An assessment system for measuring levels of sustainability in area development

Through preference-based decision-making modeling

by

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Preface

Dear reader,

This report marks the end of my career at the Delft University of Technology. The past few years have been centred around my studies and I am happy to conclude it this way. My Master thesis report named ”An assessment system for measuring levels of sustainability in area development, through preference-based decision-making modeling” is focused on improving the assessment performed in tenders for area development. It has been carried out at Planmaat, a company specialised in consultancy for area development. I like to thank all colleagues for welcoming me into their company and for their patience while I was learning to play table football. In particular I would like to thank Patrick Nan, my company supervisor, for the dedication and attention he has paid to me and my thesis. The same applies to Ian Slettenhaar who substituted Patrick for the last part of my thesis.

Next, I would like thank my academic committee: Ruud Binnekamp as the chairman and my second supervisor, for assisting me all the way from the start when choosing a graduating topic untill finalising my thesis. I also want to thank Leo Gommans for being my main supervisor and contributing to my knowledge of sustainable area development and pointing out important aspects that I did not identify myself at first.

Finally, I would like to thank friends and family for their support. In particular, I would like to thank my father Jeroen for his helpful comments on the report. And last but not least, big thanks to Karo, for his motivational words and for being my tutor in programming.

S.C.M. (Sylvana) van Kessel
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Executive Summary

Currently, submitted bids of tenders in area development from client Ontwikkelingsmaatschappij het Nieuwe Westland (ONW) are evaluated on five selection criteria on a non-quantified scale. One of these selection criteria is called 'Vision of sustainability', for which bids are assessed on a scale from inadequate to excellent. With a view to the future, sustainability is becoming increasingly important in itself, but also in area development. Elaborating on sustainability during tenders through quantification in a model, making it measurable, would considerably improve this process. Such a preference-based model considers the preferences of all stakeholders and persists on finding the group optimum. This is the research goal of this thesis and to it belongs the following research question:

> *'How can sub-criteria of sustainability in area development be quantified and implemented into a preference-based decision-making model?'*

The quantification of sustainability sub-criteria was carried out based on the DCBA method. In it, forty sustainability characteristics in area development are defined. For each characteristic, the DCBA method outlines four sustainability scenarios (D, C, B and A), running from least sustainable to most sustainable. For this thesis, some characteristics were elaborated, acting as a prototype. The scenario differentiation is used in the model to test the degree of sustainability. Sustainability characteristics are transformed into model objectives and variables and are quantified based on costs and revenue. Using the Preferendus tool (a combination of Preference Function Modelling and Tetra software), a model was created that optimises the housing differentiation of an area, and ranks different tender bids. The Preferendus tool acts as the base of the model. A key input for this are the numerical preferences that stakeholders enter for different features after which the model searches for the group optimum. The Tetra software compares all alternatives based on the preference and creates a ranking.

Two user experiments were conducted with employees of Planmaat (participants), showing that the complexity of the model calls for technical support while using it. Due to logistical issues, Planmaat employees substituted ONW in the experiments, what may cause different outcomes, as their opinions could differ. Participants only see value in using the model as an assessment tool (entering bids and ranking these) and not as a design tool (using optimisation). This is because ONW uses a tender process where one design from a developer is chosen. ONW has no say in detailed features, they only provide constraints. The design tool can be used by a party that works with a detailed programme of requirements. After composing this programme of requirements one or more developers can be approached for potential cooperation. What ONW could use the optimisation for is to steer developers, without sharing precise results. What participants found difficult was the varying results of optimisations. Because of the nonlinear optimisation, local optima and random starting points, the

result is not set. This showed difficulties for use in practice, but this problem could be solved when the model is worked on in a mathematical way (not in the scope of this thesis).

Incorporating sustainability in an optimisation model shows potential for quantifying and properly weighing sustainability in area development tenders. It offers an opportunity to compare bids and stakeholder preferences, a strong improvement compared to the current process where only a summary vision of sustainability is required. However, it should be noted that some points of discussion arise. Discussion points in this thesis were the amounts of experiments conducted, with substitute participants. Ideally, multiple experiments should be conducted to have an iterative process. In addition, the building requirements incorporated into the scenarios from the DCBA book are outdated. They do not correspond to current construction requirements. It is recommended to incorporate more sustainability sub-criteria, potentially from an updated source. In addition, it is recommended to commence experiments with stakeholders, preferably the ultimate users, while expanding the model. Continuing to improve and validate the model, and to find out which way and approach works best to use the model, focusing on the practicalities.

Concluding, the DCBA method, utilises various characteristics (sub-criteria) to describe sustainability in area development across different scenarios (D, C, B, and A). These sub-criteria are converted into quantifiable objectives within the model, which is designed to optimise scenario and housing differentiation. The main research question is answered by examining how sub-criteria are quantified and integrated into a preference-based decision-making model. Sustainability sub-criteria are quantified based on costs and revenue and are implemented into the model by incorporating them as both objectives and variables in the model. The report provides a rationale for the model's development, supported by relevant theory, concluding this thesis.

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1 Introduction

Higher standards of living, rapid urbanisation, and a diverse range of lifestyle preferences have led to an escalation in housing demand. As the largest component of urban land use, residential areas play a crucial role when looking at the development of sustainable cities (Yigitcanlar et al., 2015). Since the Brundtland report (what presented the concept of sustainable development and outlined strategies for its achievement), sustainability has remained a topic of debate, characterised by numerous definitions and a lack of consensus on a singular term that would enable straightforward measurement of the concept (Brundtland, 1987) (Masnavi, 2007).

Experts have long debated the definition of sustainability. In 1972, the discourse focused on the limitations imposed on ecological systems, focusing on tasks like waste absorption and recycling from human activities, alongside challenges of enhancing societal well-being, education, healthcare, and employment opportunities. By 1987, sustainable development had emerged as a concept encapsulating the idea of progress that fulfills present requirements, while safeguarding the capacity of future generations to fulfill their own needs. By 2019, sustainability has evolved to encompass the concept of meeting the needs of both current and future generations, contingent upon the judicious utilisation of human, natural, and economic resources to promote human welfare (Hajian & Kashani, 2021).

Sustainability is a key consideration in urban planning, yet its implementation in neighborhood development remains uncertain. While cities have prioritised sustainable initiatives, neighborhoods have received comparatively less attention, especially regarding spatial factors' contribution to sustainability. There is a need for establishing effective measures to evaluate neighborhood sustainability initiatives and integrate sustainability principles into neighborhood development effectively (Moroke et al., 2019).

Challenges in the built environment arise from building structures that don't align with stakeholder preferences as well as engineers focusing solely on technical aspects. According to Wolfert (2023), policymakers' non-transparent decision-making processes often result in projects lacking socio-economic purpose. These issues stem from oversimplifying complex problems, neglecting their integrative nature. Addressing these challenges requires an approach considering both technical and social aspects. Transparent design models bridge the gap between human preferences and engineering solutions, enabling effective solutions within complex socio-technical systems (Wolfert, 2023).

Two primary challenges are outlined: the necessity for sustainability in area development, including its measurement, and the prevalent disconnect between built structures and stakeholder preferences, with engineers favoring technical aspects over stakeholder needs. This report endeavors to address both issues comprehensively. By advocating for a holistic approach that integrates sustainability principles into area development and that emphasises stakeholder engagement, it is aimed to create solutions that effectively bridge the gap between technical requirements and community preferences.

In this report, there will be a focus on improving the decision-making process in area development, by quantifying selection criteria focused on sustainability, as well as improving the incorporation of every stakeholder's preference. Due to the complexity of many projects, accommodating every party's viewpoint can be problematic, often leading to non-optimal builds (Wolfert, 2023).

1.1. Research problem

Ontwikkelingsmaatschappij het Nieuwe Westland (ONW) is the land owner/provider of the land sales of the Waelpolder development fields. ONW is a collaboration between the municipality of Westland and 'Bank Nederlandse Gemeenten Gebiedsontwikkeling'. As with other projects, ONW puts out a tender for the selection of developers for these development fields. Logically, it is in ONW's favor to optimise the selection process of developers. It is desirable to formulate its request in a way that the bids will optimally meet its needs. Additionally, ONW needs to determine the best method for comparing different bids and selecting the most suitable one.

At this moment, the selection criteria provided by the client (ONW) for the developers, seem to be quite general, leaving room for interpretation. This is partly due to the assessment scale, which is extensively explained in section 2.2. The assessment scale is formed in a non-quantified way, as criteria are ranked as 'good' or 'sufficient'. This may make outcomes less objective. ONW specifies five selection criteria when choosing developers. One of those is 'Vision of sustainability', the only criterion ONW uses to assess the focus on sustainable development. This criterion is focused on in this thesis, substantiation is given in section 2.2.

The problem statement (**PS**) describes in a concise manner the research problem that will be addressed in this report:

PS: 'Due to tender requests and therefore selection criteria occurring in an non-quantified manner, the concept of sustainability is not being optimally integrated into bids in area development.'

1.2. Research questions

With the problem statement now clearly defined, the focus shifts towards seeking a solution. The proposed approach entails the development of a preference-based decision-making model tailored to measure sustainability in a quantified manner. This model aims to provide a structured framework for evaluating various aspects of sustainability in area development, enabling ONW to make informed decisions based on their preferences and priorities. The model seeks to offer a systematic approach for assessing sustainability across different domains, thereby facilitating more effective and transparent decision-making processes.

In order to solve the research problem for this thesis, a main research question (**RQ**) needs to be answered. This reads as follows:

RQ: 'How can sub-criteria of sustainability in area development be quantified and implemented into a preference-based decision-making model?'

After completion of the thesis, an answer to this question will be given. The formed model will play a big role into answering this question. In order to build this model, certain knowledge is required. Because of this, next to the main research question, also sub research questions (**SQ**) are formed. Answering these sub-questions can be seen as the tasks that need completion to finish the project. These are given below.

SQ1: 'What sustainability measures and measuring instruments are relevant for Dutch area development?'

This sub-question is essential to address because it is crucial to understand the current sustainability measures being implemented in Dutch area development. Gathering knowledge on this matter is necessary to determine whether or not these measures can be implemented into the model. An appropriate method for quantifying sustainability must be sought. This sub-question will be answered in chapter 2.

SQ2: 'What sub-criteria explain the concept of sustainability in area development?'

By addressing this sub-question, it becomes evident which indicators can be utilised to measure sustainability in spatial development. This step is crucial as these indicators will be integrated into the model. When answering this sub-question, a method is chosen that provides the framework to be able to quantify the concept of sustainability. This sub-question will be answered in chapter 3.

SQ3: 'Do quantified sub-criteria of sustainability implemented in a preference-based decision-making model add value, in comparison to the rating system for tenders as used by ONW?'

The final sub-question addresses validation of the formed model. Its answer either confirms or refutes whether the quantification is of added value. It becomes evident whether or not the model represents an advancement over the current method of tender assessment. Before this sub-question is answered, in chapter 4 a model explanation is given and chapter 5 provides the implementation of the model. That information helps to answer the third sub-question in chapter 6, that presents the results.

1.3. Research goal

This research aims to develop a method for integrating quantified sustainability criteria into the assessment of tender bids for area development projects. The objective is to explore the creation of a model that facilitates the incorporation of sustainability metrics into the evaluation process, thereby enhancing decision-making and promoting sustainable development practices.

1.4. Research relevance

1.4.1. Scientific relevance

This thesis is considered scientifically relevant because of the following. The existing literature shows that the quantification of sustainability is already practiced. Huang et al. (2015) describes how ‘urban sustainability indicators’, also known as USIs, are developed. This is done because of the importance of sustainability in urban areas, as this is connected to the sustainability of bigger areas like regions, nations and eventually the world. The USIs are being used to measure the conditions and the progress of urban sustainability (Huang et al., 2015). So, it is clear that the quantification of sustainability aspects is not a new thing. However, the combination of the quantification and the relatively new method (state-of-the-art) from the book ‘Open Design Systems’ (Wolfert, 2023), seems to be valuable. This view is shared by experts in the field (Planmaat employees). In this thesis, the quantification will be focused on the case-study, Waelpolder: development field 4 (further explained in section 5.1). Making it most valuable to ONW, to use it for this field and comparable cases. As described before, there are many gains to be made. The result is expected to be significant.

1.4.2. ONW's relevance

This research is considered relevant to ONW as it aims to improve their selection process in tenders. The model will provide tools to compare bids, and to perform an optimisation for the housing differentiation of an area. The quantification of sustainability sub-criteria ensures that the assessment will be objective, and therefore equal for each bid. This prevents room for interpretation of different assessors, which could lead to unequal assessment.

1.4.3. Societal relevance

By emphasising the integration of sustainability criteria into area development processes, the report not only promotes environmental responsibility but also advocates for social equity and economic resilience. In light of growing concerns over climate change, resource depletion, and urbanisation pressures, the societal relevance of this report lies in its potential to guide decision-makers and stakeholders towards more sustainable pathways that meet the needs of present and future generations.

1.4.4. Masters' relevance

This report, while centered on area development, holds relevance for the Construction Management and Engineering master program due to its focus on improving design processes for enhanced efficiency. By understanding how to integrate quantified sustainability criteria and streamline design processes. Thus, the report offers valuable insights into effective project management strategies despite its primary emphasis on area development.

1.5. Structure of the report

In chapter 2, the foundational concepts and principles relevant to the case study's topic are explored, providing a necessary theoretical framework. Following this theoretical foundation, the report moves to the quantification of sustainability (chapter 3), where methodologies and metrics for assessing sustainability within the study's context are elaborated upon. In chapter 4 the theoretical concepts and practical explanation that are underlying the model are explained. Next, chapter 5 provides an explanation for the implementation of the created model. After this, chapter 6 presents the results. In chapter 7, the results of the experiment are critically analysed and discussed, and recommendations are given. Finally, the report concludes with chapter 8, summarising key findings and answering the research questions.

2 Theoretical Background

This chapter provides an overview of the role of Ontwikkelingsmaatschappij Het Nieuwe Westland, and explains the process of how tenders are assessed. The land owner plays a crucial role in the shaping of development of the area. An exploration is given how tenders are evaluated and bids selected. Additionally, Dutch sustainability measures are examined. Through this exploration, insights are gained into the dynamics of area development and sustainability integration. The theoretical background acts as a base for the following chapters.

