Decision-Making Stalemate Resolution in Complex Construction Projects

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By

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Executive Summary

Large and complex construction projects are routinely late, over budget, under scope or any combination of the three. Academic literature identifies the area of conflicting stakeholder objectives, also called social complexity, as the most challenging and problem-prone aspect of complex construction projects. This view is also shared by the industry, which is evident from the recent introduction of Collaborative Project Delivery (CPD), a form of project delivery that involves a large number of project participants early into the scope definition stage to enhance project performance. An example of CPD is Bouwteam contracts. However, despite successfully addressing many issues, research shows that CPD still encounters problems associated with social complexity. The encountered problems have to do with the decision-making.

Decision-making literature, like project management literature and the industry, identified the need for new decision-making methodologies for contexts when a large number of decision-makers with varying competencies are involved into a decision process at the same level of influence. These contexts are also referred to as network decision-making. This need is answered by the Open Design methodology, which puts all decision-makers at the same level and leverages social complexity to arrive at group optimal solutions. The latest addition to Open Design is the Preferendus, which is a system that allows to arrive at a group optimal project design by means of stakeholder preference optimization.

In some applications of Preferendus onto projects no acceptable group optimal solution can be identified due to the high degree of conflict of stakeholder objectives. These situations are referred to as stalemates. Stalemates in collaborative contexts can potentially lead to conflict escalation and have a destructive effect on the collaborative process they arose from. From this a development gap is identified and a development statement is formulated:

- *To develop a Preferendus-based system to enable stalemate resolution in network decision-making for large and complex construction projects*.

In fulfilment of this development statement, a Preferendus-based Python decision support system (DSS) is created that enables stalemate identification and resolution by two approaches: consultation and mediation. Over three design cycles a Stalemate Resolution Mechanism is formulated that identifies the smallest extension of acceptability of project performance needed to achieve the group optimal solution. In other words, the smallest concession to resolve the stalemate.

The developed DSS is applied onto the Duurzame Polder case, which is an ongoing sustainable energy generation project by the municipalities of Oss and ‘s-Hertogenbosch currently in the scope definition stage with public project information.

The DSS is validated via two workshops with TU Delft Master students who take on the roles of the decision-makers in the project and use the DSS to identify and resolve the stalemate. The results indicate that the produced system successfully enables decision-makers to understand and discuss the reasons behind the stalemate to arrive at the final project decision. In both testing rounds the decision-makers arrived at a solution consistent with the real-world development of the project.

The main limitations of this thesis are a lack of access to industry professionals, relative case modelling simplicity and the required model runtime. Recommendations for increasing the accuracy and efficiency of the produced system are provided.

Contents

1. Introduction

1.1. Problem Statement

1.1.1. Industry Context

Large and complex construction projects are routinely late, over budget, under scope or any combination of the three. By this point in time, this statement has become an axiom (Kent & Becerik-Gerber, 2010; Hertogh & Westerveld, 2010; Van Gunsteren,2011; Flyvbjerg & Gardner, 2023). According to Flyvbjerg & Gardner (2023), only 0.5% of all projects deliver on the initially promised cost, time and scope.

Different views exist on what is the most important factor contributing to the failures of large and complex construction projects. For example, Hertogh & Westerveld (2010) point towards social complexity as the most impactful factor out of the six elements of complexity defined by practitioners. Social complexity arises at points where conflicting interests of various stakeholders intersect and the question of how to manage them comes up. The recommendation given to improve complex project performance is to find the right balance between the loose and adaptable Interaction approach and the strict and structured Control approach. In the same vein, a more radical view is presented by Van Gunsteren (2011). He states that the reason for the failure of large and complex projects comes from using traditional project management methods, also defined as P1, on projects where a more stakeholder-oriented management approach is required, also defined as P2. This is synonymous with the view of Hertogh & Westerveld (2010), since both emphasize stakeholder interaction as the key to project complexity and solving it. However, Van Gunsteren (2011) states that instead of a balance between traditional and stakeholder-oriented management measures, the only correct way is a full lean towards the stakeholder-oriented management, as traditional practices can only hurt a complex project.

Another prominent perspective is provided by Flyvbjerg & Gardner (2023). They claim that the core of large and complex project failure lies in how projects start, stating that “projects do not go wrong, as much as they start wrong”, with project participants being too eager to get to the execution stage. This results in projects starting without a full understanding of the goal and scope. As a solution, Flyvbjerg and Gardner advocate for the “think slow, act fast” approach, highlighting measures such as giving more time for planning and minimizing the execution time, asking “why?”, simulation as a design tool and knowing when to say “no” to a project. In other words, emphasizing the importance of planning and the front-end.

In response to the continued underperformance of large and complex construction projects, new project delivery methods emerged in the construction industry (Engebø et al., 2020), which are collectively referred to as Collaborative Project Delivery (CPD). There are many variations of collaborative project delivery such as Integrated Project Delivery (IPD) (Kent & Becerik-Gerber, 2010), Early Contractor Involvement (ECI) (Song et al., 2009), Two Phase Contracts, Bouwteam (Design Team) and others (Engebø et al., 2020). Each of them has its own specifics and some, such as the Bouwteam (Chao-Duivis, 2014), are fully formed contract structures. The uniting factor among all of them is that they aim for early involvement of project participants that traditionally only join the project in the detailed design or execution stages. This way, "thinking slow" (Flyvbjerg and Gardner, 2023) is encouraged by including more participants with varying expertise in the early decision-making processes. As well as that, this addresses the social complexity issues raised previously by involving all the stakeholders into the decision-making process from the start. This is supported by a literature review by Babalola et al. (2024), who analysed literature on three forms of CPD: IPD, design-build (DB) and construction manager at risk (CMAR). The advantages brought up across literature for all three forms, according to the review, consistently fall in line with enhancing collaboration, facilitating teamwork and an atmosphere of collaboration and fairness, all acting in the realm of social complexity.

Traditional Project Delivery		**Integrated Project Delivery**
Assembled on "just-as-needed" or "minimum-necessary" basis, strongly hierarchical, controlled.	Teams	An integrated team entity composed key project stakeholders, assembled early in the process, open and collaborative.
Distinct, segregated, knowledge gathered "just-as-needed", information hoarded, and silos of knowledge and expertise.	Process	Multi-level, early contributions of knowledge and expertise, information openly shared and stakeholder trust respect.
Individually managed.	Risk	Collectively managed, appropriately shared.
Paper-based, two-dimensional, and analog.	Communications/ technology	Digitally based, virtual, and Building Information Modelling (three-, four- and five-dimensional).
Individually pursued and minimum effort for maximum return.	Compensation/ reward	Team success tied to project success and value-based.
Encourage unilateral effort, allocate and transfer risk, and no sharing.	Agreements	Risk sharing, encourage, foster, promote and support multilateral open sharing and collaboration.

Figure 1 Traditional Project Delivery vs Integrated Project Delivery. Taken from Kahvandi et al. (2020), originally from AIA (2007).

What can be inferred from the complex project characteristics and the emergence of CPD as a response to the faults of these projects, is that a significant amount of emphasis is placed on solving problems in decision-making at the front-end of the project, where the scope and goals are set. Both Hertogh & Westerveld (2010) and Van Gunsteren (2011) address this, for example with the Alignment strategy of the former and the open communication / solution space thinking of the latter. Meanwhile Flyvbjerg & Gardner (2023) address the front-end directly as the most problematic area.

This is further supported by the barriers to the successful implementation of collaborative project delivery methods in the industry. These are usually split into financial, social/cultural, legal and technical. While these barriers are context-dependent and vary from country to country, the technical barriers are somewhat common across contexts, as they refer to implementation issues. Out of the technical barriers, the one that gets brought up the most is establishing common goals in the early stage of a CPD project (Roy et al.,2018) (Saukko et al., 2020) (Elsayegh & El-Adaway, 2021), also referred to as goal alignment and integration phase. Meanwhile, it is a crucial step and one of the core success factors of collaborative project delivery (Kent & Becerik-Gerber, 2010). In the analysis by Babalola et al. (2024) such disadvantages of CPD methods as difficulties with scope, schedule and budget definition consistently take third or fourth place, with the first places taken by communication or team interaction problems specific to their CPD method. This clearly indicates that the problem of decision-making at the early stages in the context of social complexity remains universal both for complex projects and across CPD methods.

1.1.2. Decision-making

According to Bakht & El-Diraby (2015), who performed an analysis of decision-making research in construction of the last 50 years from the date of the article, various understandings of decision-making gained prevalence. To take an example from the author, the 1960s were dominated by an almost exclusively technical, industrial approach to decision-making in construction, accordingly supported by deterministic tools. Over the years, construction moved from this technocratic approach, to recognizing the importance of “soft” criteria and integration of more stakeholders into the process in a network manner. Similarly, decision support tools moved from searching for an objective solution via stochastic or optimization models to tools and methodologies such as the Urban Decision Room (Van Loon et al., 2008), which recognizes the decision process more as a social network of stakeholders. Bakht & El-Diraby (2015) state that with the shift from hierarchical to network decision-making, an environment will arise in which both professionals and non-professionals will participate in the same decision processes, so it is necessary to create tools or decision support systems which can explain the behavior of parties, help non-technical participants understand projects and generally facilitate information flow, so that all stakeholders can communicate on a level playing field. This is in line with the social complexity problems encountered in large projects today, even in those addressed with by CPD. This indicates that to solve problems in addressing the social complexity of projects, there is a need for a network-based decision methodology.

Bakht & El-Diraby (2015) not only formulate the direction of development of decision-making, but also the fundamental needs for this development to occur. These can be structured as follows:

1. Decision-making in the heterogeneous network requires a change of mindset.
2. Development of decision tools to help non-technical contributors understand projects.
3. Development of selection techniques to support professionals in capturing innovative ideas and testing consensus.

All three aspects are addressed by the Open Design methodology, most fully formulated in Binnekamp, Van Gunsteren & Van Loon (2006), along with the core developments of Binnekamp (2010), Zhilyaev et al. (2022), Wolfert (2023) and Van Heukelum et al. (2024). This section will show how each fundamental need of Bakht & El-Diraby (2015) is addressed by the Open Design and its expansions, along with defining the needs for the tool which is proposed in this thesis.

A Change of Mindset

From Bakht & El-Diraby (2015), the most fundamental change of mindset required is the shift from expert-dominated technocratic decision-making to a network of decision-makers with both experts and non-experts. This change is one of the first issues addressed by the Open Design methodology (Binnekamp et al., 2006). The authors state that the cycles of expert-dominated decision-making that involve a design decision from experts and then “selling” it to other stakeholders result in a limited range of designs and omissions of stakeholder wishes. As an alternative, the authors propose to involve all stakeholders in the design process on equal grounds, effectively making them decision-makers and allowing for a wider variety of perspectives in design options, increasing both variability and ownership of the solution by the participants.

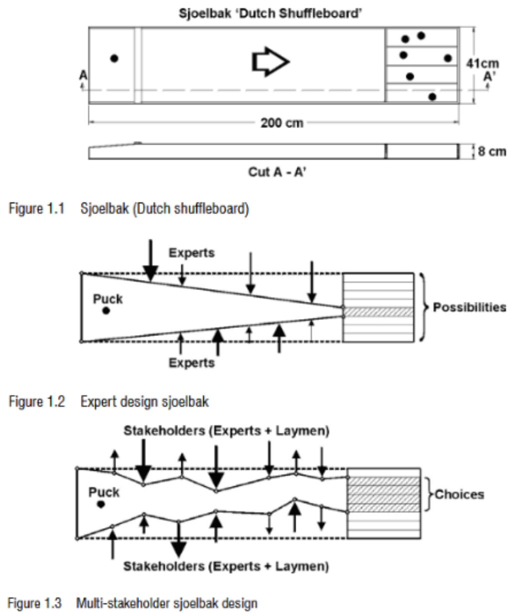

Figure 2 An example of the design process via the Dutch Shuffleboard (Sjoelbak). Taken from Binnekamp et al. (2006)

As previously established, in a network structure the questions of how to deal with conflicting interests of decision-makers arise, which is what Hertogh & Westerveld (2010) referred to as social complexity. In another instance of a change of mindset, the Open Design methodology instead uses conflicting objectives as a means to synthesize a solution.

When two or more parties with conflicting objectives collide, they enter a process of negotiation with one another. According to Fisher et al. (1987), the most common practice for the parties involved is to start bargaining on positions, perceiving the situation only in terms of a dimension relevant to them, for example price, project execution time or location. This involves a process in which the parties alternate demands and concessions either until one of the parties gives up or the negotiation escalates to the point that communication breaks off. Fisher et al. (1987) however argue that there is a more effective way to approach negotiations that can not only prevent total communication collapse but also enable the parties to come up with a mutually beneficial arrangement. The key to this is the shift from positional-based negotiation to interest-based negotiation. In other words, considering what is the interest and motivation of the involved parties, which helps them find common ground.

In Open Design, via additions by Binnekamp (2010) and Zhilyaev et al. (2022), this shift to interest-based bargaining is implemented by means of Preference Function Modelling (PFM), as developed and formulated by Barzilai (2010). After identifying what the main project objectives are, the minimum and maximum achievable values of each of those objectives are calculated, and decision-makers are asked to provide ratings on a defined scale, which is normally 0-100 in PFM, to each of the points, depending on the interest of a given decision-maker in the project.

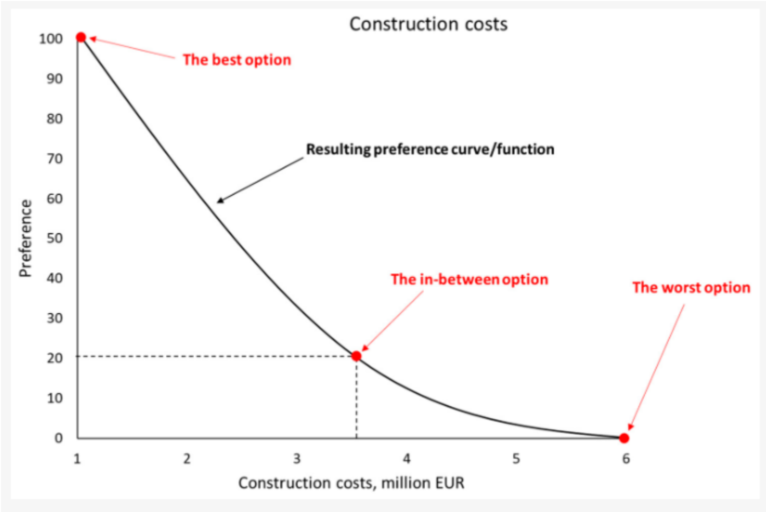

Figure 3 Example of a preference curve, taken from Zhilyaev et al. (2022)

This allows each decision-maker to make a visual and meaningful expression of their interest, without needing extra communication or having to disclose sensitive information. As well as that, each decision-maker is free to see how every other one perceives that project. The inclusion of this system marks another fundamental change of mindset, as it serves as a means of transition from positional negotiating to interest-based negotiating, in accordance with Fisher et al. (1987).

Tools to Help Understand the Project

When considering the shift from a technocratic expert-based approach to a network approach, one of the core issues is to ensure that all decision-makers are on the same level of understanding the project, regardless of specialized knowledge or experience (Bakht & El-Diraby, 2015). The current gold standard in the construction industry is to perceive projects in terms of the Iron Triangle (Pollack et al., 2018). Under this system any project is represented by categories of Time, Cost and Quality, with Quality sometimes called Scope. While Cost and Time are straightforward and there is a consensus about their importance and definition, Quality is more ambiguous with various definitions present in literature.

Within the Open Design methodology, an overarching definition of Quality is provided by Van Gunsteren (2011). He states that “Quality is fitness for purpose” (Van Gunsteren, 2011, p.15). With this he establishes that there are no absolute standards of quality. The definition of quality always depends on the purpose of each stakeholder involved in the project and what exactly they want to get from the project. Another important aspect of Quality that affects the view on projects as a whole, is how this definition of Quality fits in with Time and Cost. Van Gunsteren (2011) states that the traditional approach is to manage projects based on Time and Cost, with Quality as an indicator of made or proposed changes. However, when projects become large and complex, Time and Cost no longer reflect all the core aspects of the project. Therefore, projects need to be managed based on and using Quality, with Time and Cost as indicators of proposed changes.

This definition of Quality, along with all conclusions stemming from it, is in synergy with the proposed usages of PFM as an Open Design tool by Binnekamp (2010) and Zhilyaev et al. (2022). By defining their preference curves, decision-makers essentially define the Quality that the project should achieve. In that way, decision-makers get to control the development direction of the project through preference functions, managing it by Quality (Van Gunsteren, 2011). Decision-makers of various competencies and expertise are provided with not just a tool to understand projects, but a tool with which they can control project development.

Selection Techniques to Capture Ideas and Test Consensus

According to Marcher et al. (2020), the most popular decision support method in construction is Multi-Criteria Decision Analysis (MCDA) coupled with Analytical Hierarchy Processes (AHP). Within the Open Design methodology and the theoretical basis behind it, alternatives are suggested for both.

Firstly, according to Barzilai (2022), AHP is not a valid methodology, because it is based on mathematical errors. In summary, the two highlighted issues are that the preference scales generated by the AHP method do not enable addition or multiplication and that the assignment of numbers 1-9 is arbitrary, therefore producing results that are effectively meaningless. An alternative presented by Barzilai (2010) is Preference Function Modelling (PFM), which was previously described and is used as a basis for establishing preference scales within the Open Design methodology.

Zhilyaev et al. (2022) state that the currently prevalent assessment-based project development cannot fulfil the needs of the increasingly complex construction projects of today. Two major factors are pointed out. Firstly, assessment-based methods, such as the Lifecycle Analysis (LCA), rely heavily on project information that only becomes available when making changes to the project is no longer feasible. Secondly, assessment-based methods are usually also alternative-based, such as MCDA, which significantly narrows down the range of considered solutions and the opportunities to find the more optimal ones. As a solution, Zhilyaev et al. (2022) propose an optimization-based preference aggregation approach, which was later formulated as the fully formed tool called Preferendus by Van Heukelum et al. (2024).

$$\underset{\mathbf{x}}{Maximise}\ U = T\left[P_{k,i}\left(O_i\left(F_1(\mathbf{x},\mathbf{y}), F_2(\mathbf{x},\mathbf{y}), ..., F_J(\mathbf{x},\mathbf{y})\right)\right), w'_{k,i}\right] \text{ for } \quad k = 1,2,...,K \quad i = 1,2,...,I \tag{1}$$

Subject to:

$$g_p(O_i(F_{1,2,...,J}(\mathbf{x},\mathbf{y})), F_{1,2,...,J}(\mathbf{x},\mathbf{y})) \leq 0 \text{ for } p = 1,2,...,P \tag{2}$$

$$h_q(O_i(F_{1,2,...,J}(\mathbf{x},\mathbf{y})), F_{1,2,...,J}(\mathbf{x},\mathbf{y})) = 0 \text{ for } q = 1,2,...,Q \tag{3}$$

With:

- T: The aggregated preference score determined using the PFM theory principles (see Barzilai (2022)).
- $P_{k,i}(O_i(F_{1,2,...,J}(\mathbf{x},\mathbf{y})))$: Preference functions that describe the preference stakeholder k has towards objective functions, which are functions of different design performance functions and dependent on design and physical variables.
- $O_i(F_{1,2,...,J}(\mathbf{x},\mathbf{y}))$: Objective functions that describes the objective i, functions of different design performance functions and dependent on design and physical variables.
- $F_{1,2,...,J}(\mathbf{x},\mathbf{y})$: Design performance functions that describe the object, depending on one or multiple design variables x (i.e. controllable endogenous variables) and one or multiple physical variables y (i.e. uncontrollable exogenous variables).
- $\mathbf{x}$: A vector containing the (controllable) design variables $x_1, x_2, ..., x_N$. These variables are bounded such that $lb_n \leq x_n \leq ub_n$, where lb_n is the lower bound, ub_n is the upper bound, and $n = 1,2,...,N$.
- $\mathbf{y}$: A vector containing the (uncontrollable) physical variables $y_1, y_2, ..., y_M$.
- $w'_{k,i}$: Weights for each of the preference functions. These weights can be broken down into weights for the stakeholders and weights for the objectives:
  - w_k: weights for stakeholders $k = 1,2,...,K$. These weights represent the relative importance of stakeholders.
  - $w_{k,i}$: these weights represent the weight stakeholder k gives to objective i.

  The final weights $w'_{k,i}$ can be constructed via $w'_{k,i} = w_k \cdot w_{k,i}$, given that $\sum w'_{k,i} = \sum w_{k,i} = \sum w_k = 1$
- $g_p(O_i(F_{1,2,...,J}(\mathbf{x},\mathbf{y})), F_{1,2,...,J}(\mathbf{x},\mathbf{y}))$: Inequality constraint functions, which can be either objective function and/or design performance function constraints.
- $h_q(O_i(F_{1,2,...,J}(\mathbf{x},\mathbf{y})), F_{1,2,...,J}(\mathbf{x},\mathbf{y}))$: Equality constraint functions, which can be either objective function and/or design performance function constraints.

Figure 4 Preferendus mathematical statement, directly from Van Heukelum et al. (2024)

In short, Preferendus is a design tool that produces the final design by means of aggregated preference optimization, while accounting for bounds and constraints imposed on the model. This tool allows to include several project objectives in the calculation, as well as the perspectives of different stakeholders on the objectives via preference curves and the importance of each objective for a given stakeholder via weights. Preferendus is a basis, on top of which a wide variety of decision tools can be created. At the same time, it can also be used as a group decision tool in its pure form, but it requires an operator familiar with the methodology to act as a proxy for all other decision-makers (Van Heukelum et al.,2024).

Moreover, the Preferendus features two ways of searching for solutions. The first is minimizing maximum dissatisfaction of each stakeholder, also referred to as minmax or compromise. It can also be interpreted as making all parties equally dissatisfied. The second, and a large part of the innovation of Preferendus, is Integrative Maximized Aggregated Preference (IMAP), also referred to as the best fit for common purpose approach. It maximizes overall group preference, rather than focusing on individuals. It can be considered a direct mathematical implementation of the utilitarian principle of “the greatest good for the greatest number”, with the “greatest good” quantified by Preference Function Modelling.

At this point a distinction needs to be made in the used definitions. Here the terms “project design” or “design variant” are used to refer to the solution generated by the Preferendus, as it is an instance of all possible project designs in the solution space. The limitations imposed on the Preferendus model, such as the geographical limits of the project area, materials under consideration or variable bounds are called the “project configuration”. In this way, a solution space full of design variants is limited by the project configuration.

It is also important to note that there are two main ways to use the pure Preferendus system: the design way and the decision way. The design way means that the objective functions part of the Preferendus is emphasized. The stated preference of stakeholders is taken as constant, and a search for the fitting design variant takes place, including changes to the objective functions, bounds and constraint (project configuration). The decision way emphasizes interaction with decision-makers and how their project interests, represented by preference curves, can change within the limitations of one project configuration, which is taken as constant. In real life the process of designing is a back and forth between these two alternatives.

All of the described functionality allows the Preferendus, as the latest embodiment of the Open Design methodology, to act as the necessary tool for capturing ideas and testing consensus.

1.2. Development Gap

According to Van Heukelum et al. (2024), some applications of Preferendus result in an empty design solution space, also called a “stalemate”. This is characterized by the proposed solution scoring 0s or 100s on all objectives, meaning that this outcome is unacceptable to a portion of decision-makers. According to Glasl (1982), in collaborative processes where parties with conflicting interests are not able or willing to reconcile their positions, such as situations indicated by a Preferendus stalemate, conflict escalation will occur. Figure 5 shows stages of conflict escalation according to Glasl (1982).

