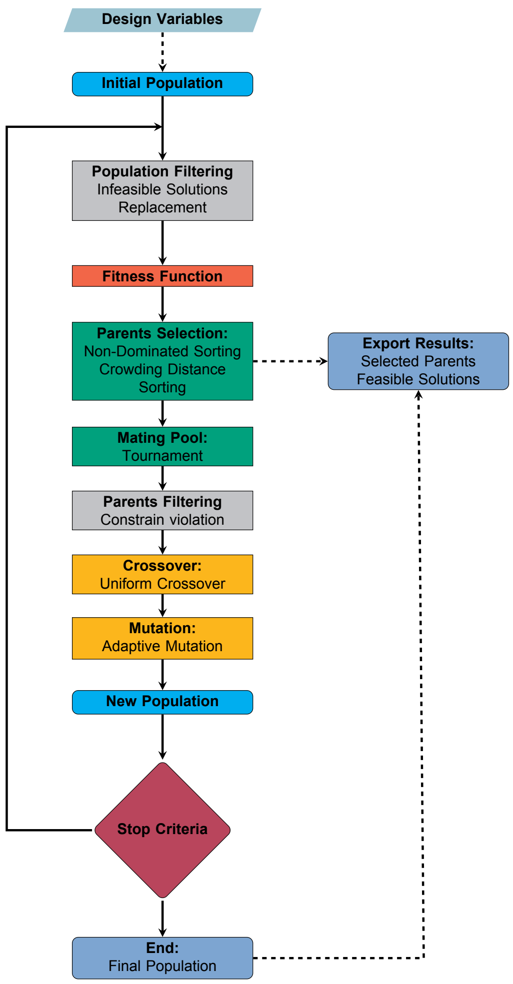


Figure 1: Overview of the model framework

7.3 Data

This section presents the data used for model optimisation, including material data for various pole variations and the selected pole shape designs with their dimensional ranges. The material dataset for the model is sourced from Granta Edupack 2023 R2, specifically the Level 3 Materials dataset. This dataset provides detailed properties for each material, categorised by family in Granta EduPack. All materials from Granta Edupack were reviewed to ensure that they possessed the requisite properties for model input. Any materials that lacked any required property were excluded from the dataset. An overview of the ranges of the material properties selected for model input is provided in Table 1

Table 1: Material Properties: Level 3 Materials Dataset

Dataset	Level 3 Materials	
Total number	166080	
Selection	97293	
Material Property	**Min**	**Max**
CO_2 Footprint Typical [kg/kg]	0.025	45900
CO_2 Footprint Recycling [kg/kg]	0.025	2200
CO_2 Footprint Virgin [kg/kg]	0.025	65100
Density [kg/m^3]	$7.32 \cdot 10^{-6}$	570
Embodied Energy Typical [MJ/m^3]	400000	$1.12 \cdot 10^{12}$
Embodied Energy Recycling [MJ/m^3]	400000	$2.8 \cdot 10^{8}$
Embodied Energy Virgin [MJ/m^3]	400000	$1.37 \cdot 10^{12}$
Poisson Ratio [-]	0.06	0.5
Price [€/kg]	0.0187	603000
Yield Strength [MPa]	1130	$3.6 \cdot 10^{9}$
Young's Modulus [GPa]	7320	$5.7 \cdot 10^{11}$

The model employs nine standard pole shapes as design variables, including Solid Rectangular Beam, H-Beam, I-Beam, UNP, T-Beam, and various Tubular Beams. The dimensional design variable ranges, detailed in Table 2, adhere to practical minimum and maximum limits from the Bouwen met Staal profile database [64]. Initially, the use of broader intervals led to the generation of shapes that were not feasible, prompting the introduction of these specific limits in order to enhance the validity of the model.

Table 2: Range for Dimensions of Design Variables

Dimension	Min	Max	Step size
Height [mm]	100	500	10
Width [mm]	100	400	10
T_w [mm]	2	20	1
T_f [mm]	2	30	1
T_t [mm]	2	40	1

T_w, T_f, and T_t denote the web, flange, and tubular thicknesses, respectively, for UNP, H-, I-, and T-beams. For round tubular sections, the diameter is the maximum of width or height.

7.4 Software Implementation - Python

The Python programming language [65], known for its open-source nature and extensive library of modules, was utilised to develop the model for the optimisation problem. For this, the PyGad package [66] was used, which offers various genetic algorithms including NSGA II, which was used in its tournament selection version to enhance optimisation. Furthermore, the PyNite package [67] facilitated the analysis of finite elements of elastic 3D structural engineering under combined load conditions, allowing the evaluation of deflections in the support structures according to the specified standards and constraints.

This section discusses the fitness function formulated for the model. Initially, a graphical representation of the function is shown in Figure 14, which is followed by an explanation of the function flow.

8 Model Validation

This section discusses the validation of the model, its sub-modules, and the data used. It begins with the structural analysis, followed by the environmental data, and concludes with the model's validation using Hyper Volume and constraint score.