2.1. Ontwikkelingsmaatschappij Het Nieuwe Westland

Ontwikkelingsmaatschappij Het Nieuwe Westland (ONW) is a collaboration of the Municipality of Westland and Bank Nederlandse Gemeenten Gebiedsontwikkeling. Apart from being the landowner for different areas, ONW also acts as the client. For every area development project, they select developers in order to realise housing plans. This is done via publishing tenders. A tender, or invitation to tender, is a procedure in which a client asks companies to perform a particular service or product. Companies submit bids for the work or service. The client then weighs which bidder is awarded the contract based on price and quality (Van Leest, 2022). The client, in this case ONW, specifies their needs and wishes (as mentioned in subsection 5.1.2), and interested developers can register.

After the developers have registered and submitted their designs, the client will assess these based upon predefined selection criteria and an accompanying assessment system. The current assessment system is explained in section 2.2.

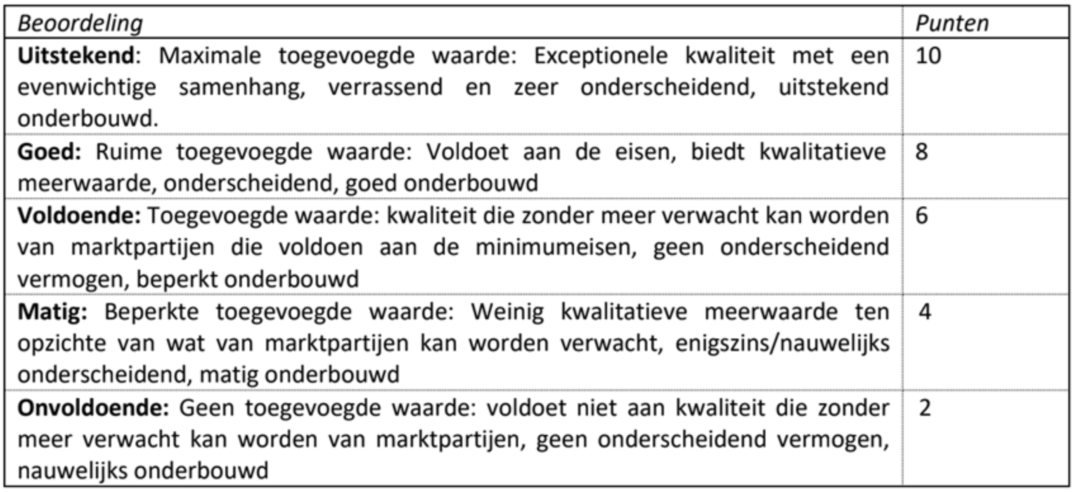
2.2. Current assessment system

At this moment, when ONW publishes a tender, an assessment is executed during application and during offer. This is the case when the tender has two phases. The first phase uses selection criteria, these need to be predefined and known to the developers.

The current selection criteria are (ONW, 2023a):

1. Vision for urban development of the issuable area;
2. Vision for architecture of the proposed homes;
3. Vision for parking solution(s) within the issuable area and access towards the public area;
4. Vision for sustainability;
5. Opportunities & risks.

It becomes clear that the selection criteria are defined in a general manner. The visions for a certain design will be judged, but the general formulation can leave room for one's interpretation. There is a need for builds to become more sustainable, in order to lower the energy consumption and the emissions (Soares et al., 2017). Therefore, the criterion of sustainability has a high priority into becoming more quantifiable. In this thesis, this will be the focus. The goal is to subdivide this sustainability criterion into multiple sub-criteria. This way, it will be easier to judge and rank all received bids. Every selection criterion that is previously mentioned, is assessed based on a scale. The scale reaches from insufficient, moderate, sufficient, good to excellent. Each point on the scale is assigned to a certain number of points. The total amount of points leads to the ranking of all applicants. This is shown in Figure 2.1. The goal of this thesis is to change this scale, to one that fits the quantification of every sub-criterion.



Beoordeling	*Punten*
Uitstekend: Maximale toegevoegde waarde: Exceptionele kwaliteit met een evenwichtige samenhang, verrassend en zeer onderscheidend, uitstekend onderbouwd.	10
Goed: Ruime toegevoegde waarde: Voldoet aan de eisen, biedt kwalitatieve meerwaarde, onderscheidend, goed onderbouwd	8
Voldoende: Toegevoegde waarde: kwaliteit die zonder meer verwacht kan worden van marktpartijen die voldoen aan de minimumeisen, geen onderscheidend vermogen, beperkt onderbouwd	6
Matig: Beperkte toegevoegde waarde: Weinig kwalitatieve meerwaarde ten opzichte van wat van marktpartijen kan worden verwacht, enigszins/nauwelijks onderscheidend, matig onderbouwd	4
Onvoldoende: Geen toegevoegde waarde: voldoet niet aan kwaliteit die zonder meer verwacht kan worden van marktpartijen, geen onderscheidend vermogen, nauwelijks onderbouwd	2

Figure 2.1: Assessment at registration (ONW, 2023a)

2.3. Sustainability measuring instruments

In this section the sustainability measuring instruments that are used for area development in the Netherlands are discussed. This is because ONW is located in the Netherlands and all (future) involved parties are presumably Dutch. Understanding how this is done can help figure out how to measure sustainability sub-criteria for this thesis. These instruments will be discussed below.

2.3.1. Omgevingswijzer

The Surroundings Guide (Omgevingswijzer) helps you understand how sustainable and integral a project or area development is or can be. This is done in a systematic way, with attention to social, ecological and economic sustainability (people, planet and profit). The Surroundings Guide facilitates a structured discussion on this topic. The tool has been specially developed for the civil engineering sector (GWW) and is in line with the Sustainable GWW Approach. The Surroundings Guide does measure sustainability, based on multiple subjects. For every subject a score of 'positive', 'neutral', or 'negative' can be given by stakeholders (Rijkswaterstaat, n.d.). There is no further explanation given that helps stakeholders to make a choice between these three scores. While this is some sort of quantification, to reach the goal of this research, it is still too general.

2.3.2. Bouwbesluit

The Building Code (Bouwbesluit) sets requirements for the energy efficiency of new homes and utility buildings. The most important requirements in new construction are the requirements for Nearly Energy Neutral Buildings (BENG). The Building Code focuses on four main subjects; ventilation, air tightness, insulation value and the environmental performance of buildings (Mpg) (Ministerie van Algemene Zaken, 2024). The BENG and Mpg are discussed separately below.

2.3.3. Milieuprestatie gebouwen (Mpg)

The Environmental Performance of Buildings (In Dutch: Milieuprestatie gebouwen (Mpg)) is required with every application for an environmental permit. The Mpg indicates the environmental impact of the materials used in a building. This applies to new office buildings (larger than 100 m^2) and to new housing developments (RVO, n.d.-b).

The Mpg is considered an important measure of a building's sustainability. The lower the MPG, the more sustainable the use of materials. The environmental performance of building materials will become an increasingly important factor in the environmental impact of a building. The Mpg is an objective tool in the design process and it can be used in a Program of Requirements (written by the client) to define the outcome. The MPG is calculated using a number of factors that determine the environmental impact of a building throughout its life cycle. These indicators are of a very specific nature (e.g. dimensions of mol H^+-eq. and kg CO_2-eq.) (Stichting Nationale Milieudatabase, 2023).

The Mpg limit value is now likely to be tightened from 1.0 to 0.8. This is because a lower Mpg value indicates a more sustainable use of materials. Because the Mpg only focuses on material use, this may clash with BENG requirements; choosing thick insulation improves energy performance, and therefore BENG, but actually worsens the Mpg. This is due to the environmental impact of producing the materials.

The calculation of the Mpg is time consuming. To determine the environmental impact of a single material, a Life Cycle Analysis is performed, the LCA must be carried out by a qualified expert. The LCA results in 11 indicators (as of 1 January 2025, there are 19), and these values are aggregated into one value, the shadow cost. These

11 indicators thus give a certain environmental value to a type of material. Once the LCA of a certain type of material has been calculated by an expert, this information is placed in the National Environmental Database, so that the LCA does not have to be recalculated for the same type of material.

After determining the shadow costs, the calculation is not yet complete. The materials that will be replaced during the life of the building must also be taken into account. To finally calculate the Mpg, each material used must be mapped out with exact quantities (RVO, n.d.-b).

At first glance, because of the quantitative nature of the Mpg, it seems usable for this research. However, as explained above, the calculation is extensive and specific. In order to calculate the Mpg, all used materials for a house need to be known, including the amount of material. The formed model in this thesis is created to be used at the beginning of the tender process. This is when developers are making (or before making) their first designs. In this stage, materials and their precise amounts are not disclosed. Also the Mpg displays a limit value, fundamentally there is not a qualitative explanation coupled. Leaving this instrument only for use of experts already familiar with it.

2.3.4. Bijna Energieneutrale Gebouwen (BENG)

For all new construction, both residential and non-residential, permit applications since January 1st, 2021, must meet the requirements for Nearly Energy Neutral Buildings (In Dutch: Bijna Energieneutrale Gebouwen (BENG)). Those requirements stem from the Energy Agreement for Sustainable Growth and from the European Energy Performance of Buildings Directive (EPBD) (RVO, n.d.-a).

The energy performance in BENG is determined based on three individually achievable requirements (RVO, 2017):

- The maximum energy demand in kWh per m2 of usable area per year (kWh/m2.yr)
- The maximum primary fossil energy use, also in kWh per m2 of usable area per year (kWh/m2.yr)
- The minimum share of renewable energy in percent (%)

All three requirements must meet a limit value. The BENG requirements are tested at (residential) building level. For apartment buildings, the energy performance must also be calculated for each individual residential object (RVO, n.d.-a).

BENG requirements could be used as boundaries in the model, but this role in the optimisation process is considered doubtful. Preference goes out to a method that consists of a sliding scale of possibilities, rather than a discrete requirement. Because the optimisation will be used to choose between different possible outcomes.

2.4. Conclusion

The aim of this chapter was to explore the existing sustainability measures in the Netherlands, potentially aiding in the quantification of sustainability for this thesis. The role of the landowner, ONW, was highlighted, as well as the process of tender assessment and selection criteria employed in development projects.

Moreover, the chapter delved into Dutch sustainability measures relevant to area development, including the Omgevingswijzer, Bouwbesluit, Milieuprestatie gebouwen (Mpg), and Bijna Energieneutrale Gebouwen (BENG). It became evident that methods such as the calculation for the Mpg are not suitable for this thesis. This is because it gives one limit value, and no extensive qualitative explanation. The Mpg will be familiar to experienced experts, but the model made in this thesis is meant for all ONW employees in this case. The BENG presents three different requirements, leaving no room for optimisation purposes, as BENG presents three hard constraints. Consequently, alternative methods must be sought to quantify sustainability criteria. However, these mentioned instruments are crucial in assessing the dimensions of sustainability within the Dutch context, and for answering the first sub-question: 'What sustainability measures and measuring instruments are relevant for Dutch area development?'. These measures and measuring instruments are the Omgevingswijzer, Bouwbesluit, Milieuprestatie gebouwen (Mpg) and Bijna Energieneutrale Gebouwen (BENG).

The exploration of sustainability measuring instruments underscores the importance of quantifying sustainability criteria for informed decision-making in development endeavors. These findings lay a foundational understanding for further exploration into sustainability within area development projects.

3
Quantification of Sustainability

In the previous chapter, general Dutch sustainability measures were stated and discussed whether or not they could effectively quantify sustainability within this research. However, it became apparent that the indicators used were not suitable for this model's inputs. This realisation prompted the search for an alternative method that fits better as input for optimisation.

A suitable way to quantify sustainability indicators is with the DCBA method. It operates by delineating various scenarios and situations, offering a more adaptable and feasible approach to quantifying sustainability for this thesis (Teeuw et al., 2011).

3.1. Method

The method that is used to quantify the sustainability indicators in the model, is called the four-variant or DCBA method. This is a Dutch method developed by Prof. emeritus Kees Duijvestein, where different sustainability themes are divided into four sustainability scenario's; D, C, B and A. This method is developed in order to explain sustainability in area development to municipalities, acting as an advisory tool (Teeuw et al., 2011). The explanation of every scenario can be found below, the corresponding letters might not make sense as they are based on the Dutch explanation. Scenario D represents the least sustainable scenario, while scenario A represents the most sustainable situation.

- D: The normal situation, where sustainable development is not the focus;
- C: Correct for normal use, where sustainable development does have attention;
- B: Minimize damage, where sustainable development is the focus;
- A: Absolutely the best choice for the relevant theme, where maximum sustainability for that theme is achieved.

The literature of Teeuw et al. (2011) consists of ten sustainability themes, each containing four sub-themes. The complete list with all forty sub-themes can be found in section A.1.

3.2. Chosen sub-themes

From the list of sub-themes, four are chosen to be incorporated into the model. For the purpose and scope of this thesis, not all forty sub-themes are prepared and incorporated into the model. The four sub-themes serve as an example, a prototype. In a potential follow-up study, all sub-themes could be incorporated so that the model users could have a choice between these sub-themes. For now, every chosen sub-theme belongs to a different theme, making the input diverse, presumably giving a complete understanding for the concept of sustainability.

The sub-themes that are selected are:

- Building materials
- Humidity and ventilation
- Solar energy
- Groundwater

The elaborated explanation that belongs to each scenario of these sub-themes can be found in section A.2.

3.3. Contents of the scenarios

As explained before, the DCBA method does not require specific measurements, the scenarios are explained by an outlined situation. However, for the implementation into the model, the scenarios need to be quantified. The quantification is based on costs and revenue. For every scenario-variable combination, a corresponding balance is calculated. The model variables are explained in subsection 5.3.1, these represent different house types. This means that the costs and revenues for every house type are calculated for sustainability measurements belonging to a corresponding sustainability scenario.

How this quantification is assembled, is described below.

3.3.1. Balance of each scenario

To every scenario a balance is coupled, this is the delta to the 'normal situation', in this case this is scenario D. So first, for every variable (house-type) the starting balance (house price - realisation costs) is determined. These values are retrieved from different tools that are provided by Planmaat. The house prices are calculated via a service called OPENRED, which calculates house prices based on the exact location and competitive characteristics (V.F. Real Estate BV, n.d.). The construction costs for all house-types are retrieved from Bouwkostenkompas (IGG Bouweconomie, n.d.). The results are displayed in Table 3.1, and are estimations.