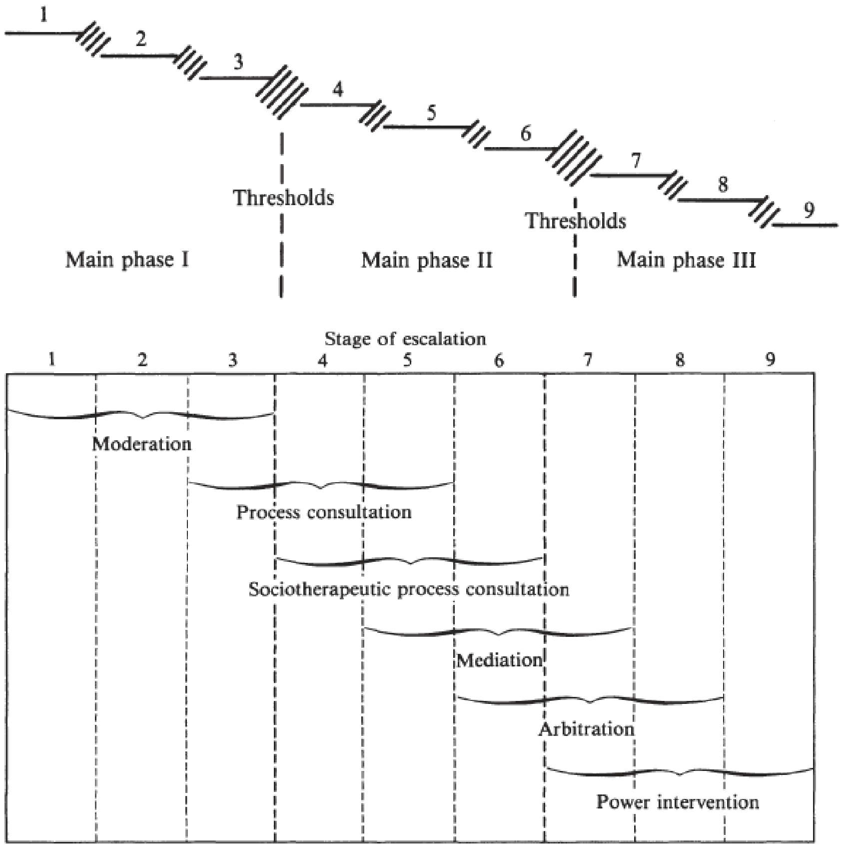

Figure 5 Stages of conflict escalation and recommended third-party interventions, taken directly from Glasl (1982)

Glasl (1982) identifies 3 main phases of conflict escalation. During phase 1 parties still attempt collaboration, but their differences drive them first towards a non-productive debate and eventually towards acting independently, only accounting for their own needs. Phase 2 displays increasing psychological distance between the parties and active verbal conflict. Phase 3 is described as an all-out war when destruction of the opponent becomes a goal in itself. The phases are separated by thresholds, which also act as points of no return. Once a conflict escalates from one phase to another, it is no longer possible for parties to return to the previous phase.

Evidently, conflict escalation is destructive to the process it arises from. To address issues in complex construction projects, the significant development gap of a lack of stalemate resolution capacity in the Preferendus needs to be addressed.

2. Development Statement and Design

The development statement for this thesis is formulated as follows:

- *To develop a Preferendus-based system to enable stalemate resolution in network decision-making for large and complex construction projects*.

The development process that will be followed by this thesis is shown in Figure 6.

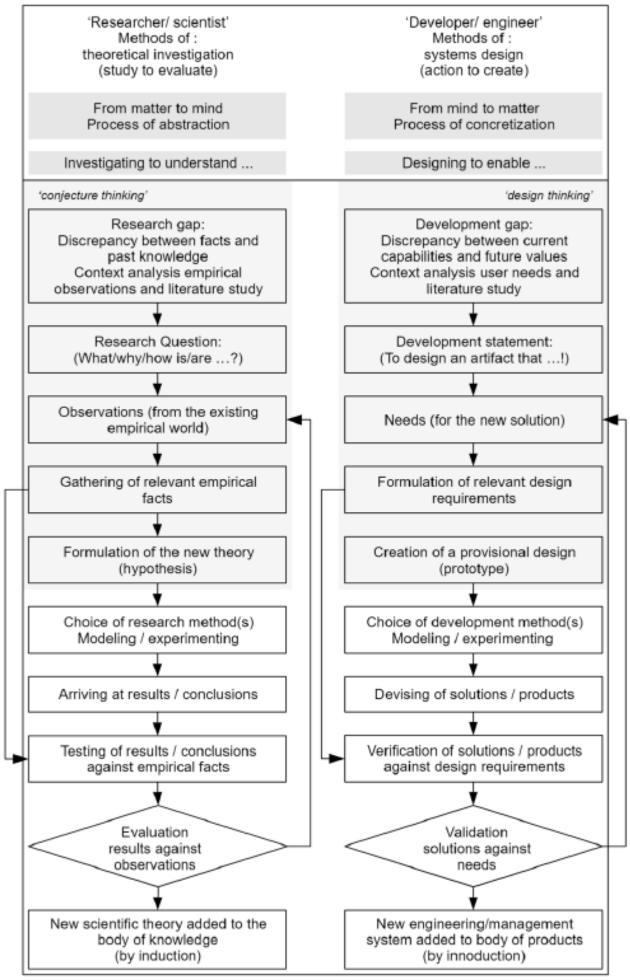

Figure 6 Research and Design processes. Extended by Binnekamp and Wolfert from Roozenburg & Eekels (1995). Taken from Wolfert (2023).

In Figure 6 the column on the right represents the development design chosen for this thesis work. The following is a description of the main steps of the process.

Needs

Needs are taken here as high-level requirements drawn from literature, that will define the structure of the produced system.

Design Requirements

Desing requirements determine the performance metrics of the produced system. They will be formulated in line with the Specific, Measurable, Achievable, Relevant, Time-bound (SMART) principle.

Creation of the Provisional Design

At this point in development, needs will be transformed into an overall prototype structure that will be built upon and interpreted during the design cycles.

Choice of Development Method(s)

After that, the methods of applying the developed structure will be defined, as well as the procedures for validation and verification of results.

Design Cycles

This section will document the design cycles and the changes of understanding that came in the process of development and testing of the prototype.

Devising of Solutions/Products

The process of generating a set of solutions is described and the solutions are documented.

Verification of Solutions Against Design Requirements

As the first model results are produced, they are verified against the established requirements.

Validation of Solutions Against Needs

After verification, the results are validated by means established in the methodology. At this point future development or research directions can be defined and an overall discussion of the design process can take place.

3. Needs and Design Requirements

3.1. Needs

As defined in the Development Gap, the problem that is to be addressed by the proposed system is a lack of stalemate resolution functionality in the current Preferendus. The core of the Open Design methodology has to do with decision-making, therefore any produced extensions are automatically in the realm of decision-making. Therefore, the produced system to resolve stalemates can only be implemented and tested in the context of a decision-support system (DSS). According to Keen (1980), the main difference between a model and a DSS lies in the interconnected nature of the user, the DSS and the DSS builder. The DSS shapes perceptions of the user, providing new insights. New insights lead the user to create new uses for the DSS. This leads to increased problem understanding of the model builder, who, in turn, shapes the DSS. These relationships are shown in Figure 7.

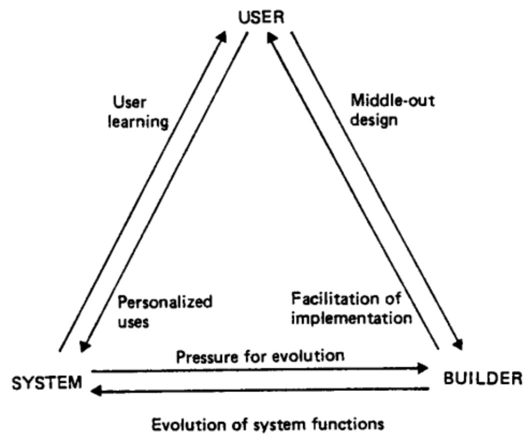

Figure 7 Relationships in the DSS, taken from Keen (1980)

Considering the problem lies in the realm of decision-making, a successful product can only be achieved by means of the described relationships. This allows to formulate the first need:

1. *The produced system needs to be a Decision Support System and will follow trifold relationships of User – DSS – Builder.*

Secondly, the problem area needs to be specified. As mentioned previously, Glasl's (1982) model of conflict escalation describes the stages conflict escalation goes through. To preserve the collaborative process, it is crucial to ensure that any conflict does not pass the threshold from phase 1 into phase 2. Glasl (1982) recommends using moderation as a third-party intervention strategy for phase 1, which allows to clarify misunderstandings and deal with differences. One of the moderation strategies recommended by Glasl (1982) is described by Eisemann (1978). The core aspect of this strategy is to encourage parties to look beyond the dimension where the conflict arises, to see if common ground can be found in other dimensions. This is already included into the Preferendus via the use of PFM, so more detail is necessary. Fisher & Keashly (1988) distinguish between consultation and mediation, both of which fall under Glasl's definition of moderation. Consultation is defined as facilitating communication by analyzing and stating the differences between conflicting parties. Mediation is defined as a direct intervention into the conflict and suggestion of alternatives that can lead to conflict resolution. Similarly, consultation is already an intrinsic part of the Preferendus. However, mediation is not. In some situations, mediation is preferable, while in others, consultation is preferable (Wall & Callister, 1995). Therefore, the decision support system needs to account for both approaches. This allows to formulate the second need:

2. *The produced DSS needs to include and make use of both the consultation and mediation mechanisms to reach the solution to the stalemate.*

Finally, it is necessary to establish at what point the stalemate can be considered resolved. According to Eisemann (1978), the conflict can only be considered resolved if all decision-makers understand three points:

a) Why at the outset each decision-maker embraced their initial position.
b) Why the initial positions of the decision-makers are incompatible.
c) How the conflict resolution reconciles the initial positions.

This allows to formulate the third need:

3. *After using the proposed system, all decision-makers need to understand the provided solution to the stalemate according to Eisemann's (1978) three main points.*

3.2. Design Requirements

First, it is necessary to know how to reliably identify the stalemate and whether the proposed solution resolves it. In the initial problem statement by Van Heukelum et al. (2024), the need to help decision-makers arrive at an acceptable solution space is highlighted. This means that resolving the stalemate has to do with solution acceptability. This issue was addressed in one of the first iterations of the Open Design methodology when it was still based on linear programming (Binnekamp et al., 2006). Stakeholders were asked to provide three values for objectives relevant to them: the ideal value from their viewpoint, the acceptable value that the stakeholder would accept without much discussion and the walkout value, which could only be accepted in extreme circumstances. These values were then input into a linear model as constraints. In situations where an empty solution space would come up, similarly to the Preferendus stalemate, these constraints would be lifted one-by-one and that would determine the decision-maker who needs to adjust their project goals for the solution space to not be empty. The current Preferendus does not have this clear separation, which allows to formulate the first design requirement:

1. The produced DSS must have a clear and quantifiable indication of the Preferendus-produced design variant acceptability to enable stalemate resolution.

As mentioned previously, the Open Design methodology distinguishes between compromise solutions and best fit for common purpose (group optimal) solutions. Within Preferendus, the group optimal solution, by nature, has a higher overall preference score than a compromise solution, which means that it leads to a better project outcome. Typically, more compromise solutions exist for a problem than group optimal solutions, as compromises are sub-optimal in Open Design. In resolving stalemates, similarly, if the proposed stalemate resolution has a lower preference score than the stalemate situation, this would mean that this resolution is a compromise, meaning that it is suboptimal. In line with this logic, the second design requirement can be formulated:

2. The resulting stalemate resolution must have a higher preference score than the initial stalemate situation to ensure that it is best fit for common purpose.

4. Formulation of Prototype

This chapter is split into two parts, the Overall Structure and Specific Decisions. The Overall Structure is derived from the Needs, while Specific Decisions are derived from Design Requirements.

4.1. Overall Structure

This sub-chapter is going to explain the choices made for the general structure of the model, in line with the defined model needs. This structure is shown in Figure 8.

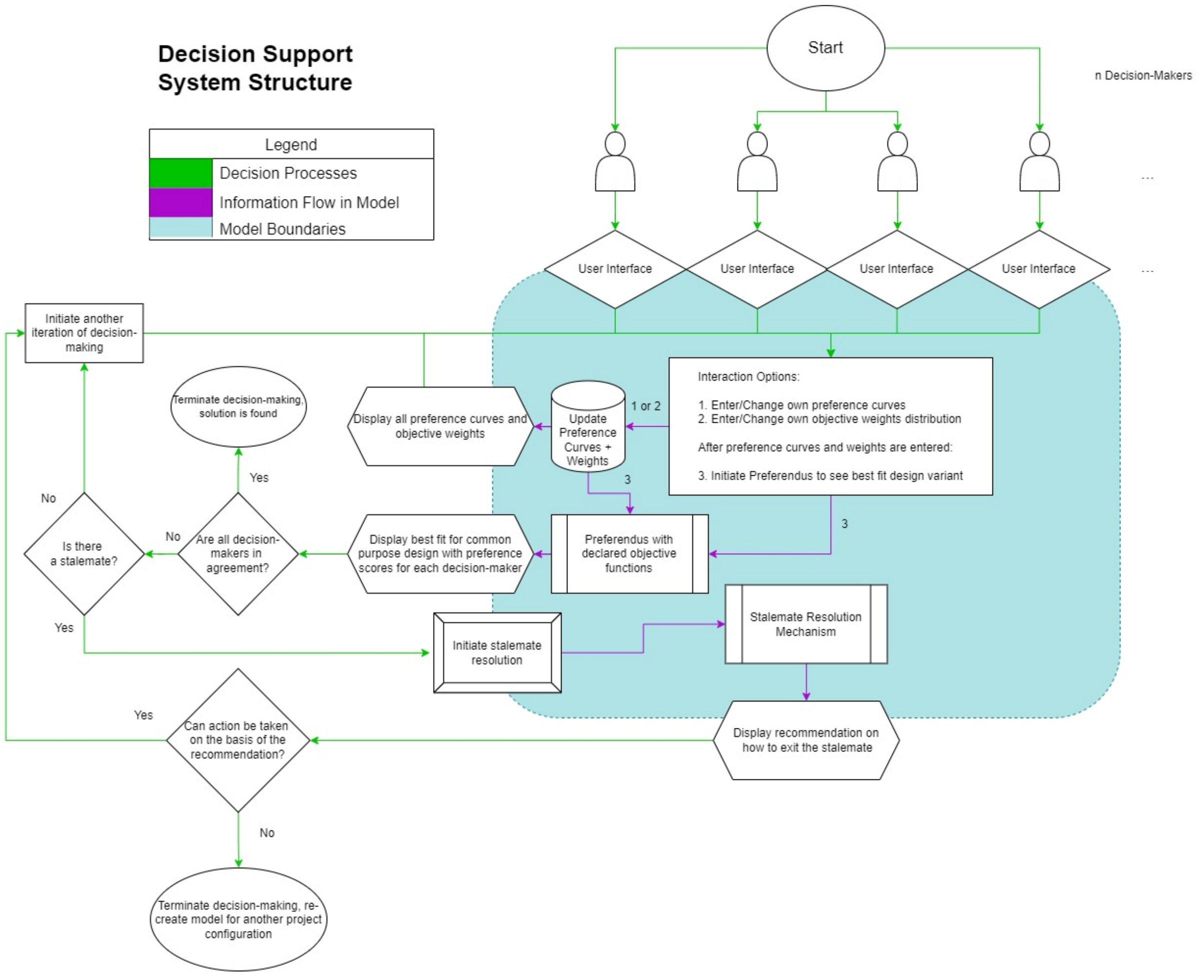

Figure 8 Overall structure of the proposed Decision Support System. Displays and interfaces are at the edge of the model to signify that they bridge the model boundary

4.1.1. The Workflow

Within this prototype structure, the workflow starts with the decision-makers creating preference curves to describe their project interests and assigning weights to those interests. After the decision-makers are finished establishing their respective preference curves, they can initiate the Preferendus to see what the current group-optimal solution is. After seeing the result, they have several decisions to make. Firstly, if the current group-optimal solution is satisfactory to all parties, decision-making can stop. If not, it is necessary to determine if there is a stalemate between the decision-makers. If decision-makers are still willing to negotiate changes in opinions, they are encouraged to do that and initiate the Preferendus as many times as needed. However, if a stalemate is identified where the decision-makers are not willing to make changes anymore, the Stalemate Resolution Mechanism is initiated. It outputs a recommendation or indication of potential ways of exiting the stalemate and then it is up to decision-makers to implement them or not. Implementing the recommendations leads to further iterations of decision-making. Not implementing the recommendations means that to continue a change of project configuration is required. This can mean either taking another physical design as basis for the Preferendus or withdrawing from the decision altogether.

4.1.2. Addressing Need 1 - DSS

The guiding principle in creating this structure is enabling the back-and-forth relationship of the decision-maker and the DSS, according to Keen (1980). For this reason, every decision-maker has their own user interface, through which they can create or change their preference curves and set objective weight distributions. It also allows them to inspect the preference curves and weight distributions of other decision-makers, to encourage transparency and discussion. The importance of having such an interface for Preferendus is also supported by the master thesis of Raaphorst (2024). As well as that, the model workflow is built in such a way that its conclusion is dependent only on the user. To a significant degree, this system is a facilitation of the general Preferendus process that emphasizes the decision-making aspect. In other words, the project configuration is kept constant while the range of interests that can fit that configuration is explored.

One example of how this Preferendus-based decision process enables the mutual DSS-user learning relationship is based on the behavioural theory of Argyris & Schön (1976) as summarized by Binnekamp et al. (2006). In short, Argyris & Schön (1976) sate that there are two forms of theory of action: espoused theory and theory-in-use. Espoused theory is what a person says guides their behaviour, while theory-in-use means what actually guides their behaviour when it comes to action. An example of this can be a company that says its guiding principle is preserving the environment but consistently prefer cost-cutting solutions to environmentally friendly ones. In a decision support system this can be exemplified by how a decision-maker changes their preference during the decision process. This can happen either because the decision-maker gains new insights, or because they are deciding to take a step back from an over-exaggerated position which they thought could give them an edge in the negotiations. Regardless of the reason, it can be stated that during Open Design decision-making, decision-makers will eventually transition to their theories-in-use, represented by changes in preference curves and weights. Through this transition the insights of the user on their own position change, and accordingly the function of the model alternates between a design tool and providing insight.

4.1.3. Addressing Need 2 – Mediation and Consultation

The key point of this structure lies in the step where the stalemate is identified, as this is where. From this point the DSS starts fulfilling the moderation role to prevent the conflict from escalating and potentially leading to the failure of the project. The first step in stalemate resolution is to initiate the Stalemate Resolution Mechanism to produce a suggested path out of the stalemate. This fulfils the mediation function of moderation, directly intervening into the conflict and presenting the decision-makers with an alternative. After that, it is up to the decision-makers to decide if they are willing to act on the basis of the recommendation or if a different project configuration needs to be considered, which leads to the termination of this decision-making instance. If they decide to continue, the model loops back into the normal Preferendus workflow, which at this point starts fulfilling the consultation function of moderation, providing the decision-makers with information on how their changes of preference and weights affect the group solution and consequently the stalemate. This means that the model workflow is developed in line with the second established Need.

4.2. Specific Decisions

Only one specific decision can be specified at this point of prototype development. It has to do with Design Requirement 1, clear indication of solution acceptability. As mentioned in the design requirement description, in the past there was a system of 3 levels of linear constraints for every decision-maker (Binnekamp et al., 2006). In order to more clearly define degrees of solution acceptability, it has been decided to re-interpret this system for this thesis to enable stalemate resolution.

Since the introduction of PFM into Open Desing, solution acceptability was a matter of preference. Normally in Preferendus application cases, a preference scale of 0 to 100 is used. As stated by Van Heukelum et al. (2024) and then confirmed by Teuber & Wolfert (2024), this scale can be used to identify a stalemate situation, but does not give an indication of how a stalemate can be solved. To enable stalemate resolution, a new scale is proposed:

- The proposed preference score scale ranges from -100 to 100, with the best solution scoring 100 and the worst solution scoring -100.
- Solutions that score above 0 are desirable solutions that the decision-maker accepts without much discussion.
- Solutions that score 0 are acceptable to the decision-maker, but with extra negotiation.
- Solutions that score below 0 are unacceptable to the decision-maker, or only acceptable in the most extreme scenario.

The direct usefulness of this scale is that the decision-maker unambiguously declares which project outcomes are acceptable for them and which are not. From the very first run of the model it will be possible to see if a commonly acceptable group optimum exists within the current project and preference configuration. As well as that, this gives more flexibility to the system itself. It is not always possible to account for all the possible extra measures that can exist for a project, therefore having a 0 region where negotiation on these measures can take place enables the model to more accurately represent the decision process.

With regards to fulfilling Design Requirement 2, this concerns the implementation the Stalemate Resolution Mechanism. Over the course of the project, the Stalemate Resolution Mechanism underwent many changes. As is in line with the definition of Keen (1980), through user interaction with the DSS and general experimenting new insights became apparent to the model builder. These changes, along with the final version of the Stalemate Resolution Mechanism will be expanded on in the Design Cycles section of the thesis.

5. Development Methods

5.1. Model Development Methods

This section describes the main steps taken in developing the DSS from the established prototype structure to deploying it as interactive software online.

A Case as Model Basis

The success of a DSS, in line with the definition of Keen (1980), is directly dependent on the user-model interaction. This is especially true for the Preferendus, as it is based on decision-maker preference. For this interaction to be as authentic as possible, the DSS must be built based on a real construction project (case). Ideally this would be an ongoing project with various parties open to being involved in testing the constructed DSS. A project with large amounts of public information is also feasible, as long as it allows not only to assess the technical aspects, but the perspectives of the stakeholders as well.

Another key characteristic of a project like this is that it must be a complex project. This thesis addresses the problem of decision-making stalemates, so it needs to be a project with a high degree of social complexity, or conflicting stakeholder interests. A project that has just arrived at a standstill is ideal, as issues in social complexity would be fresh in the minds of the stakeholders.

Preferendus Formulation of the Case

After the case has been identified, it is necessary to make a Preferendus Formulation of that case. This involves establishing design variables, bounds, constraints, identifying decision-maker goals for the project, creating objective functions, setting decision-maker preference curves and weights. These steps are described in detail by Wolfert (2023) and Van Heukelum et al. (2024).

Programming the Model

After the case has been formulated, it can be put into code. The Programming language used for this thesis is Python. All the information on versions and Python packages used in development is available in Appendix C.1.

The core elements for creating the Preferendus model are taken from the TU Delft Odesys GitHub page, specifically the Preferendus Core Scripts repository (Van Heukelum, 2023). As well as that, the A-Fine-Aggregator is taken from the repository by the same name on the Royal Boskalis Westminster GitHub page to replace the Tetra aggregation and speed up the calculation process (Van Heukelum, 2024).

The case itself is transferred into code along the lines of the examples provided on the Preferendus GitHub page.

For developing the rough initial versions of the model JupyterLab version 4.3.4. is used. The final stages of development that involve creating and interactive element for the DSS took place in PyCharm Community version 2024.2.0.1.

Deploying the Model

Deploying the model means making it open for public use. This step is necessary due to the model being a decision support system that defines its success by user interaction. For this thesis, a service called PythonAnywhere is used. It is chosen for its relative simplicity and a free tier that allows to keep the model online indefinitely.

5.2. Model Validation Methods

Validation asks the question “Did we build the right model?”. Answering this question in light of the established Needs requires testing with live decision-makers. This testing is performed in the form of a workshop where decision-makers for a certain project gather in a War Room format to solve a decision problem with the use of the created DSS. The workshop’s audio is recorded for transcription and notes are taken in the process. After the workshop is concluded, decision-makers are given an anonymous survey where they are asked about their experience in interacting with the model and their understanding of the process and its conclusions.

The exact format of the workshops and the survey highly depends on the decisions made during the development process, therefore it will be given in full in the Verification and Validation section of the thesis.

6. Project Case and Preferendus Formulation

To test the application of the proposed decision support system, a large and complex project is needed. This is provided by the ongoing Duurzame Polder (Sustainable Polder) project, which is currently in its Assessment Phase. The application of a decision support system on this project is based on and inspired by the work of Teuber & Wolfert (2024) with some expansions.

