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# Decision Analysis in Situations with Conflicting Interests

Tobias Fasth

Doctoral Thesis in Computer and Systems Sciences at Stockholm University, Sweden 2019

# Decision Analysis in Situations with Conflicting Interests


## Tobias Fasth


Academic dissertation for the Degree of Doctor of Philosophy in Computer and Systems Sciences at Stockholm University to be publicly defended on Friday 3 May 2019 at 10.00 in Lilla hörsalen, NOD-huset, Borgarfjordsgatan 12.


### Abstract

Decision problems in participatory decision making involve multiple stakeholders, who often have conflicting preferences concerning the actions under consideration. Decision problems such as these can be structured as multi-criteria problems, which enables the actions to be evaluated in terms of more than one single criterion. In these situations, the complexity of the problem increases when the objective is to select a portfolio of actions. Another aspect to take into consideration is that the choice of actions often has a long-term impact on the lives of the stakeholders. It is therefore not surprising that these problems often are sources of costly and time-consuming conflicts.

This thesis presents artifacts in the form of methods and applications aiding the decision maker in participatory decision making problems in highlighting stakeholder conflict. The artifacts are DANCE, XPLOR, POLA, and SENS. DANCE is a framework of methods that are used to elicit preferences, and to measure and analyze conflicts between and within stakeholder groups regarding the performance of an action. The framework uses three novel artifacts: i) CAR-CE a method for preference elicitation, ii) two indices, one for measuring the conflict within one stakeholder group, one for measuring the conflict between two stakeholder groups, and iii) an approach to portfolio optimisation and robustness analysis. XPLOR is a web-application that is used to explore and visualise stakeholder conflicts. POLA is a web-application for evaluating commercial development policy in cooperation with key stakeholders. The last artifact, SENSE, is a method for sensitivity analysis of portfolios.

The artifact development followed the design science methodology, where the aim of the artifact is to solve a practical problem and where, in this case, the artifacts were evaluated against a set of requirements. The preference elicitation method, CAR-CE, was implemented in a web-questionnaire and was used in a real-world survey in cooperation with Upplands Väsby municipality. The elicited preferences were used in illustrative scenarios to demonstrate both the DANCE framework and XPLOR. POLA was demonstrated in three examples based on results from workshops that were conducted together with the municipalities of Norrköping, Katrineholm and Filipstad. Altogether, these artifacts support decision makers in modeling and analyzing decision problems, with the purpose of avoiding future costly and time-consuming conflicts in land use planning.



**Keywords:** *Multiple Criteria Decision Analysis, Portfolio Decision Analysis, Conflict Analysis, Decision Tools, Land Use Planning.*

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DECISION ANALYSIS IN SITUATIONS WITH CONFLICTING INTERESTS

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To Artur & Astrid

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This thesis presents artifacts in the form of methods and applications aiding the decision maker in participatory decision making problems in highlighting stakeholder conflict. The artifacts are DANCE, XPLOR, POLA, and SENS. DANCE is a framework of methods that are used to elicit preferences, and to measure and analyze conflicts between and within stakeholder groups regarding the performance of an action. The framework uses three novel artifacts: i) CAR-CE a method for preference elicitation, ii) two indices, one for measuring the conflict within one stakeholder group, one for measuring the conflict between two stakeholder groups, and iii) an approach to portfolio optimisation and robustness analysis. XPLOR is a web-application that is used to explore and visualise stakeholder conflicts. POLA is a web-application for evaluating commercial development policy in cooperation with key stakeholders. The last artifact, SENSE, is a method for sensitivity analysis of portfolios.

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# Sammanfattning

Beslutsproblem som involverar många intressenter karaktäriseras ofta av att intressenterna har motstridiga preferenser. Sådana problem kan med fördel struktureras och analyseras som multikriterieproblem, där de övervägda handlingsalternativen bedöms utifrån ett antal kriterier. I vissa fall ökar problemkomplexiteten när målet är att välja en kombination (en portfölj) av handlingsalternativ. Ytterligare en aspekt att ta hänsyn till är att valet av en eller flera handlingsalternativ ofta påverkar intressenterna under en lång tid, vilket kan leda till kostsamma och tidskrävande konflikter.

I avhandlingen presenteras artefakter i formen av metoder och webbapplikationer som kan användas som stöd för en beslutsfattare med att belysa den eventuella oenighet som kan finnas mellan intressenter. Fyra artefakter har utvecklats: DANCE är ett ramverk av metoder som används för att elicitera preferenser, och för att mäta och analysera konflikter mellan och inom intressentgrupper gällande handlingsalternativ. DANCE använder följande nyutvecklade metoder i) CAR-CE är en metod för elicitering av preferenser, ii) två konfliktindex, den ena för att mäta konflikten inom en intressentgrupp och den andra för att mäta konflikten mellan två intressentgrupper, samt iii) en metod för att ta fram portföljer av handlingsalternativ med olika nivåer av associerad konflikt och för att utföra en robusthetsanalys av handlingsalternativen. XPLOR är en webbapplikation som används för att utforska och visualisera intressentkonflikter. POLA är en webbapplikation som används tillsammans med intressenter för att modellera och analysera hållbara handelspolicys.

Utvecklingen av artefakterna har följt design science, där målet är att de utveckla artefakter som löser ett praktiskt problem, och där artifakterna i det här fallet har utvärderats mot ett antal krav. CAR-CE implementerades i ett webb-baserat frågeformulär som sedan i samarbete med Upplands Väsby kommun skickades till ett urval av invånarna. De insamlade preferenserna används i illustrativa scenarier för att demonstrera funktionaliteten hos DANCE och XPLOR. POLA demonstrerades i tre exempel baserade resultat från workshops utförda tillsammans med kommunerna Norrköping, Katrineholm och Filipstad. Sammantaget stödjer artefakterna beslutsfattare i att modellera och analysera beslutsproblem, med syftet att i minska risken för kostsamma och tidskrävande konflikter vid planering av markanvändning.

# List of Papers

The following papers, referred to in the text by their Roman numerals, are included in this thesis.

Paper I: Tobias Fasth, Aron Larsson, and Maria Kalinina. Disagreement Constrained Action Selection in Participatory Portfolio Decision Analysis. *International Journal of Innovation, Management and Technology*, 7(1):1–7, 2016.

Paper II: Tobias Fasth, Aron Larsson, Love Ekenberg, and Mats Danielson. Measuring Conflicts using Cardinal Ranking: An Application to Decision Analytic Conflict Evaluations. *Advances in Operations Research*, Article ID 8290434, 14 pages, 2018.

Paper III: Tobias Fasth, Samuel Bohman, Aron Larsson, Love Ekenberg, Mats Danielson, Portfolio Decision Analysis for Evaluating Stakeholder Conflicts in Land Use Planning, *Submitted journal manuscript*.

Paper IV: Tobias Fasth, and Aron Larsson. Sensitivity Analysis in Portfolio Interval Decision Analysis. In *Proceedings of the Twenty-Sixth International Florida Artificial Intelligence Research Society Conference*, pages 609–614, 2013.

Paper V: Samuel Bohman, Tobias Fasth, A Web-Based Visualization Tool for Exploring Stakeholder Conflicts in Land Use Planning, *Transactions in GIS*, In press.

Paper VI: Aron Larsson, Tobias Fasth, Mathias Wärnhjelm, Love Ekenberg, and Mats Danielson. Policy Analysis on the Fly with an Online Multi-Criteria Cardinal Ranking Tool. *Journal of Multi-Criteria Decision Analysis*, 25(3-4): 1—12, 2018.

## Related Publications (not included in the thesis):

- Tobias Fasth, and Aron Larsson. Portfolio Decision Analysis in Vague Domains. In *Proceedings of the 2012 IEEE International Conference on Industrial Engineering and Engineering Management*, pages 61–65, 2012.
- Tobias Fasth, Aron Larsson, and Love Ekenberg. Attitude Ranking. In: Love Ekenberg, Karin Hansson, Mats Danielson, Göran Cars et al. *Deliberation, Representation, Equity: Research Approaches, Tools and Algorithms for Participatory Processes*, pages 133–142. Open Book Publishers, 2017.

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# Contents

# Abbreviations

| | |
|---|---|
| **AHP** | Analytic Hierarchy Process |
| **BtC** | Benefit-to-Cost |
| **CA** | Conflict Analysis |
| **CAR** | Cardinal Ranking |
| **CAR-CE** | Cardinal Ranking for Conflict Evaluations |
| **CDIO** | Conceive – Design – Implement – Operate |
| **CI** | Core Index |
| **DA** | Decision Analysis |
| **DANCE** | Decision Analytic Conflict Evaluation |
| **DS** | Design Science |
| **DSRM** | Design Science Research Methodology |
| **DSRP** | Design Science Research Process |
| **MACBETH** | Measuring Attractiveness by a Categorical Based Evaluation Technique |
| **MAUT** | Multi-Attribute Utility Theory |
| **MAVT** | Multi-Attribute Value Theory |
| **MCDA** | Multiple Criteria Decision Analysis |
| **MO** | Mathematical Optimisation |
| **MOZOLP** | Multi-Objective Zero–One Linear Programming |
| **PDA** | Portfolio Decision Analysis |
| **PDM** | Participatory Decision Making |
| **PROBE** | Portfolio Robustness Evaluation |
| **PROMETHEE** | Preference Ranking Organisation Method for Enrichment Evaluations |

| | |
|---|---|
| **ROC** | Rank Order Centroid |
| **RPM** | Robust Portfolio Modeling |
| **RR** | Rank Reciprocal |
| **RS** | Rank Sum |
| **SKL** | Swedish Association of Local Authorities and Regions |
| **SMART** | Simple Multiattribute Rating Technique |
| **SMARTER** | SMART Exploiting Ranks |
| **SMARTS** | SMART using Swings |
| **VMT** | Value Measurement Theory |

# Acknowledgements

First of all, I would like to express my deepest gratitude to my supervisor Aron Larsson, and my co-supervisors Love Ekenberg and Lisa Brouwers for your support and guidance. I would also like to thank my co-authors in various papers, Samuel Bohman, Mats Danielson and Maria Kalinina for valuable discussions and great collaboration. Thanks to Göran Cars, Karin Hansson and Mathias Wärnhjelm for great cooperation and project management during the two research projects. My fellow Ph.D. students within the DECIDE Research Group and at the department who contributed to a stimulating research environment, thank you, Anton, Isak, Osama, Javier, Beatrice, Irvin, and Ram. Last, but not least, I would like to thank my family, without you this thesis would never have existed.

# 1. Introduction

This thesis examines the design of artifacts within the area of Decision Analysis (DA). The goal of the artifacts is to support participatory decision making (PDM) processes in situations with conflicting interests, particularly in land use planning cases. DA is the realisation of decision theory, where the decisions are structured and analyzed (Keeney and Raiffa, 1994; Raiffa, 1968) with the aim of supporting a decision maker in making better-informed decisions (Keeney, 2004). In this thesis, PDM is defined as an approach that actively engages and involves the participants in the decision-making process. For instance, a decision problem where a municipality involves the citizens in the process of choosing which actions to implement in the future, such as to "Offer more waterfront residences" or to "Renovate old schools". The decision problems are formulated, structured and analyzed as Multiple Criteria Decision Analysis (MCDA) problems, which is also closely related to how humans make decisions (Greco et al., 2016). In MCDA, the performance of the actions are evaluated in terms of multiple criteria, and the criteria are given weights. The role of the criteria is to describe the factors that are considered to be important (e.g., the actions' "environmental" or "social/economic" impact) when making the decision, see, for example, (Belton and Stewart, 2002; Greco et al., 2016).

The complexity of the problem may increase in situations where the decision makers want to select multiple actions (a sub-set) from a larger set of actions. In these situations, the actions can either be modeled as packages of actions where the performance of each package is evaluated (Bana e Costa, 2001; Danielson et al., 2007, 2008) or as portfolios of actions where each action is evaluated individually. This latter approach is often referred to as Portfolio Decision Analysis (PDA), see (Liesiö et al., 2007, 2008; Lourenço et al., 2012; Phillips and Bana e Costa, 2007) for implementations. One motivation to choose a PDA approach in a PDM setting is that the chance of finding compromises between the stakeholders increases when the goal is to choose a portfolio of actions rather than choosing one single action (Salo and Hämäläinen, 2010).

Unfortunately, PDM problems often lead to conflicts between stakeholders. The actions may, for example, have a long-term impact on the daily lives of the stakeholders and the stakeholders will naturally have different views and values. This may lead to conflicting and diverging opinions regarding the actions under consideration. Thus, it is not surprising that these decision problems are often characterised by time-consuming and costly conflicts, which may delay the decision process (Danielson et al., 2007, 2008; Hansson et al., 2012).

Thus, it is of interest to highlight conflict-prone actions. Conflict Analysis (CA) is a group of methods that support this type of analysis. CA methods use the preferences stated by the stakeholders to analyze the degree of conflict, such as in the performance of alternatives (Bana e Costa, 2001), in criteria weights (Luè and Colorni, 2015; Ngwenyama et al., 1996), or in rankings (Cook et al., 1997; Ray and Triantaphyllou, 1998). The different views of the stakeholders can also be taken into account, for example, by using Decision Conferencing, which is an approach where the stakeholders structure a decision problem led by a facilitator and supported by a decision analytic model (Phillips, 2007).

In PDA, an action is typically associated with a value and a resource (such as cost). Meanwhile, a portfolio is constrained by resources (such as a monetary budget) and possibly other constraints (Salo et al., 2011). However, from a CA point of view, it could be interesting to investigate how conflict-prone the actions are to avoid potential future disputes. These actions could then be associated with a measure of the degree of conflict (instead of a cost). This measure can then be used as an indicator of how conflict-prone each action is, enabling an analysis of robust actions, which is accepted by most stakeholders.

A prerequisite for the CA method is to elicit stakeholder preferences concerning the actions using some elicitation method. Given that having opposing preferences is a concern, the preferences can preferably be elicited relative to a "do nothing" alternative, which makes it possible to distinguish two opposing sides—one positive and the other negative—concerning the implementation of the action.

One group of methods for preference elicitation that have favorable features over methods supporting more precise elicitation, such as being less cognitively demanding and facilitating agreement within groups are rank-ordering methods (Barron and Barrett, 1996a; Kirkwood and Sarin, 1985). These methods rank the elements from the most preferred to the least preferred (Barron, 1992; Barron and Barrett, 1996b; Stillwell et al., 1981), which results in the obvious drawback of not considering more precise preference information (Jia et al., 1998). The Cardinal Ranking (CAR) method preserves more precise information. In addition to the rank order, CAR takes the strength of preference between ordered pairs into consideration (Danielson and Ekenberg, 2016; Danielson et al., 2014).