The complete explanation of the balance calculation for every scenario and house-type can be found in the appendix. In Table B.1, the highlights of each scenario are presented that determine the measures that need to be taken to fulfill it. Also in the appendix (subsection B.1.1), the sources that are used to calculate the costs are given. Note that every scenario has been translated into real-life measures, where the costs

Table 3.1: Balances per house type

	House price	Realisation costs	Balance
Detached house	€800.000	€635.000	€165.000
Small row house	€390.000	€285.000	€105.000
Big row house	€475.000	€350.000	€125.000
Small apartment	€360.000	€260.000	€100.000
Big apartment	€435.000	€310.000	€125.000

are based upon. These estimations, based on given sources can be found in Table B.2. It should be made clear that these remain estimations, an attempt was made to obtain the amounts as precisely as possible within the scope of this thesis.

Every DCBA-scenario is coupled to a delta in house price and a delta in construction costs. This displays how much more the house is going to be worth when fulfilling the specific scenario, and what these costs are. When combining these two amounts the balance coupled to the scenario is calculated. The balances of the chosen scenarios are added to the balance of scenario D, as this scenario represents the current situation. The deltas in house price for each scenario are checked by experts in the field (employees of Planmaat). The table that expresses all of the above mentioned can be found in Table B.3.

3.4. Conclusion

In this chapter, the challenge of quantifying sustainability within the context of this thesis was explored. Despite considering general Dutch sustainability measures initially, their type of measuring proved impractical for integration into the model. Consequently, an alternative method was sought that is fitting the model in this thesis.

The DCBA method emerged as a suitable approach, offering a flexible and scenario-based framework for sustainability quantification. DCBA focuses on delineating various scenarios, ranging from the least to the most sustainable. Through this method, sustainability can be accurately assessed within the model, paving the way for informed decision-making in development endeavors.

Furthermore, the implementation of the DCBA method within the model was detailed, focusing on the selection of relevant sub-themes and the quantification of scenarios. The method provides a total of forty sub-themes, who all explain the concept of sustainability in area development. However, the chosen sub-themes for this thesis are; building materials, humidity and ventilation, solar energy, and groundwater. Reflecting the diversity of sustainability considerations in the model and acting as a prototype. This answers the second sub-question: 'What sub-criteria explain the concept of sustainability in area development?'. All forty sub-themes described in the DCBA literature are suitable as sub-criteria that explain the concept of sustainability in area development. Furthermore, the quantification process, which involves balancing scenario-specific factors was elaborated.

Overall, the adoption of the DCBA method represents a significant step forward to quantify sustainability within the model, and for promoting sustainable development practices. Concepts of the applied model are explained in the next chapter. In subsection 4.2.2, the quantification of how sustainability takes place within the model is discussed in more detail. Explained concepts in chapter 4 are necessary to better understand the quantification within the model.

4
Model Explanation

This chapter discusses the created model. It explains the underlying theoretical concepts and the practical explanation. As the book 'Open Design Systems' explains, often there are builds, that don't comply with the combined preferences and needs. The decision-making process takes a lot of time, and it is hard to combine every opinion into one plan (Wolfert, 2023). This is why a computer model could be helpful. In this thesis, such a model is created, which searches for a group optimum through (non-)linear optimisation. To better understand this model, the theoretical concepts and model structure are described.

4.1. Theoretical concepts

4.1.1. (Non-)linear optimisation

The ultimate goal of optimisation is to find the values closest to one's, or more than one's, preferences (Charnes & Cooper, 1977). For optimisation problems with multiple objectives, various approaches can be taken. The difference lies in the timing of the definition of the preferences. These approaches are defined by Wolfert (2023):

- "A priori – preferences of stakeholders are defined before the beginning of the optimisation process."
- "A posteriori – preferences are defined after the optimisation process is complete and a set of possible solutions is found."
- "Interactive – a combination of the abovementioned methods where preferences are provided during the optimisation run."

For this thesis, stakeholders are asked to express their preferences at the start. Their preferences consist of preference scores, as well as weights, both of these are linked to model's objectives. Because the preferences are defined before the start of the optimisation process, this thesis uses only 'a priori' methods.

A distinction can be made between various optimisation algorithms. Starting with linear or non-linear optimisation. Linear algorithms deal with problems where constraints and objectives are linear, logically. These algorithms work relatively fast, and the outcome is straightforward. However, real-life problems tend to be complex and most of the time they are not strictly linear. When this is the case, which means objectives and/or constraints in a problem are not linear, non-linear optimisation can be applied (Wolfert, 2023).

Within non-linear optimisation methods, another distinction can be made between local and global optimisation algorithms. The downside of local algorithms is that they do not guarantee to reach the 'real'/global optimum, it could just be a local optimum, when dealing with non-convex objective functions. This difference is shown in Figure 4.1. That's why global optimisation algorithms are created. Even though the chances are higher of reaching the global optimum, even global optimisation algorithm cannot guarantee to find these.

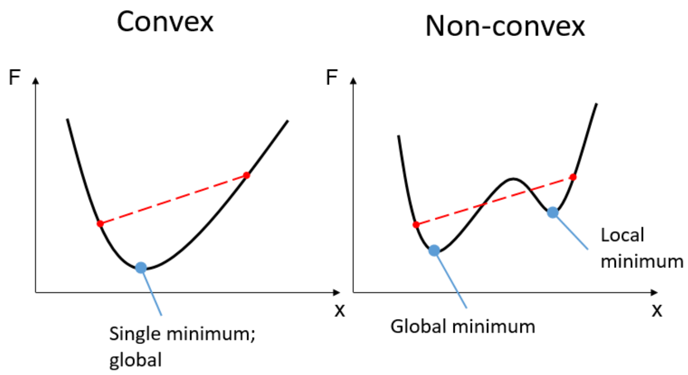


Figure 4.1: Difference between convex and non-convex functions (Wolfert, 2023)

Global optimisation algorithms in return consists of population-based, single-point and surrogate algorithms. Because of the method used in this research, population-based algorithms will be explained. In these types of algorithms there are no single-point solutions, but there are populations of solutions. A population consists of multiple feasible solutions. The initiation is based on a random starting point, and after this, with every step (generation), will be better than the last one and so will be closer to the optimum. The best member of the last generation will be chosen as the optimum solution. Because of the above mentioned, population-based algorithms are more universal than local ones (Wolfert, 2023).

4.1.2. Preference Function Modeling

Preference Function Modeling (PFM) is a mathematical economics theory aimed at rectifying fundamental modeling errors found in classical decision and utility theories like Pareto. Rather than merely identifying errors, PFM offers both proof and solutions that facilitate the design of pure open systems engineering. This methodology has culminated in the creation of Preferendus, an advanced design optimisation tool recently introduced by Wolfert (2023).

In the PFM, stakeholders are ought to provide several input. In short it comes down to the following components: variables, objectives, stakeholder preferences and weights, and constraints. The variables, through formulas, determine the values of objectives. Each stakeholder determines his or her preferences for each of these objectives, and if desired, weightings can be given to them. These are the preferences that are optimised by means of (non-)linear optimisation. To account for limits and other requirements, there are constraints. Each of these is described in more detail in subsection 4.2.1.

For this thesis, preference scores are bound between 0 and 100. Stakeholders are expected to provide a preference score corresponding to every objective value. A low preference score (approaching zero) represents an undesire, while a high preference score (approaching a hundred) represents contentment. This is represented in Figure 4.2. There isn't a predefined scale that must be chosen. However, it's crucial to establish and well-define the scale for the purpose at hand (Barzilai, 2005). This is crucial so that users know how to translate their preferences. This translation is only possible and valid when the dimensions of the scale are known. The stakeholders can fill in their preferences in the Excel model.

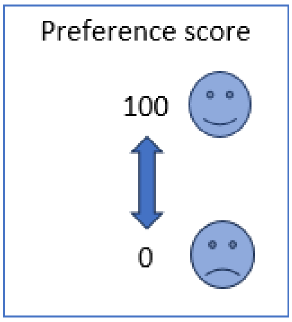


Figure 4.2: Range of a preference score

While the preference scores represent the input of the model, the output of the consists of housing differentiation with corresponding sustainability scenarios. The model establishes how many houses of each type should be build and what scenario should be coupled to it. This output is then processed by Tetra, as explained in subsection 4.1.3, to rank all alternatives.

4.1.3. Preferendus tool

For this research and thus the creation of the model, the Preferendus methodology is used. This is based on different standard Genetic Algorithm (GA) solvers. GA is a form of population-optimisation. The Preferendus Tool is a link between this optimisation algorithm (explained in subsection 4.1.1) and the Tetra software (Wolfert, 2023).

Tetra is a software tool for Multi-Criteria Decision Analysis (MCDA) that utilises Preference Function Modeling (PFM) (see subsection 4.1.2. Its non-linear solver algorithm works by minimising the least-squares difference between the overall preference score and each individual stakeholder score across all decision criteria, determining the closest match for each (Wolfert, 2023).

The task of Tetra in the model is to compare all alternatives/designs. This is done by aggregating the preference scores of the stakeholders, to compute the group preference. Tetra does this by giving each alternative a score between 0 and 100, these are the aggregated preference scores. The rating is based on a comparison, so the 'best' alternative receives a score of '100', and the 'worst' alternative receives a score of '0'. The remaining alternatives are scaled in between 0 and 100. The scores are not absolute values, what should be looked at is only the distance between each score (Barzilai, 2005). If one's not aware of this method, a score of '0' could give a negative message, while in fact this is not necessarily the case.

4.2. Practical explanation

4.2.1. Model requirements

As shortly introduced in subsection 4.1.2, within the Preferendus model, several input components are required. These model requirements are listed here to give a sound overview, including an example that captures everyone's imagination - money:

- **Variables** are the inputs that are adjusted by the model to find optimal variable values. They represent the different values that can be set to minimise or maximise the objectives. This can, for instance, be different types of houses, each with their own costs and revenue to earn money.
- **Objectives** are the desired outcomes, the component the model looks to optimise. These values of objectives are calculated, with a formula, using the values of the variables. It could, for example, be maximising profits by building the right amount of the right housing types. It is possible that an objective itself is also a variable.
- **Stakeholder preferences and weights** are the preferences a stakeholder attaches to the objectives, accompanied by how important the stakeholder considers the objective to be, represented by the weights. This also includes the mutual weightings between stakeholders, how much power one stakeholder has compared to another. These together makes whether an outcome from the model, a set of variable values, can be considered a good or bad outcome. In the example, one might want a minimum turnover of 10 million and attach great importance to this, while another stakeholder places less value on turnover but more on another objective. Each stakeholder indicates its preferences with a score between 0 and 100 for different objective values, as indicated in subsection 4.1.2.
- **Constraints** are the limitations or requirements on variables or objectives that must be met in the model. These include bounds on the variables, ensuring they stay within acceptable limits. To stay with the example, one can, for instance, set that negative turnover is not allowed, but similarly the bound can be set that a negative number of houses cannot be built.

As becomes evident from the given examples, each of these components is closely interrelated. In short, it can be said that: by optimising for the variable values, one obtains the objective values that have the highest stakeholder preferences, accounted for their weights and within the bounds set by the constraints.

4.2.2. Quantification of sustainability in the model

To better include sustainability in tender processes, and to include sustainability in optimisation models, sustainability sub-criteria are quantified in chapter 3. Since basic concepts of optimisation have been explained, the quantification of sustainability in the model can be elaborated on.

The quantification of sustainability takes place in two ways: incorporating sustainability sub-criteria as both objectives and variables in the model, and processing these alternatives based on balance.

Sustainability sub-criteria, and the accompanied DCBA alternatives, serve both as variables and objectives. Naturally, sustainability sub-criteria are included as objectives in the model; one could want to maximise the use of sustainable materials. To measure various sustainability sub-criteria, DCBA alternatives are processed as variables in the model. This creates the possibility for the PFM to vary the values of variables and look for the best alternative (the described D, C, B, or A alternative) for that sustainability measure. To do this, DCBA alternatives are essentially written as integer values between 1 and 4, where 1 represents the D-alternative and 4 represents the A-alternative. This can also be varied by creating separate variables for each variable already in the model, such as a variable that represents the scenario of applying sustainable materials for a specific house type.

Secondly, and certainly of great importance, is the quantification of sustainability in the balance objective. This makes sense, as implementing certain sustainability alternatives generally costs money. As a result, it also serves as a balancing mechanism, because without inclusion in the balance, everyone will generally apply all the best possible sustainability alternatives. If it is known how much a sustainability alternative costs, this can be calculated via the variables in the balance of the model. The PFM model then optimises on this.

4.2.3. Relation of input to output

In order to get a better understanding of the model, it is essential to explain how the input relates to the output of the model. As the designed model is of a certain complexity, something that is inevitable with the chosen method and goals of this thesis, it could feel like a black box to the user. To prevent that this model will raise concerns, and give the feeling of a black box, this section outlines the relation between the input, the model optimisation, and the output.

Input

The input of the model consists of all the model requirements described in subsection 4.2.1. Important to note is that the stakeholders enter preference scores for each objective, as well as the corresponding weights. There are two types of weights; personal weights (distributed among the stakeholders, determining how much power they have) and objective weights (distributed among the objectives of one stakeholder, determining how important these are found to be). It is up to the model user how these weights are distributed and who can manipulate these.

These preference scores will be used to make preference curves through interpolation, one for every stakeholder-objective combination. This curve shows the course of the preference linked to the corresponding objective value.

Input for the model that is not entered by the stakeholders but by the 'expert' before-hand are the variables, constraints and other aspects, such as formula values, that define the case study. Though, they can be adjusted by the stakeholders.

Optimisation
The optimisation algorithm uses these preference curves, with the objective weights to form an optimal result. This consists of an optimal value for all variables that are predefined in the model. The optimisation is carried out when pressing the ”Run optimisation” button, in the Excel file.