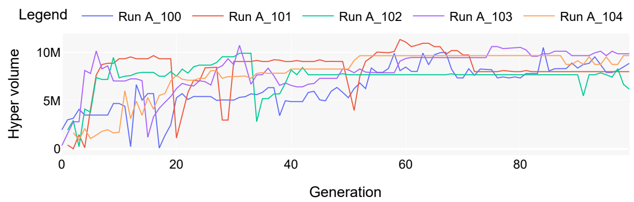
The Pynite package, used for the structural analysis of the pole and portal designs, facilitates 3D modelling, support structure analysis, and deflection computations. First-order analysis determines deflections and stress distribution, complying with [30] and [38]. To validate the module, both pole and portal models were confirmed. Additionally, an expert[1] reviewed the structural model for result accuracy and practical applicability. Deflections in the pole design were validated against RLN0009.v5 [38], showing similarities to example results. Note, minor discrepancies may occur due to Python's float handling.

To validate the environmental data in the model and ensure result applicability, CO_2 footprints and embodied energy for H beams were recalculated based on the LCA by ProRail for NMD [56]. The environmental profile yielded impact categories such as Global Warming Potential and Climate Change for CO_2 footprint, and 'Energy, primary, renewable', 'Energy, primary, non-renewable', and 'Resource use, fossils' for Embodied Energy. The model uses typical values from the Granta Edupack dataset, with CO_2 footprint for structural steel S235 at 1.85 kg/kg and embodied energy at 17.5 MJ/kg. The CO_2 footprint values align with Granta Edupack, suggesting similar emissions. However, embodied energy values differ significantly from S235, resembling the impact category of Resource Use, Fossil. These discrepancies arise from source type dependencies. The Granta Edupack val-

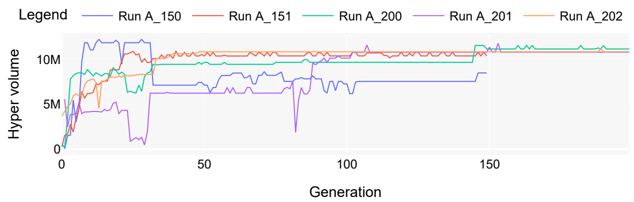
[1] Wim Golverdingen, Senior Consultant OCLS, SWECO Nederland

ues, based on literature and life cycle inventories, are estimated when data is lacking [68]. Thus, model results are indicative and should be considered arbitrary in impact determination.

The hyper-volume indicator evaluates multi-objective optimisation algorithms by measuring the volume dominated by non-dominated solutions. A reference point, defined by the maximum values in each dimension for minimisation problems, bounds this volume. The volume, composed of hyper-rectangles with a common vertex at the reference point, quantifies the coverage of the objective space by these solutions [69]. Higher hyper-volume values suggest a closer approximation to the true Pareto front, though computational costs must be considered [70]. Hyper-volume also validates NSGA-II models in these problems [71], [58]. For model validation, hyper-volume is calculated using the algorithm from Fonseca, Paquete, and López-Ibáñez [69], considering cost, CO_2 footprint, and embodied energy, but excluding circular efficiency objectives due to unknown reference values. Only solutions that meet all constraints are considered. Plots in Figure 2 show hyper-volume over 100, 150, and 200 generation runs, indicating model stabilisation and consistent coverage of the objective space, validating the model's consistency [69].



(a) Runs 100 Generations



(b) Runs 150 and 200 Generations

Figure 2: Convergence Plots of Hyper Volume

Three runs with 250, 500, and 1000 generations were conducted to examine the model's behaviour with increasing generations. The hyper-volume plot is shown in Figure 3. The model stabilises upon reaching the Pareto frontier, though occasional hyper-volume drops indicate the detection of new potential Pareto frontiers, highlighting the model's ability to escape local optima. These drops also show the model's sensitivity to local optima, a result of the algorithm's inherent randomness. This sensitivity is an important consideration when interpreting results, despite the model's generally quick stabilisation.

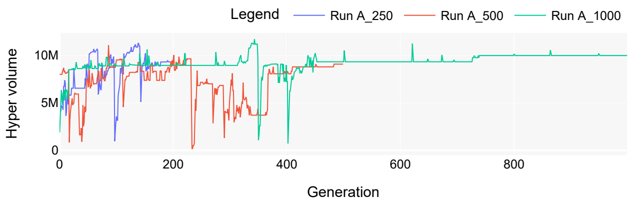
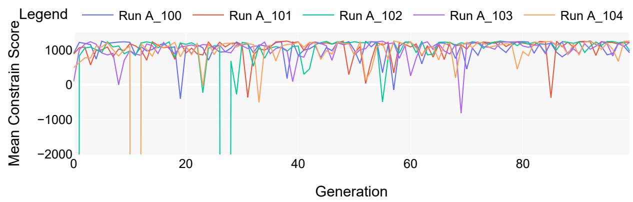
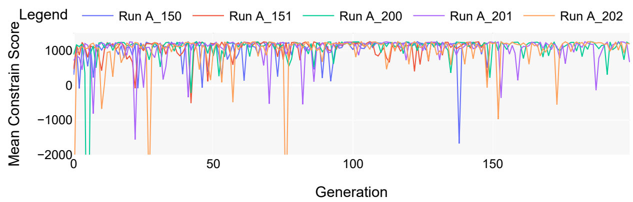