Another important aspect to consider when managing conflicts is a sensitivity analysis of the results. A sensitivity analysis of the decision model is often conducted with the purpose of investigating how a change in a certain value, such as due to uncertainty, will affect the results (Belton and Stewart, 2002). This uncertainty or imprecise information can, for example, be modeled as interval statements (Danielson and Ekenberg, 1998).

The research presented in this thesis is part of two research projects: the Formas funded project "Multimodal Communication for Participatory Planning and Decision Analysis: Tools and Process Models", and the Swedish Association of Local Authorities and Regions (SKL) funded project "Decision support for municipal policy". These research projects were conducted in co-operation with stakeholders. The formulation of the overall research problem was based on the problems identified through meetings and discussions within the project groups, consisting of researchers and public officials.

In the first project, we developed the Decision ANalytic Conflict Evaluation (DANCE) framework (a series of interconnected methods) for preference elicitation, and to measure and analyze potential conflicts regarding an action's performance in multi-stakeholder multi-criteria problems. The DANCE framework utilises three novel methods, i) CAR for conflict evaluations (CAR-CE) an application of the CAR method for preference elicitation, which enables statements regarding the performance of the actions relative a "do nothing" action, ii) two indices for measuring the conflict within and between stakeholder groups regarding the performance of an action, and iii) an approach to portfolio optimisation and robustness analysis. CAR-CE was implemented in a web-questionnaire survey and was used in a real world survey in cooperation with Upplands Väsby municipality. The conflict indices and the approach to portfolio optimisation were implemented in XPLOR, which is a web-based visualisation tool for exploring stakeholder conflicts in land use planning. The project also resulted in SENS a method for portfolio sensitivity analysis. The result of the research was documented in Papers I–V.

In the second project, we developed POLA, a web-based tool to facilitate participatory land use planning. POLA was demonstrated in three examples based on results from workshops conducted together with the municipalities of Norrköping, Katrineholm and Filipstad. POLA was developed in close collaboration with the problem owner, with the aim of facilitating interaction between stakeholders to identify their conflicting objectives and to develop a common sustainable land use plan, see Paper VI.

In summary, the use of these artifacts can help decision makers to identify actions that could potentially lead to conflicts, and thereby support a pro-active management of these actions before they become issues of costly and time-consuming conflicts.

## 1.1 Research Questions

The overall research question guiding the research process is:

> *How can decision analysis be used as a foundation to evaluate stakeholder conflicts in multi-stakeholder problems?*

Two sub-questions address the overall research question:

I. *How can conflict between stakeholders be modeled and measured in a multi-stakeholder multi-criteria decision problem? And, what are the properties required when eliciting preferences?* (Papers I, II, III and VI)

II. *How can portfolio decision analysis, including sensitivity analysis, be utilised in the context of conflicting stakeholders?* (Papers I, III, IV, and V)

The purpose of this thesis is to support decision makers in multi-stakeholder multi-criteria decision problems to elicit preferences, model, measure and highlight stakeholder conflicts. The relationship between the research questions, the developed artifacts and the papers are presented in Figure 1.1.

## 1.2 Disposition

The rest of this thesis is structured as follows. The current chapter presents the introduction of the research problem and the research questions. The second chapter presents the underlying theoretical framework of the thesis and it introduces multiple criteria decision analysis, preference elicitation, portfolio decision analysis, conflict analysis, and participatory decision making. The third chapter presents the methodological framework, consisting of an introduction to design science, the research projects, the requirements and the evaluation of the artifacts, and ethical considerations. The fourth chapter provides a summary of the papers. The fifth and last chapter presents a discussion and describes the prospects for further research.

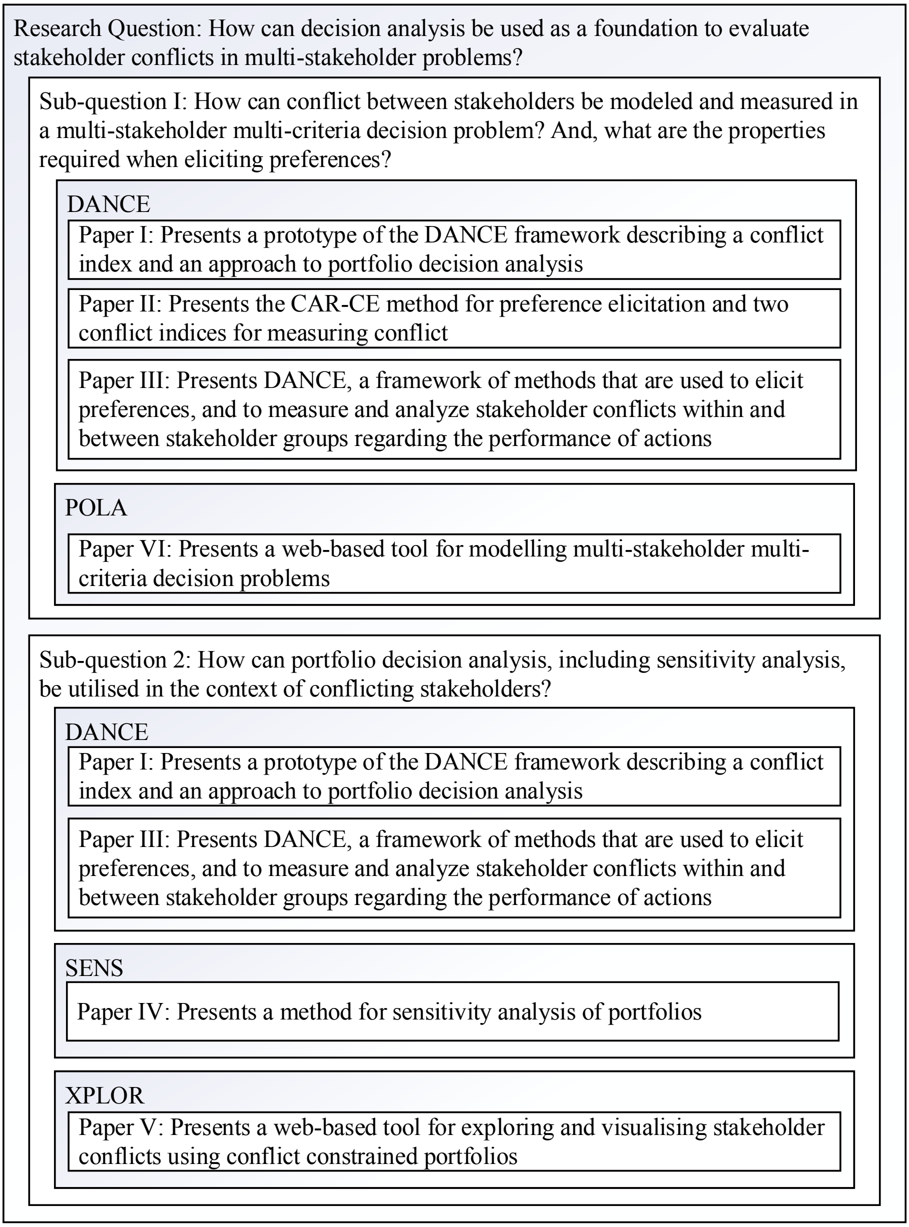


**Figure 1.1:** The relation between the research questions, the developed artifacts and the papers.

# 2. Background

This chapter describes the research on which the papers included in this thesis have been based. It is divided into five sections, which describe the related theories and methods.

## 2.1 Multi-criteria Decision Analysis

When making a decision, the performance of the alternatives can often be judged from different viewpoints/criteria, which also is related to how humans make decisions (Greco et al., 2016). MCDA helps to structure a decision problem, to challenge preconceived ideas and to explore new ones. It should not be regarded as being a replacement for intuitive judgment; rather it should be considered to be a complement (Belton and Stewart, 2002).

Decision problems structured with multiple criteria often involve conflicting criteria. Conflicts between criteria occur in situations when the criteria interact. For example, in a decision problem of choosing a car, a performance criterion will most probably conflict with a cost criterion because an increase in performance will likely increase the cost. The criteria are then used to assess the performance or attractiveness of the alternatives, with the final goal of choosing the most desirable (Belton and Stewart, 2002). A general method for MCDA consists of the following three parts: a set of alternatives, two or more criteria, and one or more decision-makers (Greco et al., 2016).

The process for MCDA can be described as consisting of the following three phases, where the goal is to: i) structure and identify the problem, ii) build and use the model, and iii) create appropriate action plans. In the first phase, the stakeholders create a shared view of the problem, the decision, and the evaluation criteria. In the second phase, the model is developed. In the third phase, the results are used to formulate action plans (Belton and Stewart, 2002).

### 2.1.1 Methods

The aim of the decision (i.e., to choose, rank, sort or describe alternatives) may, as described by Belton and Stewart (2002), vary depending on the type of decision problem. These four aims (or problematics, initially described in (Roy, 1996)) define in what manner the decision problem is analyzed and how the results will be presented. In the choice problematic, one single alternative is chosen from a set of feasible alternatives. In the sorting problematic, the alternatives are sorted into predefined categories, which describe certain characteristics; for example, if they are acceptable or not acceptable for implementation. In the ranking problematic, the alternatives are ranked by order of preference. In the fourth problematic, description, the alternatives and their associated consequences are described. In addition to these four problematics, (Belton and Stewart, 2002) describe two more: the design problematic and the portfolio problematic. In the design problematic, the decision objectives are used to guide the generation of new alternatives; see, for example, (Keeney, 1996). In the portfolio problematic, the goal is to select a subset of alternatives. A common characteristic in portfolio problems is the existence of interactions between alternatives, see, for example, (Salo et al., 2011).

Furthermore, Belton and Stewart (2002) categorise MCDA methods into three groups: i) value measurement methods, ii) goal and aspiration methods, and iii) outranking methods. In value measurement methods, the alternatives are given criterion-specific scores, representing the decision maker's preferences. These scores are then aggregated into an overall score for each alternative, see, for example, (French, 1988; Keeney and Raiffa, 1994; Von Winterfeldt and Edwards, 1986). In goal and aspiration methods, satisfaction levels are defined for each criterion. These are then used to explore which alternatives satisfy the performance levels, see, for example, (Lee and Olson, 1999; Simon, 1997; Wierzbicki, 1999). In outranking methods, the alternatives are pairwise compared to each criterion to identify the dominance relations between the alternatives. This preference information is then aggregated to find the most preferred alternative, see, for example, (Roy, 1996; Vincke, 1999).

The aim of the decision problems, and the methods and applications developed and used in this thesis are part of the choice and the portfolio problematics. This has been operationalised by the use of Value Measurement Theory (VMT), and more specifically Multiattribute Value Theory (MAVT), which are described in the following section.

### 2.1.2 Multiattribute Value Theory

MAVT is based on the VMT, which describes how to associate a value $V(a)$ to an alternative $a$. This value information can be used to describe the preference order of alternatives, such that alternative $a$ is strictly preferred to alternative $b$ ($a \succ b$), and if and only if $V(a) > V(b)$, and that indifference exist between $a$ and $b$ ($a \sim b$), if and only if $V(a) = V(b)$. It is important to note that the preference order must be complete; that is, the relation between two alternatives must be either strictly preferred or indifferent. The preferences and indifferences must also be transitive, for example if $a \sim b$ and $b \sim c$, then $b \sim c$ must hold (Belton and Stewart, 2002).

To model preferences, the first step is to create a partial value function $v_i(a)$ for each criterion $i$. Similarly to the preference order described above, it must hold that if alternative $a$ is preferred to alternative $b$ with regard to criterion $i$, then also $v_i(a) > v_i(b)$ must hold as well, and analogously for the indifference relation. To describe the strength of preference between a pair of alternatives, and not just their ordering, each criterion $i$ can have an associated attribute $z_i(a)$; that is, $v_i(z_i(a))$, often simplified to $v_i(a)$ (Belton and Stewart, 2002). For instance, in a car choice decision problem, one criterion might be performance and the associated attribute will be horsepower.

Value function methods, such as MAVT, use both preference information regarding the performance of the alternatives in terms of the criteria, and information regarding the relative weight of each criterion. This information is then aggregated for each alternative into an overall score. Additive aggregation is a common approach to aggregation (Eq. 2.1). The value of an alternative $a$ is denoted by $V(a)$. The performance of alternative $a$ in terms of criterion $i$ is denoted by $v_i(a)$, and the weight of criterion $i$ is denoted by $w_i$ (Belton and Stewart, 2002).

$$V(a) = \sum_{i=1}^{m} w_i v_i(a) \tag{2.1}$$

Multiattribute Utility Theory (MAUT) is an extension to MAVT, which takes probabilities and statistical expectations into consideration to model uncertainty (Belton and Stewart, 2002). For a detailed explanation, see (Keeney and Raiffa, 1994).

### 2.1.3 The DELTA method

DELTA is a framework for decision analysis which supports numerically imprecise information. The imprecision can either be expressed as comparative statements—that is, 'the probability of consequence $c_{ij}$ is greater than the probability of consequence $c_{kl}$', which corresponds to $p_{ij} \geq p_{kl}$—or as interval statements—for example. 'the probability of consequence $c_{ij}$ has a weight that lies between $a_k$ and $b_k$', which corresponds to $w_i \in [a_k, b_k]$. The imprecision is modeled in two constraint sets, the probability (or weight) base $P$ where the probabilities (or weights) sum to 1 ($\sum_j p_{ji} = 1$), and the value (or utility) base $U$. For each alternative $A_i \in \{A_1, ..., A_n\}$, a consequence set $C_i = \{C_{i1}, ..., C_{ih_i}\}$ is used to represent the consequences of that alternative.

This consequence set and the two bases $P$ and $U$ are captured in an information frame $\langle\{C_1,...,C_n\},P,U\rangle$ (Danielson and Ekenberg, 1998; Danielson et al., 2003).