As explained before in subsection 4.1.1, the optimisation process starts with a random starting point, and with every next step the model searches for a point better than the last one (based on the input). The last generation forms the optimum. During each optimisation step, the model calculates the outcomes of every objective. The model is basically testing what value of each variable makes a desired outcome for the objectives. While optimising, the model takes the constraints, bounds and input into account.

Output
Logically, the output of the model consists of the optimum solution. However, this solution, together with the manual solutions will be interpreted. This interpretation is done with the Tetra software (explained in subsection 4.1.3). Based on the input (preference scores, weights) Tetra calculates the ranking between all alternatives (manual solutions and optimisation). This ranking is the final output and can be used by stakeholders to retrieve more insight into the development of the case study area.

4.2.4. Model knowledge

To best facilitate use, accounting for limited model (and programming) knowledge, accessibility for users to work with the model themselves is important. The basis of the model is written in Python, but to facilitate usage, a link to Excel has been made. With minimal effort within and knowledge of Python, the model can be changed to the desired use case, with changes in, for instance, the number of variables, objectives or stakeholders. This means, once the case study is designed, the stakeholders do not need to use Python at all, it runs in the background. Users use buttons in Excel to control the Python model. The only mandatory thing is for the users to save the Python files in the same folder as the Excel file on their computer.

The programming package that is used to connect the Python model with Excel is called ’xlwings’. With User Defined Functions (UDFs), functions that are made in Python, are imported and used in Excel, just like original Excel functions (Zoomer Analytics GmbH, 2024).

4.2.5. Model usage

The model is created with intention to be used at the beginning of the tender process. It’s goal is to open a ’sustainability-dialogue’ for the client.

First, the client needs to define selection criteria. This is to let the contractors know on what criteria they will be judged and therefore selected (Van Leest, 2022). The model can be used during that definition process. This way, the contractors know what is expected of them and the designs will be presumably more to the expectations of the client.

The model can be utilised in two different ways: as an assessment tool and as a design tool. Through optimisation, the model produces an optimal solution. This outcome stems from non-linear optimisation. The optimisation can serve as a component of the design tool. Clients specify their preferences, and the model generates an optimal solution accordingly. This is useful for clients that work with a detailed predefined program of requirements, when approaching one or more contractors.

Additionally, the model can function as an assessment tool. This is achieved by inputting various contractor designs into the model (manuals), such as bids from different developers. The model then compares all designs and, based on a scoring system, determines which design best aligns with the group preference. In this case, contractors will need to receive information about the assessment process (transparency is mandatory). Contractors will receive the sustainability objectives they will be assessed upon, and what objectives are perceived as more important by the client. This information is brought together in collective preference curves, with collective weights for every objective.

4.3. Code

The complete code (i.e. all python files), the Microsoft Excel file and all other needed files can be found on Github via: https://github.com/sylvanavankessel/thesis.git. Instructions are provided through 'README' files that explain the use of the code.

4.4. Conclusion

In conclusion, this chapter describes the theoretical concepts and the practical application that are underlying the created model. It shows what is required for the user (in terms of input but also knowledge) and when the model can be used in the larger process. The model is designed to address the complexities inherent in aligning stakeholder preferences and project objectives, offering a systematic approach to optimise design solutions.

The model, constructed within Python code, serves as a mechanism for generating optimal housing solutions based on input parameters such as housing types and stakeholder preferences. By employing a non-linear optimisation approach, the model navigates through various scenarios to identify the most suitable one. Central to the model's functionality is the Preference Function Modeling (PFM) framework, which enables stakeholders to articulate their wishes through preference scores. A global optimisation algorithm (population-based) is used, however even these algorithms cannot guarantee to result in the global optimum.

Furthermore, the integration of the Python model with Microsoft Excel enhances its accessibility and usability for stakeholders, allowing for seamless interaction without requiring expertise in Python programming. Leveraging the 'xlwings' package, the model can be easily deployed within Excel environments, simplifying user interactions.

Overall, the implementation of this Python-based model represents a significant advancement in decision-making processes within the area development domain. By leveraging optimisation techniques and stakeholder preferences modeling, the model offers a systematic approach to navigate the complexities of project design and stakeholder engagement, ultimately fostering sustainable and inclusive development practices.

The next chapter describes the implementation in more detail, with a general user guide, including the application to the case study.

5
Model Implementation

This chapter serves as a user guide for the model. First, the case study is presented. After this, the general user guide is explained, thereafter the implementation of the model to the case study is given. Lastly, an explanation about the conducted experiments is presented.

5.1. Case study

5.1.1. Location

The case study that is used for this project is part of Waelpolder, located in the Municipality of Westland, the province of South-Holland in the Netherlands. Waelpolder is part of the Waelpark development project. It will consist of about 720 homes, with half of them being affordable, including some social housing. The area is subdivided into seventeen development fields. There will also be a school and other community places. The green area with lots of water and nature will connect the different neighborhoods. Each area will have different kinds of houses and styles. Waelpolder is in a quiet, countryside area near the village and the sea. It's close to 's-Gravenzande and accessible to go to the beach by bicycle (ONW, 2023b).

5.1.2. Development field 4

Because of the scope and time limits of this thesis, the project Waelpolder as a whole is not used as the case study. For this thesis, there will be a focus on development field 4. A map of Waelpolder with field 4 outlined is displayed in Figure 5.1. The model that will be created in this thesis, will use the characteristics of this field as the input. The land owner ONW (explained in section 2.1) has issued several obligations for this area, that developers need to take into account when starting their proposal (ONW, 2023a):

- A maximum of 81 houses
- A minimum of 54 affordable houses
- 7 m^2 of public greenery per house

- A playground for the age category of 0-6 years
- Parking requirements are in accordance with the municipal policy
- (And more obligations about the appearances)

Figure 5.1: Map of Waelpolder (field 4 outlined in red) (ONW, 2023a)

5.2. User Guideline

The user guideline helps potential users in implementing the model themselves for their respective use case. In this report, a distinction is made between the guide for the client (usually a municipality, in this case ONW) and the contractor (developers). This shows how it can be used by possible parties. Please note, this is an example, everyone is free to use the model in a different way, for example clients together with contractors.

All necessary steps are outlined in different phases. These phases should not be mixed up with phases in a tender process. These phases represent only the steps to use the model. This manual is intended as an aid in addition to an expert explanation session. Next to this, it should be seen as a manual of the model. No visual images are shown, but it is clearly described what part of the model is discussed. In section 5.3 images are given as examples.

The first phase starts at the beginning of the tender process. There is a plan for area development, and the client wants to look for contractors. The location and requirements are known.

5.2.1. First phase

The first phase takes place prior to actually running the model. The preparatory measures are explained below.

Client guide

All files that are on the Github page (https://github.com/sylvanavankessel/thesis.git) should be downloaded and saved to the same folder on a computer. The main file is called ”Preferendus_model.xlsx”, and should be opened to start. As mentioned in section 4.3, instruction files are present to guide the user through the Python files.

First, all hard constraints and bounds need to be entered into the model. These serve as constraints for the developers' designs, and are non-negotiable. The variables (in this case different house-types) and their characteristics should also be entered. This can be done on the ”Assistance” tab. Then, the client must select the sustainability themes that will be included in the model. There is a choice of 10 themes with each 4 sub-themes (total of 40), which can be selected on the ”Start” tab. Two of the ten themes are displayed in Figure 5.2. The choice will depend on the interests the client has for the case location.

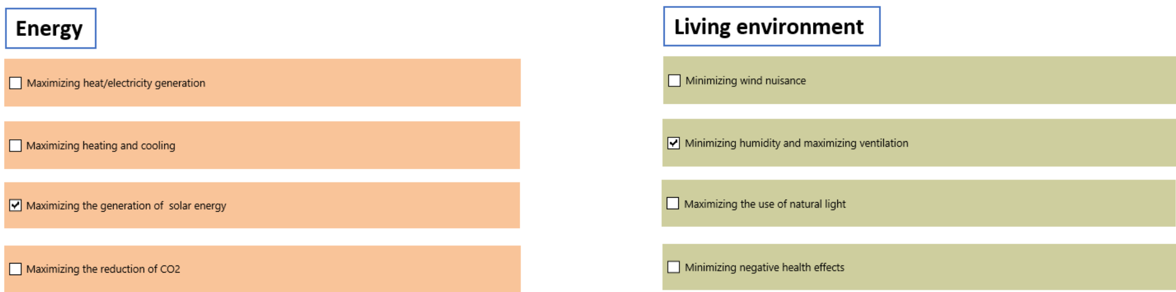


Figure 5.2: Example of selection of sub-themes

Once the hard constraints are put in the model, the client can provide their preferences (soft constraints). On the ”Preferences Input” tab, the chosen sub-themes appear and are transformed into objective variables. A standard objective variable focused on the balance is also included. The model accommodates four stakeholders, four departments within the client, each with their own opinions. These stakeholders must enter their preference scores for all objective variables. This score ranges from 0 to 100. A score approaching 0 indicates dissatisfaction, and a score approaching 100 indicates ultimate satisfaction. These preference scores are linked to sustainability scenarios. Each sub-theme has four scenarios (D, C, B, and A), and the explanation of each scenario can be found on the ”Start” tab.

In order to make the DCBA methodology easier to understand, a quartet game is available. Stakeholders can play this game with each other to get a good idea of all the characteristics and associated scenarios. This can help make a choice between all sustainability characteristics and to link a preference to them.

In addition to the preference scores, stakeholders (i.e. different departments of the client) must also fill in objective weights. One weight per objective variable, indicating how much it should be weighted in the model, how important it is considered to be. The total sum of weights must be equal to 1 at all times. In addition to these weights, a personal weight is also existent, indicating the power relationship between the stakeholders. It is up to the client how these weights are distributed.

When completing all of the above, the model will form preference curves, one for each stakeholder and objective combination. These curves show the progression of preferred scenarios. In order to inform the developers, about the interests of the client; these preference curves are combined into one collective preference curve per objective. This collective preference curve together with the collective weights (objective weight x personal weight) are communicated to the developers.

Contractor guide

The contractor receives all necessary information via an online communication system between the contractor and the client.

The contractor (developer) receives the collective preference curves with collective weighting, this acts as a replacement to how the assessment of selection criteria is currently communicated. Examples of this and other components are given in section 5.3.

The developer receives the explanation about the sustainability scenarios of each chosen sub-theme. The variables and the hard constraints are also communicated to the developers. When submitting their design, the developer must indicate what sustainability scenarios have been chosen for every variable.

5.2.2. Second phase

The second phase takes place when potential developers have submitted their design to the client, or when the client will use the optimisation tool of the model.

Client guide

Optimisation

The client can choose to use the optimisation tool in the model. In order to run this, the button ”Run optimisation” should be pressed on the tab ”Preferendus tool”. This takes a few minutes and the file should not be clicked during this optimisation. The interpretation of the results will be explained later in this chapter.

Next to the ”Optimisation” column, the ”Multiple runs” column can be found. Because of the non-linear origin of the optimisation, there is a high chance every run produces a different outcome. That's why the multiple runs tool has been designed. The model will run a specified number of times, and prints the most preferred (the best) outcome. So these runs are already ranked, before being printed next to the alternatives, where these will be ranked again. This could provide a more reliable outcome. It's the client's choice whether or not this will be used.

Ranking submitted designs

Another function of the model is to add submitted designs to the model. This can be added on the tab ”Preferendus tool” under ”Manual 1” to ”Manual 3”. The developers should have provided the right format, so the adding should be straightforward. After adding the designs, the model will show whether or not the developer has complied with the constraints. If not, the relevant cells will turn red. Furthermore, no button needs to be pressed, the manuals will be processed right away.

Contractor guide

From this phase on the contractor does not play a big role anymore in providing input for the model, other than their design submission. It is important that they submit their design in the right format. Meaning that for every chosen sustainability sub-theme, it must be communicated what scenario (D, C, B or A) is chosen. Next to this, all other standard tender obligations must be fulfilled (like the tender bid).

5.2.3. Third phase

The third phase specifies the correct interpretation of the model results.

Client guide

On the right side of the tab ”Preferendus tool”, the results are displayed. For every alternative the balance is calculated, but for the three manual alternatives the tender bid (of the developer) should be manually added. This is because the tender bid is decisive in the ranking process.

The ”Total weighted score” shows the final ranking of all alternatives, based on the predefined preferences of the stakeholders. This is reflected in the chart below it, named ”Ranking of alternatives”. This ranking is based upon the scores per stakeholders, which can be found below this graph. The scores are multiplied with their personal weight in order to calculate the ”Total weighted score”.

Every stakeholder has a score for each alternative between 0 and 100, provided by Tetra software. The alternative with 0 is the least in accordance with the predefined preferences of the stakeholder, and the alternative with a score of 100 is the most in accordance with this. The other alternatives are scaled between these two alternatives. Only the distance is defining the ranking, they are no absolute values.

To dive deeper into the matter, the rows below the scores can be unfolded to see the exact preference scores by objective and alternative. It is advised only doing this when desired, to prevent unnecessary complexity.

Optimisation (Design tool)
The optimisation part of the model can be used to form a detailed programme of requirements (PvE in Dutch). A client can approach a contractor with this, and call for a collaboration. This way the model is used as a design tool.

Ranking submitted designs (Assessment tool)
Now the contractor can use the ranking as inspiration in order to choose a winning design based on Manual 1 to Manual 3. The model now acts as an assessment tool. It becomes clear what alternative is the most in accordance with the preferences of the stakeholders.

Contractor guide

At this stage, the developer waits to see if their design wins. It may also be the case that a client approaches a developer with a detailed programme of requirements, as a result of the optimisation of the model.

5.3. Case study implementation

In this section it is described how the case study is implemented into the model. The same structure as in section 5.2 is used, for easy comparison.

5.3.1. Implementation of first phase

Within the model, different variables, objectives, constraints, objective formulas and preferences are defined. These are described below.

Variables

For this model five variables are defined, they consist of different housing types. This is because the goal is to find the optimal housing types combination for the case study. These specific variables are based on the requirements file that is portrayed in section 5.1. The variables can be found in Table 5.1.