Figure 3: Convergence Plots of Hyper Volume of Runs With 250, 500 and 1000 Generations

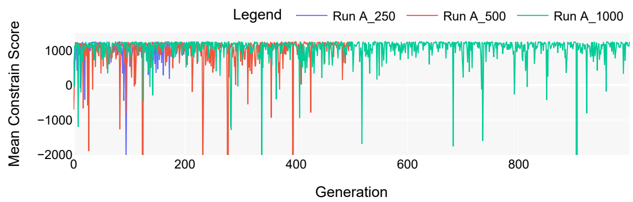
The constraint score validates the model by indicating if a solution violates any constraints. It reflects the algorithm's effectiveness in identifying compliant solutions. Ideally, all parent-selected solutions should be compliant, forming a non-violating new population. For validation, both the aggregated and mean constraint scores per generation of parent-selected solutions are monitored. These scores should ideally increase and stabilise at the maximum value of 37800, indicating full compliance across generations.



(a) Runs 100 Generations

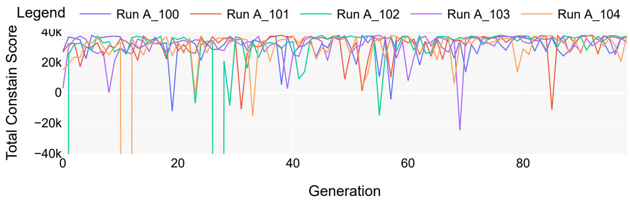


(b) Runs 150 and 200 Generations

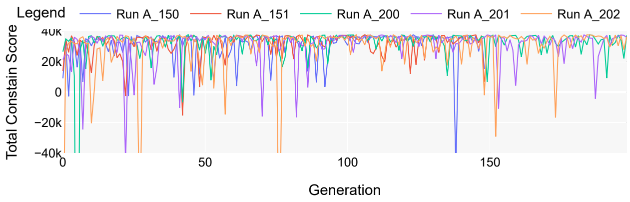


(c) Runs 250, 500 and 1000 Generations

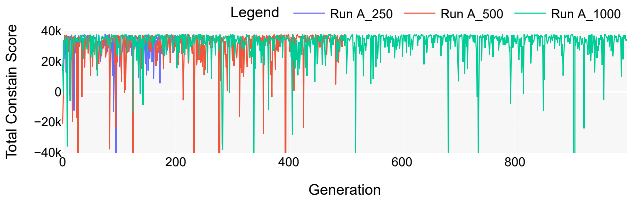
Figure 4: Evolution of Mean Constraint Score of Parents per Generation



(a) Runs 100 Generations



(b) Runs 150 and 200 Generations



(c) Runs 250, 500 and 1000 Generations

Figure 5: Evolution of the Total Constrain Score of Parents per Generation

The plots indicate that the model struggles to stabilise and maintain non-violating solutions, suggesting a tendency to identify viable but constraint-violating solutions. These results should be seen as indicative of potential directions rather than optimal solutions. The observed volatility in the model may stem from the experimental design or the employed crossover and mutation methods.

9 Case Study and Experimental Setup

This section presents the results of the optimisation model and outlines the case study and experimental design used in the simulations.

9.1 Case Study

Two cases are developed within the main Dutch rail network, differing in the design of the support structure: a single pole and a portal design. Only the pole design is optimised, as detailed above in the assumptions. The portal configuration employs the standard double-track design using ProRail's RHS300 beam. Both cases utilise the PVR-GC for the 25kV gauge, a Dutch adaptation of the European GC gauge, compatible with a 25kV catenary system. The Dutch B4 catenary system, operating at 1500 V DC and capable of 160 km/h, is selected for its ability to be upgraded to 25 kV AC. The system specifications are described in OVS00024-5.4 [72], using specified wire types for 1500 V DC and a maximum field length of 60 m. The contact wire, supported in the pull-off position to manage the impact of the load, zigzags between structures. Support arms for the B4 system are detailed in SPC00121, chosen based on the contact wire design and configuration. The pole height is standardised at 8.6 m throughout the optimisation.

9.2 Experimental design

The experimental design, including the parameter configurations for the algorithm and the simulations conducted, is outlined below. It also describes the operational environment for these simulations.

The settings for population size, number of parents, uniform crossover, and adaptive mutation for both low-ranking and high-ranking solutions are detailed in Table 3.