The strength $\delta_{ij}$ is measured by taking $E(C_i) - E(C_j)$, which is the same as $\sum_k p_{ik} \cdot v_{ik} - \sum_k p_{jk} \cdot v_{jk}$. The strength of alternatives ${}^{PV}\max(\delta_{ij})$ is calculated by choosing the combination of values and weights that is most favorable to $E(C_i)$, and the combination that is least favorable to alternative $E(C_j)$, that is ${}^{PV}\max(\delta_{ij} = {}^{PV}\max(E(C_i))$ - ${}^{PV}\min(E(C_j))$, ${}^{PV}\min(\delta_{ij} = {}^{PV}\min(E(C_i))$ - ${}^{PV}\max(E(C_j))$. However, in some situations, the one alternative might not dominate the other alternative since the results overlap. In such a situation, the dominance relation can be further analysed by contracting the bases. Let $X$ denote a base with the variables $x_1,...,x_n$, with their focal points $k = (k_1,...,k_n)$ and where $x_i \in [a_i, b_i]$,. Let $\pi \in [0,1]$ be the level of contraction. The contraction is then conducted by including $\{x_i \in [a_i + \pi \cdot \pi_i \cdot (k_i - a_i), b_i - \pi \cdot \pi_i \cdot (b_i - k_i)] : i = 1,...,n\}$ in $X$ (Danielson et al., 2003).

## 2.2 Preference Elicitation

This section presents techniques for the elicitation of performance scores, value functions and criteria weights.

### 2.2.1 Scores

Scoring is the elicitation of a decision maker's preferences regarding the performance of the alternatives in terms of the criteria. Hence, scoring is the act of stating how 'attractive' an alternative is in terms of a certain criterion. In value theory, scores lie in an interval measurement scale. On such a scale, the distance between two consecutive points is of equal size. A measurement scale consists of two reference points: the lower and upper bound of the scale. Usually, these points are assigned the values 0 and 100, respectively. Two types of scales can be distinguished, the local and the global scale. A local scale is only based on the values of the alternatives under consideration. The worst alternative is given the value 0 and the best alternative is given the value 100. All other alternatives are given values in between these two reference points. A global scale includes values that lie outside the boundaries of the local scale. These values could be the worst or best possible values of alternatives that are not included in the analysis (Belton and Stewart, 2002). The following three sections present methods for eliciting scores and for defining a partial value function.

**Indirect Methods** Two approaches for creating partial value functions, as described in Belton and Stewart (2002), are the Bisection method and the Difference method. In the Bisection method, the goal is to identify the values on the attribute scale (the 'real world' values of the attribute/criterion) that correspond to three midpoints on the value scale. First, the value on the attribute scale that corresponds to the halfway value of the value scale is identified. Then, the two halfway values between the two endpoints and the midpoint are defined similarly (Von Winterfeldt and Edwards, 1986; Watson and Buede, 1988).

The Difference method determines how much a certain amount of increase in value on the attribute scale is worth on the value scale. This approach can be conducted in different ways. For example, Watson and Buede (1988) presented a method where the attribute scale is divided into a number of sub-intervals. The intervals are then ranked based on the increase in value. The shape of the value function can then be outlined based on the ranking. Von Winterfeldt and Edwards (1986) presented another method, where the first step is to define a unit level. This unit level is suggested to be 1/10 to 1/5 of the difference in value between the endpoints of the attribute scale. The second step determines how large the increase in value from the unit level to a higher value must be to be worth the same as an increase from the minimum attribute value to the unit level. This process is then repeated.

**Direct Rating Methods** The second family of elicitation methods is direct ratings. The first step in the direct rating approach is to define the endpoints. When using a local scale, the best alternative is given the value 100, and the worst the value 0. The other alternatives are then assigned values relative to the endpoints (Belton and Stewart, 2002).

**Pairwise Comparisons Methods** Lastly, the method used by both MACBETH (Bana e Costa and Vansnick, 1994; Bana e Costa et al., 2005) and AHP (Saaty, 1980; Saaty and Vargas, 2012) compares the alternatives pairwise. This approach determines the strength of preference between all pairs of alternatives. However, an obvious drawback with this method is that $n(n-1)/2$ comparisons are needed.

### 2.2.2 Weights

Criteria weights are scaling constants used to relate the different value scales. The weights should be based both on the importance of the criteria and the actual value scales used to score the actions (Belton and Stewart, 2002).

**Swing** One way of eliciting weights is to use the Swing method. Its first step is to determine a ranking of the criteria. The criterion that gives the greatest increase in value when swinging its attribute value from the worst value to the best value is ranked as the most important criterion. This process is then repeated for the remaining criteria. When all criteria are ranked, the weights are determined by estimating the swings' relative values, by comparing the highest ranked criterion's swing value relative to the second-ranked criterion's swing value. This process is then repeated. The weights are then normalised to sum to either 1 or 100 (Belton and Stewart, 2002).

**Rank-order Methods** Another family of weight elicitation approaches are the Rank-order methods. These methods take a rank order of the criteria and convert it into cardinal weights. Three common methods are Rank Sum (RS) weights, Rank Reciprocal (RR) weights (Stillwell et al., 1981), and Rank Order Centroid (ROC) weights (Barron, 1992; Barron and Barrett, 1996a). These methods have features that are attractive compared to more precise elicitation methods, for example being less cognitively demanding, and facilitating agreement within groups (Barron and Barrett, 1996a; Kirkwood and Sarin, 1985). However, even though more precise preference information may exist, these methods do not take this information into consideration (Jia et al., 1998). An extension that takes this more precise information into account is the Cardinal Ranking (CAR) method, which takes a rank order of the criteria and extends it with cardinal information regarding the difference in importance between pairs of criteria (Danielson and Ekenberg, 2016; Danielson et al., 2014).

**Variations of SMART** Two methods which utilise the ROC method and the Swing method are SMARTER (SMART Exploiting Ranks) and SMARTS (SMART using Swings) (Edwards and Barron, 1994). Both methods are refinements of the original SMART (Simple Multiattribute Rating Technique) method (Edwards, 1977), where SMARTS corrected the problem that SMART did not consider the spread (the value range of the attribute scale), and where SMARTER uses the ROC method for calculating weights (Edwards and Barron, 1994).

## 2.3 Portfolio Decision Analysis

In some situations, it is not only of interest to choose one single alternative from a set of alternatives, such as in the choice problematic described in Section 2.1.1, but it is also of interest to choose a set of alternatives (or projects in PDA terminology). In these problems, the selection of projects is constrained by some resource, often a monetary budget. Often, such problems are referred to as Portfolio Decision Analysis (PDA) problems (Salo et al., 2011).

The portfolio problem is a common type of decision problem and is an important part of decision analysis (Salo et al., 2011). PDA has been widely applied in various domains, see among others, for example (Cardinal et al., 2011; Phillips, 2011; Toppila et al., 2011). Typical characteristics of projects in PDA are that they i) have shared resources; ii) are comparable in some aspect, for example in associated cost; iii) have relations between them, for example the choice of one project will affect the attractiveness of another; and iv) the organisation has a shared interest in the portfolio (Salo et al., 2011).

Fasolo et al. (2011) describe a simple generic model for PDA. Consider a set $I = \{1, ..., i\}$ of projects, where the decision variable $x_i = \{0, 1\}$ denotes the inclusion or exclusion of the $i$th project from a portfolio. The composition of a portfolio is described by a decision vector $x = (x_1, ..., x_i)$. A function $f()$ is used to map the portfolios to a space of consequences which are evaluated by a value function $v()$. A resource constraint $B$ is used to constrain the portfolio, and a cost function $c(x)$ to calculate the portfolio cost. The set of projects $I$ can be divided into subsets representing units within the organisation.

It can be problematic to generate all portfolios because the number of portfolios is $2^n$, where $n$ is the number of alternatives. The number of portfolios generated from 10 alternatives is $2^{10} = 1024$, and from 40 projects, 1,099,511,627,776. It is easy to see that the portfolio generation must be conducted in a structured manner. Two commonly used approaches are the benefit-to-cost ratio and mathematical optimisation, which will be described in the following sections.

### 2.3.1 Benefit-to-Cost Ratio

In the benefit-to-cost ratio (BtC) approach, the project's benefit (value) is divided by the project's cost; that is, ratio $= \frac{\text{benefit}}{\text{cost}}$. Based on this ratio, the projects are ordered in descending order, with the most preferred project being the one with the highest benefit per unit cost. The projects are then selected until the resource constraint is reached (Kirkwood, 1997). However, the portfolios found by the benefit-to-cost ratio approaches do not necessarily have to be the same as those found by the mathematical optimisation approach because the portfolio might not be resource efficient. There might, for example be a combination of projects that use the resources more efficiently and provide a higher overall value. Another difference is that the benefit-to-cost ratio only handles one constraint at a time (Kirkwood, 1997). The BtC approach has, as noted in a review of software packages for multi-criteria resource allocation (Lourenço et al., 2008), been applied in the software package HiPriority, and as described in (Phillips and Bana e Costa, 2007), has been implemented in Equity, which has, for example been used in battleship design (Phillips, 2011). It is of note that Equity supports the modeling of organisational units/functions to represent the structure of organisations. (Phillips and Bana e Costa, 2007)

### 2.3.2 Mathematical Optimisation

An advantage of mathematical optimisation (MO), as opposed to the BtC approach, is that it can handle more than one constraint at a time. It is, for example possible to model interdependencies between projects and other constraints (Kirkwood, 1997). One MO approach is to solve a Knapsack problem. Solving a Knapsack problem (Martello and Toth, 1990) yields the portfolio (knapsack) with the maximum overall portfolio value given a resource constraint such as a monetary budget $B$, see Eq. 2.2. An alternative $j$ $(j = 1,...,n)$, has a cost $c_j$ and a value $v_j$. The decision variable $x_j$ is either $x_j = 1$ if the alternative is part of the knapsack or $x_j = 0$ if it is not.

$$\begin{aligned} \text{maximise } & \sum_{j=1}^{n} v_j x_j \\ \text{subject to } & \sum_{j=1}^{n} c_j x_j \leq B \\ & x \in \{0,1\}, i = 1,...,n \end{aligned} \tag{2.2}$$

RPM and PROBE are two prominent methods that are based on value measurement theory. PROBE (Lourenço et al., 2012) and the original PRM (Liesiö et al., 2007) implement a knapsack type approach; RPM later changed its implementation enabling it to solve multi-objective zero–one linear programming (MOZOLP) problems (Liesiö et al., 2008). It is noteworthy that Knapsack problems are NP-hard optimisation problems, which in turn means that there is no known algorithm for solving them in polynomial time. However, pseudo-polynomial algorithms are known for the Knapsack problem and many of its variations (Kellerer et al., 2004). One difference between RPM (Liesiö et al., 2007, 2008) and PROBE (Lourenço et al., 2012) is how they incorporate a sensitivity analysis into the model. Both use incomplete information regarding the projects' costs, the performance scores in terms of the criteria, and the relative weight of each criterion. RPM takes an a priori approach, meaning that uncertain information is included before and used during the portfolio generation, while PROBE uses crisp numbers in the portfolio generation, and then a posteriori includes the uncertain information in the sensitivity analysis. Core Index (CI), RPM's approach to portfolio robustness analysis approach is compelling in its simplicity. The approach takes a set of non-dominated portfolios

$P$, where $p$ is portfolio in $P$, and measures each action $A_j$'s degree of inclusion (that is $0 \leq \mathrm{CI}(A_j), \leq 1$), such that,

$$\mathrm{CI}(A_j) = \frac{\{|p \in P | A_j \in p|\}}{|P|} \tag{2.3}$$

A *core action* is then defined as an action included in all portfolios ($\mathrm{CI}(A_j) = 1$), an *exterior action* is not included in any portfolios ($\mathrm{CI}(A_j) = 0$), and a *borderline action* lies in between ($0 < \mathrm{CI}(A_j) < 1$) (Liesiö et al., 2007, 2008).

Other methods for PDA are, for example, two outranking methods, one based on Electre Tri (Cardinal et al., 2011) and one based on PROMETHEE (Vetschera and de Almeida, 2012), an inverse optimisation method (Gustafsson et al., 2011), and the software packages Expert Choice Resource Aligner, and Logical Decisions Portfolio (Lourenço et al., 2008).

## 2.4 Conflict Analysis

In decision situations with multiple stakeholders, it may be of interest to measure the level of conflict among the stakeholders. This type of conflict analysis can be conducted by using the preferences stated by the stakeholders to measure the degree of conflict.

Beinat (1998) point out that the level of conflict can be measured using a conflict index. With such an index, 0 implies no conflict, and a higher positive value implies more conflict than a lower positive value. Furthermore, they describe that conflict analysis often has four goals: i) to highlight conflicts between stakeholders, ii) to highlight the stakeholders in conflict, iii) to enable the measurement of conflict, and iv) to enable conflict management and negotiation. In this thesis, the focus points of CA are both on software implementations supporting decision makers, and on methods for measuring the degree of conflict related to the alternatives. One such method is presented in Bana e Costa (2001), where the conflict analysis is conducted by, for each alternative, dividing the stakeholders into two subsets: those who thought it was attractive, and those who thought it was unattractive. Two indicators are then defined, representing the collective attractiveness and collective unattractiveness of each alternative. The indicators can then be used to measure the level of conflict. For example, if either indicator is zero for an alternative, this implies that all stakeholders agree that it is either attractive or unattractive, that is there is no conflict. Both indicators' having small values implies a neutral/low-level conflict, and both indicators' having large values implies a conflict-prone alternative. A related type of measure is Ward's method, or the incremental sum of squares method, used in cluster analysis (Rencher, 2003, p. 466). In addition to this, other approaches have been suggested, for example methods for measuring conflicts about criteria weights (Luè and Colorni, 2015; Ngwenyama et al., 1996), and about rankings (Cook et al., 1997; Ray and Triantaphyllou, 1998), and software implementations, such as, a multi-criteria analysis supported spatial decision support system used to investigate stakeholder conflicts (Feick and Hall, 2001), and a public participation GIS system used to support conflict resolution (Zhang and Fung, 2013).

## 2.5 Participatory Decision Making

Land use planning problems often involve the active participation of various stakeholders. In such problems, it is important to find the right balance between the current and the future need of the units of land, while at the same time avoiding stakeholder conflicts. Often, such conflicts arise due to a disagreement between stakeholders regarding, who has the right to the land, the right to participate in the process, and the impact of using the unit of land (Hersperger et al., 2015). To get a better understanding of the types of land use planning conflicts that can arise, and in turn, to make better-informed decisions, von der Dunk et al. (2011, p. 149), created a typology of conflicts. This typology consisted of six types of conflicts: 'noise pollution, visual blight, health hazards, nature conservation, preservation of the past, and changes to the neighborhood'. Typically, the characteristics of such problems, such as involving multiple stakeholders and having multiple conflicting objectives, means that they are well adapted to MCDA; see, for example, (Malczewski and Rinner, 2015).