Table 5.1: Variables of interest

Name	Variables of interest
X1	Number of detached houses, expensive
X2	Number of small row houses, affordable
X3	Number of big row houses, expensive
X4	Number of small apartments, affordable
X5	Number of big apartments, expensive

Objectives

The objectives that are chosen for this model are based upon the chosen sub-themes from section 3.2. The chosen sub-themes are part of the prototype that is created for this thesis. Based on the scope of this thesis, four sub-themes are chosen and implemented into the model. The book consists of forty sub-themes, the idea is that, in the future, stakeholders can select any of these forty sub-themes. Instructions are specified in subsection 5.2.1.

The sub-themes need another formulation because objectives in a model require a direction. The model optimises different values, either minimise or maximise it. Next to these sustainability objectives, the influence of money is also important to include in the model. The solution should also be based on money, as this gives constraints in real life as well. That's why 'Maximizing balance' is the fifth and last objective of the model. The objectives are described like this:

- Maximizing sustainable **building materials**
- Minimizing **humidity** and maximizing **ventilation**
- Maximizing the generation of **solar energy**
- Maximizing the stabilization of **groundwater**
- Maximizing balance

Objectives as variables

As mentioned before, quantification of sustainability is based upon the scenarios. These sustainability objectives are objectives as well as variables, they also provide input for the model. This is because one alternative is based upon the different values for the house types, as well as the scenarios for the sustainability objectives/variables. The scenarios are an input as well as an output. For the balance objective this is not the case, because the value of balance is calculated based upon the 'choice' of the scenarios. So only this objective is not defined as a variable, as can be seen in Table 5.2. As well as that the four sustainability objectives/variables have multiple names. They are actually used as five different variables, different for each housing-type. This means that the model will optimise the sustainability objectives for every housing-type separately. This gives a more precise outcome, and more options to interpret.

Table 5.2: Objectives

Name	Objectives
X6 / x10 / x14 / x18 / x22	Maximizing sustainable building materials
X7 / x11 / x15 / x19 / x23	Minimizing humidity and maximizing ventilation
X8 / x12 / x16 / x20 / x24	Maximizing the generation of solar energy
X9 / x13 / x17 / x21 / x25	Maximizing the stabilization of groundwater
-	Maximizing balance

Constraints

In subsection 5.1.2, the constraints placed by ONW were given. These are repeated below together with their mathematical interpretation, as well as additional constraints.

1. The total amount of houses must have a maximum of 81 (Equation 5.1).
2. The total amount of affordable houses must have a minimum of 54 (Equation 5.2).
3. The minimal amount of houses must be 35 (Equation 5.3).
4. The total amount of used surface must be equal or below the surface of the case study plot (Equation 5.4).

The above mentioned constraints are formulated in a mathematical way like this;

$$x^1 + x^2 + x^3 + x^4 + x^5 < 81 \tag{5.1}$$

$$x^2 + x^4 > 54 \tag{5.2}$$

$$x^1 + x^2 + x^3 + x^4 + x^5 > 35 \tag{5.3}$$

$$(x^1 * S(x^1)) + (x^2 * S(x^2)) + ... + (x^5 * S(x^5)) < \text{Total S} \tag{5.4}$$

$$\text{where } S = \text{Surface} \tag{5.5}$$

Objective formulas

Objective formula for the four sustainability objectives (explained in Table 5.3.1):

$$(x^1) + (x^2) + ... + (x^5)/n, \tag{5.6}$$

$$\text{where } n = \text{total number of houses} \tag{5.7}$$

Objective formula for the one balance objective (explained in Table 5.3.1):

$$(x^1 * B(x^1)) + (x^2 * B(x^2)) + ... + (x^5 * B(x^5)), \tag{5.8}$$

$$\text{where } B = \text{Balance} \tag{5.9}$$

Preferences

The preferences input for stakeholder one is displayed in Figure 5.3 as an example. The stakeholders are ought to only change the dark blue values in the model. This means also the value of the balance, they are free to choose what amount of money is coupled to their preference scores. This is different to the sustainability objectives, as the scenarios are set. They are also free to choose their preference scores, because everyone's preference could be different. Therefore, it is chosen to not set a score of 0 to for example scenario D, and/or a score of 100 to scenario A. It is not certain that every stakeholder appreciates sustainability the same way.

Objectives stakeholder 1		
Weight table		
Objectives	**Weight objective**	
Maximizing sustainable building materials	0	
Minimizing humidity and maximizing ventilation	0	
Maximizing the generation of solar energy	0	
Maximizing the stabilization of groundwater	0,1	
Maximizing balance	0,9	+
	1	
Preference tables		
Maximizing sustainable building materials	**Scenario**	**Preference (0-100)**
	D	10
	C	20
	B	30
	A	80
Minimizing humidity and maximizing ventilation	**Scenario**	**Preference (0-100)**
	D	20
	C	40
	B	60
	A	80
Maximizing the generation of solar energy	**Scenario**	**Preference (0-100)**
	D	20
	C	40
	B	60
	A	80
Maximizing the stabilization of groundwater	**Scenario**	**Preference (0-100)**
	D	50
	C	60
	B	90
	A	90
Maximizing balance	**Value (€)**	**Preference (0-100)**
	€ 6.000.000	20
	€ 6.500.000	40
	€ 7.000.000	60
	€ 7.500.000	100

Figure 5.3: Preferences input for stakeholder one

A preference curve is displayed in Figure 5.4. This curve is based on objective one for stakeholder one, the curve corresponds to the values in Figure 5.3 for the objective 'Maximizing sustainable building materials'.

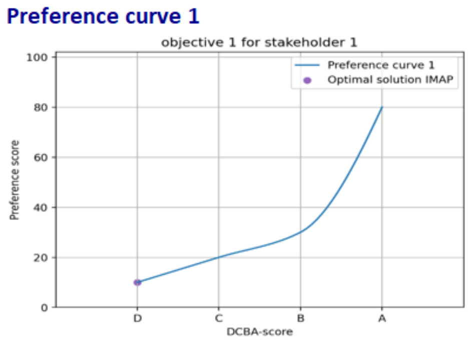


Figure 5.4: Preference curve of objective one for stakeholder one

Contractors receive collective preference curves, to get a hold of the preferences of the client. These curves look the similar to the preference curve in Figure 5.4, the only difference is that the preference curves of all stakeholders for one objective are combined. In addition, the collective weights are provided (Figure 5.5), to inform the contractor about the importance ratio between objectives. These come about by multiplying the objective weight with the personal weight of the given stakeholder and adding these values for all stakeholders.

Collective weights of objectives

Objectives	Collective weight
Maximizing sustainable building materials	0,15
Minimizing humidity and maximizing ventilation	0,14
Maximizing the generation of solar energy	0,31
Maximizing the stabilization of groundwater	0,08
Maximizing balance	0,33

Figure 5.5: Collective weights of objectives

5.3.2. Implementation of second phase

In Figure 5.6 the Preferendus tool with input is displayed. The three manuals, as well as the optimisation and multiple runs column are shown. The rows of x6 to x25 can be hidden and these scenarios are averaged below for easier interpretation. However, the rows of x6 to x25 for Manual 1, 2 and 3 must be filled in based on the bids of contractors (dark blue cells). After this, these rows can be hidden. The same rows for the Optimisation and Multiple run remain untouched, as the model calculates these scenarios.

5.3.3. Implementation of third phase

In Figure 5.7 the results of the Preferendus tool are shown, based on the input described above.

At the top the housing differentiation and averaged sustainability scenarios are displayed. Below this, the calculated balances and tender bids (only for the manuals) can be found. The total weighted score shows how the five alternatives score based on the preferences of the stakeholders and their power (personal weight). The bar chart in the middle represents the ranking of the alternatives based on the total weighted score.

The personal preference scores per alternative are displayed below the bar chart. These scores are calculated by Tetra software (explained in subsection 4.1.3). The alternatives are ranked with a score between 0 and 100, a higher score represents a higher preference. The values are not absolute, attention should only be paid to the distance in scores between the alternatives. The preference scores are based upon the predefined input preference scores by the stakeholders.

From these results can be concluded that the Optimisation alternative is the best (highest score), followed by Manual 2. Manual 1 is ranked the lowest, the personal preference scores show that it is the least favorite alternative for stakeholders 2, 3 and 4. However, stakeholder 1 has a relatively high preference for this alternative.

5.4. Experiments

5.4.1. Experimental set-up

An important aspect of this thesis is to perform experiments. The idea is to perform an experiment with employees of ONW, to figure out whether the new quantified criteria contain added value opposed to how ONW currently performs the assessment. This is part of validating the model.

According to Wolfert (2023), both a technical and social cycle need to be executed when creating a model. For this thesis, there is a requirement of a minimum of two iterations. This means that after completing the first stage of building the model (first technical cycle), the first experiment (first social cycle) should be executed. By performing the experiment, stakeholders will give feedback, what are the strong points and what aspects can be improved. These suggestions should be incorporated when adjusting the model (second technical cycle). After these adjustments, the second experiment can take place (second social cycle). Stakeholders will again provide their feedback, and these suggestions will be incorporated while making the last adjustments to the model. Ideally more iterations would take place, but due to time restrictions of this thesis this is not feasible.

The participants were asked after every experiment to fill in a survey. The questions in this survey where based upon the System Usability Scale (SUS) test, which consists of ten questions (Brooke, 1996). These ten questions are to be answered on a scale of 'totally agree' (1) to 'totally disagree' (5). The results should be interpreted in a certain way, and can be calculated to a score on a scale of 0-100. This scale is defined in Figure 6.1, where the experimental results are discussed also. By doing this, the results give a subjective rating of a product's usability, in a quick manner (Bangor et al., 2008).

Additional questions are specified to retrieve information about potential suggestions for the model and whether or not the model is an improvement to the current situation. All survey questions and answers can be found in Appendix C.

5.4.2. Participants

Unfortunately, due to time constraints and busy schedules among ONW employees, it wasn't possible to conduct an experiment with them. Consequently, both experiments were carried out with employees from Planmaat instead. Based on their experience, Planmaat employees have the ability to perform an experiment acting and thinking like ONW. While it would have been preferable to involve ONW employees, this adjustment ensured that the research could proceed despite the logistical challenges encountered. As the model is designed to be used by four stakeholders, in every experiment four participants took part.

5.4.3. Experimental process

The experimental process ran as follows. First, participants were given a small presentation explaining what the model entails, why it exists and its purpose. In this way, more clarity was created.

All experiments were conducted with four participants, as the model is set up for this. First, all participants were assigned roles, half were told that they had a high interest in money, and the other half had a high interest in sustainability. In addition, they received the explanation of all sustainability scenarios, belonging to the chosen objectives in the model. The chosen objectives are the ones that are elaborated on in this thesis, as described in Table 5.3.1.

After participants were given some time to determine their preferences, they were asked to list them so that they could be entered into the model. In addition to their preference scores, participants should also provide their objective weights. The personal weights (power) were left the same for convenience; each participant's input counted equally in the model.

After entering the input, the 'Preferendus Tool' tab is displayed. Here, three different designs can be entered first. Since this is an experiment, and there are no developers with designs, the participants are allowed to come up with the designs themselves. After this, the optimisation is run.

After the optimisation is performed, the results can be interpreted. During the experiment, the results were discussed. Questions were asked about ambiguities and conclusions were drawn. Suggestions for improvement are given, and the strengths of the model are highlighted. This information can be found in section C.2.

At the end of the experiment, all participants receive a digital survey, where they can provide their suggestions for improvements and fill in the SUS test, as described in subsection 5.4.1.

5.5. Summary

This chapter presented the case study, followed by the guide to the model, which was then also applied to the case study. The chapter contains an explanation, no new insights are gained. Hence, this chapter does not contain a conclusion, but a summary. Having discussed the use of the model in detail in this chapter, the next one (chapter 6) will discuss the results.

Preferendus tool

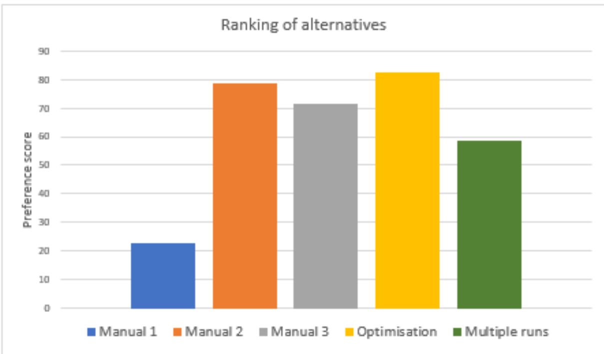
Please only change the dark blue values in order to influence the model's outcome

	Name	Variables of interest	Manual 1	Manual 2	Manual 3	Optimisation	Multiple runs
						Run optimisation	Run multiple runs
General	x1	Number of detached houses, expensive	1	0	1	2	0
	x2	Number of small row houses, affordable	10	25	10	14	15
	x3	Number of big row houses, expensive	5	5	5	9	6
	x4	Number of small appartments, affordable	44	39	44	45	41
	x5	Number of big appartments, expensive	20	5	20	5	13
X1	x6	Maximizing sustainable building materials	D	A	A	B	D
	x7	Minimizing humidity and maximizing ventilation	D	B	A	A	A
	x8	Maximizing the generation of solar energy	D	A	A	A	A
	x9	Maximizing the stabilization of groundwater	D	D	A	A	A
X2	x10	Maximizing sustainable building materials	C	A	A	D	A
	x11	Minimizing humidity and maximizing ventilation	D	B	A	A	A
	x12	Maximizing the generation of solar energy	D	A	A	B	A
	x13	Maximizing the stabilization of groundwater	D	D	A	A	A
X3	x14	Maximizing sustainable building materials	C	A	A	D	A
	x15	Minimizing humidity and maximizing ventilation	D	B	A	A	A
	x16	Maximizing the generation of solar energy	D	A	A	B	A
	x17	Maximizing the stabilization of groundwater	D	D	A	A	A
X4	x18	Maximizing sustainable building materials	C	A	A	D	A
	x19	Minimizing humidity and maximizing ventilation	D	B	D	A	A
	x20	Maximizing the generation of solar energy	D	A	A	B	A
	x21	Maximizing the stabilization of groundwater	D	D	A	A	A
X5	x22	Maximizing sustainable building materials	D	A	A	D	A
	x23	Minimizing humidity and maximizing ventilation	D	B	D	A	A
	x24	Maximizing the generation of solar energy	D	A	A	B	A
	x25	Maximizing the stabilization of groundwater	D	D	A	A	A
	Average	Maximizing sustainable building materials	D-C	A	A	D-C	B-A
		Minimizing humidity and maximizing ventilation	D	B	B	A	A
		Maximizing the generation of solar energy	D	A	A	B	A
		Maximizing the stabilization of groundwater	D	D	A	A	A
		Sum of houses	80	74	80	75	75
		Sum of affordable houses	54	64	54	59	56
		Covered surface with houses (m2)	8270	8370	8270	8500	8030
		Public greenery (extra) (m2)	230	130	230	0	470