6.1. Project Description

Duurzame Polder is a joint project of the municipalities of Oss and ‘s-Hertogenbosch and the province of Noord-Brabant that has been initiated in 2017 to generate renewable energy in fulfilment of the provincial sustainable energy generation goals. To be more exact, Noord Brabant aims to have 50% of its energy generated from sustainable sources by 2030 and 100% by 2050. In 2021 the Oss and ‘s-Hertogenbosch municipalities were appointed as the competent authorities for the project.

6.1.1. Location

The project is located in the big polder that lies between Oss and ‘s-Hertogenbosch, which includes the Lithse, Geffense, Rosmalense and Nulandse polders. The project’s location is the main reason for the project to be a cross-municipal venture.

Figure 9 Duurzame Polder project area. Taken from Duurzame Polder Plan of Approach (2022)

At one of the development stages of the project the municipalities Oss and ‘s-Hertogenbosch set requirements for the minimum distance from the project area to the built-up areas. For Oss this limit is 2km away from built-up areas, while for ‘s-Hertogenbosch this limit is 1km. This results in the project area shown in Figure 10.

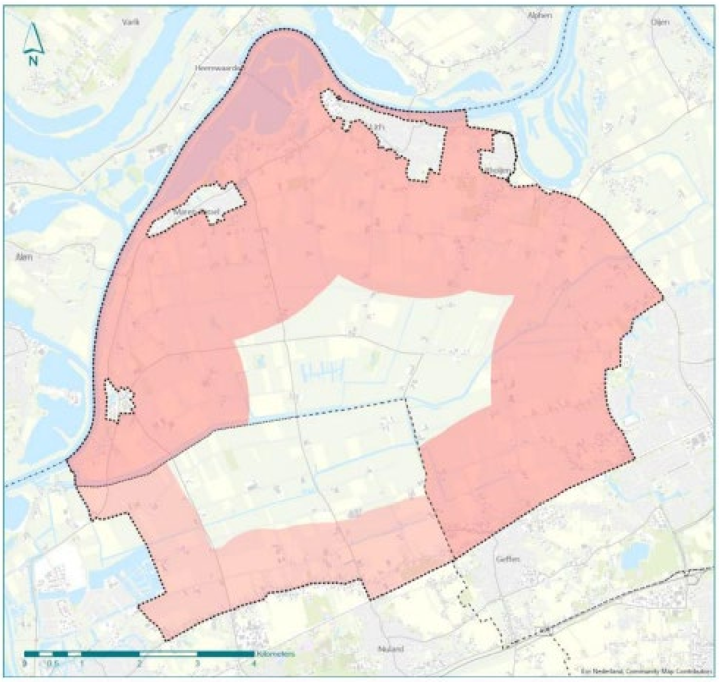

Figure 10 Project area limited by municipality requirements. Taken from Taken from Duurzame Polder Plan of Approach (2022)

6.1.2. Technical Context

From the beginning there was no concrete vision for what renewable energy sources were to be the focus of the project. During the investigation phase various energy providers were consulted on this topic and their recommendation was to use a combination of wind turbines and solar panels to compensate the weaknesses of each. However, eventually a decision was made to stay only with wind turbines.

The energy providers also stated that, depending on the installed capacity of the wind park, the electricity might require extensions and upgrades, which would extend the project time. The costs of the necessary upgrades would be collected via increased rates to consumers, without incurring costs for the company operating the wind park or the municipality.

Another technical restriction present in the area is from the Dutch Military. The area is used for both low-altitude flight exercises and radar monitoring. Therefore, any plans for installations above 90 meters above NAP would have to be submitted to the military for inspection. This aspect further reflects the complexity of the case.

The two municipalities also explicitly stated how much energy they want to generate per year from this wind park. For ‘s-Hertogenbosch it is 144 GWh and for Oss it is 143 GWh. The ‘s-Hertogenbosch municipality also stated that they want to realize 16 wind turbines in this project.

6.1.3. Social Context

Since the project’s initiation, some controversy was raised around it. The primary and most direct opposition to the project comes from the local residents, especially in the area of the polder itself. The opinions expressed mostly contained doubts about the efficiency of a purely wind turbine – driven approach, benefits the local residents would receive, threat of noise pollution, particle pollution from turbine blade erosion and damage to the natural aesthetic of the area. Several resident groups were actively involved in communications with the project team to make their preferences known.

Some opposition also came from environmental protection groups, who pointed out that both solar and wind energy generation options would ultimately negatively impact endemic meadow bird populations. Their perspective was also incorporated into the overview that was provided in the Assessment Phase report (Witteveen+Bos, 2024).

Various questions have also been raised with regards to the land usage within the polder. As most land there is owned by farmers and used for agricultural purposes, using it for renewable energy purposes might affect their quality of life and business. For this purpose, several alternatives were proposed such as “miller houses”, which involve a farmer agreeing to have a wind turbine built closer to their home, resulting in higher levels of noise pollution, while at the same time earning a share of the profit from electricity sales. As well as that, there were several alternatives to the general and financial structure of the project such as keeping it decentralized and letting each interested party settle issues with the relevant municipality or doing it in an integrated manner. The choice was made towards an integrated approach, which is what can be seen today – a large project involving many parties. It needs to be noted that no more in-depth information on the financial structure was made public.

6.1.4. Current State

Currently, according to the project website, the project is in the so-called "Assessment Phase”, where the final design variant is presented to the public and municipalities for feedback and remarks to be used in further decision-making. The project area variant that was proposed, also referred to as “Preferred Alternative”, is shown in Figure 11.

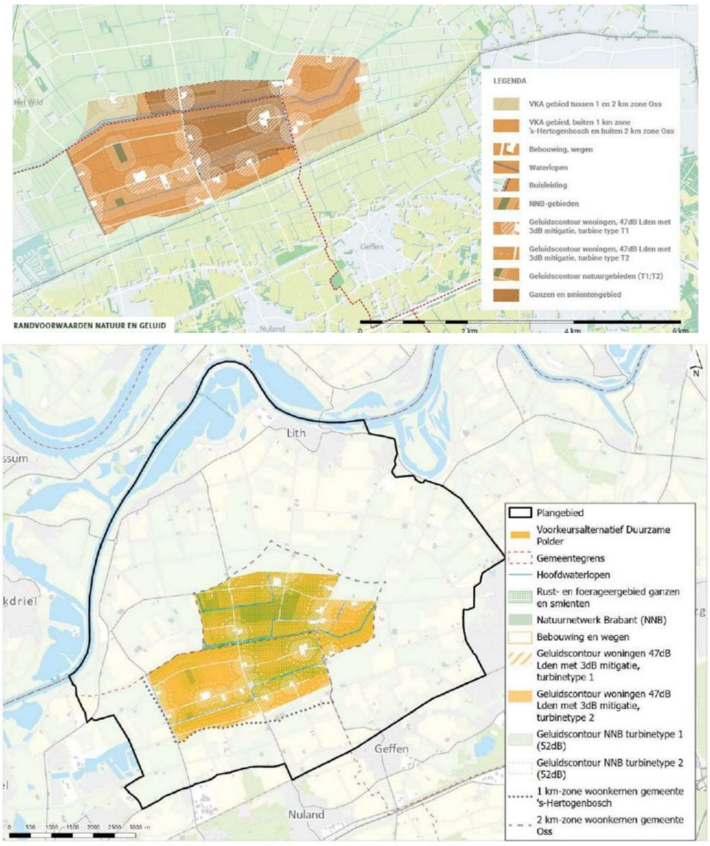

Figure 11 Initial (top) and revised (bottom) Preferred Alternative for the Duurzame Polder (Witteveen+Bos, 2024)

According to the analysis performed by Witteveen+Bos, the best possible option within the bounds of the Preferred Alternative scores below satisfactory on all performance metrics except energy generation capacity, which means negative impact on natural habitats as well as nuisance and discomfort for the local residents.

It is necessary to state that, as seen in Figure 11, the project area was revised as this thesis was being written. Since the underlying model is built according to the initial project formulation and because time constraints are an issue, the initial Preferred Alternative will be used instead of the revised one.

6.2. Preferendus Formulation of the Case

Since the proposed decision support system will be based on the Preferendus, the case needs to be formulated accordingly. This means that it must be broken down in terms of design variables, variable bounds, objective functions, constraints and preference functions.

6.2.1. Case Simplification, Design Variables and Bounds

The focus of this thesis work is designing a Preferendus-based decision support system, rather than solving the Duurzame Polder project. For this reason, the case application will not be a one-to-one representation of the Duurzame Polder, which is outside of the scope and timeframe of this thesis. The Discussion and Limitations section will discuss how the case can be represented more realistically.

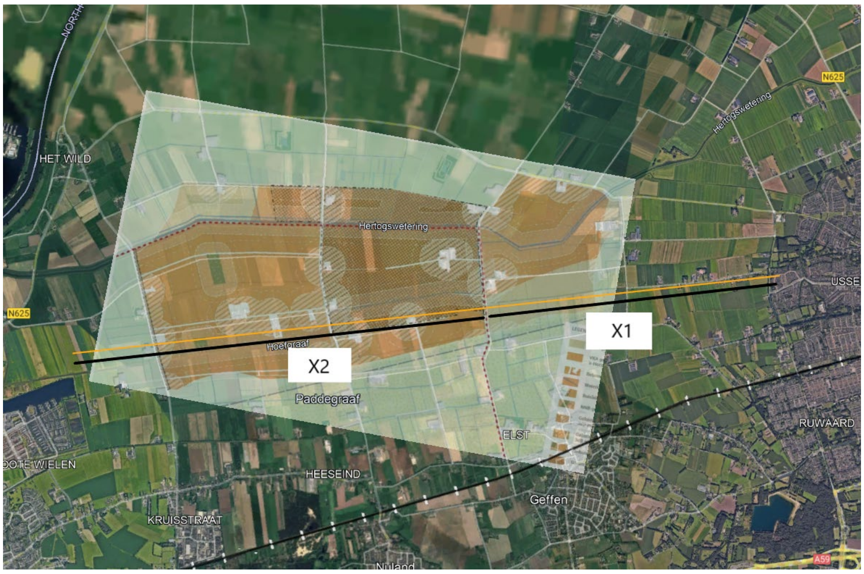

Figure 12 Initial Preferred Alternative in Google Earth, red dotted line is the municipality boundary

The project is represented via the following variables:

- x1 - Distance to the Oss built-up area (km).
- x2 - Distance to the ‘s-Hertogenbosch built-up area (km).
- x3 - Number of wind turbines in the Oss project area.
- x4 - Number of wind turbines in the ‘s-Hertogenbosch project area.
- x5 - Turbine hub height in the Oss project area (m).
- x6 - Turbine hub height in the ‘s-Hertogenbosch project area (m).

The choice of location of the wind park takes place along a straight line, which is marked in orange in Figure 12. The following bounds apply to the variables:

- 0.1 km ≤ x1 ≤ 3.5 km – geographical restriction.
- 0.1 km ≤ x2 ≤ 5 km – geographical restriction.
- 1 ≤ x3 ≤ 12 – based on first municipality estimate of wind turbines for Oss.
- 1 ≤ x4 ≤ 16 – based on first municipality estimate of wind turbines for den Bosch.
- 50 m ≤ x5 ≤ 200 m – based on wind turbine height used in Duurzame Polder documents.
- 50 m ≤ x6 ≤ 150 m – based on wind turbine height used in Duurzame Polder documents.

These variable boundaries allow to ground the case to the physical and geographical context. At the same time, some variable bounds intentionally ignore some restrictions, such as the minimum distance to built-up areas imposed by the municipalities. This is done to allow the model to consider all options without prejudice and not miss out on potential design variants. However, to make the case modellable within the stated scope it is important to make and outline the key assumptions:

- It is assumed that the Energy Provider is fully financially responsible for the construction but also receives the financial benefits.
- It is assumed that the resulting project can be split into two separate sub-wind parks: one on the Oss side and the other on the ‘s-Hertogenbosch side.
- The model considers the search for the project location along a straight line.

6.2.2. Objective Functions

Objective functions are calculations that indicate the project performance of a certain project configuration. They are formulated according to project performance indicators as formulated by Van Gunsteren (2011): Time, Cost and Quality. Quality indicators are established from the goals of stakeholders involved in the project. The following list of indicators can be established:

- Net Present Value (NPV). Core stakeholder: Energy Provider. This indicator includes the calculation of both cost and benefits.
- Noise Pollution in Oss and ‘s-Hertogenbosch. Core stakeholders: local residents of Oss and ‘s-Hertogenbosch, RIVM.
- Bird Mortality. Core stakeholder: Ecologists.
- Particle Pollution. Core stakeholder: RIVM.
- Energy Production of each sub-park. Core stakeholders: Oss and ‘s-Hertogenbosch municipalities.
- Project Completion Time. Core stakeholders: Oss and ‘s-Hertogenbosch municipalities.

It is important to note that project time is also important for the NPV indicator. However, the relationship between project time and NPV is not necessarily linear, therefore they are included as separate indicators. Before the calculation of each project performance indicator can per explained in detail, some universal functions used across several objective functions will be established.

Universal Functions

Due to the nature of the project, both the Oss and ‘s-Hertogenbosch sub-parks have the same performance indicators and use the same equations, but with different variables. For the sake of conciseness, the logical indicator V, meaning OR, will be used in the expression of these equations.

Firstly, the change of wind speed according to hub height (x5, x6) needs to be set. Wind data is taken for the 10% most windy areas at project location from the Global Wind Atlas (Technical University of Denmark, 2025), which is also used in the Witteveen+Bos assessment report in Appendix II (Witteveen+Bos, 2024).

$$U_{w,Oss\ \mathrm{v}\ Den\ Bosch} = \begin{cases} 6.97\ ms^{-1}, if\ 50m \leq x_{5\ \mathrm{v}\ 6} \leq 75m \\ 8.16\ ms^{-1}, if\ \ 75m < x_{5\ \mathrm{v}\ 6} \leq 125m \\ 9.3\ ms^{-1}, if\ \ 125m < x_{5\ \mathrm{v}\ 6} \leq 175m \\ 10\ ms^{-1}, if\ \ 175m < x_{5\ \mathrm{v}\ 6} \leq 225m \end{cases} \quad (1)$$

Secondly, the wind turbine blade diameter calculation, taken directly from Teuber & Wolfert (2024).

$$D_{Oss\ \mathrm{v}\ Den\ Bosch} = 1.3 * \ x_{5\ \mathrm{v}\ 6} \quad (m)(2)$$

Swept area of wind turbine blades, from Teuber & Wolfert (2024).

$$A_{Oss\ \mathrm{v}\ Den\ Bosch} = \pi * \left(\frac{D_{Oss\ \mathrm{v}\ Den\ Bosch}}{2}\right)^2 \quad (m^2)(3)$$

Power capacity per wind turbine, from Teuber & Wolfert (2024). Rho (ρ) is air density and e is wind turbine efficiency in converting wind energy into electricity. Also, total power capacity for the wind park.

$$P_{turbine,\ \ Oss\ \mathrm{v}\ Den\ Bosch} = A_{Oss\ \mathrm{v}\ Den\ Bosch} * \rho * e * U_{w,Oss\ \mathrm{v}\ Den\ Bosch}{}^3 \quad (W)(4)$$

$$where\ \rho = 1.224\ kgm^{-3}\ and\ e\ = 0.3$$

$$P_{total,\ \ Oss\ \mathrm{v}\ Den\ Bosch} = \frac{P_{turbine,\ \ Oss\ \mathrm{v}\ Den\ Bosch} * \ x_{3\ \mathrm{v}\ 4}}{10^6} \quad (MW)(5)$$

Resistance factor, from Teuber & Wolfert (2024).

$$R_{Oss\ \mathrm{v}\ Den\ Bosch} = \frac{x_{5\ \mathrm{v}\ 6} + U_{w,Oss\ \mathrm{v}\ Den\ Bosch}}{12} \quad (6)$$

Yearly energy production from the wind park, assuming the capacity factor is 100%.

$$E_{\ Oss\ \mathrm{v}\ Den\ Bosch} = \frac{P_{total,\ \ Oss\ \mathrm{v}\ Den\ Bosch} * 365 * 24}{10^3} \quad (GWh)(7)$$

Yearly profit from the wind park.

$$Profit_{Oss\ \mathrm{v}\ Den\ Bosch} = \ E_{\ Oss\ \mathrm{v}\ Den\ Bosch} * EWP - (R_{Oss\ \mathrm{v}\ Den\ Bosch} * \ x_{1\ \mathrm{v}\ 2} * 365) \quad (€)(8)$$

NPV

Setting up an NPV calculation requires establishing a timeline, cash flows at different points of that timeline and the rate of return to be used with the calculation. The timeline is taken from a consultancy report created for the Irish Wind Energy Association (Ionic Consulting, 2019).

Figure 13 Timeline of an onshore wind farm project, adapted from Ionic Consulting (2019) for the Duurzame Polder case

The main difference between what is suggested by Ionic Consulting and what is stated in Figure 13 is the Plan and Permit section. According to the European Union Renewable Energy Directive (Directive 2018/2001), all renewable energy generation projects are to be given the necessary permits within the timeframe of 2 years. However, since delays can occur due to unforeseen aspects such as construction close to Natura 2000 sites, 3 years are taken as the planning and permitting time to be conservative. Total project cradle-to-grave then becomes 31 years. This timeline allows to establish cash flows for every year of project operation. These cash flows are summarized in Table 1.

Table 1 Cash flows for the NPV calculation

Cash Flow Name	**When**	**Amount**	**Source**
Capital Expenditure (CAPEX)	Once, at the end of the Pre-Construction phase	1,600,000 € per MW installed capacity	(Wind Europe, 2022)
Operations and Maintenance (O&M)	Every year of operation	30,722 € per MW per year	(Department for Energy Security and Net Zero, 2023)
Electricity sales revenue	Every year of operation	Formula established below	Formula established below
Decommissioning (DECEX)	Once, at the end of operation	Formula derived from source, see below	(Gück, 2023)

Due to lack of reliable information on wind farm decommissioning costs, a formula was adapted from a conference presentation by Gück (2023).

$$DECEX_{Oss\ \mathrm{v}\ Den\ Bosch} = (0.1 * x_{5\ \mathrm{v}\ 6} + 31) * P_{total,\ Oss\ \mathrm{v}\ Den\ Bosch} * 1000 \qquad (€)(9)$$

As well as that, there are also important constants that must be determined for the NPV calculation. One is the rate of return, since the objective of the Energy Provider is to have a positive NPV, and for that a known rate of return is necessary. For this calculation, the Internal Rate of Return (IRR) is taken to be 4.5% according to a report by Trinomics (2020). It is important to note that this IRR is designed to encourage increased investment, therefore it can reasonably be expected to produce an optimistic NPV.

Another constant is the capacity factor. Capacity factor is a term commonly applied to energy generation facilities and reflects what percentage of the total installed capacity is producing electricity at any given time. According to the report by Wind Europe (2023), the capacity factor for new onshore wind farms is 30-35%. Here it is taken as 30%.

Finally, the electricity sale price is the last parameter needed to calculate the cash flows. Since the energy provider does not sell directly to the customers, but instead sells electricity to grid operator companies, a wholesale price must be considered. According to the European Electricity Wholesale Price Data by Ember (2025), a reasonable wholesale price for the

Netherlands can be assumed to be 0.59 cents per kWh. It is assumed that this price stays constant through the project lifecycle, which is a significant limitation of the model.

To summarize, these are the important constants other than those in Table 1:

- IRR = 0.045
- Capacity Factor = 0.3
- Electricity Wholesale Price = 0.059€ per kWh

Another important factor to note when it comes to installation of renewable energy sources is grid resilience, which has been a significant discussion point in the Netherlands in recent years. According to the report on the Exploration (Verkenning in the original) phase of the Duurzame Polder (2020), the two grid operators who consulted the project team, TenneT and Enexis, expressed significant doubts about the grid being able to accommodate a large windfarm. They estimated that for a grid connection of 80 MW to 300 MW a renovation of 3-7 years would be necessary and for a connection of more than 300 MW a renovation of 7-10 years. However, these estimates can be scaled down by 2 years, as it can be assumed that parts of the plan and permit phase can take place in parallel with grid extension operations. To summarize:

- No grid extension is necessary for a wind farm below 80 MW, which means no delay.
- For a wind farm of 80MW to 300 MW a delay of 3 years occurs.
- For a wind farm of more than 300 MW a delay of 6 years occurs.

Applying everything above onto the NPV formula allows to establish the calculation.

$$NPV = \sum_{t=0}^{T+d} \frac{C_t}{(1+NPV)^t};\ T = 31\ years, NPV = 4.5\% \qquad (€)(10)$$

Cash flow number	Calculation
C_{4+d}	$-CAPEX * (P_{total,Oss} + P_{total,Den\ Bosch})$
$C_{6+d} - C_{30+d}$	$Capacity\ Factor * (Profit_{Oss} + Profit_{Den\ Bosch}) - O\&M * (P_{total,Oss} + P_{total,Den\ Bosch})$
C_{31+d}	$-(DECEX_{Oss} + DECEX_{Den\ Bosch})$

$$d = \begin{cases} 0, if\ (P_{total,Oss} + P_{total,Den\ Bosch}) < 80\ MW \\ 3, if\ 80MW \leq (P_{total,Oss} + P_{total,Den\ Bosch}) < 300\ MW \\ 6, if\ (P_{total,Oss} + P_{total,Den\ Bosch}) \geq 300\ MW \end{cases} \qquad (Years)(11)$$

Project delays due to necessary grid extension are applied in the beginning, offsetting the timeline by the delay amount (d).

Noise Pollution

Noise pollution is taken as the sound pressure level (SPL) at the closest residential area to the wind park. This calculation is taken from Teuber & Wolfert (2024), with slight alterations. The calculation does not account for aspects such as sound reflection and absorption. However, the increase of sound pressure level with source height and wind speed are taken into account for the worst-case scenario. The validity of these aspect is verified by Trikootam and Hornikx (2018) and Scholes and Parkin (1967), since the original work does not provide sources.

Firstly, wind and height adjustments are calculated by accounting for base wind speed ($U_0 = 3ms^{-1}$) and base height ($H_0 = 50m$)

$$AdjW_{Oss\text{ v }Den\ Bosch} = \left(U_{w,Oss\text{ v }Den\ Bosch} - U_0\right) * 0.2 \qquad (dB)(12)$$

$$AdjH_{Oss\text{ v }Den\ Bosch} = (x_{5\text{ v }6} - H_0) \qquad (dB)(13)$$

Then, the sound pressure levels of all wind turbines are combined to be taken as one source in further calculations. The noise from one turbine is taken to be constant 104 dB (L_w).

$$SPL = 10\log\left(x_{3\text{ v }4} * 10^{\frac{L_w}{10}}\right) \qquad (dB)(14)$$

SPL at a distance can then be calculated.

$$SPL_{Oss\text{ v }Den\ Bosch} = SPL + AdjW_{Oss\text{ v }Den\ Bosch} + AdjH_{Oss\text{ v }Den\ Bosch} - 20\log\left(\frac{x_{1\text{ v }2} * 1000}{1}\right) (dB)(15)$$

Bird Mortality

Part of the project area contains a nesting ground for small meadow birds, which has recently been a point of concern for the conservation effort in the Netherlands (Vogelbescherming Nederland, 2024).