Another related area is e-Participation, which is characterised by the involvement of multiple stakeholders, often with diverging preferences. In the view of French et al. (2007), e-participation are web-based interactions that are used to support participation. The design and implementation of a participatory process is a time consuming and complex endeavor. For instance, Bayley and French (2007) showed how a participatory process could be structured for a specific context using resource allocation. In their illustrative example, the e-participation process consisted of three phases: formulate, analyze, and decide (based on the decision process described by (Holtzman, 1989)). In each phase, the public and stakeholders were involved at different levels, ranging from no involvement to full involvement. In their example, the formulate phase consisted of six levels, the analyze phase consisted of seven levels, and the decide phase consisted of five levels. In total, this gives $6 \times 7 \times 5 = 210$ different combinations of stakeholder involvement. Related to implementation, French et al. (2007) outlined an architecture for a web-based e-participation, together with a description of the practical issues for e-participation. They note that the most difficult issues are 'behavioral, cognitive, cultural, legal, political, and psychological', and not the technical issues (French et al., 2007, p. 219). These processes must also be evaluated to ensure their quality; different objectives for this have been suggested, see, for example (Beierle, 1998; French et al., 2005). Lastly, in relation to structuring and analysis, French et al. (2007); Gregory et al. (2005) describe that decision analysis, and more specifically MAVT/MAUT (Clemen and Reilly, 2013; Keeney and Raiffa, 1994), can be useful in structuring a participatory process.

Ekenberg et al. (2017) describe a model to analyze participation—the Participatory Analytic Decision Model. This model consists of three interacting layers. The inner layer, conceptualisation, describes the development of public opinion. In the second layer, elicitation, stakeholder data and preferences are elicited. In the third layer, calculation, an MCDA-model describing the problem is developed based on the collected data. Furthermore, they point out that the actual decision problem is commonly defined within the public sphere, which does not provide a representative view of the problem. Therefore, the focus should lie on getting a better understanding of public opinion.

# 3. Methodology

This chapter describes the methodological choices that form how the research presented in this thesis was conducted. This chapter also motivates the choice of research methods and motivates the research process. The research outputs in the studies described in the thesis are artifacts, in the form of methods and applications that can be used in a decision analytic context. The methods developed for supporting decision-makers were based not only on related research but also on interaction and cooperation with the problem owner. Based on the characteristics of the problem and the solution, it is natural to carry out the research following Design Science (DS), which is a methodology used to guide the development of an artifact that solves a humanly defined problem, where the artifact is evaluated by the utility that it provides (March and Smith, 1995). The following sections present the methodology. Section 3.1 describes DS, Section 3.2 describes the research projects and the research processes, Section 3.3 describes the requirements and the evaluation, and Section 3.4 describes the ethical considerations.

## 3.1 Design Science

March and Smith (1995) developed a framework for DS research divided into two parts. The first part consists of four types of artifacts (research outputs): constructs, models, methods, and instantiations. The *construct* is a conceptualisation of the concepts used to describe a problem and its solution. The *model* is a representation of the state of the problem or a solution which outlines the relationships between different concepts. The *method* describes the steps that must be conducted to complete a task, such as algorithms or guidelines based upon concepts and models. The *instantiation* is the realisation or implementation of the constructs, models, and methods. The second part of the framework consists of two research activities: building and evaluating. During the first activity, the artifact (construct, model, method for instantiation) is created to solve a predefined problem with the intent of proving the feasibility of such an artifact. During the second activity, the criteria for evaluating the artifact are developed. The artifact is then assessed against the criteria. The performance of the artifact is measured with the purpose of evaluating the artifact's viability.

Nearly a decade after the introduction of the design science research framework, Hevner et al. (2004) presented guidelines for how DS research should be conducted, evaluated, and presented. Their framework consists of seven guidelines that should be addressed during the research. Briefly, the guidelines state that the artifact should (as mentioned previously) be a construct, model, method, or an instantiation. It should solve some previously unsolved problem or improve an already existing solution. The research should result in contributions to the research area. The artifact should be thoroughly evaluated and the utility of the artifact should be a focus. The development and the evaluation of the artifact should be guided by the use of rigorous methods. The design should be a search process that is based on existing knowledge and theories, and the result is an artifact that solves the defined problem. The results should be communicated to both a technical and a managerial audience.

A few years later, Peffers et al. (2008) introduced the DS Research Methodology (DSRM). The DSRM was based on, and is consistent with, the previous research. It consists of principles, practices, procedures and the DS Research Process (DSRP) describing how to conduct DS research. The DSRP consists of six activities. First, in *Problem identification and motivation*, the problem is identified, defined, and motivated, with the goal of describing and justifying the value of a solution. Second, in *Define the objectives for a solution*, the objectives are defined, for instance, to develop an artifact solving a previously unsolved problem, or to develop an artifact producing more efficient results than the existing solutions. Third, in *Design and development*, the artifact (construct, model, method or instantiation) is developed, and documented in a specification of its functionality and architecture. Fourth, in *Demonstration*, it is shown that the artifact can solve the predefined problem. Fifth, in *Evaluation*, it is examined whether the artifact fulfills the objectives. If the artifact does not fulfill the objectives, then the researchers may go back to activity three to refine the artifact. Finally, in *Communication*, the research is communicated to the research community. It should be noted that these activities do not have to be carried out sequentially.

CDIO is a related approach in engineering practice, which consists of four activities: Conceive, Design, Implement, and Operate. First, in *Conceive*, a general understanding of the problem is formed, and a system is conceptually designed. Second, in *Design*, the system is designed, and the system and its components are described. Third, in *Implementation*, the system is implemented, tested, and validated. Lastly, in *Operate*, the operation of the system takes place, from implementation to retirement, including maintenance and further development (Crawley et al., 2014). The research presented in this thesis was guided by the DS paradigm. Even though CDIO is related, it was not considered to be relevant because it is mainly used in engineering practice.

In this thesis, the research conducted followed the *method framework for design science research* (Johannesson and Perjons, 2014). The framework consists of five activities (similar to the first five activities of the DSRP), in which different research strategies, research methods, and creative methods can be used. The framework consists of the following activities:

**Explicate problem** The problem is identified and defined, and the importance of the problem is motivated.

**Define requirements** An artifact is outlined together with artifact requirements.

**Design and develop artifact** The development of an artifact in accordance with the defined requirements.

**Demonstrate artifact** A demonstration of the artifact showing its feasibility; for example, using an illustrative scenario or a real-life case.

**Evaluate artifact** This examines to what degree the artifact fulfills the requirements and solves the problem.

### 3.1.1 Evaluation and Validation

In DS, the artifact evaluation step is closely related to the notion of validity. For instance, Worren et al. (2002) state that the pragmatic validity of an artifact is shown by evaluating the utility (i.e. the fulfilment of the design objectives/requirements) provided by the artifact. However, even though utility is fundamental in DS, both internal and external validity are important in artifact evaluation. The internal validity describes the degree to which the causal relations between variables can be controlled, while external validity describes to what extent the results can be generalised to other situations (Johannesson and Perjons, 2014).

The goal of the evaluation step in DS is to investigate to what degree the artifact fulfills the design requirements and solves the specified problem. The evaluation strategy can have different characteristics. One characteristic is whether the strategy evaluates an artifact under development and not in use (ex ante) or an operational artifact in use (ex post). A drawback with the former approach is that the evaluation is not conducted on a functional artifact, which may give a false understanding of the artifact's functionality. In the latter approach, the artifact is fully functional and, therefore, can be evaluated more accurately. However, this strategy is more time consuming and requires more resources (Johannesson and Perjons, 2014).

Another type of characteristic is the environment in which the artifact is evaluated. In an artificial evaluation, the artifact is evaluated in an environment created for the purpose of assessing the artifact (for example a laboratory experiment). In a natural environment, the artifact is evaluated in the actual setting for which it was designed. A benefit of an artificial strategy is that it provides a means for obtaining a high internal validity because the evaluation can be conducted in a controlled environment. The naturalistic strategy has the benefit of enabling a high external validity because it is conducted in the environment the artifact is designed for, and the results can thereby be generalised to similar contexts. However, in a complex setting, the strategy may lead to a weaker internal validity because it may not be possible to control some of the interfering factors (Johannesson and Perjons, 2014).

In this thesis, I used the following three approaches in the demonstration and evaluation of the artifacts: i) *logical/informed arguments* to motivate the artifacts' fulfilment of the requirements, ii) *action research* by developing the artifact in close cooperation with the problem owner and demonstrating the artifact using real-world data, and iii) *illustrative scenarios* by showing the artifacts functionality using synthetic or real-world data (Peffers et al., 2012).

An overview of the demonstration and evaluation of the artifacts presented in this thesis is described in Chapter 4. The requirements and the informed arguments are presented in Section 3.3.

### 3.1.2 Research Processes

The research processes used to guide the research are described using IDEF0. An IDEF0 diagram consists of a series of interrelated activities, and four types of channels (Johannesson and Perjons, 2014):

**Input** The type of knowledge input (right pointing arrow).

**Output** The type of knowledge output (left pointing arrow).

**Control** The type of knowledge (research strategies and research methods and creative methods) used as a control (downwards pointing arrow).

**Resource** The knowledge base (upwards pointing arrow).

DS research can be carried out in different contexts. Iivari (2015) distinguishes between two types of DS research: strategy 1 and strategy 2 research. The problem addressed in strategy 1 is of a general form, solving a general problem and without a specific practitioner in mind. In contrast, strategy 2 research address a specific problem, solving a specific problem in close cooperation with the practitioners. The research presented in this thesis is of both types. Research processes 1, 2 and 4 resemble the second type, while research process 3 resembles the first type.

## 3.2 Research Projects

The research was conducted in two research projects "Multimodal Communication" and "Decision Support for Municipal Policy". The "Multimodal Communication" project (Section 3.2.1) consisted of three research processes: DANCE a framework for conflict evaluations, XPLOR a web-based visualisation tool for exploring stakeholder conflicts in land use planning, and SENS a method for sensitivity analysis of portfolios. The "Decision Support for Municipal Policy" project (Section 3.2.2) consisted of the fourth research process, POLA a web-based tool to facilitate participatory land use planning. The research processes are described in Figure 3.5, 3.6, 3.7, and 3.8.

### 3.2.1 Research Project: Multimodal Communication

This section presents an overview of the project and the interaction with the stakeholders. The definition of the problems and the requirements were based on exploitative discussions with the municipality representatives and on discussions between the researchers. Starting in 2012, Upplands Väsby conducted a paper based survey, the SKOP survey, as a basis for their work with the development of a Vision for year 2040. As part of the project, the research group analysed that survey. In the analysis we found areas where the respondents had conflicting interests; for example, between "preserving the nature" and "building new homes". This sparked an idea of combining the actions into portfolios of actions constrained by a conflict measure. As a first step, we developed a method for sensitivity analysis of portfolios (Paper IV). To further investigate the conflicting issues we developed a paper based questionnaire based on both the SKOP survey and on the municipalities vision for 2040. The municipality representatives reviewed the questionnaire and suggested a number of focus groups to which we could send the survey. The results of the questionnaire were presented to municipality representatives. We then developed a web-based questionnaire to further investigate potential areas on conflict. The questionnaire was based on experiences from the two previous surveys, and the idea of conflict constrained portfolios. In parallel we developed a conflict index to measure the actions' associated conflict (Paper I). The design of the questionnaire was discussed within the project group consisting of researchers and representatives from the municipality, and later the results were presented to the municipality. During this time, the elicitation technique and the conflict indices were further developed (Paper II), and the portfolio optimisation (Paper III). Furthermore, early in the project, one idea was to develop a democracy toolbox implemented in a web-portal, among others consisting of tools for negotiation, decision analysis and portfolio decision analysis. This idea evolved into the idea of creating XPLOR, a web-application for visualising the results from the web-based questionnaire (Paper V). XPLOR was later presented to the municipality for feedback.

### Research Process 1: DANCE

The research addresses sub-questions I and II. The artifact developed during the research process was the DANCE framework (a series of methods), which is used to elicit preferences, and to measure and analyze stakeholder conflicts regarding the performance of actions. The artifact was developed iteratively, from a prototype (Paper I, sub-question I and II) to the final artifact which utilises three novel methods: i) CAR-CE, an application of the CAR method, which enables statements regarding the performance of the actions relative a "do nothing" action (Paper II and III, sub-question I); ii) two conflict indices used to measure the conflict within one stakeholder group and between two stakeholder groups (Paper II and III, sub-question I); and iii) an approach to portfolio optimisation and robustness analysis (Paper III, sub-question II). Figure 3.1 shows the relation between sub-questions, artifacts and papers.

The refined problem guiding the research was "How to elicit stakeholder preferences, use the preferences to measure stakeholder conflict, and use the preferences to highlight conflict-prone actions". This problem was based on discussions within the project group consisting of researchers and representatives from the municipality. The definition of requirements was based on a document study where related research were analyzed, and on discussions between the researchers. The requirements—including motivations, sources and how they were elicited—are presented in Section 3.3.1. In the design and development of the artifact, we used creative methods and discussions between researchers to design the artifact. To demonstrate CAR-CE and the conflict indices, we used illustrative scenarios (Paper II). To further demonstrate the preference elicitation method (Paper II), we applied a survey strategy, where an implementation of the method was used in a web-based questionnaire. Johannesson and Perjons (2014) describe that a survey strategy gives a broad but shallow understanding of the subject. In our case, this strategy enabled us to both demonstrate the preference elicitation method and to elicit the preferences from a large group of people. The preference data was then used in illustrative scenarios to demonstrate the conflict indices (Paper II), and the portfolio optimisation and robustness analysis (Paper III). The DANCE framework was evaluated using informed arguments, see Section 3.3.1 for further details.