Table 3: Parameter Settings used for Simulation Runs

Parameter	Value
Population Size	60
Number of Parents	30
Uniform Crossover	Percentage: 0.6
Adaptive Mutation	Low-ranking: 0.8, High-ranking: 0.15

Simulations were conducted for 100, 150, and 200 generations, with additional single runs for 250, 500, and 1000 generations to evaluate the effects of longer generational spans on the 'All Material' dataset.

The following input sets were used for the materials in the All Materials dataset: ceramic (non-technical), composite (natural), elastomer (thermoplastic, TPE), metal (ferrous), metal (non-ferrous), plastic (thermoplastic, amorphous). The materials families were chosen for their potential to build compliant support structures. All pole-shaped designs were considered in the simulations. The plots are denoted as follows: '*A_..RunNumber..*'. The All Materials* dataset includes the same material families as the All Materials dataset, but excludes pole-shaped designs from UNP and T-beam, which were prevalent in previous simulations but impractical for poles. In the plots, these simulations are labelled as '*Aa_..RunNumber..*'. The Ceramic (non-technical) dataset exclusively features the ceramic material family for focused evaluation. The dataset includes all pole-shaped designs, which are denoted in plots as '*C_..RunNumber..*'. The Metals (non-ferrous) dataset contains only the metal (non-ferrous) material family, which is used for the specific evaluation of the material family. All pole-shaped designs are included in the runs. In the plots, these simulations are referred to as: '*MNF_..RunNumber..*'.

In Table 4 an overview number of runs for the states numbers of generations stated above, for each of the specified material input data set. In total, a number of 34 simulations have been conducted.

Table 4: Runs per number of generation for each material dataset

Material Input Dataset	Number of Generations					
	100	150	200	250	500	1000
All Material	5	2	3	1	1	1
All Material*	4	-	3	-	-	-
Ceramic (non-technical)	3	-	-	-	-	-
Metal (non-ferrous)	4	-	4	-	-	-

The results of the simulations conducted over 100, 150, and 200 generations for each material dataset were consolidated. In the event that no non-violating solutions were identified, the saved parent solutions were utilised. The data were initially filtered, with the non-dominated parents from each generation with positive constraint scores, deemed 'feasible', selected. This method was applied to the nonferrous metals and nontechnical ceramics simulations, with the result that no non-violating solutions were yielded.

9.3 Operating environment

The results generated by the proposed model in the previous chapter were obtained within an operating environment of Windows 10 Home 64-bits with an Intel(R) Core(TM) i7-7700HQ CPU @ 2.80GHz processor and 16,0 GB random access memory. The Python Integrated Development Environment used for the model is PyCharm Community Edition 2024.1 x64, with Python version 3.12.

10 Results

The results of the optimisation model runs are presented. First, an overview of the distribution of objectives is discussed. Subsequently, the results for objectives are discussed. Finally, conclusions are drawn on the basis of the results.

10.1 Objective Distribution

The Pareto frontier distribution for all material runs is illustrated below, plotting the current poles for cost, CO_2 footprint, and embodied energy. The Pareto fronts, shaped by the results, highlight cost as a primary trade-off factor among the objectives. The frontiers for CO_2 footprint and embodied energy demonstrate the potential for minimisation without increasing costs. In particular, the distribution of embodied energy is highly clustered, whereas the distribution of CO_2 footprint is more widely dispersed.

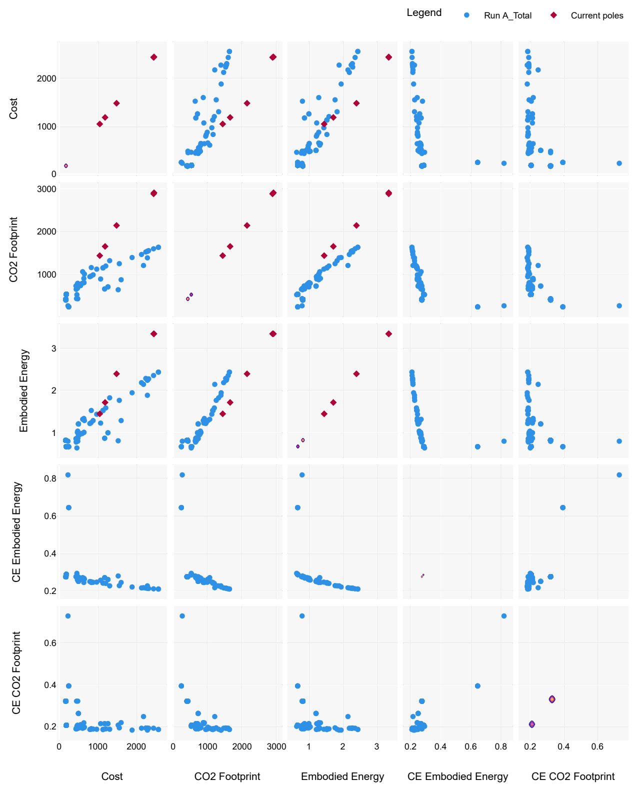


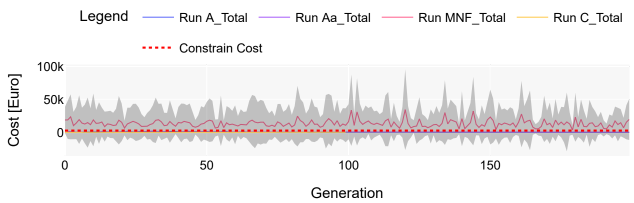
Figure 6: Scatter Matrix Representation of Objectives Distributions