Bird mortality is challenging to estimate, especially since most gathered data on bird mortality is underestimated due to measurement issues, as laid out by Nilsson et al. (2023). The same article measures the actual mortality rate of meadow birds for a wind park that is located on the migration path. The number provided in the article is 0.62 birds per GWh of energy produced. However, that can only be applied to the actual nesting area. The assumption is made that bird mortality outside of the nesting area is 4 times less, 0.155 birds per GWh of energy produced.

$$Mc_{Oss} = 0.155 \qquad \left(\frac{birds}{GWh}\right)(16)$$

$$Mc_{Den\ Bosch} = \begin{cases} 0.155, if\ x_2 < 3\ km \\ 0.62, if\ 3km \le x_2 \le 5km \end{cases} \qquad \left(\frac{birds}{GWh}\right)(17)$$

Since energy production is taken in GWh per year, mortality is also going to indicate bird deaths per year.

$$M = E_{Oss} * Capacity\ Factor * Mc_{Oss} + E_{Den\ Bosch} * Capacity\ Factor * Mc_{Den\ Bosch} (birds/year)(18)$$

Particle Pollution

In the process of erosion of wind turbine blades, microplastic particles get released into the air, which may have an effect on the health and well-being of both humans and animals in the area (Soldberg et al., 2021). This calculation is taken from Teuber & Wolfert (2024) directly.

$$E_{Oss\text{ v }Den\ Bosch} = U^3_{w,Oss\text{ v }Den\ Bosch} * f * \left(\frac{A_{Oss\text{ v }Den\ Bosch}}{30000}\right); where\ f = 0.001 \qquad (g/day)(19)$$

$$E_{total} = E_{Oss} * x_3 + E_{Den\ Bosch} * x_4 \qquad (g/day)(20)$$

Energy Production

The energy production formula is already outlined in the Universal Functions section, since it is used in several other functions. At the same time, these other functions have other variable aspects influencing their performance, therefore the Energy Production function can stand on its own. For each municipality the energy production is accounted for separately.

Project Completion Time

Project completion time stands for the time that has to pass until the wind farms can be in operation, assuming they are started, constructed and finished in parallel. Comparatively to other onshore civil engineering structures, the construction time of a wind park does not have many causes for uncertainty. This can be attributed to such factors as modularity and assembly of prefab parts. The main uncertainties arise with regards to permitting times and whether an adjustment of the surrounding energy infrastructure is required. For this reason, the Project Completion Time function is based on the time until operation shown in Figure 13 and the delay from Equation 11.

$$t_{total} = 5.3 + d \qquad (years)(21)$$

6.2.3. Preference Functions and Objective Weights

The interactive nature of the model means that decision-makers themselves, both in real and testing applications, will construct and adjust their own preference functions and objective weight distributions. However, for the sake of internal testing, a set of preference curves and weights will be created based on what stakeholder attitudes can be inferred from public project information.

Therefore, preference curves and weight distributions will be given according to what is inferred as the theory-in-use (of Argyris & Schön, 1976) for each decision-maker.

Energy Provider

The Energy Provider's sole interest in the Duurzame Polder project is the project's NPV, as it directly influences their profit. This assessment is based on the work of Teuber & Wolfert (2024), as the Duurzame Polder project documentation does not mention the involvement of an Energy Provider organization.

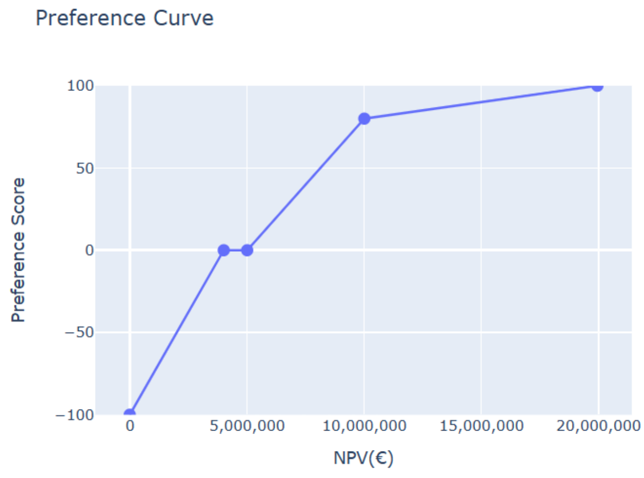

Figure 14 Goals of the Energy Provider for the Duurzame Polder project

Since there was no information on the Energy Provider and their project expectations, a narrative was created. In that narrative, the Energy Provider expects the project to have an NPV of at least 4-5 million euro. At the same time, if the project achieves an NPV of 8 million euro, it will also enable the Energy Provider to initiate another wind park project in parallel. This translates into the preference curve on Figure 14.

This also allows to establish the following weights distribution.

Table 2 Energy Provider Weights Distribution

Decision-maker	NPV	Noise – OSS	Noise – Den Boscsh	Bird Mortality	Particle Pollution	Energy – Oss	Energy – Den Bosch	Project Time
Energy Provider	1	0	0	0	0	0	0	0

Local Residents – Oss & Den Bosch

According to the recorded interactions of the project team and the local residents, the main aspect of the project they want to have in check is noise pollution. At the same time, they raised concerns about possible particle pollution and nuisance due to project construction, but nothing concrete. Similarly, most stated that in principle they support sustainable energy generation but want to ensure their peace and quiet at the same time.

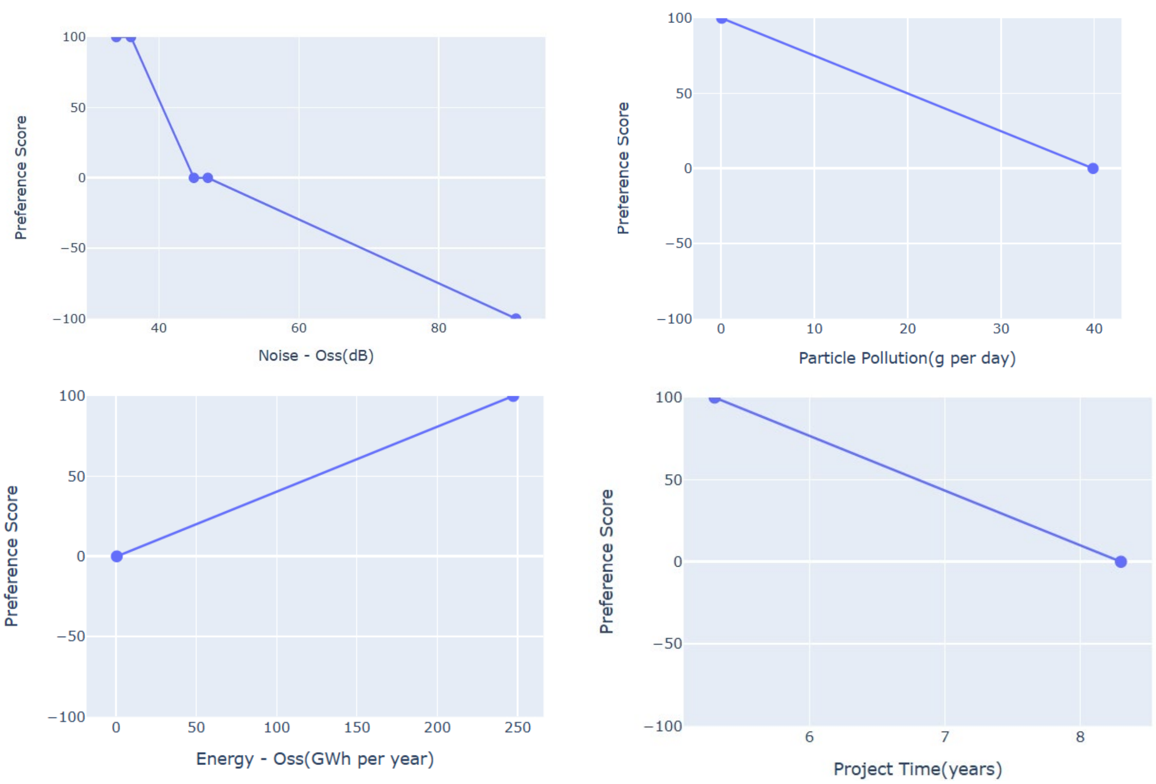

Figure 15 Preference Curves of the Local Residents of Oss

The noise preference curve is based on the work of Teuber & Wolfert (2024). The three other curves are only plotted in the section of the graph that ranges from 0 to 100, because the local residents do not have an unacceptable outcome for those objectives. For example, the energy curve illustrates that they are in principle supportive of increasing sustainable energy production, but they are also content with the project not going ahead at all. Similar logic is applied to curves for particle pollution and project time.

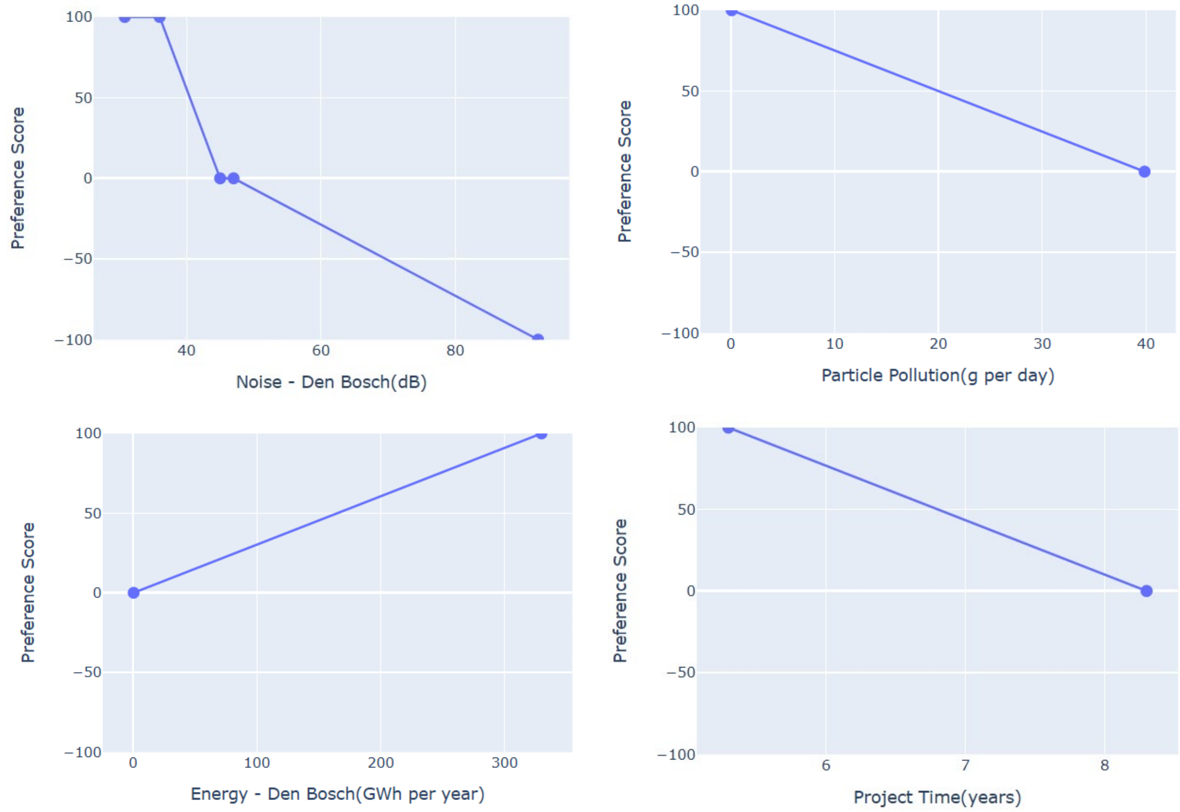

Figure 16 Preference Curves of the Local Residents of Den Bosch

The preference curves for the local residents of Den Bosch are identical to the curves of the residents of Oss, only for Den Bosch objectives.

Table 3 Local Residents Wright Distribution

Decision-maker	NPV	Noise – OSS	Noise – Den Boscsh	Bird Mortality	Particle Pollution	Energy – Oss	Energy – Den Bosch	Project Time
Local Residents - Oss	0	0.7	0	0	0.1	0.1	0	0.1
Local Residents – Den Bosch	0	0	0.7	0	0.1	0	0.1	0.1

Ecologists

According to Teuber & Wolfert (2024) the main interests of the Ecologist groups lie with protecting meadow bird population and minimizing particle pollution, as this also affects the flora and the fauna in the area. As no exact information on Ecologist positions in the project are recorded, they are assumed for the sake of the decision process.

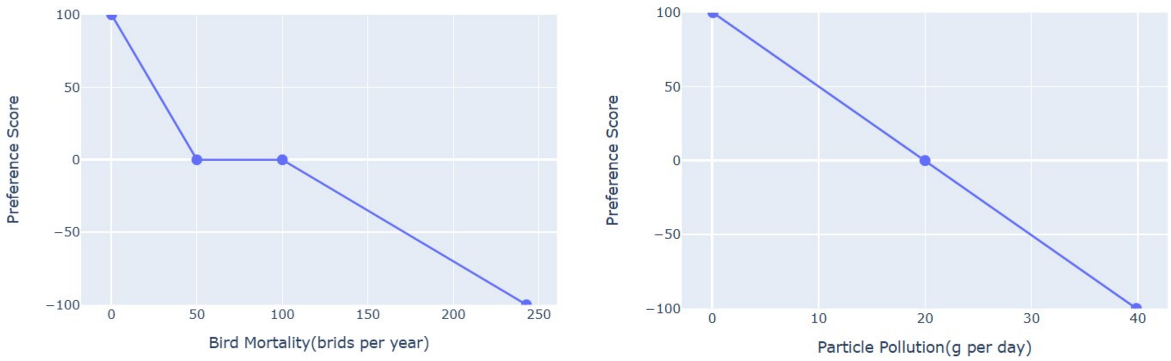

Figure 17 Preference curves for the Ecologist groups

Table 4 Ecologist groups objective weights distribution

Decision-maker	NPV	Noise – OSS	Noise – Den Boscsh	Bird Mortality	Particle Pollution	Energy – Oss	Energy – Den Bosch	Project Time
Ecologists	0	0	0	0.8	0.2	0	0	0

Rijksinstituut voor Volksgezondheid en Milieu (RIVM)

As the observing and controlling body for both health and the environment, the RIVM has a wide range of interests to be observed in this project. The preference curves and weights are based on the work of Teuber & Wolfert (2024).

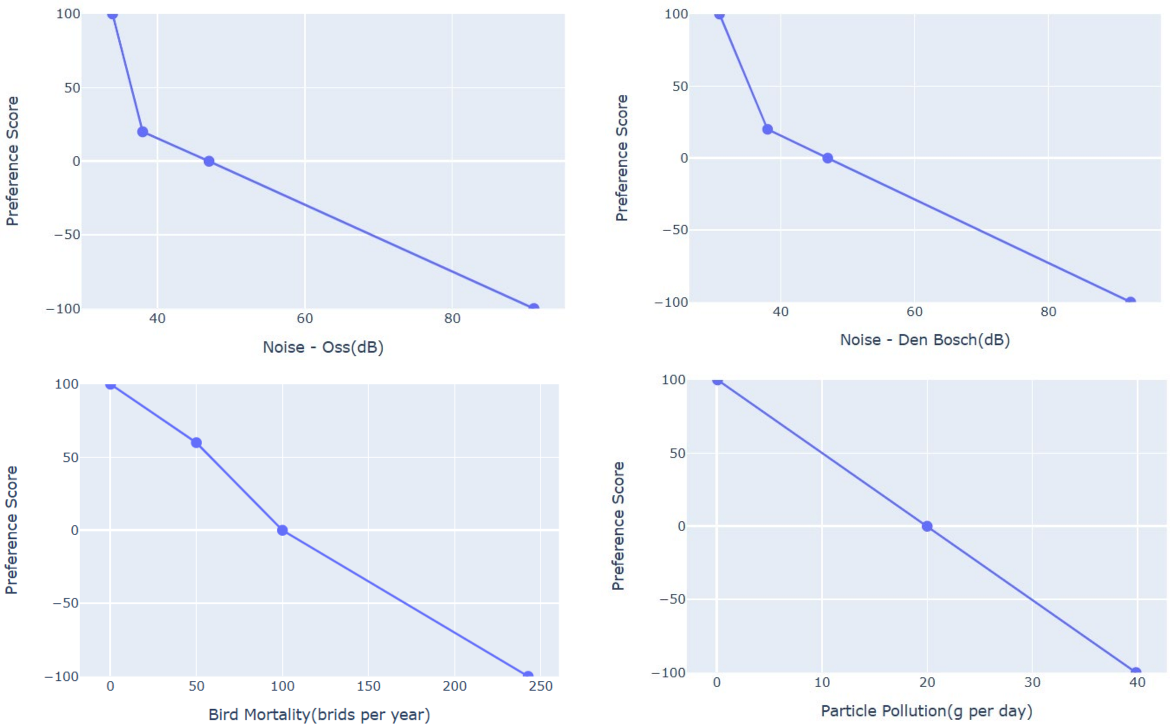

Figure 18 Preference curves for the RIVM

Table 5 RIVM objective weights distribution

Decision-maker	NPV	Noise – OSS	Noise – Den Boscsh	Bird Mortality	Particle Pollution	Energy – Oss	Energy – Den Bosch	Project Time
RIVM	0	0.1	0.1	0.05	0.75	0	0	0

Municipalities – Oss and Den Bosch

According to the publicly available project documentation, the main goals of the municipalities for the Duurzame Polder project are energy generation for their regions and overall project time. The core objectives for energy generation of the Oss and Den Bosch municipalities a 143 GWh and 144 GWh per year respectively. For the time objective, acceptability is taken to complete the project by 2031, according to the municipalities sustainable energy generation goals.

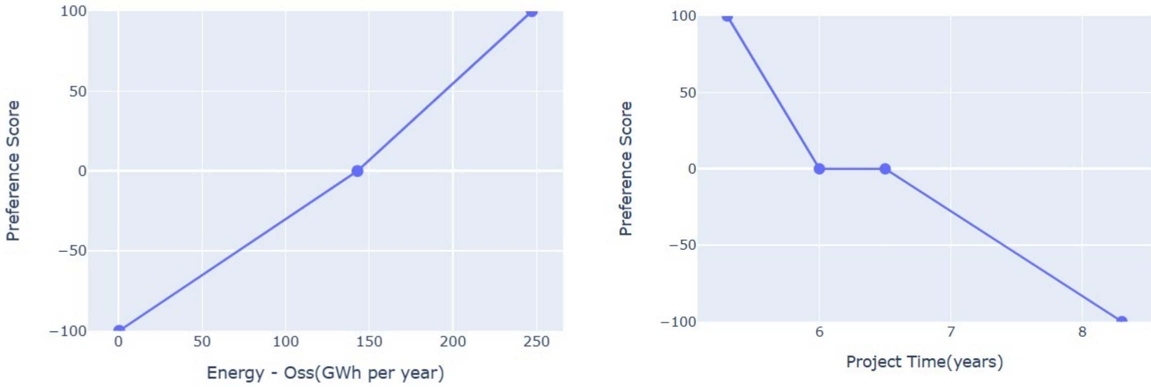

Figure 19 Preference curves for the Oss Municipality

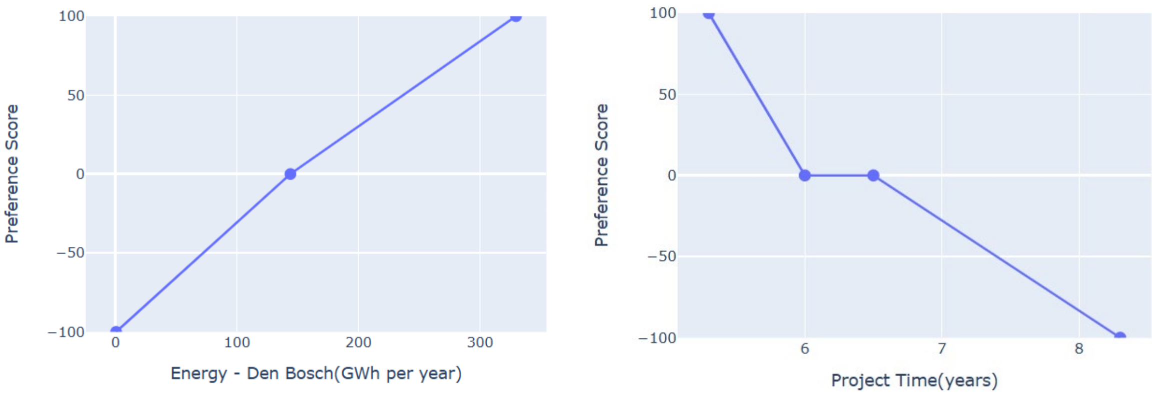

Figure 20 Preference curves for the Den Bosch Municipality

Table 6 Municipalities objective weights distribution

Decision-maker	NPV	Noise – OSS	Noise – Den Boscsh	Bird Mortality	Particle Pollution	Energy – Oss	Energy – Den Bosch	Project Time
Municipality-Oss	0	0	0	0	0	0.8	0	0.2
Municipality – Den Bosch	0	0	0	0	0	0	0.8	0.2

7. Design Cycles

Over the course of the project, the whole DSS and the Stalemate Resolution Mechanism specifically went through several design cycles, during which significant changes occurred to both the solution structure (model) and the overall problem understanding (scope). These design cycles will be chronologically documented in this chapter.

7.1. The First Cycle

7.1.1. Development

At the starting point of the development process, the overall work scope was perceived differently compared to what it has become now. The initial scope was taken as a case application of the Preferendus onto a stalemate project to demonstrate how the core Preferendus can lead to a better outcome than traditional decision-making practices. Because of this, significantly less emphasis was placed on producing a stalemate resolution and more was placed on equipping the decision-maker with more insight to come to an outcome by themselves, using the core Preferendus functionality. This was first done by an interactive dashboard, which displayed the group optimal project outcome, the preference curves and allowed the decision-maker to run model "benchmarks". If one or more decision-makers were unhappy with the group optimal solution produced, they could run a benchmark to see what is the group optimal project design under which they achieve a certain goal for the objective of their interest. Alternatively, this benchmarking function could also be used to answer the question "What is the group optimal project design under which this decision-maker is at least at 0 or above preference score?". This benchmarking function was realized by using Preferendus constraints.

The benefit of this function was that it allowed to identify so-called coalitions. If a preference benchmark of 0 or above was set for a certain decision-maker, those decision-makers that received a negative preference score as the outcome were in direct conflict with the first decision-maker. However, the problem of not knowing how to resolve the stalemate situation remained. If anything, something like this could further antagonize the decision-makers, escalating the conflict. For this reason, the benchmarking functionality was abandoned in development.

Instead, in an attempt to find common ground for the case, the Preferendus was used with the constraint that the preference score of each decision-maker could only be 0 or above. This resulted in an empty set. This initiated the idea that the changing of preference by decision-makers was key to finding an acceptable group optimal solution.

In line with the belief that stalemates could be bridged with the basic Preferendus functionality, a new idea was attempted. As stated previously in this thesis, application of Preferendus in a decision-making context required the presence of a model operator who would translate decision-maker preference into preference curves. This was also the case for PAS (Arkesteijn, 2019), another PFM-based methodology, where stakeholder preferences were set during the interview and left unchanged during the portfolio design process. So, an assumption was made that if decision-makers were given the option to create and adjust the preference curves dynamically, reacting to the group optimal solution produced by the Preferendus, they could get out of the stalemate situation by themselves. It was assumed that the difference between a normal project with stalemate and a Preferendus-supported stalemate were all the insights Prefendus provides, which were the missing piece to exiting a stalemate. '

To test this, an interactive page was developed for decision-makers to enter preference and added to the group optimal solution display dashboard.

7.1.2. Testing

The first testing for this system occurred on the 12th of February 2025. To test this system, 4 master students of TU Delft were invited to take on the roles of decision-makers in the Duurzame polder case. As the case has a total of 7 decision-making parties in total, 3 participants took 2 roles each and 1 participant took 1 role. Each invited master student was studying in the spere of construction, but each had a different specialty. Only one participant had previous experience with PFM and the Preferendus. Every participant was given a role description where the main goals and the position of the decision-maker they were representing was described.

During the workshop numerous technical issues with the model were identified, that prevented the decision-makers from entering and displaying their preference at the same time. For this reason and due to time limitations, the decision was made to turn this workshop into an open discussion/experimentation session on the proposed solution.

It became apparent that an unstructured process during which the decision-makers were left up to their own devices quickly went off track and resulted in even more confusion than the initial stalemate. This meant that while the workshop was useful to identify technical issues with the model, a change of approach was necessary. Firstly, a more structured decision process was needed. Secondly, as a result of discussion it became clear that even with extra tools, pure discussion was not a productive and consistent way to find an acceptable group optimal solution.