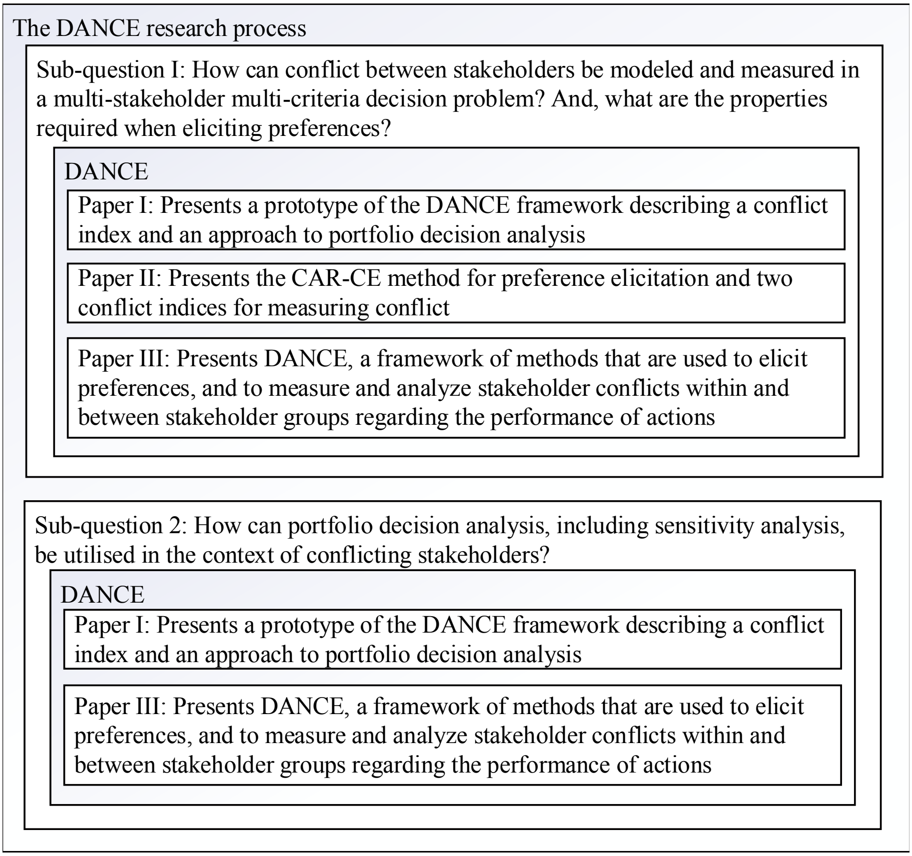


**Figure 3.1:** The relation between sub-questions, artifacts and papers.

### Research Process 2: XPLOR

This research addresses sub-question II. The artifact presented in Paper V, was a web-based application for visualising the stakeholders' conflicts and values regarding a set of actions and for analyzing the robustness of each action. Figure 3.2 shows the relation between sub-question, artifact and paper.

The refined problem guiding the research was "How to visualise stakeholder conflicts using web-based technologies". The problem was based both on discussions within the project group consisting of researchers and representatives from the municipality. The definition of requirements was based on a document study where related research was analyzed, discussions with the municipality representatives, and on discussions between the researchers. The requirements, including motivations, sources and how they were elicited are presented in Section 3.3.2. In the design and development of the artifact, an early design was evaluated by students and the development followed an agile

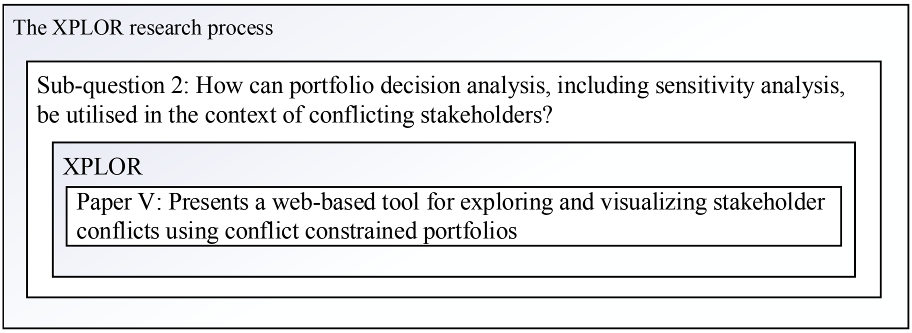


**Figure 3.2:** The relation between sub-question, artifact and paper.

software development approach; for example, by developing the artifact iteratively. The artifact was demonstrated using an illustrative scenario, showing its functionality (Paper V). The illustrative scenario was based on data from the web-based questionnaire survey presented in Paper II. The XPLOR web-application framework was evaluated using informed arguments, see Section 3.3.2 for details.

### Research Process 3: SENS

This research addresses sub-question I, particularly how to conduct sensitivity analysis. The artifact presented in Paper IV was a method extension of the DELTA method, enabling sensitivity analysis of portfolios. The primary motivation for developing this method was that it would support decision-makers in real-world decision problems and because sensitivity analysis is a vital part of any MCDA approach; see, for example, (Belton and Stewart, 2002). It is, therefore, a natural extension of the methods presented in this thesis. Figure 3.3 shows the relation between sub-question, artifact and paper.

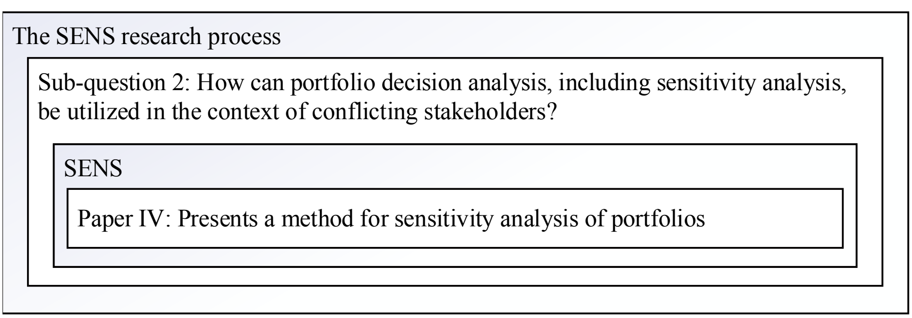


**Figure 3.3:** The relation between sub-question, artifact and paper.

The refined problem guiding the research was "How to extend the DELTA method's approach to embedded sensitivity analysis to include portfolios". The problem explication and the definition of requirements were based on a document study where related research was analyzed, and on discussions between researchers. The requirements—including motivations, sources and how they were elicited—are presented in Section 3.3.3. We used creative methods to design and develop the artifact, such as discussions between the researchers and analysis of related research. The artifact was demonstrated using an illustrative scenario (Paper IV). The method for sensitivity analysis was evaluated using informed arguments, see Section 3.3.3 for further details.

### 3.2.2 Research Project: Decision Support for Municipal Policy

This section presents an overview of the project and the interaction with the stakeholders. The problem definition and the requirement elicitation was based on discussions with the problem owner. Starting in 2013, the problem owner together with the research group noticed a need for a simplified version of the decision analysis software DecideIT. The problem owner drafted an initial system specification, which was discussed within the research group and with the problem owner. Throughout the project, the research group and the problem owner had regular meetings discussing the software development and the requirements. The artefact was further demonstrated using results from workshops conducted together with the three municipalities of Norrköping, Katrineholm and Filipstad. The artifact was also demonstrated during a workshop at SKL with representatives from different municipalities.

**Research Process 4: POLA**

This research addresses sub-question I, particularly how to model conflict between stakeholders. The artifact, presented in Paper VI, was a web-based application for structuring and analyzing commercial development policy decisions in cooperation with stakeholders. Figure 3.4 shows the relation between sub-question, artifact and paper.

The refined problem guiding the research was "How to develop and utilise a web-based multi-criteria decision analysis tool in municipal commercial development, to acknowledge the preferences and objectives from both national and local stakeholders". This project was characterised by active participation of the problem owner through regular meetings. It was, therefore, natural to apply an action research strategy in the activities of the research process. Action research is conducted in the real world, with a focus on changing and evaluating the local practice, and where a key characteristic is the active participation

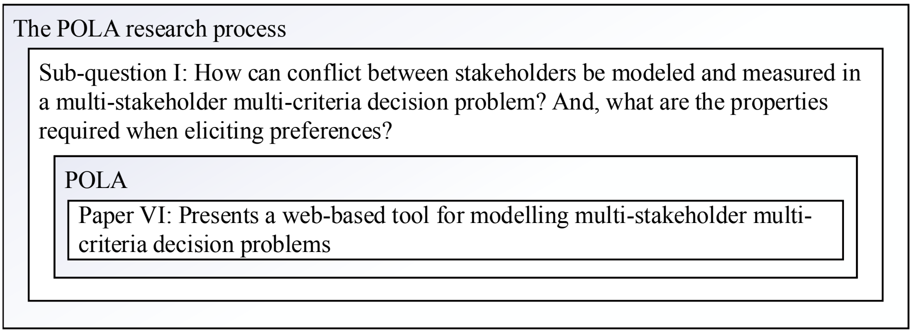


**Figure 3.4:** The relation between sub-question, artifact and paper.

of practitioners, which means that they are active contributors (Johannesson and Perjons, 2014).

To explicate the problem and define the requirements, we used an action research strategy in which the problem was explicated through regular discussions and meetings between the researchers and the problem owner. The requirements—including motivations, sources and how they were elicited—are presented in Section 3.3.4. The artifact was designed and developed using an agile software approach with multiple deliveries to the problem owner. The artifact was demonstrated using results from workshops conducted together with three municipalities (Paper VI). The tool was evaluated using informed arguments, see Section 3.3.4 for further details.