Figure 5.6: Input of the Preferendus tool

Results

	Manual 1	Manual 2	Manual 3	Optimisation	Multiple runs
Number of detached houses, expensive	1	0	1	2	0
Number of small row houses, affordable	10	25	10	14	15
Number of big row houses, expensive	5	5	5	9	6
Number of small appartments, affordable	44	39	44	45	41
Number of big appartments, expensive	20	5	20	5	13
Maximizing sustainable building materials	D-C	A	A	D-C	B-A
Minimizing humidity and maximizing ventilation	D	B	B	A	A
Maximizing the generation of solar energy	D	A	A	B	A
Maximizing the stabilization of groundwater	D	D	A	A	A
Calculated balance	€ 7.657.500	€ 6.903.000	€ 6.654.000	€ 7.640.975	€ 6.005.475
Tender bid	**€ 7.750.000**	**€ 7.200.000**	**€ 6.750.000**	**€ 7.640.975**	**€ 6.005.475**
Total weighted score	**23**	**79**	**71**	**83**	**58**



	Manual 1	Manual 2	Manual 3	Optimisation	Multiple runs
Score stakeholder 1 →	**91**	**58**	**36**	**100**	**0**
Score stakeholder 2 →	**0**	**99**	**98**	**69**	**100**
Score stakeholder 3 →	**0**	**93**	**100**	**61**	**91**
Score stakeholder 4 →	**0**	**65**	**51**	**100**	**43**

Figure 5.7: Results of the Preferendus tool

6 Results

This chapter outlines the model outcomes, the validation and verification process, the model's relation to the current practice and the experimental results. Participants engaged in experiments, in order to validate the model. The results are presented, based upon the feedback of the participants, as well as the proposed surveys. Recommendations are provided for refining the model based on user feedback to enhance its usability and integration into real-world decision-making processes.

6.1. Model outcomes

In Table 6.1, the objective weights provided by the users (stakeholders, S1-S4)) are shown. For every stakeholder the sum of the weights must be equal to 1. The personal weights were equal in this case (25% for every stakeholder).

Table 6.1: Objective weights for stakeholders 1 to 4

	S1	**S2**	**S3**	**S4**
Maximizing sustainable building materials	0	0.3	0.2	0.1
Minimizing humidity and maximizing ventilation	0	0.2	0.2	0.15
Maximizing the generation of solar energy	0	0.5	0.5	0.25
Maximizing the stabilization of groundwater	0.1	0	0.1	0.1
Maximizing balance	0.9	0	0	0.4

The Preferendus tool results are shown in Figure 5.7. The influence of the objective weights is apparent when comparing the preference scores of stakeholder 1 with the scores of the other stakeholders. Stakeholder 1 has a preference score of 91 for Manual 1, while the other stakeholders perceive this alternative as their least favorite. This difference lies in the weight distributed to the objective of balance. Manual 1 has the highest balance, and because stakeholder 1 assigned 90% of its weight to this objective, it scores high. The other stakeholders distributed 0% of 40% to this objective, valuing the other objectives more. The other preference scores can be substantiated the same way.

6.2. Model verification

The verification of the model is performed to ensure the preference function model was implemented correctly. Regarding verification, the question that one can ask themselves is ”Are you building it right?”. There are many different forms of verification, among which formal tests such as: unit testing, system testing and integration testing. These tests check whether the code components work as intended in isolation, and they check whether all individual components are properly linked to each other within the model (Beizer, 1984) (Holling et al., 2016). One could also think of code reviews and simulation runs as verification methods. During the creation and testing of the model, checks are constantly performed whether the model produces outcomes as expected. Thus, simulation runs on both units in isolation as the integrated system has been tested exhaustively while creating and writing the code in the model. Several people also looked at the model under the guise of 4-eye principle. Together, this minimises the risk of technical inaccuracies in the model.

6.3. Model validation

A validation is performed to found out the answer to this question; ”Are you building the right thing?”. The model can be technically perfect, when the verification is successfully performed as prescribed in section 6.2. However, it is possible that the model is not right for the client. For example when the model produces the wrong type of results. In this case the validation is done via a scenario test and a survey, that is presented to the participants after every experiment. This is called an User Acceptance Test (UAT) (Ganesh et al., 2014).

6.3.1. Scenario test

For the scenario test, four different scenarios are tested, these are displayed in Table 6.2.

Table 6.2: Scenario testing

Scenario	Description
A1	All stakeholders place a high value to sustainable area development
A2	All stakeholders place a low value to sustainable area development
B1	One stakeholders owns 50% of the power, valuing sustainability high, money low.
B2	One stakeholder owns 50% of the power, valuing sustainability low, money high.

The distinction between the different scenarios is made based upon weights. As for scenario A1 and A2, stakeholders expressed a high weight either for the sustainability objectives or for the balance objective. The results were as expected as the outcome of the model was corresponding to the input. For example, for scenario A1, the optimisations had a high value for the sustainability objectives, whereas with scenario A2 the balance objective had a high value. The same applies to scenario B1 and B2. When stakeholders get more power (more personal weight), this results in expected outcomes.

6.3.2. Experimental results

As mentioned in section 5.4, after the experiments participants received a digital survey they were asked to fill in. This survey consisted partially of questions regarding a SUS-test (also explained in section 5.4).

From the answers to the SUS-test, scores from both experiments can be derived. These have a average score of 53,1 and 52,5 respectively. These scores are based on the SUS-scale. All scores can be found in section C.2. On a scale of 0 to 100, these average scores are not high, as can be seen on the scale in Figure 6.1. To determine which aspect had the largest share in this score, the questions with the lowest rating are looked into.

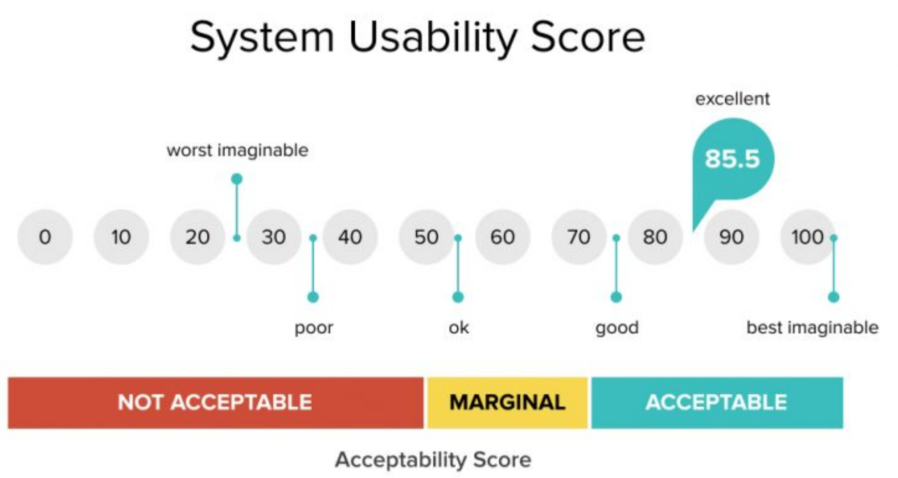


Figure 6.1: Scale of System Usability Score test (Smyk, 2021)

When examining the responses to the User Acceptance Test (UAT) questions, it becomes apparent that the complexity of the model emerges as the primary obstacle. Interestingly, there are only few suggestions for technical adjustments to the model. Therefore, while the model is technically sound, it appears to be perceived as somewhat complicated. All participants are convinced that people will not be able to get used to the model quickly. The model obviously takes time to be understood. A clear explanation is needed, perhaps together with technical support. This could be in the form of an expert who is there for guidance, while using the model.

The suggestions for improvements that all participants agreed on were incorporated into the model. These consisted of technical adjustments, as well as adding more practical instructions.

With the suggestions implemented, most participants see potential. One point of concern is the method; due to the non-linear optimisation with local optima, a different outcome is computed with each run. This can come across as unreliable because the optimum is not fixed. Because of this, a multiple runs tool is added to the model. The user can select the number of times the model should run, these runs are ranked against each other and the best outcome, is shown.

The above mentioned concern is one that is embedded in the method, and is not something that can be changed within the scope of the thesis. The multiple runs tool is the only way to try to take away this concern. When reaching beyond the scope of this thesis, the varying outcomes can be prevented. One of the possibilities is to establish a set of conditions for the design parameters, to stabilise the predictive controllers (Fontes, 2001). Or instead of random starting points (as in this thesis), fixed starting points can be assigned. When each runs starts from the same starting point, varying outcomes are less common. The concern still exists for the model in this thesis, but there are ways to change it.

6.3.3. Relation to current practice

The aim of this thesis is to quantify sustainability criteria and subsequently incorporate them into a model for better evaluation of designs in tenders for area development. The model developed for this thesis represents a significant change from the current practice. As discussed in section 2.2, the selection criterion ”vision of sustainability” is currently evaluated on a scale ranging from insufficient to excellent. Following this assessment, a certain number of points are assigned to a design. However, this approach lacks quantifiability, making it less precise. Hence, the model was created to enable a quantified assessment of the sustainability of a design. In addition to quantification, the use of the Preferendus tool is also new.

As explained in subsection 4.2.5, the model can be utilised in two different ways, e.g. as an assessment tool or a design tool. When focusing on the case study, Waelpolder field 4 and the client, ONW, only the use of an assessment tool would be of added value. This is because ONW puts out a tender to developers, and will choose the one that is most to their liking. ONW is in no way giving detailed design obligations, only constraints based their wishes. So optimisation is not suitable, as the result can not be communicated with developers. However, the use of an assessment tool is of added value. With the assessment tool ONW can enter designs submitted by developers into the manual designs section of the model. Than, the model will rank these manual designs, without paying attention to the optimisation result. This outcome gives insight into which design has the highest score based on the predefined preferences. One possible approach is for ONW to utilise the optimisation results to compare with the developers’ bids. This information can guide ONW in steering the developers without revealing the exact results.

The design tool can be useful to clients that work with a detailed program of requirements (Programma van Eisen (PvE) in Dutch). Some clients, like municipalities use this and approach one or more parties. In this case, it is useful to have a optimisation solution, which can be communicated to the desired party.

The current assessment system uses a scale as explained in section 2.2. Different designs are separately rated and assigned points. After this, they are compared based on the points they received. In the model developed in this thesis all designs are rated against each other. Every design is assessed in exactly the same way, leaving no room for subjective differences. This makes the model of value for ONW, as it is a function they did not have before.

6.4. Conclusion

This chapter encompassed the results of the developed model. Despite encountering logistical challenges, the experiments proceeded successfully with the involvement of Planmaat employees instead of ONW employees. The validation process, including scenario testing and User Acceptance Test (UAT), provided valuable insights into the model's usability and effectiveness.

The scenario testing revealed that the model accurately responded to different stakeholder preferences and weight distributions, demonstrating its adaptability. However, the UAT results highlighted the complexity of the model as a significant obstacle. Participants expressed concerns about the steep learning curve and the need for clear explanations and technical support to navigate the model effectively.

In addition, this chapter addresses the verification process, emphasising the importance of rigorously testing the model's technical correctness. Through unit testing, system testing, and integration testing, the model undergoes continuous checks to ensure reliability and accuracy in its outcomes.

Interestingly, while participants acknowledged the complexity, there were only minimal suggestions for technical adjustments to the model itself. Instead, the focus was on providing clearer instructions and support mechanisms to enhance usability. These suggestions were diligently incorporated into the model, reflecting a responsive approach to user feedback.

For ONW, the model is useful but only when deployed as an assessment tool. This is because ONW does not communicate detailed design obligations, only constraints. ONW could use the optimisation results as information to steer the developers, without communicating precise results. The design tool can however be useful for clients when approaching developers with a detailed program of requirements, as in this case the optimisation solution can be used.

Overall, participants see the potential of the model, when adjustments are made to improve usability (for example clear instructions). Continued refinement and iteration based on user feedback will be essential to further optimise the model's usability and ensure its effectiveness in real-world applications. Participants believe the model has added value in integrating sustainability into design proposals, especially while comparing different bids and less so for the optimisation part. This answers the third sub-research question: 'Do quantified sub-criteria of sustainability add value, in comparison to the rating system for tenders as used by ONW?'.

7 Discussion

This chapter centers on discussing and analysing the thesis' findings. Critical reflection examines the work from various angles, highlighting the limitations and areas for improvement. Additionally, the chapter offers recommendations for guiding future research, providing valuable insights for improvement.

7.1. Discussion

The limitations encountered in this study pose important considerations for the validity and generalisability of the experimental results. The inability to conduct experiments with ONW due to time constraints led to the involvement of Planmaat employees, raising questions about the representativeness of their perspectives compared to actual ONW employees. While efforts were made to simulate ONW's viewpoints, it remains uncertain whether their opinions precisely mirror those.

Furthermore, the limited number of experiments conducted hinders the ability to thoroughly iterate and refine the model. Ideally, additional iterations would have provided more insights and opportunities for improvement. Additionally, the focus solely on Dutch area development restricts the applicability of the model to international sustainability contexts, reflecting a notable limitation in its scope.

The DCBA method is chosen for this thesis because of the type of users the model will have. These are most likely (municipality) employees that do not have much knowledge about sustainability in area development. The qualitative explanation that the method presents is intuitive and easy to understand. It is suitable to be applied early in the tender process, when there are many uncertainties existent. The method increases understanding of sustainability, especially by working with it interactively, among stakeholders, one of the original starting points for developing the DCBA method in principle. It should be said, however, that despite its intuitiveness, the model can be perceived as complex and does not have a direct link to current policies and regulations on sustainable housing construction, such as the Mpg and BENG. In this, it is useful to explore other options for quantifying sustainability. Such an application will then have a focus on a different phase in the area development (later when use of choice material has to be determined, for example), in which stakeholder preferences are of less importance.