7.2. The Second Cycle

7.2.1. Development

The two main conclusions from the first design cycle served as the guiding principles in development during the second design cycle. Firstly, a decision was made to follow the following procedure during decision-making:

- All decision-makers submit their preference curves prior to the workshop.
- During the workshop the decision-makers get an opportunity to explore the preference curves of all other decision-makers.
- The Preferendus is initiated, and a group optimal solution is produced.
- Decision-makers discuss the outcome and change preference curves according to what was discussed. OR Decision-makers opt to use the Stalemate Resolution Mechanism.
- The previous two steps keep repeating until the decision process is terminated.

This allows all decision-makers to keep the same pace and discuss any unclarities that can come up.

Secondly, a concrete recommendation on how to exit the stalemate was necessary. During the first development cycle after the constraint to produce a solution where all preference scores are at 0 or above resulted in an empty set, a different approach was attempted. The principle behind it was that it could recommend the minimal change in the preference curves of one or several decision-makers that would lead to a group optimal solutions existing. For this purpose, 10 points were taken as representations of every preference curve and used with a differential evolution optimization algorithm to try and acquire the result. As this was an inaccurate way to represent preference and because no solutions could be achieved, this development direction was left behind. However, after the insights received from the first design cycle, it became apparent that while the execution was flawed, the idea behind it was right.

7.2.2. The Initial Stalemate Resolution Mechanism

Main Principle

The thinking process behind this feature is based on a comparison. Preference curves, by their definition, represent the attitude of decision-makers to a certain problem. Then the DSS can be compared to a very smart advisor who can aggregate everybody's preferences and the project context to provide the design variant that maximizes group preference. As an advisor who is faced with a conflict situation, the first step would not be to try and address the project's desirability, because there are still key project participants who are not going to accept it under current conditions. Similarly, you would not try to "soften the blow" for those whose preference is in the unacceptable region, because it would remain unacceptable. What you would try to do first is see if the decision-makers are willing to consider more options than they are already considering.

This principle can also be expressed in terms of preference curves. For a given preference curve "S" a point P with coordinates (x;0) will be introduced between the point with negative preference and the closest point with 0 preference, as shown in Figure 21.

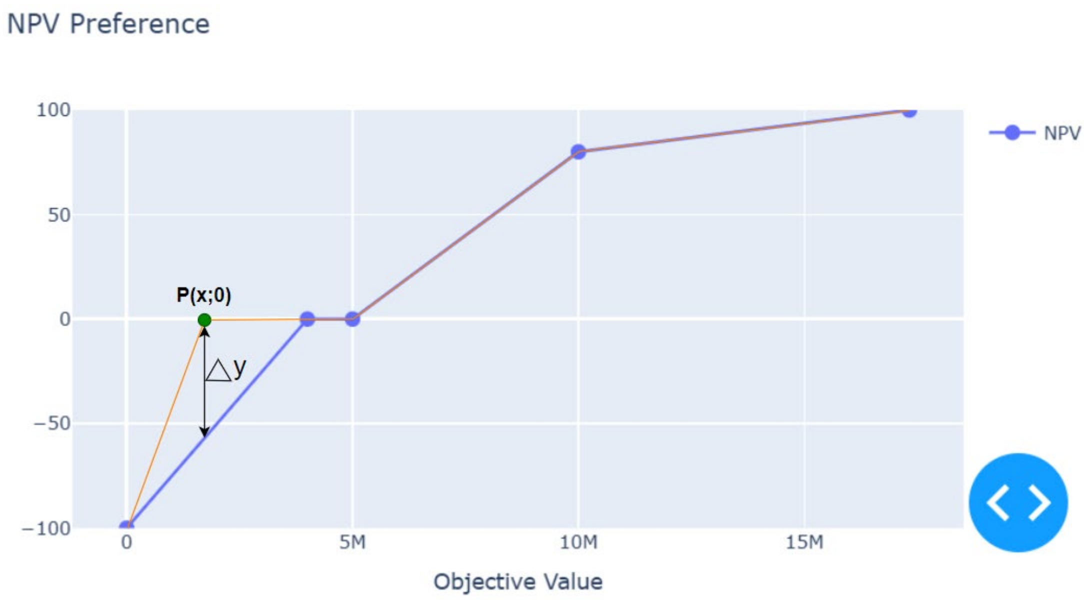

Figure 21 Principle behind the Stalemate Resolution Mechanism

P then becomes one of the points in the preference curve, creating a new preference curve, shown in orange in Figure 21. This is then performed for all preference curves involved in the decision process. This extends the range of feasible solutions and thus allows to generate new constructive alternatives outside of the stalemate. The goal is then to find all x for all curves to minimize the sum of Δy, with the constraint that running the Preferendus with the new curves must produce an IMAP result that scores 0 or above on all preference curves.

Mathematical Formulation

The following mathematical statement describes the Stalemate Resolution Mechanism (SRM):

$$\min_x \sum_{i=1}^{n} |S_i(x_i)| \tag{22}$$

Subject to the constraint:

$$S_k\big(O_j(d)\big) \geq 0 \tag{23}$$

Where:

- x is the vector containing the variables representing objective function values of the proposed points (P in Figure 21) $x_1, x_2 \dots x_n$. Each variable is bounded by the minimum or maximum objective function value x_m of the associated curve S_i at which the preference score is -100 and the closest objective function value x_a at which the preference score is 0.
- n is the number of preference curves with an unacceptability region.
- $S_i(x_i)$ is the preference value of preference curve S_i at the associated objective function value x_i.
- The constraint is that the preference curve score S_k that includes the proposed point P at the objective function value O_j at the group optimal design variant d generated by the Preferendus must be 0 or above. In other words, it has to be acceptable to the associated decision-maker.
- $k = 1,2,3 \dots K$, where K is the total number of preference curves. $j = 1,2,3 \dots J$, where J is the total number of objective functions.

Coding and Model Implementation

This calculation is implemented via a simulated annealing optimization algorithm from the SciPy library, optimization module (Virtanen et al., 2020). Simulated annealing is a stochastic optimization algorithm. The very simplified idea is that it starts with a certain "temperature value" and then bounces around the solution space of the function picking random solutions. Every time a solution is chosen, it is compared to the most optimal one found yet and is either skipped if it is sub-optimal or taken on if it is more optimal. The higher the "temperature" value, the more likely it is that the algorithm will pick a sub-optimal solution to the one that is considered optimal, which is done to help the algorithm escape local optima in search of the global optimum. As the algorithm runs, the "temperature" decreases, accepting less sub-optimal solutions.

Even if the optimization does not find the global optimum and terminates due to a runtime limit, it will still output the most optimal solution that was found. Considering that the result is used to kick-start a discussion during which the decision-makers can make preference adjustments themselves, the breadth of coverage is more important than accuracy of the given recommendation. This is why usage of this algorithm is relevant.

However, there are two challenges to the implementation of the algorithm. The first challenge is the SciPy simulated annealing algorithm does not support direct setting of constraints. This challenge can be solved by adjusting the mathematical statement of the SRM:

$$\min_x \begin{cases} \left(\sum_{\substack{i=1 \\ S_i<0}}^{n} |S_i\left(O_j(d)\right)|\right)^2, if\ \exists i\ such\ that\ Si < 0 \\ -\left(n * 100 - \sum_{i=1}^{n} |S_i(x_i)|\right), \quad otherwise \end{cases} \tag{24}$$

Where the variable definitions are the same as before. The difference in this formulation is that the conditional format allows to implement the constraint from the previous statement as a part of the optimization. The first condition states that if any preference score of the IMAP generated group optimal design variant d is below 0, then the sum of the absolute values of all the negative preference scores must be minimized. As this sum is minimized it will attempt to reach 0 but never will be 0. The sum is further squared to accelerate convergence. The second condition states that for situations where all preference scores associated with d are 0 or positive, the sum of the required change of preference from the initial curve to the curve with a point P must be minimized. In order to tailor this to the simulated annealing algorithm, this sum is subtracted from the number of preference curves with a non-acceptability region multiplied by the largest change in preference that can occur for a curve, 100. Because the lowest value that can be achieved by the sum is 0, putting it into the second condition without changes would result in the algorithm valuing no change in preference curves the same as the change that leads all preference curves to be positive. For this reason, the sum is subtracted from the largest change possible. Since the smaller the sum, the larger the subtraction, the negative of the subtraction is passed to the algorithm.

The second challenge with this approach is the time it takes to arrive to any worthwhile solution. This is because for every solution selected by the algorithm, the Preferendus has to run. Since the algorithm evaluates hundreds of solutions, this becomes very costly in terms of time. From experimenting, a run of about 1.5 hours was necessary to arrive at an acceptable solution. This also includes adjusting the Preferendus settings to make it run faster, but more likely to arrive at a sub-optimal solution, causing more decreases in accuracy.

7.2.3. Testing

Testing for the second design cycle took place on the 14th of April 2025. The participants were the same as at the first testing run to maintain consistency. This time, on top of the role descriptions, all participants were provided with a formula sheet, which described the design variables, objective functions, bounds and assumptions for the project. It was, in essence, a compressed version of the Preferendus Formulation of the Case sub-chapter of this thesis without the section describing preference functions and weights.

In contrast to the established decision process structure, the participants were asked to enter their preference into the model live at the workshop in order to monitor this process. While some minor technical issues arose, they were addressed in the final version of the DSS and did not halt the decision process. During this testing run the process got up to the point of producing a group optimal solution and identifying a stalemate. However, due to the time requirements of the Stalemate Resolution Mechanism, a recommended extension of acceptability could not be produced. Instead, results from a separate run of the Stalemate Resolution Mechanism were presented for open discussion.

In this round of testing, the participant reception was significantly more positive than in the first design cycle. The principles behind the Stalemate Resolution Mechanism received positive feedback, but there were doubts regarding the acceptance of the recommendation the mechanism produces. The participants also highlighted the need to produce a User Manual for model operation to make it more accessible.

7.3. The Third Cycle

7.3.1. Development

The need for the third design cycle emerged as a result of an unexpected error during the validation process. After all the workshop participants submitted their preference curves, the SRM could not find a resolution that would produce a group optimal design variant that is acceptable to all decision-makers, even after several independent runs were attempted.

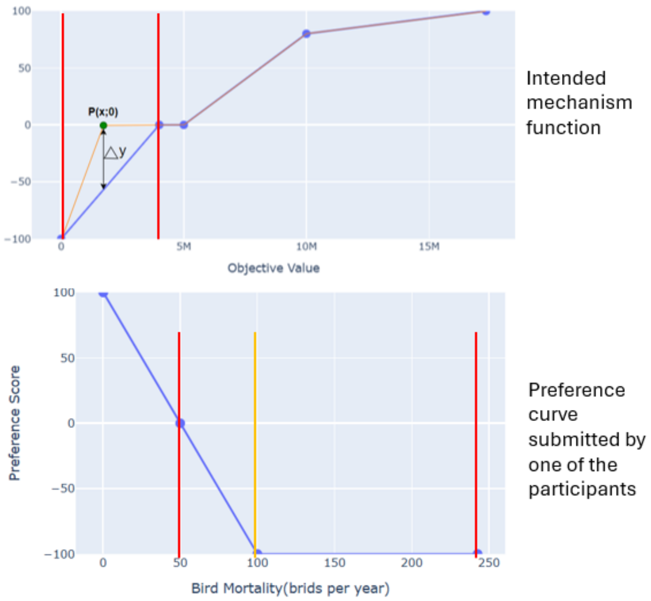

Figure 22 The mistake discovered in the SRM. Red lines represent intended bounds, while the orange line represents the misinterpretation due to a logical mistake.

As shown in Figure 22, a logical mistake in programming led to the misinterpretation of bounds for the proposed point P shown in Figure 21. Instead of the bound being assigned to the maximum point, it was assigned to the closest -100 point. This mistake happened with several submitted curves. Evidently, even with a single curve this severely limits the solution space, which was the reason why the SRM could not find an acceptable resolution. This mistake was corrected on the spot and did not affect the validity of the workshop process. However, this also prompted two final changes to be made to the model:

- To avoid the situation where a long model run time prevents an error from being discovered, the need for an optimized SRM formulation that would speed up runtime and improve the accuracy of the results became apparent. This is expanded on in the next sub-section.
- In testing the solution for the uncovered mistake it also became apparent that the Preferendus configuration used in the SRM does not produce a reliable and consistent preference score for the same set of proposed points P. This was addressed by increasing

the number of Preferendus runs per solution generated by simulated annealing from 3 to 6. This became possible due to an increase in calculation efficiency addressed in the first bullet point. The result was that preference scores per generated solution became more consistent and reliable.

7.3.2. The Final Stalemate Resolution Mechanism

As mentioned, the goal of the change to the SRM structure is to increase calculation efficiency and result accuracy. This increase was achieved by redefining the variables used in the calculation. In the previous version of the SRM a separate variable was defined for each curve that had an unacceptability region. However, because several preference curves can be defined for outcomes of one objective function by several decision-makers, only one proposed extension of acceptability P will matter, and it will be the smallest one. Because of this, instead of a variable being defined for each preference curve with an unacceptability region, a variable is defined for each objective function. This significantly reduces the number of variables that have to be processed by the simulated annealing algorithm. This change can be reflected by the following change in the mathematical formulation in the SRM (changes are *italicised*):

$$\min_{x} \begin{cases} \left(\sum_{\substack{i=1 \\ S_i<0}}^{n} |S_i\left(O_j(d)\right)| \right)^2, \mathit{if}\ \exists i\ \mathit{such\ that}\ Si < 0 \\ -\left(n * 100 - \sum_{i=1}^{n} |S_i(x_i)| \right), \qquad \mathit{otherwise} \end{cases} \tag{25}$$

Where:

- x is the vector containing the variables representing objective function values of the proposed points (P in Figure 21) $x_1, x_2 \dots x_n$. *Firstly, a set of bounds of minimum or maximum objective function value x_m of the associated curve S_i at which the preference score is -100 and the closest objective function value x_a at which the preference score is 0 is saved for each objective function. Then the maximum range out of all the bounds for an objective function O is set for the variable x_O.*
- *n is the number of objective functions associated with curves with unacceptability region.*
- $S_i(x_i)$ is the preference value of preference curve S_i at the associated objective function value x_i.
- The constraint is that the preference curve score S_k that includes the proposed point P at the objective function value O_j at the group optimal design variant d generated by the Preferendus must be 0 or above. In other words, it must be acceptable to the associated decision-maker.
- $k = 1,2,3 \dots K$, where K is the total number of preference curves. $j = 1,2,3 \dots J$, where J is the total number of objective functions.

7.3.3. Testing

Testing via several runs of the SRM with the preference curves defined in the Preferendus Formulation of the Case resulted in consistent recommendations and a runtime decrease to approximately 45 minutes per reliable stalemate resolution. The result also demonstrated a significantly lower required extension of acceptability for a group optimal outcome to exist, which also increases the quality of the recommended resolution, which can be compared in appendices A.2. and A.3.

This was also tested with participants during the last round of validation on the 16th of June 2025. The more optimal and less radical resolution produced by the SRM resulted in a higher willingness to engage in the decision-making process. This effect can also be partially attributed to the user-defined-curves used in the SRM, making them feel more connected to the problem.

The main feedback at this point was on occasional lack of clarity in the given instructions and the interface, but not on the process itself.

8. Case Results

The presented results are produced for the previously defined Preferendus formulation of the case. The finalized interactive version of the DSS can be accessed via the following link: https://ossdss.eu.pythonanywhere.com. The following repository contains the code to run a local interactive version of the DSS: https://github.com/AlexM2604/stalemate-resolution-dss.

8.1. Preferendus Results

In order to ensure the achieved result is a group optimum, the Preferendus is run 10 times and the solution with the highest aggregated preference score is taken. The following is a group optimal solution for the Duurzame Polder Case:

- The Oss wind park is to be located 3.5 km away from the border of the urbanized area of Oss. The wind park is to have 1 wind turbine of hub height 50 m.
- The ‘s-Hertogenbosch wind park is to be located 5 km away from the border of urbanized area of ‘s-Hertogenbosch. The wind park is to have 1 wind turbine of hub height 50 m.
- The overall aggregated preference score for this solution is 22.8.

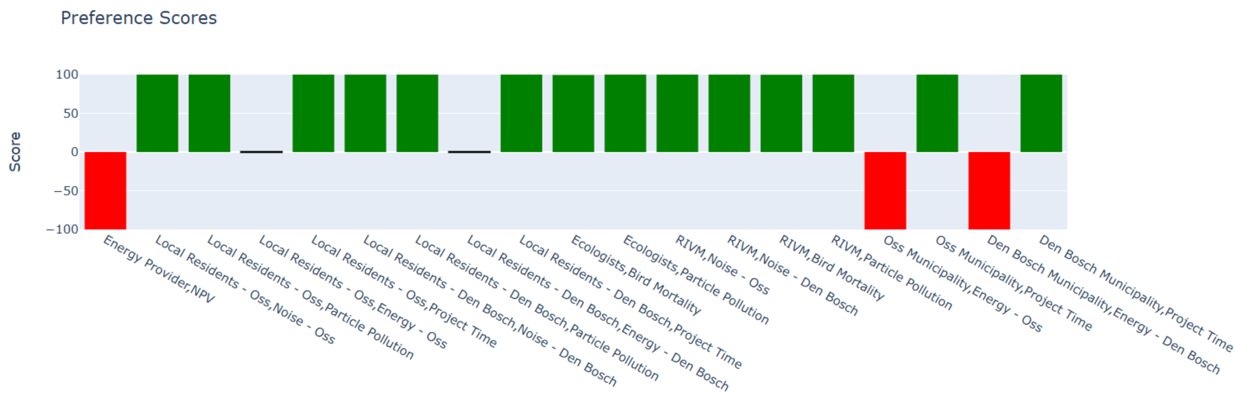

Figure 23 Bar chart of all preference scores of the group optimal solution

Clearly, this group optimal outcome represents a stalemate. Firstly, three objectives have a preference score below 0. Secondly, the group optimal solution consists of values that are all on the lowest limit of the bounds, also reflected by the preference scores of 100s and -100s. The only exceptions are the curves plotted from 0 to 100, and those have a score of 0. This group optimal solution can also be interpreted as “do not build anything”. The preference curves with the plotted group optimal solution can be found in the Appendix A.1.

This indicates a stalemate and means that the Stalemate Resolution Mechanism needs to be initiated.

8.2. Stalemate Resolution Mechanism Results

The full list of all the preference curves that feature proposed changes is comprised from 19 preference curves, therefore it will be placed into Appendix A.3. A selection of key preference curves will be featured here for analysis purposes to keep the report concise.

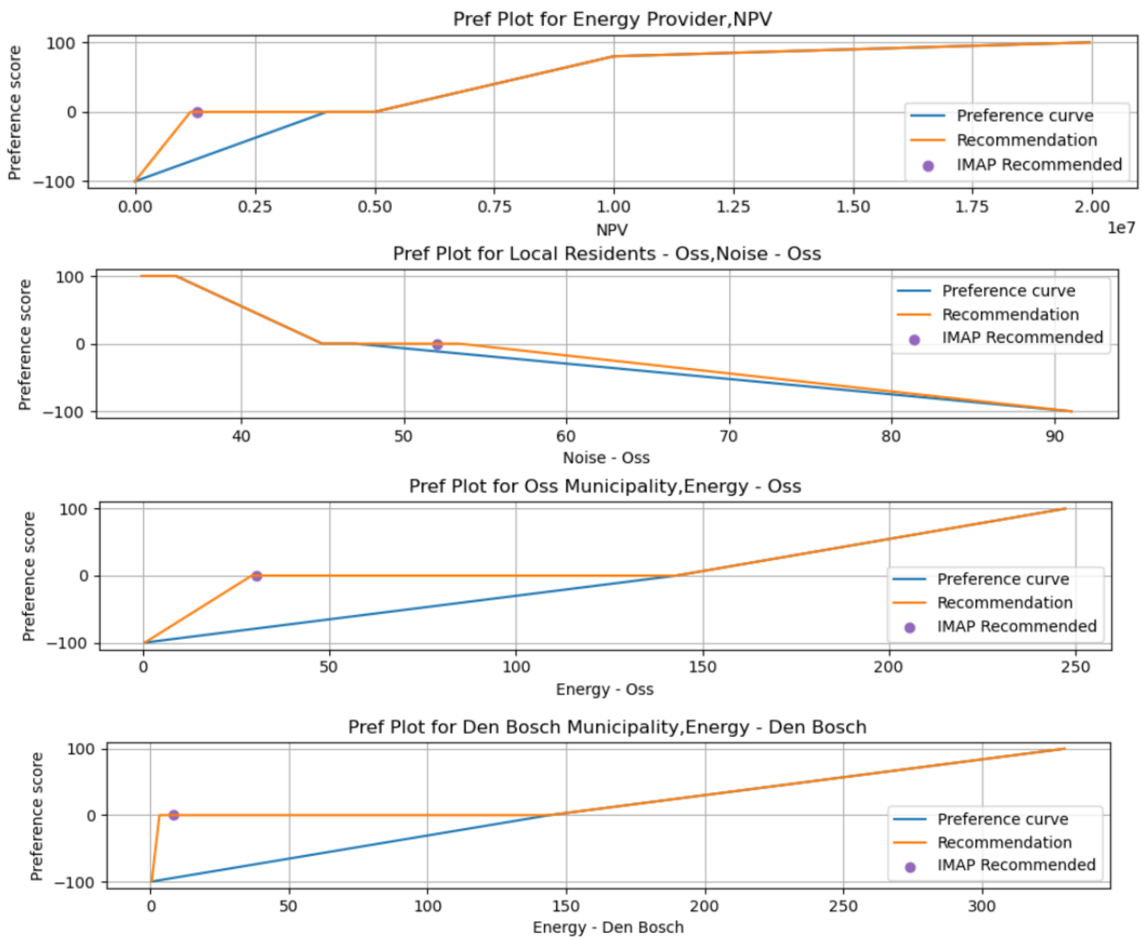

Figure 24 The main recommendations from the Stalemate Resolution Mechanism

As shown in Figure 24, the two main recommendations given by the Stalemate Resolution Mechanism are to extend the limits of acceptable noise in urbanized areas in Oss for both the local residents and the RIVM, as well as to significantly decrease the acceptable outcomes for energy generation in 's-Hertogenbosch. The generated group optimal solution for these preference curves is as follows:

- The Oss wind park is to be located 2.85 km away from the border of the urbanized area of Oss. The wind park is to have 10 wind turbines of hub height 93.5 m.
- The 's-Hertogenbosch wind park is to be located 1.97 km away from the border of urbanized area of 's-Hertogenbosch. The wind park is to have 1 wind turbine of hub height 126 m.
- The overall aggregated preference score for this solution is 40.1.

This group solution is also plotted in Figure 24 as "IMAP Recommended".

9. Verification and Validation Results

9.1. Verification

9.1.1. Design Requirement 1

This is the requirement that states that the DSS must have a clear and quantifiable indication of design variant acceptability. This is realized via the -100 to 100 preference scale. In this case, the specific boundaries of the scale are not as important, because they do not impact the functionality of the DSS or the Preferendus if applied consistently. The decisive factor is the establishment of a certain preference score as the "border" region between desirable outcomes and unacceptable outcomes. This score should also lie in the middle of the scale. For example, in case of a scale 0 to 100, the border region becomes 50. However, for the purposes of accessibility and ease of interpretation it was chosen to take the scale -100 to 100, where positive outcomes are desirable, 0s are acceptable with conditions and negatives are unacceptable. In the end, this allowed to construct the Stalemate Resolution Mechanism, which is built on providing a minimum extension of the border region.

Therefore, Design Requirement 1 is fulfilled. A quantifiable method to establish solution acceptance is included into the model and leveraged to produce a stalemate resolution.