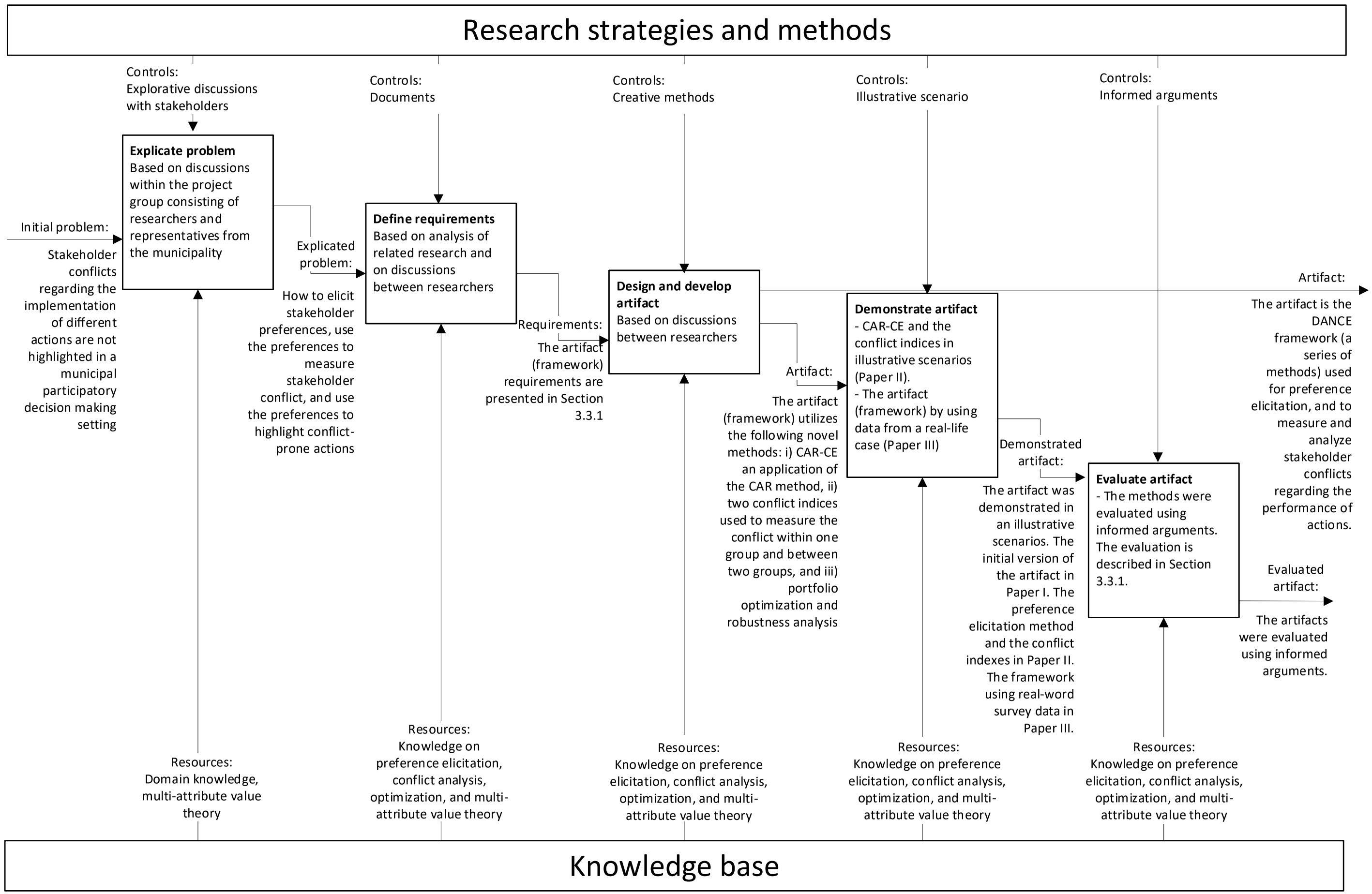


**Figure 3.5:** The research process behind the DANCE framework.

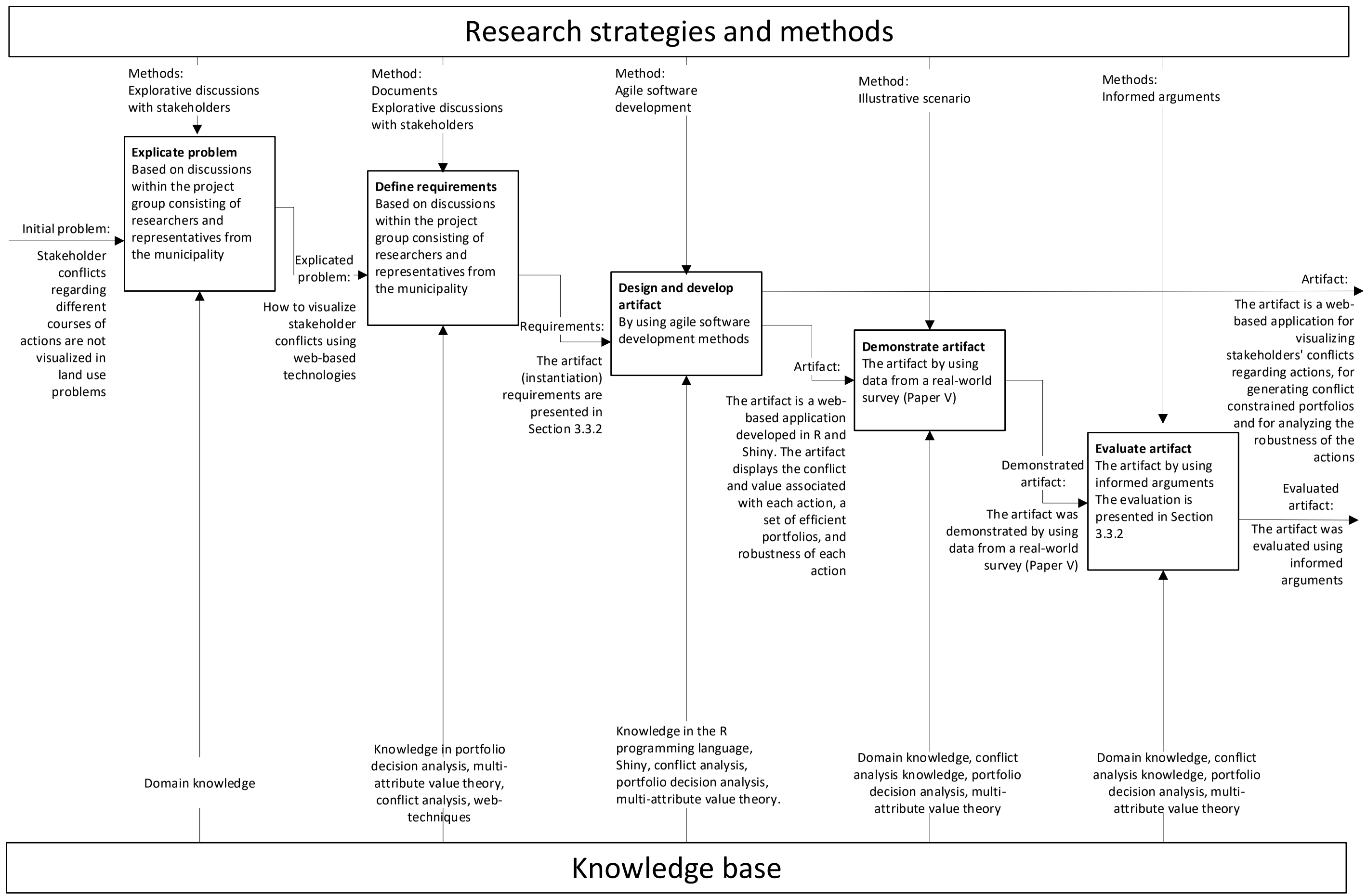


**Figure 3.6:** The research process behind the web-application XPLOR.

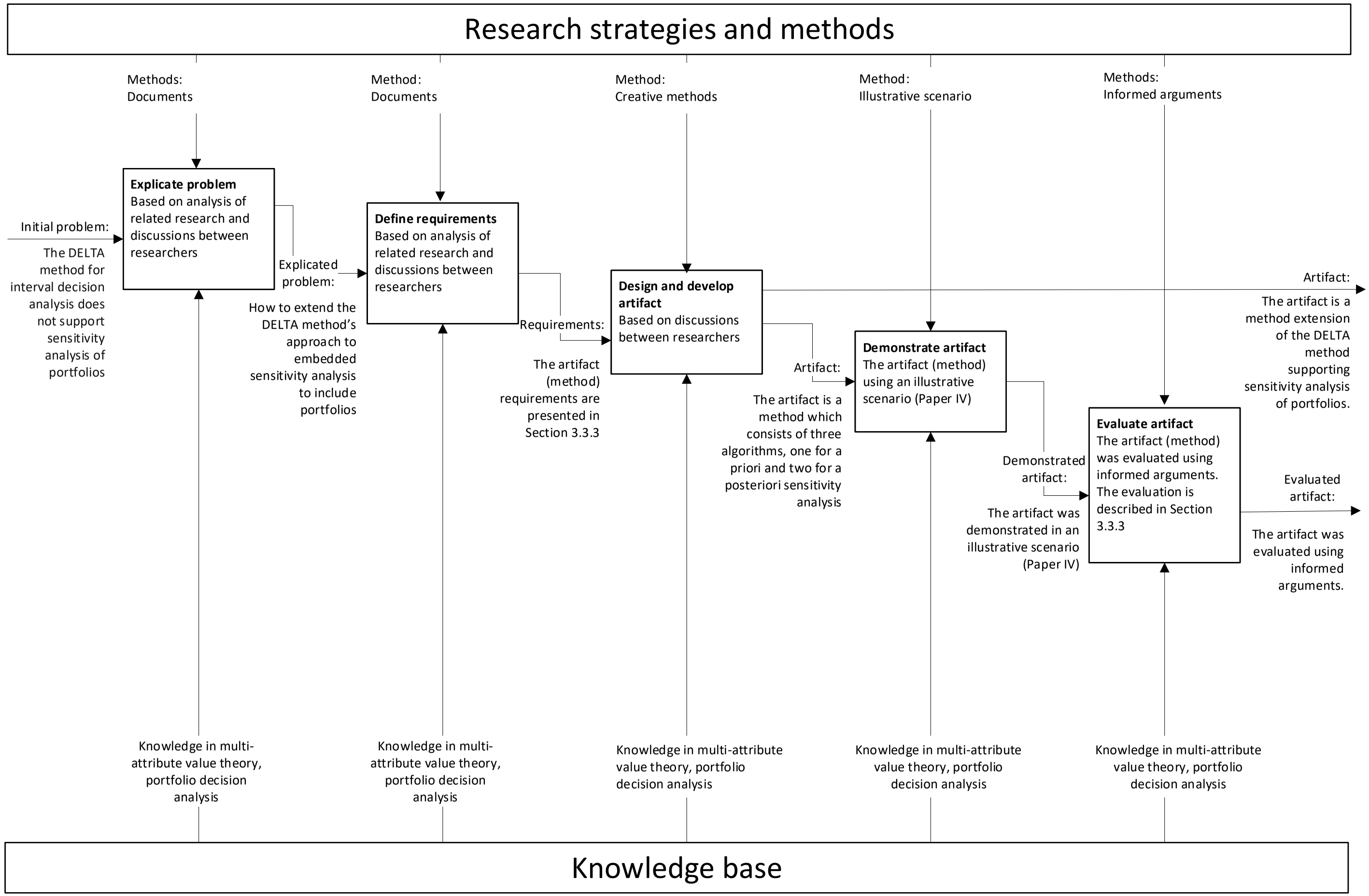


**Figure 3.7:** The research process behind the SENS method for sensitivity analysis of portfolios.

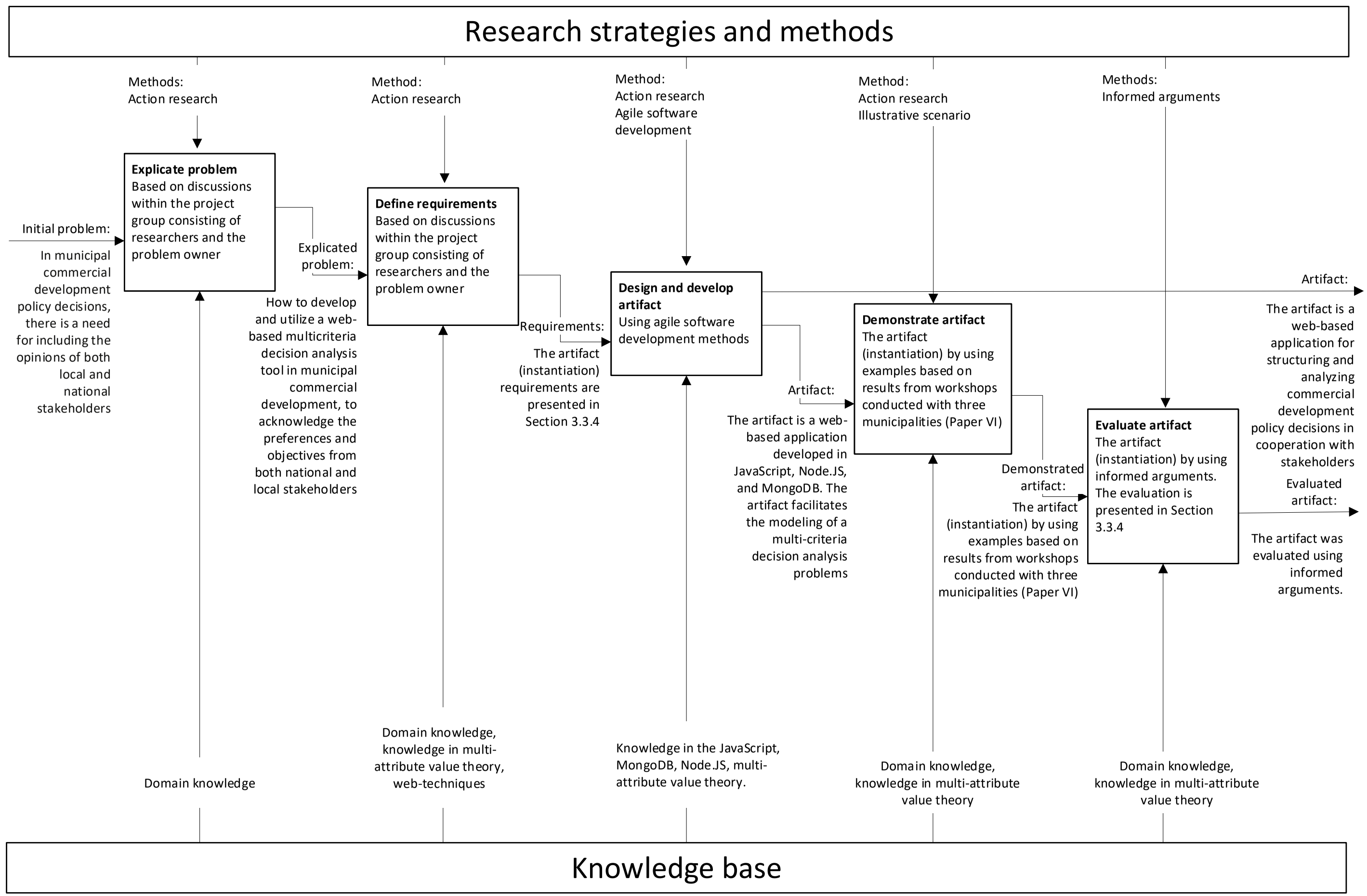


**Figure 3.8:** The research process behind the web-application POLA.

## 3.3 Requirements and Evaluation

This section presents the requirements and the evaluation (in the form of informed arguments) of the four artifacts: the DANCE Framework in Section 3.3.1, XPLOR in Section 3.3.2, SENS in Section 3.3.3, and POLA in Section 3.3.4.

### 3.3.1 DANCE

**Requirement 1.** The elicited preferences should represent a measurable value function.

**Justification** The preferences elicited and used in the conflict indices should be consistent with multi-attribute value theory, and the preferences should represent a measurable value function.

**Source** The preference elicitation method should be based on the theory of measurable multi-attribute value functions (Dyer and Sarin, 1979b).

**How** This requirement was defined by discussions within the research group and by studying the related research literature.

**Evaluation** This requirement was fulfilled. All methods have their foundation in multi-attribute value theory. The CAR-CE method builds upon the theory of measurable value functions.

**Requirement 2.** The elicitation method should capture both negative and positive preferences.

**Justification** By enabling elicitation of both positive and negative preferences regarding the performance of an action, we can easily distinguish two opposing sides.

**Source** This requirement was based on a related solution where negative and positive preferences were elicited (Bana e Costa, 2001), and on the idea of bipolar measurement scales (Grabisch et al., 2008).

**How** This requirement was defined by discussions within the research group and by studying the related research literature.

**Evaluation** This requirement was fulfilled. The preference elicitation method CAR-CE extends the prototype (which has a neutral threshold) with a "do nothing" alternative used as an anchor point between the negative and positive side of the scale.

**Requirement 3.** The conflict indices in the prototype should measure the stakeholder conflict regarding the performance of an action for a specific criterion.

**Justification** It should be possible to measure whether an action is more conflict-prone than another action.

**Source** Early in the project, when analysing the results from the SKOP survey, we noticed the need of measuring stakeholder conflict related to the performance of actions. The idea was communicated and harmonised with the municipality.

**How** Through discussions within the project group.

**Evaluation** This requirement was fulfilled. To measure the conflict (Paper I), the stakeholders are divided into two opposing groups, the con-group who's members stated that the alternative is worse than the neutrality threshold, and the pro-group who's members stated that the alternative is better than the threshold. The distance between the two groups are then measured by subtracting the arithmetic mean of the part-worth values of the two groups.

**Requirement 4.** The conflict indices in DANCE should account for measurable attribute conflict; that is, the indices should account for the difference in value between actions.

**Justification** It should be possible to make statements regarding how good or bad the actions are, these value differences can then be used to measure the actions' associated conflict. The conflict related to the performance on a certain attribute can then be aggregated into an overall action conflict. This supports the highlighting of conflict-prone actions.

**Source** Based on the theory of measurable value functions (Dyer and Sarin, 1979a,b), the ideas of collective attractiveness and unattractiveness (Bana e Costa, 2001), the power balance between stakeholders (Torrance, 1957), and the idea of eliciting negative and positive preferences (Bana e Costa, 2001; Grabisch et al., 2008).

**How** The initial idea of investigating the conflict associated with different actions emerged during the analysis of the SKOP survey. The idea of conflict indices gradually matured, through discussions between the researchers and by reviewing related research, into two conflict indices, one for measuring the conflict within one stakeholder group, and one for measuring the conflict between two stakeholder groups.

**Evaluation** The fulfilment of this requirement is described in detail in Definition 2 (p. 5) and in Section 4.2.1 (p. 5) of Paper II.

**Requirement 5.** The conflict indices in DANCE should measure the attribute conflict between multiple stakeholders; that is, between a set of negative and a set of positive stakeholders.

**Justification** The conflict index should account for multiple stakeholders.

**Source** See Requirement 4.

**How** See Requirement 4.

**Evaluation** The fulfilment of this requirement is described in detail in Section 4.2.1 (pp. 5–6) of Paper II.

**Requirement 6.** The conflict indices in DANCE should account for the power balance between the positive and negative stakeholders.

**Justification** An equal power balance can give a stronger conflict, since it is shown that weak stakeholders are more willing to accept negative consequences (Torrance, 1957).