The analysis of the principal material in the All Material set reveals that the T-beam is the primary pole shape, with ferrous metals representing the leading material family, and cast iron alloys being the most prevalent materials. The T-beam is favoured for its reduced cross-section, footprint, and embodied energy, while efficiently bearing high loads along its strong axis, which suits the main forces on the pole structure. In order to obtain a more comprehensive understanding of the data, additional datasets were examined. In the All Materials* set, the material family and materials remain consistent with the All Materials set, but the round tubular shape becomes predominant without the T-beam and UNP. In the case of the ceramic (non-technical) and metal (non-ferrous) datasets, high-performance concrete and cobalt-base super alloy are the dominant materials, respectively. The round tubular shape remains the favoured pole shape design.

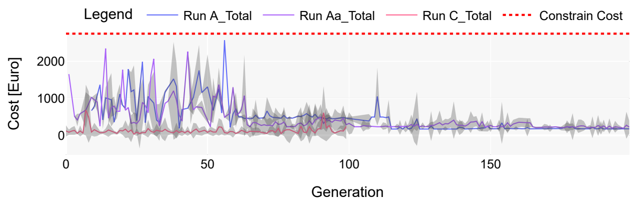
The results for the formulated objectives are detailed below, comparing different runs. Each material dataset's mean value per generation is shown in graphs with the standard deviation indicated by a grey fill.

10.2 Objective: Cost

Figure 7a illustrates that non-ferrous metal pole designs are considerably more expensive than other materials. Figure 7b demonstrates that ceramic (non-technical) rapidly reaches a lower cost compared to other materials, with all datasets aligning in cost after the 150th generation. Note that the term ”cost” in this context refers to material costs, whereas ”integrated constraint” refers to purchase cost. The figures reveal a potential for cost reduction, although it should be acknowledged that manufacturing and transportation costs, which are not included here, could significantly impact this potential. The reduction in material costs has minimal effect individually, but could be impactful at a network scale due to the volume of poles required.



(a) All Total Runs

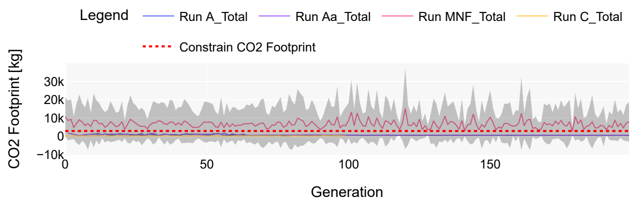


(b) All Materials and Ceramics (non-technical)

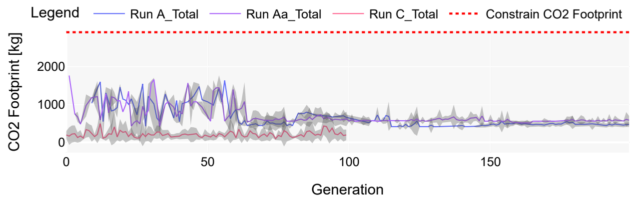
Figure 7: Evolution of Cost Objective

10.3 Objective: CO_2 Footprint

With regard to the objective of CO_2 footprint, it can be observed that a parallel phenomenon occurs with respect to cost. The metal (non-ferrous) dataset exhibits a similar performance in terms of cost, namely significantly lower performance compared to other material datasets. The emission value of CO_2 is significantly high for this material dataset compared to the other input datasets, violating the maximum constraint for all generations. A significant reduction in CO_2 footprint can be observed in all datasets of materials, as shown in Figure 8b. Both datasets are converging towards comparable emission values. The ceramic (non-technical) dataset performs even better, and these materials would allow further reduction of the footprint of a new pole design for the support structure. These results indicate the potency of ceramic materials, such as concrete, in reducing emission values. Nevertheless, the results of the all-material datasets indicate that this is also possible within the metal (ferrous) material set.