9.1.2. Design Requirement 2

Design Requirement 2 demands that the resulting stalemate resolution must have a higher overall preference score than the initial stalemate to ensure that it is not a compromise, but a best fit for common purpose outcome. This requirement is fulfilled by the preference scores stated in the Results section of the thesis. For the case of the Duurzame Polder, as interpreted in this thesis, the stalemate situation has an overall preference score of 22.8, while the recommended adjustment of acceptability has a preference score of 40.1.

This means that Design Requirement 2 is fulfilled.

9.2. Validation

As established in the Development Methods section of the thesis, the validation for this DSS takes the format of a role-play workshop or a so-called "serious game", where participants take on the roles of decision-makers in the Duurzame Polder project to try and arrive at a solution to this project. In order to recruit participants for this process, invitations were sent through student channels available to me at the time of the thesis work. A total of two workshops were organized.

The workshops took place along the structure defined in the Second Design Cycle. The roles were assigned at random. Each participant was provided access to the DSS one week in advance of the scheduled workshop. In addition to the Role Description, the participants had access to the Formula Sheet, the User Manual describing the workshop process and a brief description of how the Stalemate Resolution Mechanism works. This supplemental information is available in Appendix B. At the same time, they were asked to enter preference curves and weights of their role into the model according to their interpretation of the role description documents. To take into account the weakness of the Stalemate Resolution Mechanism, which prevents it from being run at the workshop live, decision-makers were asked to submit their preference curves one day before the scheduled workshop at the latest. The main reason for the workshop participants to submit their own interpretation of their role's preference is to increase ownership of the final resulting solution.

The audio of the workshops was recorded for analysis and notes were taken during the workshop process. As well as that, decision-makers were asked to fill out an anonymous questionnaire after the workshop where questions on the content of the workshop were asked. The questionnaire consisted of Likert-scale questions and open questions. The conclusions drawn from these three sources will be structured according to the Needs section of the thesis.

It is important to highlight that the decision process for both workshops concluded with a majority vote to consider a different project configuration. Specifically, to extend the project area North. This is consistent with the real-world progress of the Duurzame Polder project, where the project area is now being extended.

9.2.1. Need 1

The first need dictates that the produced system must be a Decision Support System according to the definition by Keen (1980), which means that it follows the relationship structure shown in Figure 7. This need was fulfilled throughout the whole process of the thesis. Model builder learning occurred over the design cycles, which lead to changes in model functions, which lead to a completely new interaction structure from the first iteration of the DSS. The workshop itself demonstrated several instances of user learning, about the DSS, about their own goals and about the goals of other participants of the decision process. Without these interactions, a solution to the stalemate could not be achieved. Therefore, this need can be considered fully fulfilled, as the produced system fulfilled the necessary definition of the DSS.

9.2.2. Need 2

Need 2 states that the produced DSS must include both the consultation and mediation functionality to act as a third-party moderator in preventing conflict escalation. Both of these functions were included into the model at the code level. The core Preferendus by its own nature provides the consultation features, so it was supported by an interactive interface. The mediation features were included via the Stalemate Resolution Mechanism, which proposes a new perspective to the decision-makers. At the user level both of these capabilities were used at different times. For example, after seeing the initial Preferendus outcome which showed a stalemate, the immediate request from all decision-makers was to see the outcome of the Stalemate Resolution Mechanism to get a starting point for further discussion. After these results (mediation) were demonstrated to the participants they quickly switched towards utilizing the consultation capacity of the model, to see how changes of preference curves and weights along the lines of the recommendation could affect the stalemate. The shifting usage of these capacities by the decision-makers depending on what insight they needed demonstrates the validity of the need for both functions, and the fact that this need was fulfilled by the produced DSS.

9.2.3. Need 3

Need 3 requires that the DSS resolves conflict in such a way that all decision-makers can answer the three questions posed by Eisemann (1978). This section is structured according to these questions.

Why at the outset each decision-maker embraced their position

According to the results of the questionnaire 80% of participants stated that they agree with the statement "Using the DSS allowed me to understand the positions of other decision-makers and the reasoning behind them", with 20% stating that they strongly agree. When given the option to expand on their answer, participants stated that the positions of other decision-makers became clear to them because of the possibility to view preference curves of any other decision-maker at any point. At the same time, several respondents emphasized that while the positions were clear the reasoning behind the positions was not. According to other responses, the positions and reasoning behind them became clear in the discussions that were prompted by the DSS, specifically discussing the proposed resolution.

Why the initial positions of the stakeholders were incompatible

According to the results of the questionnaire, 50% of respondents stated that they agree with the statement "Using the DSS allowed me to understand why initial stakeholder interest were incompatible and led to a stalemate", 40% stated that they strongly agree and 10% marked it as "Irrelevant". In expanding on this question in an open format several respondents stated that while the conflict between the positions was clear, the reason the objectives were not compatible was still unclear to them. Meanwhile other respondents stated that they interpreted the source of the incompatibility as the constraints and bounds that resulted from the chosen project configuration.

How the conflict resolution reconciles the initial positions

In the questionnaire this was asked as an open question required for every participant. Approximately 30% highlighted that during the decision process it became clear that the source of the stalemate were the physical limitations of the project configuration, so the decision to consider a different project configuration effectively addresses the root of the problem in the initial positions. The other respondents highlighted that while the stalemate is not resolved, this conclusion allows to pave the way to a project configuration that considers the existing conflict straight away, allowing to avoid it or mitigate it.

10. Discussion

The goal of the thesis was to develop a Preferendus-based system to enable stalemate resolution in network decision-making for large and complex construction projects. This was done over three design cycles by using the Duurzame Polder case as the modelling and verification basis. At the same time student "serious game" workshops were used to ensure the development process remains on track and as validation of the final product. Overall, the produced system successfully fulfils the set design requirements and addresses the established needs. The verification process confirmed that a system for identifying acceptable solutions was implemented and that the system is able to produce stalemate resolutions with a higher preference score than the initial stalemate. The system was validated on three topics: the system format, the need for mediation and consultation as parts of third-party conflict moderation and the degree of success in resolving stalemates based on decision-maker understanding. There are three main areas subject to discussion within the scope of this thesis: the Case Results, the Verification and Validation Results and an overall discussion on the implications of the produced system.

10.1. Case Results Discussion

The results acquired from the Preferendus are in line with expectations. They demonstrate a severe stalemate with polarized preference scores.

The results acquired from the Stalemate Resolution Mechanism however require more analysis. They can be split into relevant and irrelevant recommendations. Relevant recommendations are shown in Figure 24. They are relevant because they directly enable the existence of the IMAP Recommended solution. Irrelevant recommendations are shown in Figure 25. These extensions are irrelevant because they are not required for the existence of the IMAP Recommended solution.

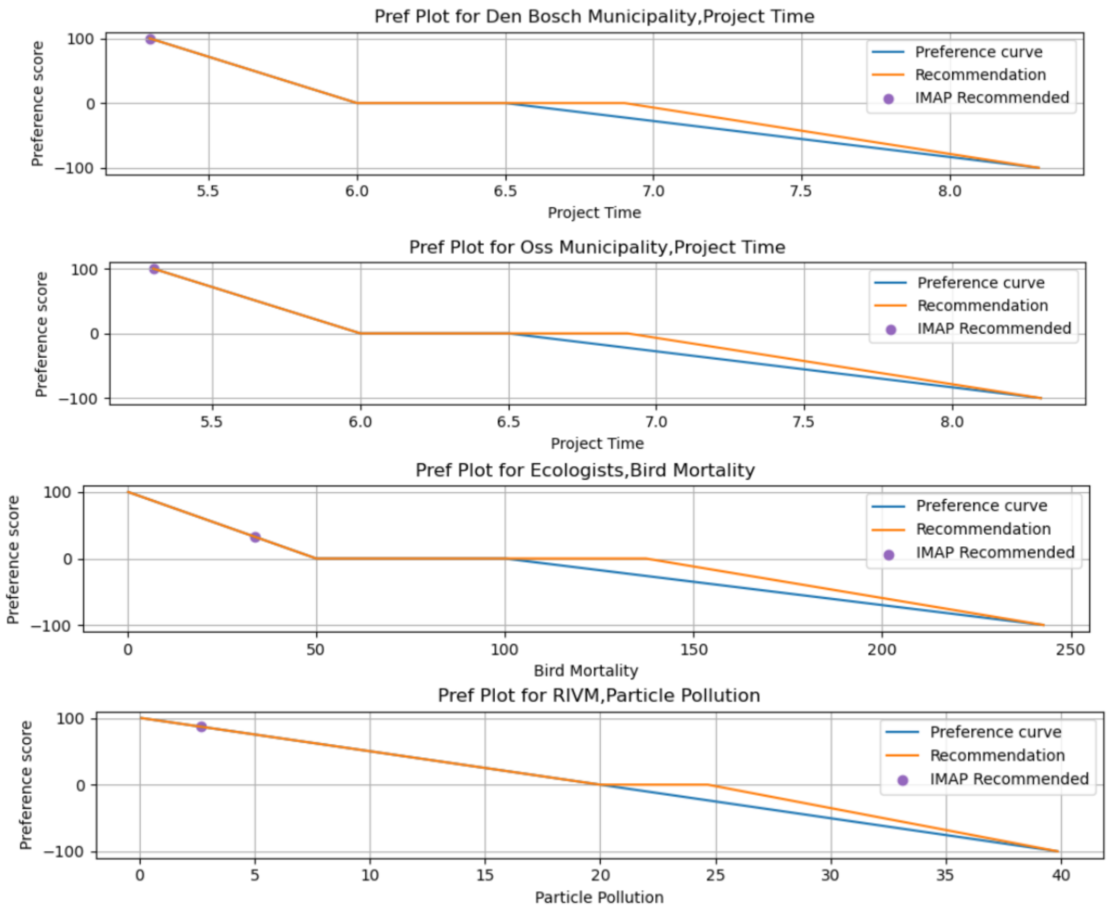

Figure 25 Examples of proposed irrelevant extensions

However, as shown in Figure 24, even within relevant extensions there are irrelevant regions. The relevant extensions for NPV, Noise in Oss and Energy in Den Bosch go beyond what is actually necessary to achieve an IMAP solution. This means that to extract meaningful proposals from the output of the Stalemate Resolution Mechanism, an analysis based on the group optimal solution needs to be performed.

It is also necessary to mention what these extensions mean for the decision-makers that are going to consider them. The core of the given recommendation is that to maintain an acceptable level of noise pollution, bird mortality, particle pollution and project time without additional mitigation measures, a significant reduction of energy production and NPV scope is required by the municipalities and the energy provider organization. This recommendation clearly points to the fact that the core of the problem lies with the project configuration in question, as it directly pits two interest groups against one another, as seen in Figure 23.

Therefore, the decision-makers of this case have to make a decision on whether to consider another configuration, change their project expectations (preference curves) or abandon the project altogether.

10.2. Verification and Validation Discussion

In the verification process the design requirements for a quantifiable indication of design variant acceptability and the ability to produce a resolution with a higher preference score than the initial stalemate are confirmed as fulfilled. Moreover, this indicates that the proposed shift to a new preference scale with regions of desirability, acceptability and non-acceptability is crucial to enabling stalemate resolution with the Preferendus.

The validation process gives rise to several conclusions. For one, it confirms the importance of the DSS format for issues such as stalemate resolution. As well as that, it shows that mediation and consultation are integral parts of the moderation process, and must be used in tandem to successfully resolve Preferendus stalemates. Most importantly, the validation process shows that using the designed DSS with Preferendus at the core and the SRM as an add-on allows decision-makers to learn positions of all other decision-makers participating the process, prompts discussions to establish the reasoning behind the positions and their incompatibility, and finally to understand the exact degree of position incompatibility via the Stalemate Resolution Mechanism. All of this leads to decision-makers to make an informed decision on how to address the stalemate, as was the case at the validation workshops.

As mentioned previously, all the performed workshops concluded with a unanimous decision to exit the decision process, because the currently established bounds of the project area require preference alignment measures that not all of the decision-makers are willing to take. This especially concerns the necessary scope reductions for municipalities who are the initiators of the project. At the same time, this conclusion is completely consistent with the actual Duurzame Polder project, where the project area is now being extended due to the unfeasibility of the Preferred Alternative. Considering all the limitations and assumptions associated with the system produced in this thesis, arriving at the same conclusion as the real case highlights its immediate usefulness within the context of complex projects.

At the same time, it must be noted that due to the limited scope of testing, the system can not be considered completely validated. While the two performed workshops showed consistent results, their number is too few. The degree of the consistency of results, however, also does not allow to disregard the approach as invalid.

Overall, this validation serves as proof of concept that with the tandem of Preferendus and the SRM issues of social complexity in construction projects can be effectively addressed and discussed before they negatively impact the process with delays, extra costs or escalating conflicts.

10.3. Implications of the Produced System

On top of the acquired results, it is important to discuss the implications of using the produced system. There are two main aspects that need to be covered: the implications arising from the internal logic of the system and the implications of how this system can be used by decision-makers.

10.3.1. Implications of Internal Logic

The Preferendus, along with the whole Open Design methodology, follows the utilitarian ethics in determining what is the “best” design of a project. By considering preference curves as an indication of happiness for certain outcomes, the Preferendus optimizes overall group happiness, following the “greatest good for the greatest number of people” principle. Since both the DSS and the SRM are built as extensions of Preferendus, they also follow this principle. This is especially evident in the results used to identify the stalemate in Figure 23, where the majority of preference curves and decision-makers score 100 and the minority score -100. After this stalemate is processed by the SRM, the produced recommendation targets the same decision-makers who were not in the majority, meaning the energy provider and the municipalities. The recommendation also includes a change in acceptance for noise pollution in Oss, but it is minor when compared to the other three major changes. The issue that can come up with a system like this is that the recommendations given can be viewed as forced alignment of decision-makers. In other words, the majority dominating the wishes of the minority. In some regard this is correct, because the algorithm does indeed prioritize the needs of the many over the needs of the few. This can result in situations where aligned interest groups can start forming coalitions that dictate their interest to the minority. However, this is only the case if the recommendations are taken at face value and are completely isolated from the context of both the case and the model they arise from.

For these reasons, the recommendations can only be considered as an indication of the minimal distance to a group optimal solution. If the decision-makers are not willing to accept this minimal distance, then the currently considered project configuration does not contain feasible design options, making the whole configuration unfeasible. This means that a new project configuration must be considered.

10.3.2. Implications of Use by Decision Makers

As previously discussed, the system basis lies is utilitarian logic. This also shapes the interactions of decision-makers with the developed system and among the decision-makers themselves. For example, in one of the performed workshops the decision-makers representing the two local resident groups realized they can reinforce each other’s interest and ensure that the SRM avoids including their preference curves into the recommendation. They did this by not only defining a preference curve for noise pollution in their area, but also in the other area as well, copying it from each other. In real terms this would be akin to the two groups standing up for each other and threatening to leave the project if both minimal requirements were not fulfilled. In modelling terms this means that they played the SRM in a way where it was averse to giving them a recommendation to extend their region of acceptability. In fact, this was the result they got in the end, as the recommendation for that workshop session did not include extensions for local residents. In this case the local residents ensured the mutual completion of interests by realizing their interests were aligned and acting on that, forming a coalition. Since the SRM looks for a minimal extension of acceptability, now each extension for noise pollution was counted double, making it a less desirable choice for the algorithm. This kind of decision-maker behaviour is also referred to as strategic behaviour and was covered extensively for the context of decision-making environments by Jongkind (2025) in her master thesis. While eliminating strategic behaviour is outside the scope for this thesis, it must be stated that stalemate situations are competitive by nature and, as the example shows, can cause strategic behaviour to emerge. For this reason, efforts must be taken to ensure that the decision environments that the developed system is applied in are as transparent and collaborative as possible.

10.4. Limitations

10.4.1. Case Modelling

There are several important modelling limitations to this development project that directly affect the flexibility and robustness of the produced system. Most of these limitations arise from the time and scope associated with this project as a master thesis.

One significant modelling limitation of this development project is that the case interpretation was based on publicly available information about the project, previous study and assumptions, rather than in-person contact with live project participants. This significantly decreases the degree of realism that could be achieved from the discussion or the outcomes. Large assumptions on project structure, such as the assumption that the energy provider company would carry all costs but earn all the revenue, lead to some confusion of the workshop participants on their actual roles, especially those representing the municipalities. In reality the cost and benefit sharing scheme would be more nuanced and therefore lead to a different decision-making dynamic. On top of the energy generation requirements, the municipalities would also face an incentive to cut project costs or increase project revenue, making their project goals more aligned with the energy provider. This would increase the stalemate even further and would most likely result in a different resolution, or lack thereof.

The most significant modelling limitation concerns the modelling scope chosen to represent the case. Specifically, the decision to model the case along a straight line. While measures were taken to make this case as open-ended as possible to avoid unnecessary limitations of the solution space, the case was still represented within the bounds of the “Preferred Alternative”, a pre-defined design variant. Ideally, the modelling scope of this case should be increased to the level of the whole polder, shown in Figure 9, with the only limitation being the already present structures. This could be achieved by linking the model with a Geographical Information System (GIS). Then the coordinates of each park, or even each wind turbine, could act as design variables, and more accurate representations of factors such as noise levels and effects on bird habitats could be achieved. This would also significantly improve the decision-making capacity of the DSS. The current decision process concluded with a decision to look at another project configuration within the polder and now requires the model to be rebuilt. If the modelling scale was set on the level of the whole polder, the decision process could continue and most likely come to a mutually acceptable group optimal solution.

As well as that, the general level of assumptions associated with the objective functions of the model reduces the realism of the acquired results. For example, there is no accounting for the space needed per wind turbine and therefore no meaningful limitation on how many could fit into the project area. This, in turn, affects the realism of all other calculations which require the number of wind turbines as a variable. The noise level calculation omits important aspects such as sound reflection and absorption. All of these factors influence how the DSS users view and interact with the outcomes and therefore such limitations influence the decision process.

10.4.2. The Stalemate Resolution Mechanism

There are also several important limitations associated with the Stalemate Resolution Mechanism. As this mechanism provides input for further discussion, it influences the decision process and therefore must be discussed.

The most important limitation associated with the Stalemate Resolution Mechanism is the runtime. Having to run it for 45 minutes at a time severely reduces its usefulness as a decision support mechanism. For it to be used during actual decision-making, it has to come to a solution in the time of a negotiation break, which is around 15-20 minutes. Otherwise, it does not allow the decision-makers to sufficiently explore the range of possible stalemate resolutions and decreases the effectiveness of the whole process. The reason behind this long runtime lies in the fact that for each result of the SRM, an instance of Preferendus has to be run.

Another limitation associated with the Stalemate Resolution Mechanism considers the metric that is used for the optimization. At this moment it is the sum of the preference changes associated with the introduced point. These preference changes are now calculated only as a straight-line distance, which is still indicative of the trend, but not exactly accurate, as it does not consider the shape of the preference curve.

10.4.3. Decision Process

There are several limitations associated with the decision process which affect different aspects of it.

One limitation of the decision process itself that is connected to the case modelling limitation is a lack of access to the actual decision-makers of the Duurzame Polder case. This causes the preference curves to be very limited in how they represent the interests of the role they are associated with. As well as that, some nuance aspects of the situation unique to each decision-maker are omitted because of that, while normally they would shape the decision process. As a result, these nuances do not get passed on to the workshop participants and this results in limited conclusions that can be drawn from this development.

Another important limitation of the decision process in this development project is the achieved scale of testing with real participants. Due to several factors which are mostly organizational, this development could only be tested in two decision-making groups. While this does not invalidate the acquired results, they cannot be considered completely conclusive, and the system would benefit from further extensive testing.

11. Conclusion

11.1. Overall Conclusion

In conclusion of this development thesis the process, outcomes and the main developments will be summarised along the lines of the development statement: "*To develop a Preferendus-based system to enable stalemate resolution in network decision-making for large and complex construction projects*."

The need for the development of the resulting system was identified based on the problems encountered by large and complex construction projects. The main problem that needed to be addressed was the social complexity, or in other words, the competing interests of stakeholders that still occurred even in Collaborative Project Delivery contracts which are designed to mitigate it. To address this problem effectively the latest tool in the Open Design methodology, the Preferendus, was taken as the main scope. This tool lacked the capacity to resolve decision-making stalemates, therefore this was taken as the development goal.

In completion of the development statement two products were delivered as parts of an overall system. The products were developed over three design cycles, where at the end of each a testing round took place via a student serious game and the products were refined. The first product is the interactive decision support system (DSS) built on top of Preferendus that allows decision-makers to identify and discuss group optimal project outcomes or stalemates. The second product is the Stalemate Resolution Mechanism (SRM), which allows to formulate the smallest adjustment of acceptability for one or more decision-makers needed to achieve a group optimal project outcome. These two products act in tandem to enable the stalemate resolution process.

The system was developed based on the publicly available information about the Duurzame Polder sustainable energy project currently in development by the municipalities of Oss and 's-Hertogenbosch. This case was chosen as it represents the decision-making stalemate that the system developed in this thesis aims to resolve.

The system was validated by two serious game workshops, in which TU Delft Master students took on the roles of decision-makers in the Duurzame Polder case. They participated in a decision-making session, during which they created their own preference curves, assigned weights, identified the stalemate and attempted to resolve it with the recommendation given by the SRM. Validation confirmed that the use of a Preferendus-based DSS along with the SRM enabled the decision-makers to understand each other's positions and the stalemate, initiated the discussion that made clear the reasoning behind the positions and the stalemate, and allowed the decision-makers to reach an aligned conclusion. In both workshops the decision-makers unanimously concluded that the main reason for the stalemate were the project boundaries, which needed to be extended for a group optimal solution to exist. This mirrors the developments in the actual Duurzame Polder project, where in the most recent development as of the time of writing project area was extended significantly. The validation process and the final outcome confirmed the achievement of the goal set out in the development statement: "*To develop a Preferendus-based system to enable stalemate resolution in network decision-making for large and complex construction projects*."

The main limitations of the study were identified as relative simplicity of case modelling, lack of access to the real decision-makers of the case for the purpose of validation and the model runtime.

11.2. Further Development

The conclusions of this project, especially the limitations, provide several avenues for further development:

- As mentioned previously, the current Stalemate Resolution Mechanism does not produce the global optimum for extension of the acceptability range because of the runtime limitation. While double-checking the recommendation with an IMAP design variant can help compensate the irrelevant recommendations which contribute to the suboptimality of the solution, it still does not guarantee that the extension is optimal. The optimality of the recommendation could potentially be increased by considering the trade-off of group preference change required to exit the stalemate vs the group preference gained by this change. This net assessment can help generate more optimal and acceptable recommendations. As well as that, a more accurate calculation of the amount of preference change required for a certain extension of acceptance could be done by taking changes in the area under the preference curve. This would not significantly increase the calculation load on the model, but would make the outcome more accurate and the optimization algorithm more likely to take solutions associated with the minimal required preference change.
- Improving the calculation efficiency of the Stalemate Resolution Mechanism by addressing the inherently high run time of the Preferendus. This could be in line with improvements proposed by Raaphorst (2024).
- This DSS was fully based on the decision-making aspect of the Preferendus, looking for preference curves to accommodate a given project configuration. An interesting avenue of development would be to consider the inherent interplay between fitting preference curves to the design variant and fitting the design variant to the preference curves. The outputs of the Stalemate Resolution Mechanism can be used as input to a parallel model which determines the minimum (optimal) change of project configuration, that would result in a commonly acceptable group optimal solution existing.