**Source** See Requirement 4.

**How** See Requirement 4.

**Evaluation** The fulfilment of this requirement is described in detail in Section 4.2.1 (pp. 5–6) of Paper II.

**Requirement 7.** The conflict indices in DANCE should measure the conflict within one stakeholder group and between two stakeholder groups.

**Justification** The conflict indices should measure the conflict within one stakeholder group (for example citizens from one residential area), and the conflict between two stakeholder groups (for example citizens from two residential areas).

**Source** See Requirement 4.

**How** See Requirement 4.

**Evaluation** The fulfilment of this requirement is described in detail in Definition 3 (p. 6) and 4 (pp. 7–8) of Paper II.

**Requirement 8.** The portfolio method should highlight how a change in the portfolio's conflict constraint affects the portfolio composition.

**Justification** When analysing how conflict-prone the actions are, it is interesting to investigate how a change in a project's overall conflict measure affects the portfolio composition, for example, if a change in the conflict measure affects the portfolio composition.

**Source** This requirement was based on the optimisation approach presented in (Lourenço et al., 2012), it was, however, modified to use conflict as a constraining resource instead of a monetary budget.

**How** Through discussions between the researchers.

**Evaluation** This requirement was fulfilled for both portfolio optimisation approaches, the one in the prototype and the one in the DANCE framework. The approaches are based on the approach presented in (Lourenço et al., 2012). The optimisation is conducted multiple times, and for each run the portfolio budget (conflict) is reduced by a small amount. This results in a set of efficient portfolios with different levels of conflict.

**Requirement 9.** The portfolio method in DANCE should enable analysis of both productive (positive) and counter-productive (negative) portfolios.

**Justification** When generating portfolios in order to investigate how conflict-prone and robust the actions are, it is not only interesting to find the productive portfolios; that is, the portfolios with positive values. It is also interesting to investigate the portfolios which gives negative overall portfolio values, so that these can be avoided.

**Source** Through discussions within the research group.

**How** Through discussions within the research group.

**Evaluation** This requirement is fulfilled. In addition of maximising the overall value of the portfolio, the overall value is minimised (Algorithm 1 in Paper III).

**Requirement 10.** It should be possible to measure the robustness of each action in a set of efficient portfolios.

**Justification** This supports the decision maker in highlighting conflict-prone actions.

**Source** This requirement was based on discussions within the research group and the Core Index (Liesiö et al., 2007, 2008).

**How** Through discussions within the research group.

**Evaluation** This requirement is fulfilled. The robustness analysis is conducted using the Core Index (Liesiö et al., 2007, 2008), and by using the two extensions *borderline action sub-types* and *core index slopes* (Section 2.2.3 in Paper III)

### 3.3.2 XPLOR

**Requirement 1.** The application should be web-based.

**Justification** The application should be accessible without installation.

**Source** Based on discussions within the project group, discussions with municipality representatives, and by reviewing related solutions such as the OECD Explorer.

**How** Early in the project, there was an idea of developing a democracy toolbox implemented in a web-portal, among others consisting of tools for negotiation, decision analysis and portfolio decision analysis. This idea evolved into the idea of creating the XPLOR web-application for visualising the results from the web-based questionnaire.

**Evaluation** This requirement is fulfilled. The application was implemented using the R programming language and the web-framework Shiny.

**Requirement 2.** The application should show the conflict and value associated to each action.

**Justification** It should be possible for the users explore each action's associated value and conflict, to get a better understanding of the stakeholders preferences.

**Source** See Requirement 1.

**How** See Requirement 1.

**Evaluation** This requirement is fulfilled. The GUI shows bar charts for the conflict and value associated to each action (the V and D tabs).

**Requirement 3.** The application should show portfolios constrained by a conflict measure and show how robust the actions are.

**Justification** This enables the user to explore the actions that can be conflict-prone so that these can be further explored.

**Source** See Requirement 1.

**How** See Requirement 1.

**Evaluation** This requirement is fulfilled. The application shows a table of all efficient portfolios, the projects included in the portfolios, and the degree of which each action is included (the Core Index (Liesiö et al., 2007)) in a set of non-dominated portfolios.

**Requirement 4.** The user should be able to select two stakeholder groups, based on demographic data.

**Justification** It should be possible for the user to explore the actions' associated preferences and conflicts for different stakeholder groups, in order to get a better understanding of the stakeholders preferences.

**Source** See Requirement 1.

**How** See Requirement 1.

**Evaluation** This requirement is fulfilled. The user can select two stakeholder groups and filter the stakeholder groups based on demographic information (tab G1 and G2).

**Requirement 5.** The application should be open source.

**Justification** It should be possible for others to audit, modify, contribute, and redistribute the source code.

**Source** See Requirement 1.

**How** See Requirement 1.

**Evaluation** This requirement is fulfilled. XPLOR is licensed under the MIT License.

#### 3.3.3 SENS

**Requirement 1.** It should be based on the DELTA framework's embedded form of sensitivity analysis, which is based on the concept of interval contractions.

**Justification** The DELTA framework's embedded form of sensitivity analysis uses interval contractions to study the dominance relation between to alternatives. Fulfilling this requirement will enable the same type of sensitivity analysis to be conducted for portfolios of projects.

**Source** The requirement was based on discussions within the research group and on related research literature, for example (Danielson and Ekenberg, 1998; Fasth and Larsson, 2012)

**How** Early in the project, there was an idea of generating portfolios of actions to highlight the trade-off between value and conflict. As part of this, we developed this method for sensitivity analysis of portfolios.

**Evaluation** This requirement is fulfilled. Paper IV shows how to use interval contractions when conducting sensitivity analysis of portfolios. The use of interval contractions in sensitivity analysis was exemplified in three algorithms.

**Requirement 2.** It should enable a priori (before portfolio generation), and a posteriori (after portfolio generation) sensitivity analysis of portfolios.

**Justification** Sensitivity analysis can be conducted before the portfolio is generated (a priori) or after the portfolio is generated (a posteriori). The two approaches give different insights into how the portfolio is affected by changes in the projects' overall values and costs.

**Source** See Requirement 1

**How** See Requirement 1

**Evaluation** This requirement is fulfilled. Paper IV describes one algorithm for a priori sensitivity analysis, and two algorithms for a posteriori sensitivity analysis.

### 3.3.4 POLA

**Requirement 1.** The application should be web-based.

**Justification** The application should be accessible without installation.

**Source** The problem owner wanted a simplified version of DecideIT. An initial specification of the application was developed by the problem owner. During the development of the application, we had a series of meetings with the problem owner, to guide the development.

**How** The requirements and the development of the artifact was developed though a series of meetings with the problem owner.

**Evaluation** This requirement is fulfilled. The web-application was implemented using Node.js.

**Requirement 2.** The application should implement a method for MCDA for group decision making. Where each stakeholder has its own set of criteria, and where the stakeholders have a common set of alternatives.

**Justification** The user should be able to structure a multi-criteria decision problem, that is to add stakeholders, criteria, alternatives, to weigh the criteria, and score the alternatives against the criteria.

**Source** See Requirement 1.

**How** See Requirement 1.

**Evaluation** This requirement is fulfilled. The application enables the facilitator to add stakeholders, criteria, alternatives, to weigh the criteria, score the alternatives. The application uses an implementation of the DELTA framework (Danielson and Ekenberg, 1998) and an implementation of the CAR method (Danielson and Ekenberg, 2016).

**Requirement 3.** The users should be able to state their preferences using cardinal ranking statements.

**Justification** It should be easy for the users to state their preferences.

**Source** The requirement is based on discussions within the project group.

**How** The requirement is based on discussions within the project group.

**Evaluation** This requirement is fulfilled. The application uses an implementation of the CAR method (Danielson and Ekenberg, 2016).

## 3.4 Ethical Considerations

In the "Multimodal Communication" project we used a web-based questionnaire survey to elicit preferences from citizens in the Upplands Väsby municipality. The invitation letter sent to the respondents contained information regarding the purpose of the study, how the answers were used, that the respondents were anonymous, and who it was that conducted the study. The questionnaire consisted of two parts, i) questions regarding the stakeholder's opinions about 50 potential courses of actions, and ii) questions regarding demography. In addition, the questionnaire system recorded respondents' IP-addresses, to avoid misuse of the questionnaire. Before making the dataset public, the IP-addresses were removed to ensure the anonymity of the respondents.

In the "Decision support for municipal policy" project, we conducted a series of workshops in cooperation with three municipalities, with stakeholders such as real estate owners, and supermarket/shop owners. The participants were informed that the workshops were part of a research project.

# 4. Results

This chapter presents the research and design motivations. For each paper, a description of the problem addressed, artifact, demonstration and evaluation, research contributions, and the author's contributions are given.

The research presented in this thesis is foremost rooted in decision analysis, and more specifically in MCDA. The decision problems are structured as MCDA problems, where the problem is represented from different viewpoints (criteria) (Greco et al., 2016). One reason to choosing MCDA to structure and analyze decision problems is that relates to how humans make decisions by dividing the problem down into the different viewpoints/criteria of interest (Greco et al., 2016). Papers I – VI use MCDA to structure and evaluate decision problems. In Paper VI, we present POLA a web-based MCDA application used for structuring and analyzing commercial development policy decisions in cooperation with stakeholders.

In Papers I, III, IV and V, the problems are structured and analyzed as PDA problems. One advantage of the PDA approach is that in problems involving multiple stakeholders, the chance of finding compromises between the stakeholders increases when multiple alternatives are chosen rather than one single alternative (Salo and Hämäläinen, 2010). Two frequently used approaches are the benefit-to-cost ratio and the mathematical optimisation approach. In Papers I, III, IV and V, we applied a mathematical optimisation approach to portfolio generation; more specifically, we structured it as a Knapsack problem similarly to PROBE (Lourenço et al., 2012). Two motivations for the choice of a mathematical optimisation approach are that the benefit-to-cost ratio approach might not find all of the portfolios that use the resources efficiently and it can only handle one constraint at a time (Kirkwood, 1997).

In some decision situations, it might not be possible or of interest to specify a monetary cost for each project: the interest might instead be to clarify which projects are prone to future conflicts. Paper II presents CAR-CE an application of the CAR method where the elicitation of preferences regarding the performance of an action is conducted relative to a "do nothing" alternative, and how the elicited preference information is then used as input to two conflict indices based on Ward's method (Rencher, 2003, p. 466), and on the approach presented in (Bana e Costa, 2001). These conflict indices measures the level of conflict within a stakeholder group or between two stakeholder groups. The measure can then be used as an alternative resource constraint for use in a PDA problem. Paper III presents the DANCE framework, which utilises the preference elicitation method and the conflict indices from Paper II, and then implements a portfolio optimisation approach. Paper V presents XPLOR a web-based application for visualising stakeholder conflicts regarding portfolios and actions. This application implements the conflict indices (Paper II) and offers an approach to portfolio optimisation.

Sensitivity analysis is an important part of any MCDA approach (Belton and Stewart, 2002). In Paper IV, we develop SENS a PDA extension to the DELTA method's embedded form of sensitivity analysis. The extension enables both a priori and a posteriori sensitivity analyses of the input statements. The DELTA method was chosen because it supports interval statements, which are advantageous when conducting a sensitivity analysis.

## 4.1 Paper I: Disagreement Constrained Action Selection in Participatory Portfolio Decision Analysis

Tobias Fasth, Aron Larsson, Maria Kalinina, Disagreement Constrained Action Selection in Participatory Portfolio Decision Analysis, *International Journal of Innovation, Management and Technology*, vol. 7, no. 1, pp. 1-7, (2016).

### 4.1.1 Problem Addressed

In some PDA problems, it is not possible or interesting to use a monetary budget as the constraining resource. It might also not be feasible or suitable to assign a monetary cost to each project. The interest might instead be in investigating any disagreement/conflict concerning a future implementation of the actions under consideration, and to examine and highlight how controversial actions affect the portfolio composition. Given that the disagreement between stakeholders regarding which actions to implement may delay the decision process, it is of interest to highlight actions prone to conflicts so that these can be handled separately. A solution to the problem enables: i) the analysis of the disagreements associated with different portfolios, which in turn can be used to highlight the actions prone to conflict; and ii) the selection of a portfolio with an acceptable level of disagreement.

### 4.1.2 Artifact

The developed artifact is a method for group portfolio decision analysis where the portfolios are constrained by a disagreement measure, instead of a monetary budget. A prerequisite for measuring disagreement is an elicitation method, which enables the elicitation of positive and negative preferences. This method was developed in Paper II. The disagreement associated with each action is measured per criterion. The criterion level disagreements are then aggregated into a total disagreement for each action. The disagreement measure approach has similarities to the method presented in (Bana e Costa, 2001). The aggregated disagreement is then used as a constraining resource in the portfolio optimisation. The approach for generating a set of efficient portfolios is similar to the approach used in PROBE (Lourenço et al., 2012). The artifact also enables an a priori sensitivity analysis, using either the actions' minimum or maximum associated disagreement in the portfolio generation.

### 4.1.3 Demonstration and Evaluation

The method was demonstrated in an illustrative scenario using an implemented prototype of the artifact. The functionality of the method was demonstrated using example data and we then showed: how to measure disagreement between stakeholders concerning an action; how the disagreement measure was calculated and how it can be used as a constraining resource when generating portfolios solving a Knapsack problem; and how sensitivity analysis of portfolios can be conducted.

The artifact was evaluated using informed arguments. The requirements and the evaluation are described in detail in Section 3.3.1. The evaluation can be classified as an ex ante evaluation in an artificial environment. The choice of evaluation strategy has implications for the validity. A benefit of an artificial environment is that it provides means for high internal validity because the evaluation is conducted in a controlled environment without interference. However, the external validity cannot be proven because the results cannot be generalised to other settings. Therefore, this method should be evaluated in a real case setting to ensure a high external validity.

### 4.1.4 Research Contributions

The main contribution of this paper was to show how a disagreement measure can be employed as an alternative resource constraint in a PDA problem. This enables a decision-maker to analyze what effect a change in the resource constraint (the overall disagreement level of the portfolio) has on the portfolio composition. In turn, this supports the decision maker in highlighting conflict-prone actions. This paper also contributes with an approach to an a priori sensitivity analysis of portfolios.

### 4.1.5 Author's Contribution

The author contributed to all parts of the paper. He identified the research gap, and jointly with the co-authors developed the method. He implemented the method and designed and carried out the illustrative scenario.