(a) All Total Runs

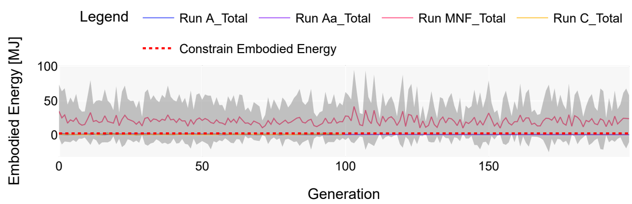


(b) All Materials and Ceramics (non-technical)

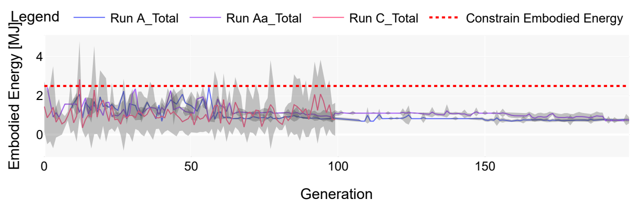
Figure 8: Evolution of CO_2 Footprint

10.4 Objective: Embodied Energy

Similar to previous objectives, non-ferrous metal design solutions exhibit significantly higher embodied energy, exceeding the maximum allowed values. Figure 9b shows the results for other data sets, demonstrating no significant differences in embodied energy values, which tend to converge despite material differences. A gradual downward trend is observed for energy, while the cost and CO_2 values stabilise at minimal levels, indicating the potential to reduce the embodied energy in a manner analogous to CO_2.



(a) All Total Runs

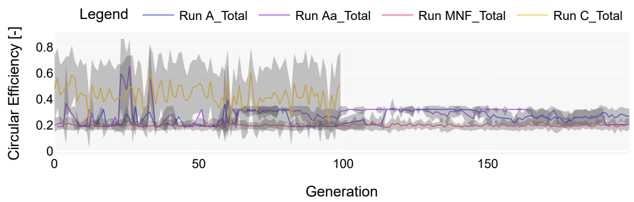


(b) All Materials and Ceramics (non-technical)

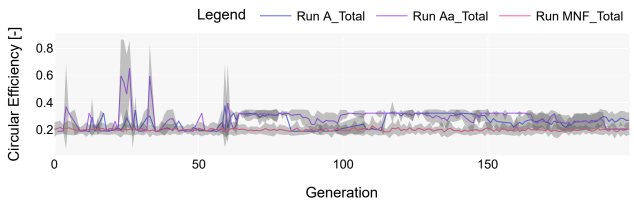
Figure 9: Evolution of Embodied Energy

10.5 Objective: Circular Efficiency

The minimal circular efficiency value indicates solutions with the highest potential for enhanced circular use. Figure 10a illustrates that non-technical ceramics perform the worst, while non-ferrous metals, previously the least effective, now exhibit the best circular efficiency for embodied energy. This suggests that the energy consumption associated with recycling these materials is likely to be less than that required for their production from raw materials. In contrast, the energy expenditure associated with recycling ceramics is likely to be greater than that required for their production from raw materials.



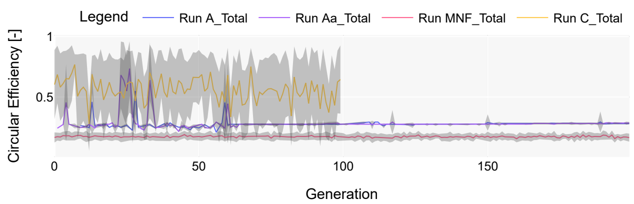
(a) All Total Runs



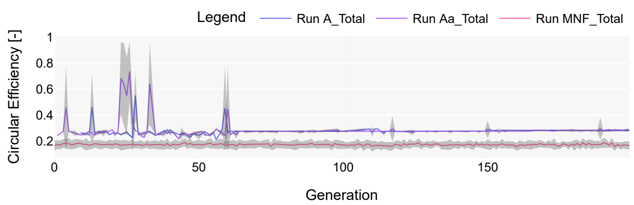
(b) All Materials and Metal (non ferrous)

Figure 10: Evolution of Circular Efficiency: Embodied Energy

The results of the circular efficiency analysis for the CO_2 footprint are comparable. The non-ferrous metals exhibit superior performance, as evidenced by the results presented in Figure 1. There is a clear distinction in the convergence goals, particularly with regard to the CO_2 footprint, with significantly improved effectiveness across all materials. Furthermore, non-ferrous metals consistently demonstrate superior performance compared to other datasets in terms of circular efficiency.



(a) All Total Runs



(b) All Materials and Metal (non ferrous)

Figure 11: Evolution of CO_2 Footprint

10.6 Deflection of Pole

The deflection results for various input data sets are shown below. As shown in Figure 12, all designs meet the deflection constraints at the top of the pole. Furthermore, these constraints are not the most restrictive as the designs have deflections well below the limits, demonstrating their stiffness.