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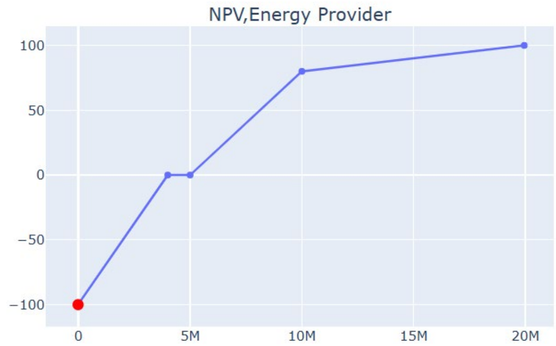
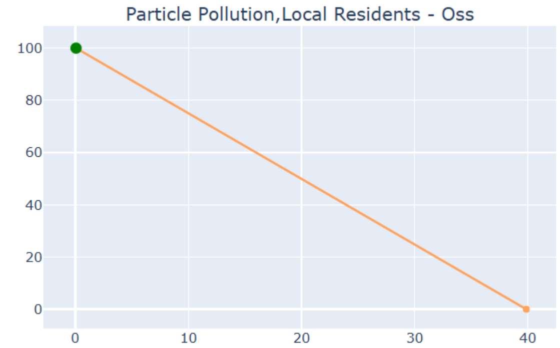
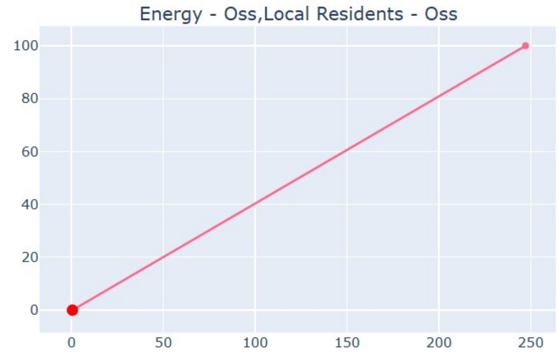
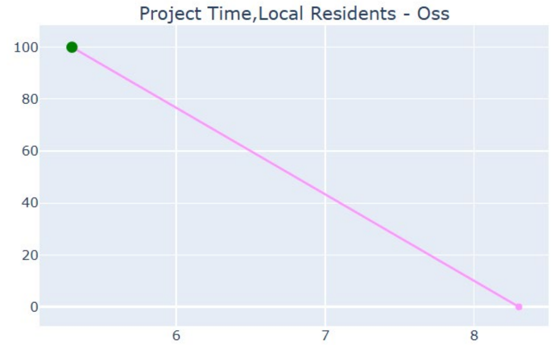
Appendix A: DSS Outcomes

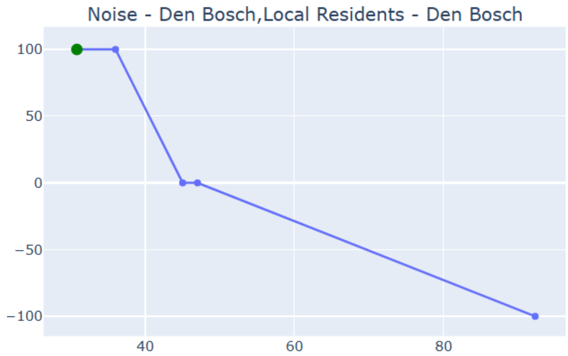
A.1. Preferendus Outcomes

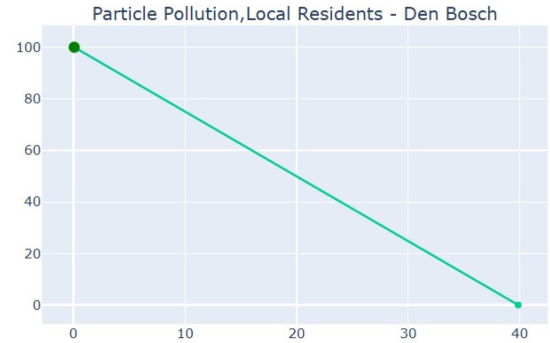


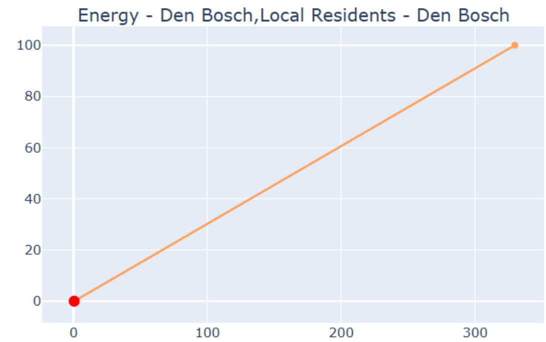






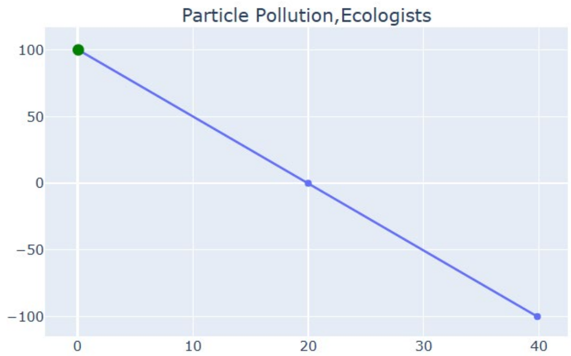


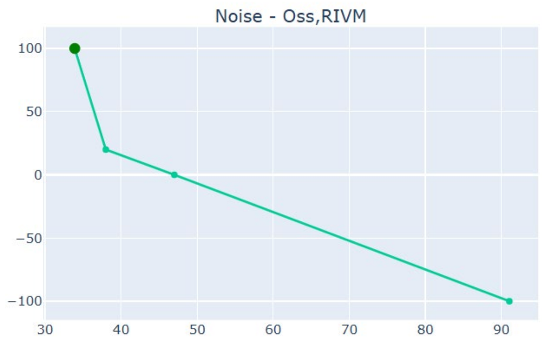


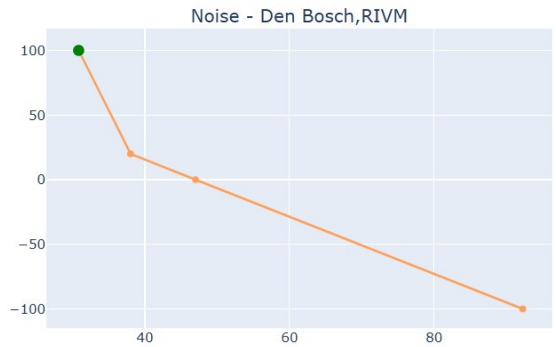



Project Time,Local Residents - Den Bosch

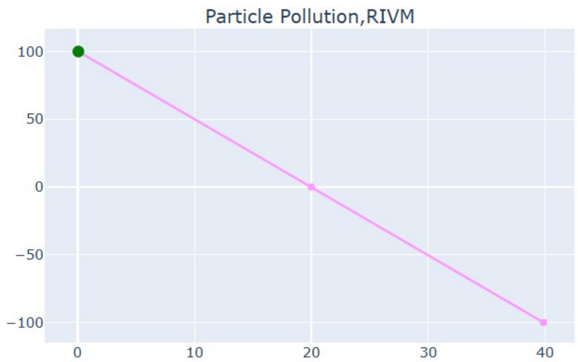

Bird Mortality,Ecologists


Particle Pollution,Ecologists


Noise - Oss,RIVM


Noise - Den Bosch,RIVM


Bird Mortality,RIVM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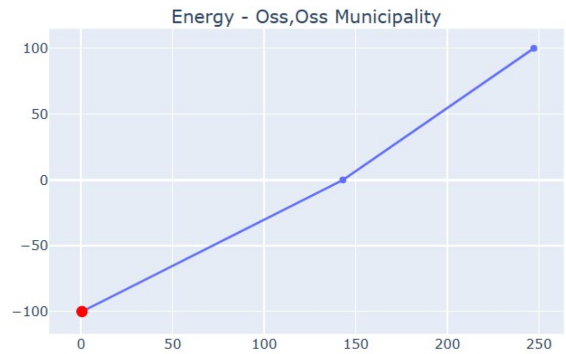
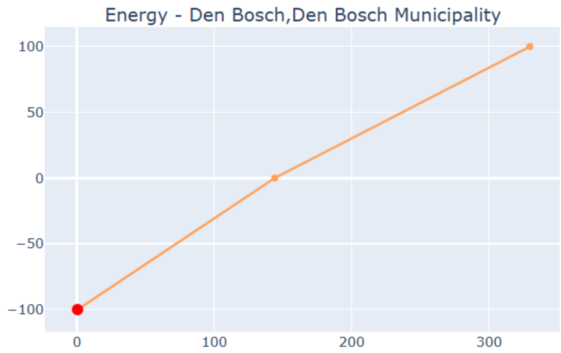
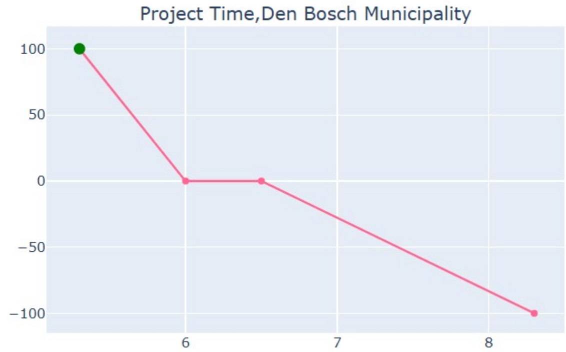

Energy - Oss,Oss Municipality

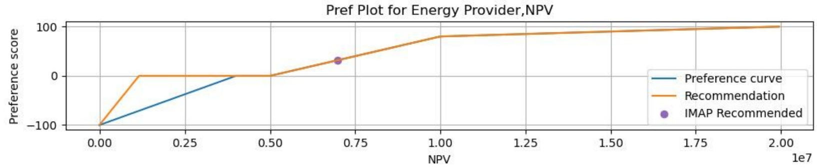




A.2. Stalemate Resolution Mechanism Outcomes – Second Cycle

The group optimal stalemate resolution:

- The Oss wind park is to be located 0.9 km away from the border of the urbanized area of Oss. The wind park is to have 11 wind turbines of hub height 190 m.
- The ‘s-Hertogenbosch wind park is to be located 5 km away from the border of urbanized area of ‘s-Hertogenbosch. The wind park is to have 1 wind turbine of hub height 87 m.
- The overall aggregated preference score for this solution is 42.4.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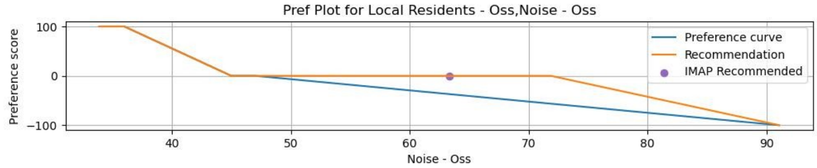
Preference score
NPV
1e7
Preference curve
Recommendation
IMAP Recommended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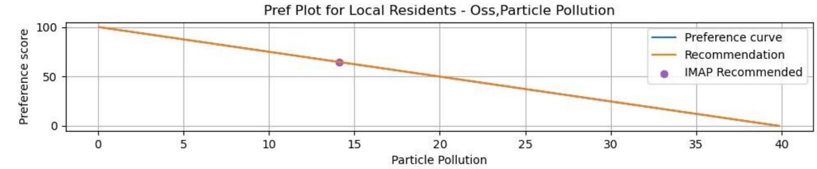
Preference score
Noise - Oss
Preference curve
Recommendation
IMAP Recommended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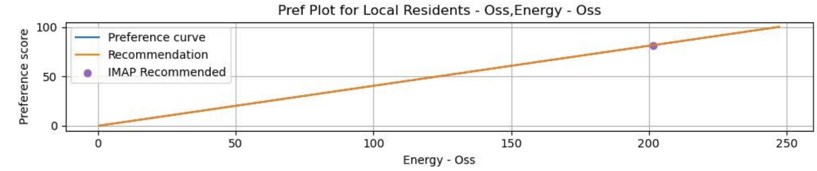
Preference score
Particle Pollution
Preference curve
Recommendation
IMAP Recommended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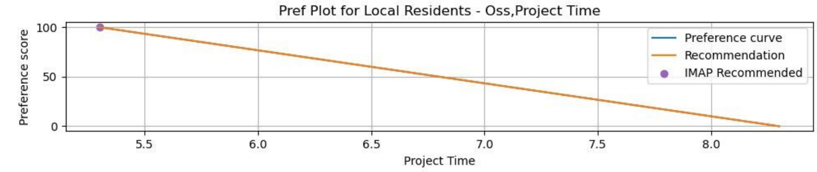
Preference score
Energy - Oss
Preference curve
Recommendation
IMAP Recommended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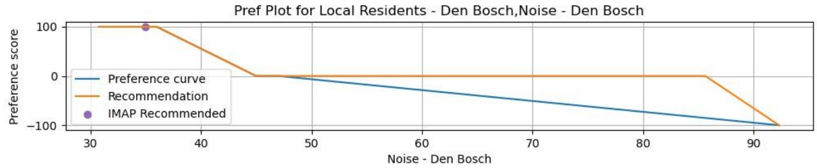
Preference score
Project Time
Preference curve
Recommendation
IMAP Recommended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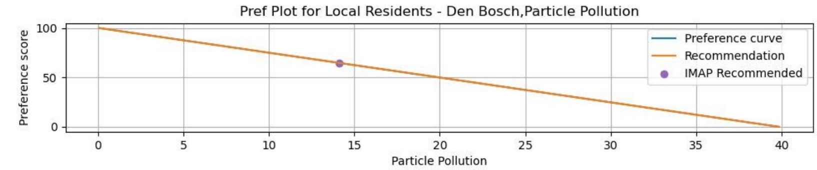
Preference score
Noise - Den Bosch
Preference curve
Recommendation
IMAP Recommended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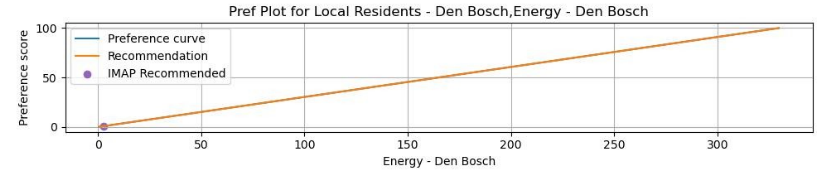
Particle Pollution
Preference curve
Recommendation
IMAP Recommended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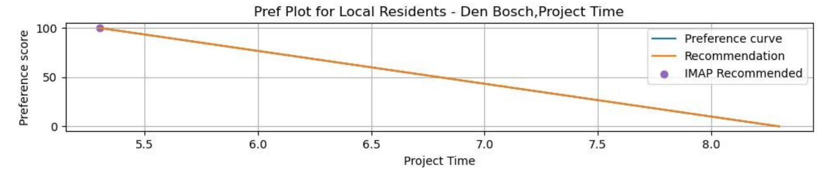
Preference score
Energy - Den Bosch
Preference curve
Recommendation
IMAP Recommended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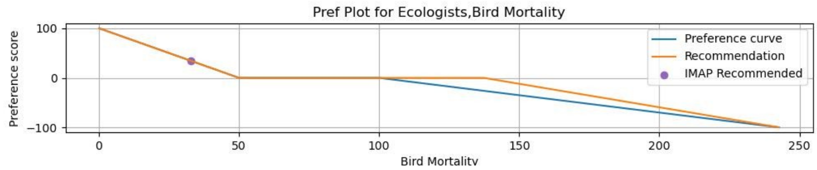
Preference score
Project Time
Preference curve
Recommendation
IMAP Recommended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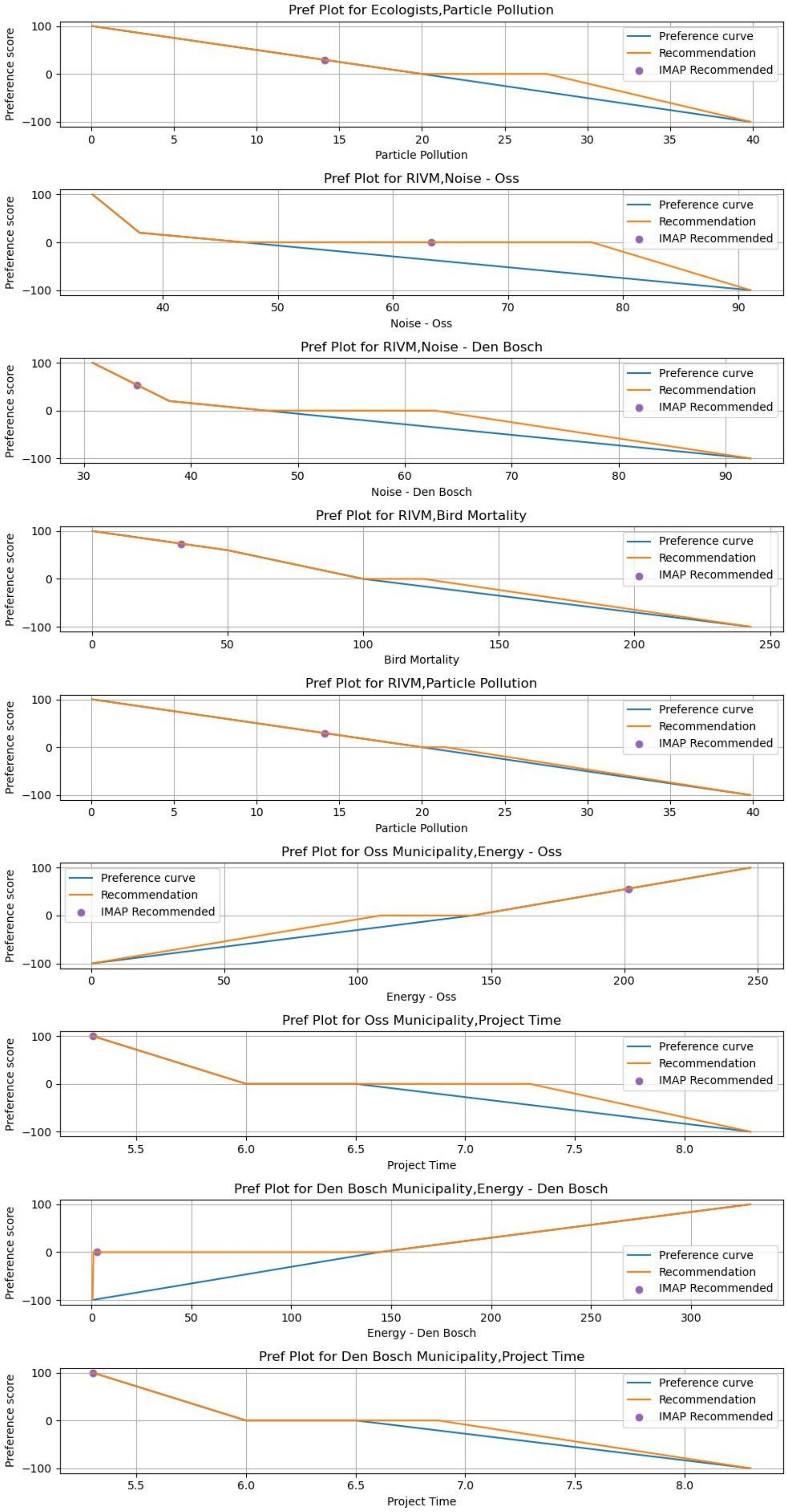
Preference score
Bird Mortality
Preference curve
Recommendation
IMAP Recommended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Preference score
Particle Pollution
Preference curve
Recommendation
IMAP Recommended
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Noise - Oss
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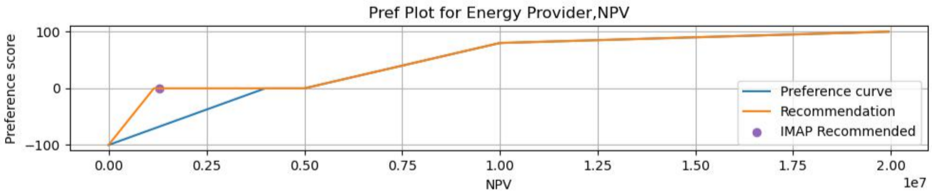
Noise - Den Bosch
Pref Plot for RIVM,Bird Mortality
Bird Mortality
Pref Plot for RIVM,Particle Pollution
Particle Pollution
Pref Plot for Oss Municipality,Energy - Oss
Energy - Oss
Pref Plot for Oss Municipality,Project Time
Project Time
Pref Plot for Den Bosch Municipality,Energy - Den Bosch
Energy - Den Bosch
Pref Plot for Den Bosch Municipality,Project Time
Project Time

A.3. Stalemate Resolution Mechanism Outcomes – Final Cycle

The group optimal stalemate resolution:

- The Oss wind park is to be located 2.85 km away from the border of the urbanized area of Oss. The wind park is to have 10 wind turbines of hub height 93.5 m.
- The ‘s-Hertogenbosch wind park is to be located 1.97 km away from the border of urbanized area of ‘s-Hertogenbosch. The wind park is to have 1 wind turbine of hub height 126 m.
- The overall aggregated preference score for this solution is 40.1.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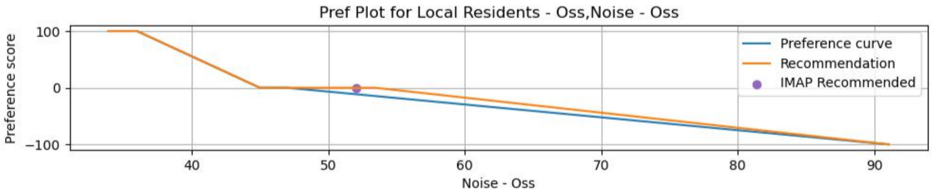
Preference score
NPV
1e7
Preference curve
Recommendation
IMAP Recommended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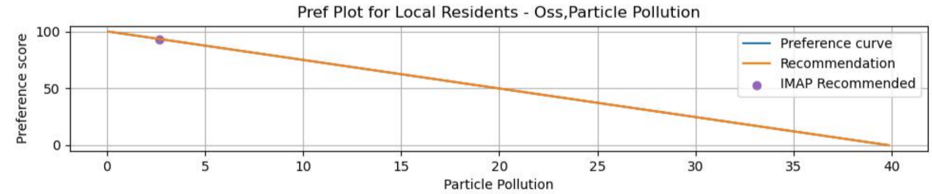
Preference score
Noise - Oss
Preference curve
Recommendation
IMAP Recommended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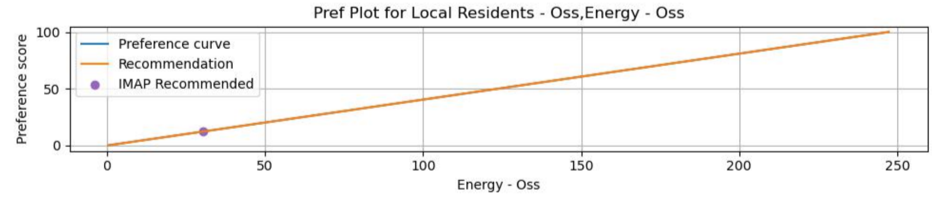
Particle Pollution
Preference curve
Recommendation
IMAP Recommended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Preference curve
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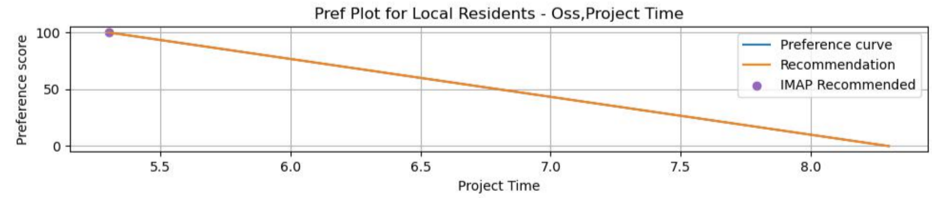
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Preference score
Project Time
Preference curve
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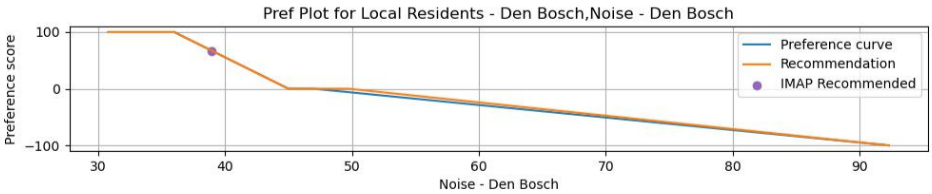
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Noise - Den Bosch
Preference curve
Recommendation
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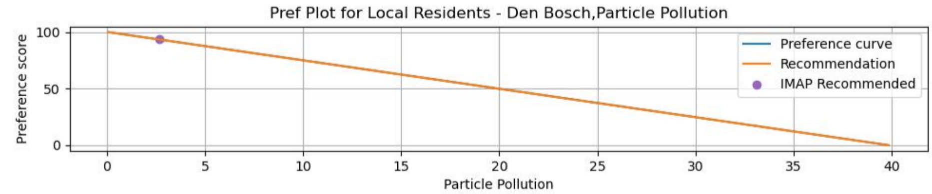
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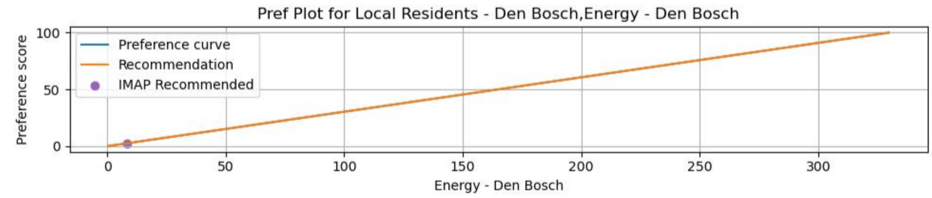
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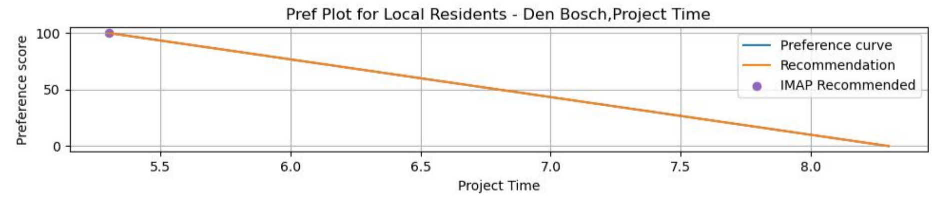
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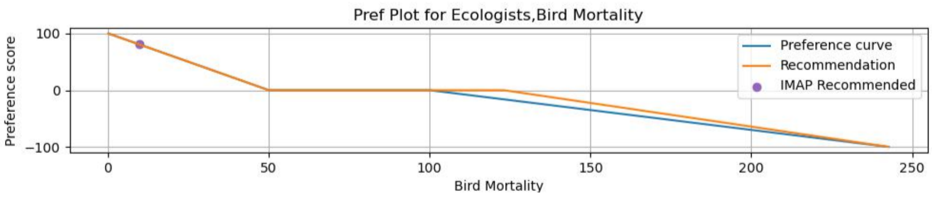
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Preference curve
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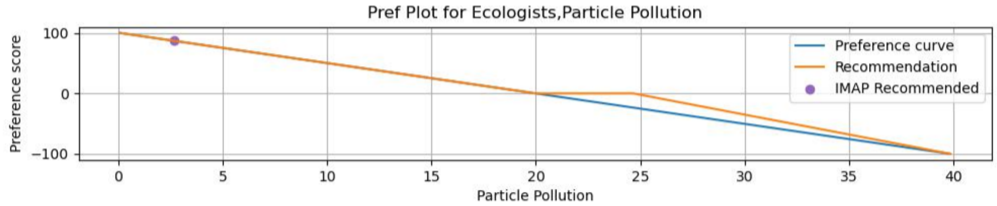
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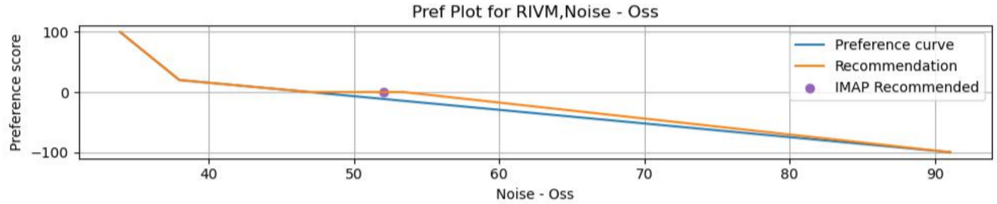
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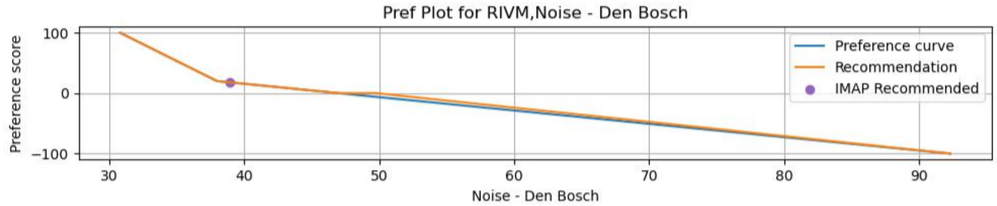
Preference score
Noise - Oss
Preference curve
Recommendation
IMAP Recommended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Preference score
Noise - Den Bosch
Preference curve
Recommendation
IMAP Recommended


Pref Plot for RIVM,Bird Mortality
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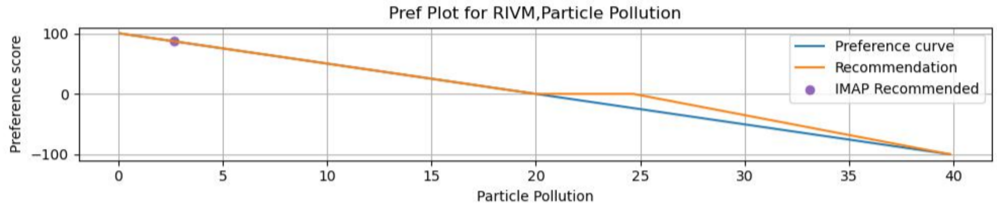
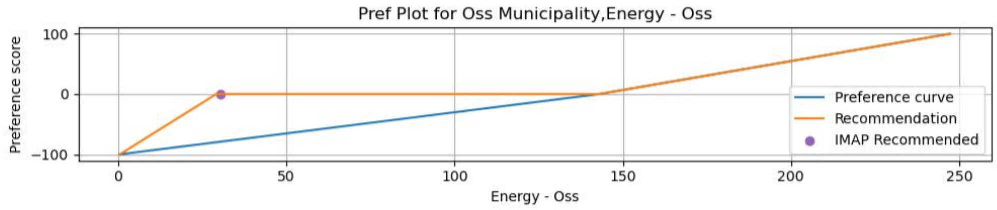
Bird Mortality
Preference curve
Recommendation
IMAP Recommended


Pref Plot for RIVM,Particle Pollution
Preference score
Particle Pollution
Preference curve
Recommendation
IMAP Recommended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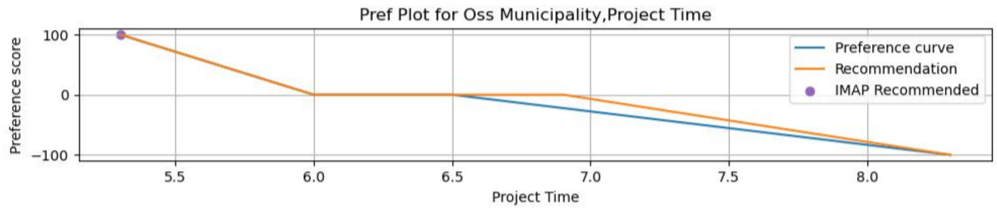
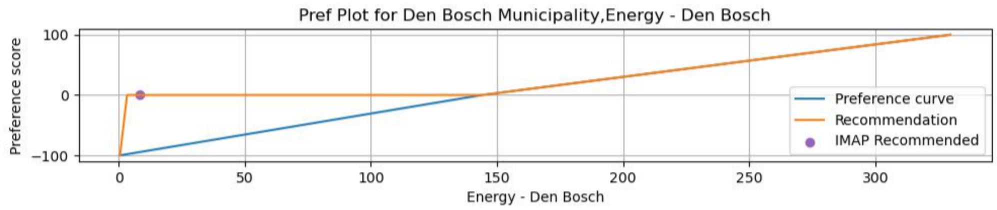
Preference score
Energy - Oss
Preference curve
Recommendation
IMAP Recommended


Pref Plot for Oss Municipality,Project Time
Preference score
Project Time
Preference curve
Recommendation
IMAP Recommended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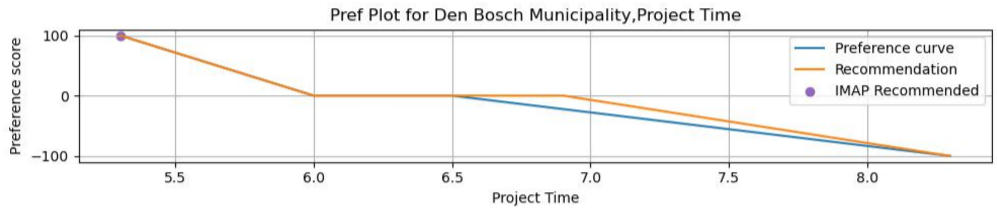
Energy - Den Bosch
Preference curve
Recommendation
IMAP Recommended


Pref Plot for Den Bosch Municipality,Project Time
Preference score
Project Time
Preference curve
Recommendation
IMAP Recommended

Appendix B: Workshop Materials

B.1. Role Descriptions

Energy Provider Organization

You have been assigned the role of a representative of the Energy Provider organization in this decision-making process. You have been granted a degree of autonomy by your organization to make the best deal you can or provide concessions.

Your interest in the project

Your interest in the project is quite straightforward – you want to make money from the project. Once the wind park is built, you will make money by selling the energy generated by the wind turbines. But, because you are reaping all the rewards, you also have to carry some of the losses as well. For this reason, the objective that represents your interest in this project is the NPV calculation of the project. In short, a bigger windfarm is not necessarily better for you, as that means more Capital Expenditure (CAPEX) in the front end and higher Operation and Maintenance Costs (O&M) through the project lifetime. Also, if the farm capacity goes above certain thresholds, the project gets delayed, which impacts your NPV.

Your goals for the project

The minimum goal that the Energy Provider organization is trying to fulfil is to achieve a project with an NPV of 4-5 million Euros. Achieving an NPV of 8 million Euros opens a possibility for the Energy Provider organization to make an initial investment on another project, which is of course desirable, but not a deal-breaker. Also, at the end of the day, even an under-performing project might be better than no project at all.

Other relevant information

- Recently the municipalities raised the possibility of involving the local residents financially. More specifically, letting them invest in the project in exchange for a share of the earnings. However, you would have to negotiate on that possibility during the live meeting.

Local Residents – Oss

You have been assigned the role of the Local Residents from Oss in this decision-making process. Being one of the more active members of your concerned citizens group, you were elected as a representative to go and participate in decision-making to ensure that your interests are not left behind.

Your interest in the project

Your main interest is to safeguard the peace and quiet of your neighborhood. Also, you would like to avoid any kind of pollution that can come because of those wind turbines.

At the same time, you quite like the idea of locally generated sustainable energy. You are not actively opposed to wind turbines, but you value your peace and quiet above all. To ensure your interests are represented in the model, a noise pollution function was included into the model.

Your goals for the project

Having done quite some research on it with your citizen group, you know that the legal limit for noise pollution in a residential area from wind turbines is 47dB. You can consult the noise table in the formula sheet to get an impression of how a certain level of dB sounds.

Other relevant information

- Recently the municipalities raised the possibility of involving local residents financially. More specifically, letting them invest into the project in exchange for a share of the earnings. However, you would have to negotiate on that possibility during the live meeting.

Local Residents – Den Bosch

You have been assigned the role of the Local Residents from Oss in this decision-making process. Being one of the more active members of your concerned citizens group, you were elected as a representative to go and participate in decision-making to ensure that your interests are not left behind.

Your interest in the project

Your main interest is to safeguard the peace and quiet of your neighborhood. Also, you would like to avoid any kind of pollution that can come because of those wind turbines.

At the same time, you quite like the idea of locally generated sustainable energy. You are not actively opposed to wind turbines, but you value your peace and quiet above all. To ensure your interests are represented in the model, a noise pollution function was included into the model.

Your goals for the project

Having done quite some research on it with your citizen group, you know that the legal limit for noise pollution in a residential area from wind turbines is 47dB. You can consult the noise table in the formula sheet to get an impression of how a certain level of dB sounds.

Other relevant information

- Recently the municipalities raised the possibility of involving local residents financially. More specifically, letting them invest into the project in exchange for a share of the earnings. However, you would have to negotiate on that possibility during the live meeting.

Ecologists

You have been assigned the role of the Ecologists in this decision-making process. You are a representative of a group of ecologists that have been consulting the Duurzame Polder from the inception of the project in 2017.

Your interest in this project

Wind turbines pose a threat to local bird populations, specifically to meadow birds who are protected across the Netherlands. More than that, a nesting ground lies within the determined project area. Your main interest in this project is to ensure that its effect on local bird populations is as little as possible.

You are also concerned about the particle pollution effect that occurs when wind turbine blades wear down and release microplastic particles into the air.

Your goals for the project

Considering the fragile state of the population, bird mortality of 50 per year will already have a negative effect, but it is still salvageable. Anything above 100 per year puts the local species on track to extinction.

While there is no conclusive evidence to indicate its direct harm to the health of humans or animals, recent studies indicate that for this project particle pollution above 20g released daily can pose health risks to both humans and animals.

National Institute for Public Health and Environment (RIVM)

You have been assigned the role of the RIVM in this decision-making process. You are a representative from the RIVM that is there to ensure that no damage to the health and environment occurs because of this project.

Your interest in this project

As you can imagine, damage to health and environment involves quite a wide range of topics. First and foremost is the particle pollution effect that occurs when wind turbine blades wear down and release microplastic particles into the air. This can be harmful to both humans and the environment. There is also the matter of noise pollution from wind turbines, which can cause adverse health effects for local residents. You want to minimize the potential for these effects.

As well as that, local meadow bird populations, which are protected across the Netherlands, can be under threat from wind turbines in the project area.

Your goals for the project

While there is no conclusive evidence to indicate its direct harm to the health of humans or animals, recent studies indicate that for this project particle pollution above 20g released daily can pose health risks to both humans and animals.

Your second priority is noise pollution as a result of the wind park. You know that 47dB is the legal limit, but you also know, as an expert from RIVM, that while 38 dB is legally allowed, it can lead to health consequences.

Your third priority is bird mortality. Considering the fragile state of the population, bird mortality of 50 per year will already have a negative effect, but it is still salvageable. Anything above 100 per year puts the local species on track to extinction.

Rijksinstituut voor Volksgezondheid
en Milieu
Ministerie van Volksgezondheid,
Welzijn en Sport

Oss Municipality

You have been assigned the role of Oss Municipality in this decision-making process.

Your interest in the project

As the Oss municipality, you were one of the initiators of the project, because for you this is a direct part of the realization of the 2030 and 2050 sustainability goals. The province of Noord Brabant established an ambitious goal, and as one of the municipalities, you must contribute to reaching it. However, not only is the size of the wind park an important factor for you, but the time the project takes as well. Considering this project has been going on since 2017, you are not sure you have the luxury of time to explore other options.

Your goals for the project

With regards to energy generation, the goal for Oss is to generate 143 GWh per year. This is what was initially defined as the acceptable minimum. With regards to time, you would very much like the project to finish by 2030 or within an acceptable range of that. Otherwise, the faster – the better.

Other relevant information

- Recently the municipalities raised the possibility of involving local residents financially. More specifically, letting them invest into the project in exchange for a share of the earnings. However, you would have to negotiate on that possibility during the live meeting.

GEMEENTE OSS

Den Bosch Municipality

You have been assigned the role of the Den Bosch Municipality in this decision-making process.

Your interest in the project

As the Den Bosch municipality, you were one of the initiators of the project, because for you this is a direct part of the realization of the 2030 and 2050 sustainability goals. The province of Noord Brabant established an ambitious goal, and as one of the municipalities, you must contribute to reaching it. However, not only is the size of the wind park an important factor for you, but the time the project takes as well. Considering this project has been going on since 2017, you are not sure you have the luxury of time to explore other options.

Your goals for the project

With regards to energy generation, the goal for Den Bosch is to generate 144 GWh per year. This is what was initially defined as the acceptable minimum. With regards to time, you would very much like the project to finish by 2030 or within an acceptable range of that. Otherwise, the faster – the better.

Other relevant information

- Recently the municipalities raised the possibility of involving local residents financially. More specifically, letting them invest into the project in exchange for a share of the earnings. However, you would have to negotiate on that possibility during the live meeting.

’s-Hertogenbosch

B.2. DSS User Manual

Document Version: 01-05-2025

This document describes the decision process of identifying and resolving stalemates with the use of the developed decision support system. The main model features will be described, as well as the steps to be taken with them.

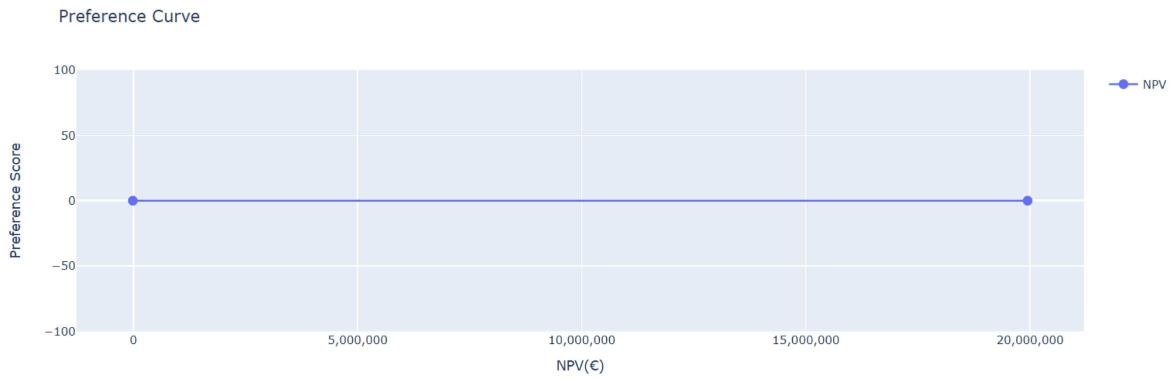
"Preference & Weights" Tab – Establishing Project Goals

Preference Curves

The decision process starts with the decision-makers outlining their goals for the project as preference curves. This includes the following steps:

1. *Select the decision-maker you represent in the project from the dropdown at the top of the page.*
2. *(Optional) Load a previously saved set of curves to adjust them or add onto them.*
3. *Select the objective for which you want to enter your goals or preferences from the dropdown.*

At this point you will see the following plot:



This is your starting plot. The two points are the minimum (left) and maximum (right) achievable values for the objective that you selected. You can hover your mouse over the points to see the exact objective values of each point.

4. *The first step of creating a new preference curve (or after resetting it) is to state your preference for the minimum and maximum points. This can be done by entering the preference score you associate with the points into the text boxes and then pressing the "Set Endpoints" button. The curve will adjust to the point values you enter. You have to do this only once.*
5. *After setting the preferences for the end points, you can enter other points of preference that you view as important to accomplishing your set of goals for the project. To do this, enter the objective value and the preference values of the point into the corresponding boxes and press "Set Point". The curve will adjust to the points you enter. You can enter as many points as you see fit here.*
6. *After your preference curve is complete press the "Save" button. This will prepare the curve for being saved to a file and ensure that you can switch between objectives without losing the curve. You can now switch to a different objective to create another*

preference curve. You can create preference curves for as many objectives as you see fit.

7. *After you have created and saved all the preference curves that represent your goals for the project, you can write these to a file that will be saved on the server. You can then load this file at the top of the page to make changes to it at any point, even after closing the web app. You can do this by entering the name for the file and pressing the "Write" button.* ***Important***: *once you are sure the entered preference curves represent you goals for the project, you can write them to a file called "final". This ensures they will be used in generating the group optimal design variant.*

Weights

After the preference curves have been defined and saved, the next step is to enter the weight distribution among objectives.

NPV	Noise - Oss	Noise - Den Bosch	Bird Mortality	Particle Pollution	Energy - Oss	Energy - Den Bosch	Project Time	Decision-Maker
1	0	0	0	0	0	0	0	Energy Provider

Save Weights

You have 1 point that you can distribute among the objectives you created the preference curves for. You can do this by entering decimal numbers between 1 and 0 directly into the cells of the table. Please use the dot as the decimal separator (e.g. 0.1). After entering the value into the table, you can press TAB on your keyboard.

Important: *Make sure that you only enter weights for objectives that you defined preference curves for. Otherwise, this will cause a model error!*

Important: *Make sure the sum of the points you enter into the table is exactly 1. Otherwise, this will cause a model error!*

After all the values were entered, press the button below the table to save the weights. The saved weights are not associated with preference files on the server, so if you decide to remove or add preference curves, ensure that this is reflected in the weights table.

"Overview" Tab – Open Information

The overview tab will show all the preference curves and weight distributions entered by all decision-makers. To ensure the displayed information is up to date you can press the associated "Refresh" buttons.

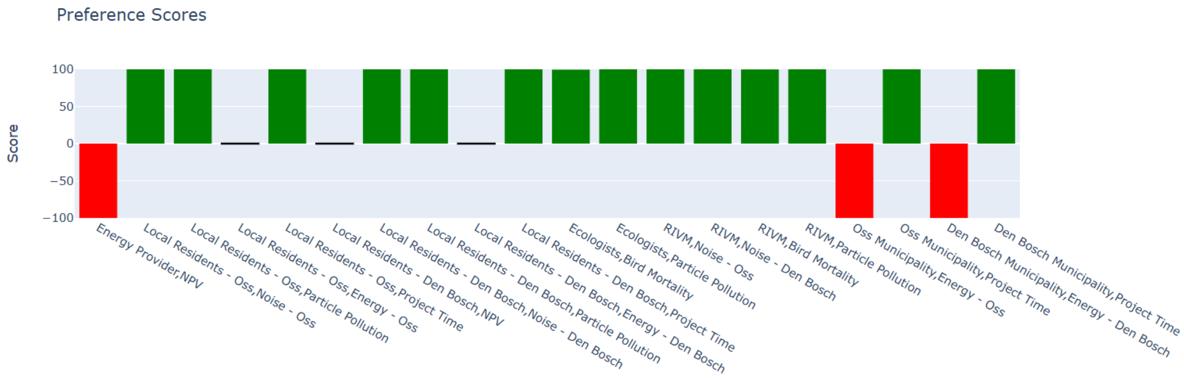
Feel free to use the information available in the Overview as you see fit. One of the core principles of Open Desing is open information, so do not hesitate to ask your fellow decision-makers questions you have with regards to their positions or weights.

"Dashboard" Tab – Generating the Group Optimal Design, Identifying the Stalemate

Group Optimal Design

This tab allows the decision-makers to run the underlying Preferendus model to generate the group optimal design based on the stated decision-maker goals. In the decision-making process this tab should be accessed by the model operator and displayed on the conference screen. This is because the underlying calculation is quite costly and having only one instance of it running will ensure smooth functioning of the rest of the model.

Pressing the "Run" button will initiate the Preferendus and after some time the group optimal design variant will be displayed. There will be two types of graphs displayed along with the results. The first is a bar chart showing the preference score of each objective involved in the decision process.



The second is a set of all preference curves similar to the one in the "Overview" tab with the group optimal solution plotted onto them.

Identifying the Stalemate

In this DSS the following definition of a stalemate is used:

If the group optimal design variant shows negative preference for at least one objective, then a stalemate is present.

From the point a stalemate is identified, the decision-makers are presented with the results of the Preference Resolution Mechanism. It is now up to the decision-makers to start a discussion to see if the stalemate can be overcome or a change in project configuration is required.

Appendix C: Programming Materials

C.1. Python Packages Used in Development

This file may be used to create an environment using:

$ conda create --name <env> --file <this file>

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created-by: conda 24.11.3

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libsodium=1.0.18=h62dcd97_0

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