The fixed values assigned to the sustainability objectives' scenarios may restrict stakeholder freedom and depart from the original method's flexibility. As with the balance objective, stakeholders are free to assign values to their preferences. While this scenario-simplification aids in decision-making, it may overlook nuanced preferences that stakeholders could provide if given more freedom in defining their values.

A discussion point in the model that arises is complexity. The application of the model is made as simple as possible with a manual and, for example, the link to Excel. However, optimisation remains some kind of a black-box unless users are willing to delve deep into the subject matter. This is something that makes acceptance difficult.

Moreover, the variability in optimisation algorithm results presents a challenge in determining the most optimal outcomes. The unpredictability of the results across multiple runs introduces uncertainty into decision-making processes, potentially impacting the model's reliability and usability. At the base of this is the use of a global optimisation algorithm, it highers the chances of reaching the global optimum but cannot be guaranteed. However, as mentioned in subsection 6.3.2, beyond the scope of this thesis, these concerns can be addressed mathematically, potentially solving this issue.

The quantified sustainability scenarios, with costs and revenue for each house-type and the costs of fulfilling each scenario rely on estimates. The total costs and revenues are derived from various sources and may therefore deviate somewhat from the actual values. Determining the exact amounts, substantiated by an expert for example, falls outside the scope of this thesis.

Lastly, the literature utilised to access sustainability sub-criteria (Teeuw et al., 2011) is outdated, as it was written in 2011. Its contents no longer aligns with current construction requirements. For instance, while it offers guidance on reducing CO2 emissions, current obligations necessitate gas-free construction methods.

7.2. Recommendations

Future research might focus on integrating all DCBA sub-criteria outlined in the literature (Teeuw et al., 2011) into the model. By incorporating these sub-themes, stakeholders will have the flexibility to select desired objectives for optimisation. This enhances the versatility of the model, making it applicable to various area development cases. It's crucial to ensure that all inputs and objectives are adaptable to different contexts and scenarios, thereby increasing the utility and effectiveness of the model.

For future research, it would be advisable to incorporate all selection criteria into the model, each with a suited methodology. This approach would enable the evaluation of the tender process for all selection criteria in a quantified manner. Attention should be payed to the increase of time spend in tender assessments. Only one selection criteria of ONW has been addressed and implemented in this thesis, which is the 'vision for sustainability'. This is done because of the scope and approach of the research. However, this implies that only a portion of the tender process stands to be improved.

It is recommended to conduct additional experiments involving stakeholders to facilitate more iterations of the model. Continuous engagement with stakeholders is essential for refining and updating the model iteratively. Regular feedback from stakeholders will help validate the changes made to the model, ensuring that they align with stakeholders' expectations and contribute to improvements in decision-making processes. Soliciting suggestions for further enhancements from stakeholders will also enrich the model's functionality and relevance.

Finally, more attention should be devoted to exploring the practicalities of implementing the model. While the prototype stage provides valuable insights, it is essential to delve deeper into the practical aspects of model deployment. An example would be to assess whether technical support is necessary upon the model's completion and consider alternative approaches, such as designating an in-house expert or relying on external expertise. Careful consideration of these practical implications will help streamline the implementation process and mitigate potential challenges associated with model maintenance and support.

8
Conclusion

In this concluding chapter, all research questions will be answered. Throughout this thesis, the primary objective has been to provide insights into sustainable area development by addressing sub-research questions. By systematically examining and answering these questions, a comprehensive understanding has been attained, paving the way for meaningful conclusions.

In order to answer the main research question **(RQ)**, the sub-research questions (**SQ**) were answered throughout the report. These answers are given below.

SQ1: 'What sustainability measures and measuring instruments are relevant for Dutch area development?'

Dutch sustainability measures pertinent to area development were investigated, such as Omgevingswijzer, Bouwbesluit, Milieuprestatie gebouwen (Mpg), and Bijna Energieneutrale Gebouwen (BENG). Some methods, like the calculation of the Mpg, proved highly precise but complex for this thesis' scope. Next to the complexity, the type of methods are also not fitting. For the optimisation of sustainability characteristics it is preferred to use a method with a predefined sliding scale of possibilities (for example having four scenarios to optimise over; D, C, B or A), instead of having a single requirement as with BENG (for example having a minimum requirement of 50% of renewable energy). As well that the DCBA method is accessible to all, due to its qualitative explanation. No prior knowledge is needed in order to understand the intended level of sustainability.

The exploration of Dutch sustainability measuring instruments was crucial for addressing and answering the first sub-question. The Omgevingswijzer, Bouwbesluit, Milieuprestatie gebouwen (Mpg) and Bijna Energieneutrale gebouwen (BENG) are sustainability measures and measuring instruments for relevant for Dutch area development. This sub-question is extensively answered in chapter 2.

SQ2: 'What sub-criteria explain the concept of sustainability in area development?'

The DCBA theory was used in this thesis, consisting of forty sub-criteria that explain sustainability in area development. Each sub-criterion consists of four sustainability scenarios, ranging from the least- to the most sustainable (D-C-B-A). Each scenario explains the corresponding sustainable measures, in order to fulfill the outlined scenario. Because of the scope and time limits connected to this thesis, not all forty, but only four sub-criteria are implemented into the model. In this way, the model consists of a 'prototype' of implemented sustainability criteria. The chosen sub-criteria for this thesis are: building materials, humidity and ventilation, solar energy, and groundwater. One of the main recommendations of this thesis is to further implement all DCBA sub-criteria, in order to complete the model.

The DCBA method offers a intuitive and comprehensive possibility to learn about sustainability in area development, and to take this into account. For those without prior knowledge of the subject, this method offers an learning possibility. However, points of discussion during the experiments were the complexity, not of the DCBA theory, but of the implementation of it into the model. Another concern is raised when looking at the contents of the sub-criteria, as the theory was written in 2011. This means that they are not up to date with current construction requirements. The DCBA theory does explain sustainability in area development, but could use adjustments in order to comply with present day. Proper instructions, perhaps with an interactive explanation, and an update on the sub-criteria could overcome these issues.

The above mentioned answers the second sub-question; the forty sub-criteria found in the DCBA book explain the concept of sustainability in area development. This sub-question is extensively answered in chapter 3.

SQ3: 'Do quantified sub-criteria of sustainability implemented in a preference-based decision-making model add value, in comparison to the rating system for tenders as used by Ontwikkelingsmaatschappij het Nieuwe Westland (ONW)?'

The validation of the model consisted of a scenario test as well as performing experiments. The experiments are the most important part of the validation, because this gives most insights in whether or not the model accommodates the wishes of the client (ONW). Participants (employees of Planmaat, substituting ONW) involved in the user experiments expressed moderate optimism about the model's potential. They furthermore provided suggestions for improving usability. The suggestions consisted of minor technical adjustments, but a clearer explanation was wished upon. More information on when the model was intended to be used in reality, was needed. These suggestions were incorporated after. Continued refinement and iteration based on user feedback will be essential to optimise the model's usability and ensure its effectiveness in real-world applications. The model is perceived by participants as fairly complex and it takes time to fully understand the model. One suggestion is to use technical support. This could be in the form of an in-house expert, so that the model can be used at all times. Should this not be possible, external support can also be an option.

An important point is that because the experiments were carried out with Planmaat, and not with ONW, it is only based on assumptions what the model could potentially mean for ONW. Also, because of the scope of the thesis only a limited amount of experiments were performed. It is recommended to further experiment with relevant parties.

Participants believe the model has added value when used for rating and comparing of different bids (use as an assessment tool). The use of the model as a design tool, which means using the optimisation, is not seen as added value as ONW does not communicate detailed requirements to developers. ONW only provides constraints and boundaries, and will choose the best bid. ONW does not approach parties with a detailed plan with requirements. An option to use the optimisation could be that ONW uses the optimisation results to compare them with the bids of the developers. This information could lead to ONW comparing the optimum with developers' bids, what could be interesting. Or it could lead to ONW steering the developers, without communicating precise results.

Moreover, because of the non-linear optimisation, the results continue to vary after each run. This is not appreciated by the stakeholders, due to the unreliability this creates. However, this issue could potentially be solved when the model is worked on in a mathematical way.

With this knowledge, the third sub-research question is answered: quantified sub-criteria of sustainability presumably do add value in comparison to the current rating systems of ONW, but only for comparing different bids, not for the optimisation part. This sub-question is extensively answered in chapter 6.

Based upon the answers of the sub-research questions and the creation of the model, the main research question can be answered, that is:

RQ: 'How can sub-criteria of sustainability in area development be quantified and implemented into a preference-based decision-making model?'

Based on an existing method (DCBA), sub-criteria that explain sustainability can be implemented into the model. For this thesis, the DCBA method is chosen, because it defines forty different sub-criteria for sustainability in area development, based on different sustainability scenarios (D, C, B and A). This method method was chosen because of the qualitative explanation it gives of sustainability, making it suitable for users without prior knowledge. The DCBA method itself could be easy to understand, but the incorporation of it into the model can be perceived as complex. This is a point of discussion and therefore it is advised to look into for future research.

The chosen sub-criteria (mentioned in the answer of **SQ2**) are transformed into objectives that are quantified in the model, provided with objective formulas. The objectives are:

- Maximizing sustainable building materials
- Minimizing humidity and maximizing ventilation
- Maximizing the generation of solar energy
- Maximizing the stabilization of groundwater
- Maximizing balance

The model is programmed in a way to optimise on sustainability scenario and housing differentiation. The sustainability objectives are quantified based on costs and revenue, specific per scenario, sub-criteria and housing type. The main research question is primarily answered by looking at the formed model, that represents the way sub-criteria are quantified and implemented into a preference-based decision-making model. This report provides a substantiation for the creation of the model while supporting this with relevant theory.

In summary, sub-criteria of sustainability in area development can be quantified by seeking for a suitable method. In this case the DCBA method was chosen, and the sub-criteria were quantified based on costs and revenue. The sub-criteria are implemented into the model by incorporating them as both objectives and variables in the model. With the above mentioned information, the main research question is answered, which brings finalisation to this thesis.

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A

DCBA method

A.1. Themes and subthemes

- Energy
  - Heat/electricity generation
  - Heating and cooling
  - Solar energy
  - CO2 reduction
- Water
  - Groundwater
  - Surface
  - Rainwater
  - Drinking water
- Greenery
  - Ecology
  - Site preparation
  - Fencing
  - Management
- Mobility
  - Non-motorized traffic
  - Collective public transportation
  - Car
  - Parking
- Materials
  - Paving

  - Public landscaping
  - Building energy
  - Building materials
- Environment
  - Wind nuisance
  - Humidity and ventilation
  - Daylight
  - Health
- Waste and pollution
  - Construction and demolition waste
  - Household garbage
  - Bulky waste
  - Air pollution
- Livability
  - Social safety
  - Social cohesion
  - Life-course sustainability
  - Neighborhood diversity
- Process
  - Certification and ambition setting
  - Participation
  - Financing structures
  - Maintenance
- Awareness
  - Education
  - Innovation and experimental garden
  - Recreation
  - Food production

A.2. Scenarios of chosen subthemes

The information of the scenarios that are given below, have been freely translated from the book by Teeuw et al., 2011, as it is originally written in Dutch.

A.2.1. Building materials

D: In accordance with the building code

Building materials are chosen primarily because they correspond to building code requirements. The cladding and roofing make the building water- and wind-proof, and the insulation material provides the appropriate insulation value. Many buildings have plastic cladding and tropical hardwood is frequently used. Plastic cladding panels usually consist of glued wood pulp with a coating. Insulation materials with high energy content are often used because the materials are derived from petroleum products.

C: Non-environmentally harmful

At this level, one chooses materials that are made from natural, low-impact raw materials and are not environmentally damaging in both the production and processing processes. As a facade material, people often choose wood or mineral stucco. Mineral wool is used as insulation. Mineral wool is not glued, making it easy to remove and suitable for reuse.

B: European, recyclable

At Level B, material use is minimized. One applies as many reusable materials as possible in addition to Level C materials. Building components must be demountable and reusable so that as many building components as possible can be reused in their entirety. The application of demountable systems makes building components and materials repairable and replaceable by the user.

A: Domestic, renewable

In addition to reuse and recycling, in the ideal situation, natural and renewable (e.g., growing) materials are mainly used. These materials fit fully into a closed natural cycle. The materials that do not fit into this cycle, such as metals, are fully recycled in a technical cycle. Thus, waste actually no longer occurs. This is a 'Cradle to Cradle' situation.

A.2.2. Humidity and ventilation

D: Standard ventilation

In the normal situation, standard ventilation is present. Usually this is a system with mechanical extraction and natural air supply or a system with balanced ventilation. Because of stricter energy requirements, this has become increasingly the case in recent years. In the ventilated crawl spaces there are grates for exhaust and in the kitchen there is an extractor fan.

C: Preventing thermal bridges

In cold places, moisture condenses, therefore energy leaks are prevented at this level. This can be done by good detailing, insulating these spots and applying well-insulating glazing. The location of mechanical extraction and ventilation facilities is also chosen very carefully. In kitchens and bathrooms, not only smooth materials are chosen, but materials such as lime and clay that can absorb moisture. Thus, condensation cannot occur. All Level D measures are also applied.

B: Continuous ventilation guaranteed

Continuous ventilation is ensured. there are also plenty of grilles and windows for additional natural ventilation. There is energy-efficient balanced mechanical ventilation with heat recovery. The crawl space will have a shell layer. Shells do not absorb moisture, unlike sand, and do not allow moist air to pass through. As a result, no moisture from the subsoil can get into the crawl space. In addition, the crawl space is fitted with grates, which ensure the removal of any moist air that may have formed there anyway. Furthermore, all measures of level D and C are applied.

A: Moisture-regulating materials

As environmental determinants, homes have no crawl space. Floors can thus be made more airtight, eliminating problems with high groundwater levels. Moisture control materials, such as stucco, loam and cellulose, are used in the home. These absorb moisture so that it does not settle. The buildings have adequate ventilation and windows can be opened in all rooms. Through proper siting of rooms, it is avoided as much as possible that large temperature differences (which produce condensation) can occur. Cold and wet rooms are located on the north side of the building, warm and dry rooms on the south side. All measures of situations D, C and B are also applied.