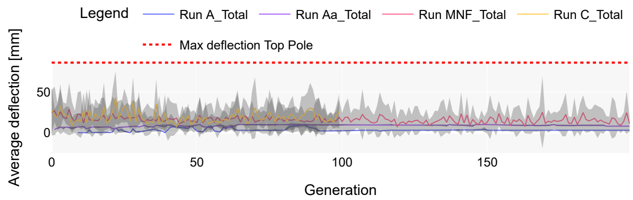
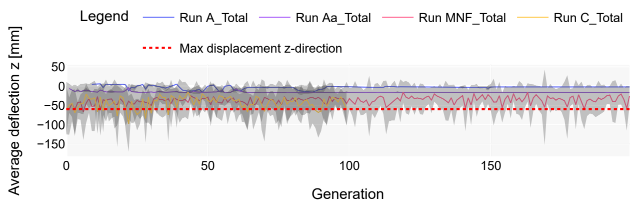


Figure 12: Evolution of Deflection at Pole Top in x-Direction

Figure 13 shows the deflection results for the contact wire. Both metal (non-ferrous) and ceramic (non-technical) designs struggle to meet the maximum deflection limits in x and z directions. However, designs using the all-material data sets meet these limits, with the all-material configuration showing the lowest deflection. This superior performance is due to the dominant T-beam pole shape in this dataset, which provides better bending resistance compared to tubular shapes. In addition, the all-material data set converges quickly.

(a) x-Direction



(b) z-Direction

Figure 13: Evolution of Contact Wire displacement

10.7 Conclusion

Analysis of material input data sets and support structure designs reveals the interplay between material properties, structural designs, and sustainability objectives. Predominantly, T-Beam and ferrous materials are prevalent in the All Materials dataset, whereas non-ferrous metals demonstrate high circular efficiency. This highlights the critical role of material selection in the improvement of sustainable design practices. The simulation results emphasise the necessity for a balanced approach in choosing materials and shapes to achieve both performance and environmental objectives. Challenges such as contact wire deflection and the evolving performance of materials require ongoing design evaluations and modifications. These simulations validate the efficacy of certain materials and designs in adhering to deflection limits and enhancing performance. Therefore, a dynamic and balanced strategy is crucial for progressing sustainable design in the face of shifting environmental and economic landscapes.

11 Discussion

Research started with reviewing the design process and stakeholders, to support determining the essential requirements. Extensive analysis of requirements and design specifications resulted in the finding of essential requirements for the design of OCLS support structures. These are a balance of safety and economic considerations. However, these are well defined via many regulations. They both allow some flexibility, due to the way one could interpate the importance of one of the aspects.

Similar, this can be seen in the need for policymakers and engineers to connect safety standards with cost efficiency. Improving the structural integrity while remaining profitable, which often turns the other way. Given these insights allow to better understand of regulatory frameworks and standards in the design process. As shown in the rail network, it is highly regulated, increasing it to implement new design in rail infrastructure projects throughout the Netherlands.

Given the aspect of sustainability, the commitment of Ducht Rail branch and all new regulations for government, shows an interesting playing field of ambitions versus practice. Certainly given the increasing importance of sustainability within projects and design. Where ProRail and the Dutch Rail branch are using environmental cost indicator. In a manner to indicate sustainability, the circularity principles are also of importance.

However, within most policies, the main focus is on the aspect of carbon footprint as the main indicator. What brings tension is a complex world of life cycle assessment. In the same case, it can be a bit concerning how certain emission can cancel each other out. On the other hand, the introduction of indicators allows stakeholders and other involved parties to take into account their impact on the environment. As stated stated before, we need each other in order to go transgress towards a more durable world. Thereby contributing to national and international policies

Implementing all these different aspects to the design of the support structure licence confirms the potential of in multi-objective appoarch. This research showed that further that appears to be a relative simple issue can be increasingly more complex. Given the different factors, especially given the importance of eco-friendly materials and construction methods. As these might allow gain forward towards sustainable world. It should be notice that will result in making trade-offs in either cost or safety to move towards a sustainable future.

Furthermore, the call to re-evaluating current design requirements in light of sustainability might unavoidable. This is also a more social question, as we need to collectively agree to accept certain consequences that will follow from it. Despite our expectations regarding technology and environmental ambitions. At some point there will be friction. Therefore, creating dilemma between how to accommodate innovations and emerging technologies versus economical concerns and sustainability. This requires a collective approach among governments, rail branch, and wider to address these problems.

Similar can be seen in the results of the model. This eventually returns to the current cross section and the materials used for the support structure. So, potently is the current design most optimal design given all the aspects. This would lead to the acceptance of certain exceptions and pollution. Despite our need to improve and try to find more innovative solutions as humans. This could lead in a worse case towards an political choice not to use overhead continuous line system, as it is on paper the most sustainable solution.

Taken together, this research showed that sustainability and circulation will play an important role within the rail infrastructure. Additionally, it showed that there is the possibility of consolidating these aspects in the current designs and requirements. However, in the design, environmental considerations, safety standards, and economic efficiency are included. The result would be an efficient and environmentally sustainable rail network. But this will require a flexible and collective approach towards a sustainable and circular future.

12 Conclusion & Recommendations

12.1 Conclusions

This research concludes that the design of a supporting structure for an OCLS in the Netherlands must balance safety and cost, as detailed in section 4. Sustainability, a crucial aspect, is assessed mainly through life cycle assessment and circularity, as discussed in section 5. The design parameters, including material choice and structural dimensions, are constrained by safety and economic factors, and are critical in defining the sustainability and functionality of the support structure (section 10). To enhance sustainability, reducing CO2 emissions through optimized material selection and design is essential. The trade-off between cost and environmental impact is significant, suggesting that material innovations could lead to more sustainable designs without compromising safety or economic feasibility.