A.2.3. Solar energy

D: Orientation homes independent of the sun

When making an urban development plan, choosing a site and determining the orientation of a building, the extent to which the building can use solar energy is determined for many decades. At this level, the possibilities of using solar energy are usually not taken into account. The subdivision in the urban plan is not optimally oriented to the sun. As a result, the sun hardly contributes to heating the main living areas in the house. Heating of a building takes place with supplied energy, mainly from non-renewable energy sources.

C: Exploit opportunities of PSE

The use of passive solar energy (PSE) involves harnessing solar energy without the intervention of installations. In a smart solar-oriented architectural design, light and heat from the sun are optimally captured and stored. Important aspects here are the orientation of the building and the living quarters, the size of the windows, the positioning of the conservatories, shading, sun shading, the layout and zoning of the building, optimal insulation and the accumulating capacity of the building mass. The most important living quarters are oriented to the south and equipped with large windows. The house does not have to be exactly south-facing, the efficiency remains good with a deviation of up to 20 degrees. If the deviation is greater, the energy consumption increases relatively strongly. On the north side are the cool rooms with small windows. This is called zoning. If solar heat is desired, then it is brought in and otherwise the sun is kept out on the outside.

B: Apply active solar energy

Active solar energy (ASE) can be divided into active solar thermal energy and photovoltaic solar energy (abbreviated PV from PhotoVoltaic). In active solar thermal energy, solar energy is collected with solar collectors in which a fluid (usually water) or air is heated by direct and diffused solar radiation. The heat is stored in a storage tank to be used for domestic hot water and/or space heating. In PV, sunlight is converted into electricity by solar cells in a solar panel. The electricity is usually stored in the grid. The potential depends on the area to be utilized. For ASE, good orientation is important; 100 percent south orientation provides the highest efficiency. For thermal ASE in the Netherlands, at an angle of inclination between 30 and 50 degrees, a 45 degrees deviation from south with 15 percent lower efficiency is still just acceptable. For PV, the optimal slope angle in the Netherlands is 36 degrees. Deviation from south orientation quickly leads to too low of an efficiency.

A: Orientation determines homes

When the orientation to the sun determines urban and architectural design, the potential of solar energy can be maximized and the sun can supply the entire energy needs of the home. All scenario C and B measures are applied. At the urban design level, as many blocks as possible are oriented with the long side facing south. In a compact urban development, it must be taken into account that high buildings and narrow streets can obstruct maximum sunlight due to shadows. Green areas can also provide a large angle of obstruction. At the housing level, the most important living areas are oriented to the south by means of zoning. A good orientation provides the highest yield for the use of both active and passive solar energy, or ensures that the use of these forms of solar energy is or will continue to be possible in the future.

A.2.4. Groundwater

D: Water level reduction/integral elevation

The common methods that keep groundwater from getting too close to buildings are lowering the groundwater level and/or integral elevation of the ground level. Groundwater level lowering is done through drainage. The consequences of groundwater level lowering are desiccation, acidification and sometimes salinization of the soil. Integral elevation of the building site puts the buildings well above the groundwater. The disadvantage of this method is that sand extraction elsewhere will damage the landscape. At the site itself, the original landscape is also disturbed and existing ecosystems disappear.

C: Limited water level fluctuation

Groundwater flooding is prevented by storing water, in the form of surface water, locally in the area itself. The surface water acts as a buffer. In wet periods, rainwater is stored, allowing the groundwater level to be maintained in dry periods. The groundwater level itself has limited fluctuation: within limits it can rise or fall to a limited extent without causing nuisance.

B: Level fluctuation/groundwater stages determining

At Level B, groundwater stages determine level fluctuation. Groundwater stages are average groundwater levels, indicating the height at which the groundwater level rises in winter and falls in summer. Due to differences in soil types and groundwater flow, different groundwater levels and fluctuations may occur within a single location. At Level B, people do not build on swampy soil. Or a special method of construction is chosen, adapted to the situation, for example floating housing or building on stilts.

A: Groundwater neutral, full storage

Level A seeks the solution for groundwater management within the site. The original groundwater level determines the design to be made. In areas that are too soggy, construction will not take place. For all areas, no water will be pumped out of the area. No foreign water will be introduced into the polder. The construction site is groundwater neutral; this means that the groundwater levels before and after construction are the same.

B

Substantiation of the Quantification

B.1. Costs and revenues of each scenario

In order to implement the DCBA-scenarios into the tool, they need to be quantified. As mentioned before, every scenario consists of a scripted situation (qualitative). Based on sources and estimations, the costs for every scenario-variable combination is predicted. This is described below.

First, in Table B.1, the summarized contents of each scenario are given. These are the highlights from each scenario, that determine what measures need to be taken to fulfill it.

In Table B.2, the before mentioned contents are translated into costs. These costs are substantiated by multiple sources (subsection B.1.1). Note that the costs are rounded on request of Planmaat employees, to increase the readability. The costs of each scenario remain an estimation after all, for each house-type (x1 to x5).

B.1.1. Sources costs of each scenario, full table: Table B.2

- Maximizing sustainable building materials
  - Scenario C: (Ministerie van Algemene Zaken, 2023) (Pricewise, n.d.)
  - Scenario B: (Mutsaers, 2023)
  - Scenario A: 75% of the costs of scenario C + B combined
- Minimizing humidity and maximizing ventilation
  - Scenario C: (Centraal planbureau, 2023)
  - Scenario B: (Alpha ventilatie, 2023)
  - Scenario A: (Solvari, 2022)
- Maximizing the generation of solar energy
  - Scenario C: (Milieu Centraal, n.d.-a) (BCD Advies, n.d.)
  - Scenario B: (Milieu Centraal, n.d.-b)

  - Scenario A: Costs of scenario C + B combined
- Maximizing balance
  - Scenario C: (Mijn Water Fabriek, n.d.)
  - Scenario B: (Bouwwereld, 2014)
  - Scenario A: Costs of scenario C + B combined

Table B.1: Contents of each scenario

OBJECTIVE	SCENARIO	CONTENTS (SUMMARY)
Null scenario	D	No sustainable measures are incorporated, only necessary the Dutch building laws.
Building materials	C	The materials used are based on natural and low environmental impact raw materials.
	B	Material use is minimized. Building materials must be demountable and reusable.
	A	Use of mostly natural and renewable materials.
Humidity / ventilation	C	Moisture condenses in cold places.
		Insulating these spots and applying well-insulating glazing.
	B	Continuous ventilation is ensured. Grilles and windows for additional natural ventilation.
		There is energy-efficient balanced mechanical ventilation with heat recovery.
	A	Floors are made airtight, eliminating problems with high groundwater levels.
		Moisture control materials such as stucco are used in the house.
Solar energy	C	Passive solar energy involves harnessing solar energy.
		Important aspects here are large windows, orientation of the house.
	B	Solar energy is collected by solar collectors.
	A	The orientation of the sun determines how the house is built.
Groundwater	C	In wet periods, rainwater is stored, allowing the groundwater level to be maintained.
		The groundwater level has a limited level fluctuation.
	B	A special method of construction is chosen, for example, floating housing.
		More level fluctuation is allowed and surface water is present as a seasonal buffer.
	A	The original groundwater level determines the design to be made.

Table B.2: Costs of each scenario

OBJECTIVE	SCENARIO	QUANTIFICATION	x1	x2	x3	x4	x5
Null scenario	Scenario D	-	0	0	0	0	0
Building materials	Scenario C	€1700/m2	50000	40000	45000	35000	35000
	Scenario B	Investment 15% of construction costs	45000	20000	25000	15000	20000
	Scenario A	75% of costs of C + B	70000	45000	50000	40000	40000
Humidity / ventilation	Scenario C	Insulation	30000	15000	15000	10000	10000
	Scenario B	Continuous ventilation	5500	4000	4500	2500	3000
	Scenario A	Moisture controlling materials	6000	3000	3900	1950	2400
		€22,50/m2 flooring					
Solar energy	Scenario C	Insulating, double-glazing	15000	6500	8000	5500	7000
		Construction costs rise 5%					
	Scenario B	Use of solar panels: €500/panel	7500	3500	5000	1000	2000
	Scenario A	Costs of C + B	20000	10000	15000	6000	9000
Groundwater	Scenario C	Rainwater is saved	4500	3500	4000	600	600
		Rainwatersystem is €4000 excl. instl.					
	Scenario B	Floating house costs 25% more	70000	35000	40000	30000	35000
	Scenario A	Costs of C + B	75000	35000	45000	30000	35000

Table B.3: Balances of each scenario

Balance		**x1**	**x2**	**x3**	**x4**	**x5**
	Base balance	165000	105000	125000	100000	125000
Maximizing sustainable building materials	D	0	0	0	0	0
	C	-25000	-20000	-22500	-17500	-17500
	B	-22500	-10000	-12500	-7500	-10000
	A	-35000	-22500	-25000	-20000	-20000
Minimizing humidity and maximizing ventilation	D	0	0	0	0	0
	C	-15000	-7500	-7500	-5000	-5000
	B	-2750	-2000	-2250	-1250	-1500
	A	-3000	-1500	-1950	-975	-1200
Maximizing the generation of solar energy	D	0	0	0	0	0
	C	1000	1300	1500	1700	1700
	B	24500	12100	14000	13400	15400
	A	20000	9500	8750	12000	12750
Maximizing the stabilization of groundwater	D	0	0	0	0	0
	C	-2250	-1750	-2000	-300	-300
	B	-35000	-17500	-20000	-15000	-17500
	A	-37500	-17500	-22500	-15000	-17500

C
Survey

C.1. Questions

The first ten questions are taken from the SUS test, the remaining questions are additional and added for the purpose of this thesis. For the SUS-questions, the participants are asked to answer these on a 5-point scale with a range from strongly disagree (1) to strongly agree (5). Keep in mind that the participants from experiment 1 and 2 are not the same, therefore comparisons of scores cannot be made one on one.

C.1.1. Experiment 1

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.
11. What improvement(s) to the model would you like to see?
12. What did you find to be a strength of the model?
13. Do you find the quantification in the model an improvement over the current assessment technique (determining sustainability in tenders based on satisfactory, good, etc)?

C.1.2. Experiment 2

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.
11. Do you have any suggestions for improvements to the model?
12. What do you think of the option of specifying the sustainability scenarios by variable? So that the outcome is 20 scenarios, instead of 4 scenarios. Does this increase or decrease clarity?

C.2. Answers

In order to retrieve the SUS score the answers to the questions need to be transformed to numbers (totally disagree (1) - totally agree (5) and calculated in the prescribed way defined by Brooke (1996). From the odd questions, one point should be deducted (score-1). For the even questions, from 5 the answer score should be deducted (5-score). After this, all scores should be added up and be multiplied by 2,5. This results in the so called SUS-score, which is shown below.

C.2.1. Experiment 1

SUS scores:

- Participant 1: 47,5
- Participant 2: 57,5
- Participant 3: 60
- Participant 4: 47,5

Answers to the additional questions:

1. What improvement(s) to the model would you like to see?
    - Better description at what time you would use the product and when not (anymore).
    - More understanding of the financial implications of an intervention, in addition to that, I think the sustainability curves are an upward trend with everyone, there are conflicts, and those are then interesting to weigh.

- Making it less transparent which stakeholder ”wins” or ”loses” to increase support for the outcome. Had they not been able to compare scores between them, some of the discussion would have been pulled out of the emotional.
- A true optimum (reproducible) increases acceptance. Understanding corners of playing field (especially financial).

2. What did you find to be a strength of the model?
    - The ability to give a weighting to my score.
    - Very clearly organized in Excel, transparency was great and that is very important in accepting the result.
    - Compact and quick so the discussion can be about the content. The trick is to keep this aspect in real life and not fall into a lot of housing types, sustainability goals and stakeholders.
    - Integral use of space, program, quality (sustainability) and money.
3. Do you find the quantification in the model an improvement over the current assessment technique (determining sustainability in tenders based on satisfactory, good, etc)?
    - With clear ground rules for use, I expect so.
    - Not yet, I think that it is not yet sufficiently clear how the scenarios can be achieved, an example with the interventions would help and be instructive for all participants.
    - I certainly believe that sustainability can be usefully quantified in this way. However, I myself have too little experience with other methods (e.g. GPR Urbanism) to judge whether it is an improvement.
    - Yes! Mainly for solicitation and bid evaluation. Less so for optimization.

C.2.2. Experiment 2

SUS scores:

- Participant 5: 45
- Participant 6: 50
- Participant 7: 60
- Participant 8: 55

Answers to the additional questions:

1. Do you have any suggestions for improvements to the model?
    - Realistic input on costs (and benefits) of sustainability ambitions/measures. White box optimisation, is that a valuable addition?
    - As discussed during the experiment, adding a bid from the tender. Breakdown of measures by housing type.

- The conclusion of the experiment was that it should also be possible to fill in a minimum land price. That seems very useful.
- I wouldn't do it by specifying more preferences. It is already difficult to specify an overall preference at the main level, let alone to do so by more specific points. I feel strongly about the discussed possibility of varying sustainability levels within housing types. This can already be done with the available data and would only be financially driven (given the preferences on sustainability). Does by less homogeneous result then yield possible scores like C+ or A-.

2. What do you think of the option of specifying the sustainability scenarios by variable? So that the outcome is 20 scenarios, instead of 4 scenarios. Does this increase or decrease clarity?

   - I think this could make the optimisation more interesting for when you 'really' dive in. Do think carefully about how you display the results. I think you should hide the house-type specific results and make them visible only if someone is interested in them.
   - This will certainly not make for a clearer model and will decrease usability for new users, but will improve the model in my view.
   - It makes the model harder to understand, but gives better results. An expert is then needed to fill in the model and draw the conclusions. Preventing the model from becoming too complex to achieve the goals: letting stakeholders determine how to achieve as many goals as possible within the (financial) conditions of a project, and being able to objectively assess the best offer.
   - Tricky. Theoretically, this gives more precision and steering possibilities and I can see the point. On the other hand, several students have now got us used to the idea of converting a preference to a curve. For someone for whom this is new subject matter, that seems very overwhelming to me to do this per variable. In my opinion, this comes at the expense of usability. Gut feeling (but hey, I'm not the one graduating on it :)) would not be the direction it should go.