12.2 Recommendations

This research supports the need for further detailed studies on regulations and sustainability in the rail sector. It proposes designing sustainable support structures and suggests future research to refine and expand the developed model. Key areas include enhancing the rail sector's sustainability, comparative sustainability studies between the OCLS system and alternative train systems, and adopting circular design principles for support structures. Additionally, the integration of environmental cost indicators, the adoption of specific standards for material types, and the testing of parameter and variable ranges are recommended to enhance the model's effectiveness and sustainability. These efforts are crucial for advancing sustainable rail infrastructure development and understanding environmentally responsible transportation systems.

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A Fitness Function Configuration

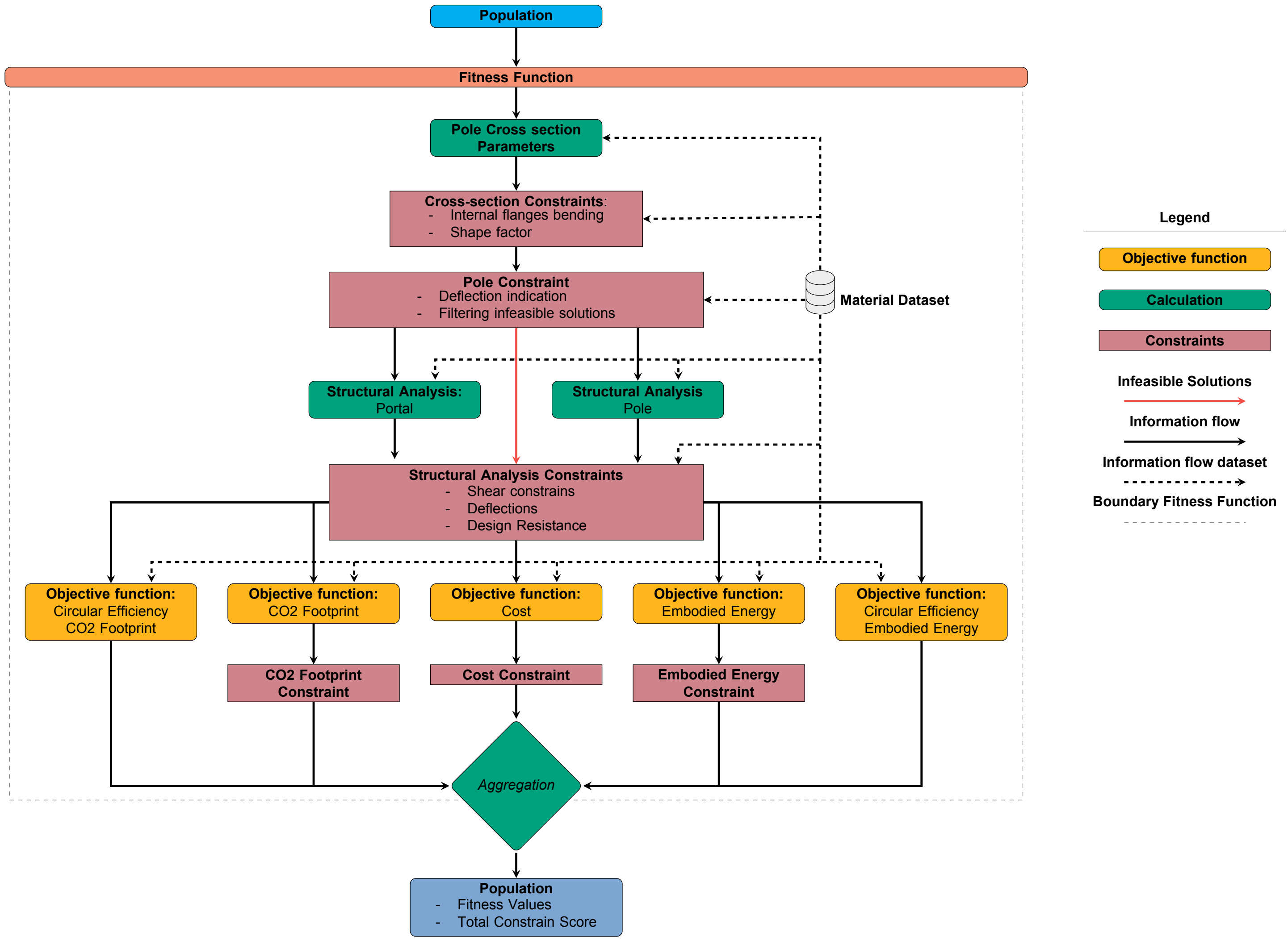

Figure 14: Overview of the fitness function used in the optimisation model