## 4.2 Paper II: Measuring Conflicts using Cardinal Ranking: An Application to Decision Analytic Conflict Evaluations

Measuring Conflicts using Cardinal Ranking: An Application to Decision Analytic Conflict Evaluations, Tobias Fasth, Aron Larsson, Love Ekenberg, Mats Danielson, *Advances in Operations Research*, Article ID 8290434, 14 pages, (2018).

### 4.2.1 Problem Addressed

Conflicts in public decision problems may delay the decision process. It is therefore of interest to become better informed of which actions may lead to potential conflicts. It is also of interest to better understand the views of the citizens, such as by eliciting their preferences relative a "do nothing" action. The problems addressed in this paper are how stakeholder preferences can be elicited to capture negative and positive affects towards an actions performance relative a "do nothing" action and how conflicts between stakeholders regarding the performance of an action can be measured in a multi-criteria problem, A solution to these problems will enable decision-makers to highlight actions prone to conflicts.

### 4.2.2 Artifacts

The paper describes an application of the CAR method to conflict evaluations (CAR-CE), in which a "do nothing" action is used to separate positive from negative actions. The elicited preferences are then used in a conflict evaluation method consisting of two conflict indices for measuring the conflicts between and within stakeholder groups regarding action performance in terms of a specific criterion.

### 4.2.3 Demonstration and Evaluation

The application of CAR-CE and the conflict indices were demonstrated in an illustrative scenario using prototypes of the artifacts. In the example, we showed how the preferences elicited with CAR-CE can be used in two conflict indices for measuring the level of conflict between and within stakeholder groups concerning an action's performance in terms of a specific criterion. The resulting conflict indices were then used to classify the alternatives into semantic consensus categories describing the level of consensus associated with each alternative.

The elicitation approach CAR-CE was further demonstrated in a natural setting together with the municipality of Upplands Väsby. This method was implemented in a web-based questionnaire, and an invitation to participate in the survey was sent to 10,000 citizens. In all, 1034 citizens answered the questionnaire.

The artifact was evaluated using informed arguments. The requirements and the evaluation is described in detail in Section 3.3.1. This type of evaluation strategy can be classified as an ex ante evaluation in an artificial environment. One benefit of artificial evaluations is that they allow means for controlling the environment and any interfering factors. One drawback with this approach is its weak external validity since the results cannot be generalised.

### 4.2.4 Research Contributions

In this paper we describe CAR-CE, an application of the CAR method in which positive and negative preferences regarding the performance of an action are elicited relative to a "do nothing" action. CAR is based on the ideas of rank order. Rank order methods have features that are attractive compared to more precise elicitation methods; such as, being less cognitively demanding, and increasing the likelihood of group agreement (Barron and Barrett, 1996a; Kirkwood and Sarin, 1985). One drawback is that even though more precise preference information might be known, this information is not taken into consideration (Jia et al., 1998). However, CAR takes this additional difference information into account by adding cardinal information to the ranking. Furthermore, we present the CAR-CE method and then show how the preferences can be used in the two conflict indices to measure the conflict between and within stakeholder groups regarding an action's performance in terms of a specific criterion. The conflict indices have similarities with the method presented by (Bana e Costa, 2001). One difference between these approaches is how the value functions are used and created. In Bana e Costa (2001), the value functions are created by using MACBETH, while our approach uses CAR-CE where the participants define the value of a "do nothing" alternative. Another difference is that (Bana e Costa, 2001) present two conflict indicators, the collective attractiveness and the collective unattractiveness. In our approach, we go one step further and develop an overall conflict index, taking both the negative and the positive preferences into consideration. It is of note is that both methods divide the participants into two subsets for each criterion and alternative combination, such that one subset consists of the positive and the other subset of the negative respondents. An implication of this and the conflict index design is that if only one subset has members, then it implies that there is no conflict. The conflict index is also based on Ward's method (Rencher, 2003, p. 466), which is extended by a positive stakeholder scaling constant.

### 4.2.5 Author's Contribution

The author contributed to all parts of the paper. He identified the research gap and developed the CAR-CE method. He developed the conflict indices jointly with the co-authors. He implemented the method and designed and carried out the illustrative scenario. Furthermore, he developed, designed and implemented a web-questionnaire that uses CAR-CE. He analyzed and presented the results from the survey.

## 4.3 Paper III: Portfolio Decision Analysis for Evaluating Stakeholder Conflicts in Land Use Planning

Tobias Fasth, Samuel Bohman, Aron Larsson, Love Ekenberg, Mats Danielson, Portfolio Decision Analysis for Evaluating Stakeholder Conflicts in Land Use Planning, in *Submitted journal manuscript*.

### 4.3.1 Problem Addressed

Land use and municipal planning involve a multitude of actors and stakeholders, which often have diverging preferences regarding the actions which are proposed to be implemented. Furthermore, the actions often have a direct and long-term impact on the daily lives of stakeholders. This, in turn, may lead to costly and time-consuming conflicts. The chance of finding compromises between stakeholders increases in situations where a portfolio of actions is chosen, instead of choosing one single action (Salo and Hämäläinen, 2010). In light of conflict analysis, it is interesting to investigate how such a portfolio approach can be used to highlight conflict-prone actions, which enable analysis of conflict robust actions, accepted by most stakeholders.

### 4.3.2 Artifact

The developed artifact is the DANCE framework, which utilises the three novel methods, i) the CAR-CE method (Paper II), ii) two conflict indices (Paper II), and iii) an approach to portfolio generation which utilises the conflict indices as a constraining resource based on (Paper I) but extended with the feature that the actions can have either positive or negative performance scores. This enables generation of both productive (positive) and counter-productive (negative) portfolios. A robustness analysis can then be conducted using the core index measure (Liesiö et al., 2007, 2008), and the introduced concepts of core index borderline sub-types and core index slopes.

### 4.3.3 Demonstration and Evaluation

A prototype implementation of the framework was used to demonstrate the artifact using an illustrative scenario, which was based on the real-world survey data elicited when demonstrating the preference elicitation method (Paper II). In the example, we showed how the preferences elicited with CAR-CE, and the conflict indices can be used as input to a portfolio generation approach, and how the resulting portfolios are analyzed using core index and core index slopes.

The artifact was evaluated using informed arguments. The requirements and the evaluation are described in detail in Section 3.3.1. The artifact was evaluated ex ante in an artificial environment. This allowed for means for controlling the environment and any interfering factors. However, this approach has weak external validity because the results cannot be generalised.

### 4.3.4 Research Contributions

This paper contributes with DANCE, a framework for conflict evaluations. The framework utilises: i) CAR-CE for eliciting preferences (Paper II); ii) the between and the within-group conflict indices (Paper II); and iii) a portfolio optimisation approach solving a Knapsack problem, which uses the actions' aggregated conflict (based on the conflict indices) as a constraining resource (based on Paper I), and where the actions' overall value can be either positive and negative.

The approach that is used here to generate a set of efficient portfolios is similar to the approach used in PROBE (Lourenço et al., 2012) and Paper I. However, because the approach allows for either positive and negative values for each action, in addition of of maximising the objective function, we apply the algorithm a second time where we minimise the objective function. This enables generation of both productive (positive) and counter-productive (negative) portfolios. Furthermore, the framework enables a robustness analysis of the actions using the Core Index (Liesiö et al., 2007, 2008), and two core index extensions: i) borderline sub-types; and ii) core index slopes, which are used for highlighting actions where the core indices of two stakeholders groups differ more than a predefined threshold.

### 4.3.5 Author's Contribution

The author contributed to all parts of the paper. He identified the research gap and the approach used to generate the counter-productive portfolios. He developed the concepts of core index slopes and borderline sub-types jointly with the second author. He implemented the approach to portfolio generation, and designed and carried out the illustrative scenario.

## 4.4 Paper IV: Sensitivity Analysis in Portfolio Interval Decision Analysis

Tobias Fasth, Aron Larsson, Sensitivity Analysis in Portfolio Interval Decision Analysis, in *Proceedings of the Twenty-Sixth International Florida Artificial Intelligence Research Society Conference*, pp. 609–614, (2013).

### 4.4.1 Problem Addressed

In PDA, one portfolio of projects is chosen from a set of portfolios. In some situations, the choice might lie between two non-dominated portfolios. In such situations, it is of interest to further investigate the dominance relation. The DELTA method (Danielson and Ekenberg, 1998) has an embedded form of sensitivity analysis, where the dominance relation is studied by contracting the input intervals until dominance occurs. This paper extends this sensitivity analysis to portfolios and it investigates how it can be used both before and after portfolio generation. A solution to this problem enables decision makers in the setting of an interval PDA problem to make better-informed decisions.

### 4.4.2 Artifact

The method extended DELTA's embedded form of sensitivity analysis to incorporate PDA problems. DELTA's information frame consisting of a weight base, a utility base, and a probability base, was extended by a cost base which includes imprecise information regarding project costs. The method consists of three algorithms, one for a priori and two for a posteriori sensitivity analyses. The algorithm for an a priori sensitivity analysis contracts the bases in steps. In each step, the project's utilities are minimised, and the costs maximised, then a portfolio is generated by solving a Knapsack problem. The two a posteriori algorithms can be employed for a sensitivity analysis of either the utilities or the costs. The two algorithms are similar. The first algorithm contracts the utility (or cost) base, step-wise, for all projects, and in each step the dominance relation is studied. The second algorithm contracts the utility (or cost) base for one project step-wise. In each step, the dominance relation is investigated. This analysis enables decision makers to examine how one single project affects the choice of a portfolio.

### 4.4.3 Demonstration and Evaluation

An illustrative scenario was used to demonstrate the artifact. The method was implemented in a prototype to exemplify how a sensitivity analysis can be conducted both a priori and a posteriori to portfolio generation.

The artifact was evaluated using informed arguments. The requirements and the evaluation are described in detail in Section 3.3.3. The chosen evaluation strategy can be classified as an ex ante evaluation in an artificial environment. Artificial environments provide a means for high internal validity since it is possible to control the evaluation setting and any interfering factors. The external validity is thereby affected because it is not feasible to generalise the results to any real-world setting. The method should, therefore, be evaluated in a real case setting to ensure a high external validity.

### 4.4.4 Research Contributions

The main contribution of this paper was the development of a method for a priori and a posteriori sensitivity analyses of portfolios. The method extended DELTA's embedded form of sensitivity analysis by extending the analysis to portfolios. This was then used in algorithms for both a priori and a posteriori sensitivity analyses.

### 4.4.5 Author's Contribution

The author contributed to all parts of the paper. He identified the research gap, developed the algorithms for a priori and a posteriori sensitivity analyses, implemented the algorithms, and designed the example.

## 4.5 Paper V: A Web-Based Visualization Tool for Exploring Stakeholder Conflicts in Land Use Planning

Samuel Bohman, Tobias Fasth, A Web-Based Visualization Tool for Exploring Stakeholder Conflicts in Land Use Planning, in *Transactions in GIS*, (In press).

### 4.5.1 Problem Addressed

Stakeholder conflicts are an inherent part of land use and municipal planning. It is therefore of interest to enable and support the decision makers in exploring and analyzing the stakeholders' preferences and to highlight both preferred and non-preferred conflict-prone actions. The problem addressed is how to visualize stakeholder conflicts using web-based technologies.

### 4.5.2 Artifact

The artifact is a web-based visualisation tool for exploring stakeholder preferences and conflicts. The tool is implemented in the programming language R and the web application framework Shiny. The artifact implements the two conflict indices presented in Paper II and an algorithm which utilises the conflict indices in the generation of a set of Pareto efficient portfolios, similarly to the approach presented in (Lourenço et al., 2012) and Paper I. The tool consists of a menu where the user selects the focus area and then defines the two stakeholder groups to be analyzed. The tool then displays the actions' value and associated conflict and a set of efficient portfolios for each stakeholder group and for a combined group.

### 4.5.3 Demonstration and Evaluation

XPLOR was demonstrated using an illustrative scenario. The illustrative scenario was based on the real-world survey data elicited when demonstrating the preference elicitation method (Paper II). In our example, we showed how the conflict index and portfolio generation could be used in a tool to support decision makers to make better-informed decisions.

The artifact was evaluated using informed arguments. The requirements and the evaluation is described in detail in Section 3.3.2. The evaluation strategy was an ex ante evaluation in an artificial environment, which means that it allows us to control the environment and any interfering factors. However, the results cannot be generalised, which means that it has weak external validity.

### 4.5.4 Research Contributions

This paper contributes with XPLOR, a web-based visualisation tool for exploring stakeholder preferences and conflicts in land use and municipal planning. The tool enables the user to define two stakeholder groups (and form a combined group) and then for each group explore: i) the associated conflict and value of each action, and ii) how a change in conflict affects the portfolio composition. This tool gives the decision makers a better understanding of the citizens' preferences, and conflict-prone actions, and therefore enable better-informed decisions. This tool implements methods for conflict evaluation (two conflict indices in Paper II), an approach to portfolio generation (similarly to the approach in I), and a core index based robustness analysis (Liesiö et al., 2007, 2008).

### 4.5.5 Author's Contribution

The author contributed to all parts of the paper. Jointly with the co-author, he identified the research gap. He contributed to the design and development of the artifact and implemented the approach to conflict analysis and portfolio generation. He jointly with the co-author designed and carried out the illustrative scenario.

## 4.6 Paper VI: Policy Analysis on the Fly with an Online Multi-Criteria Cardinal Ranking Tool

Aron Larsson, Tobias Fasth, Mathias Wärnhjelm, Love Ekenberg, and Mats Danielson, Policy Analysis on the Fly with an Online Multi-Criteria Cardinal Ranking Tool, in *Journal of Multi-Criteria Decision Analysis*, 25(3-4): 1—12, (2018).

### 4.6.1 Problem Addressed

Policy decisions in municipalities regarding the future direction of commercial development involve and affect a diverse set of stakeholders. To avoid future conflicts between the stakeholders, it is important to provide the means for the stakeholders to share their objectives, and to facilitate the development and evaluation of feasible policy alternatives. The problem addressed in this paper is how to develop and utilise a web-based multi-criteria decision analysis tool in municipal, commercial development, to acknowledge the preferences and objectives from both national and local stakeholders.

### 4.6.2 Artifact

The artifact is a web-based MCDA application for structuring and analyzing commercial development policy alternatives, in cooperation with stakeholders. The artifact supports structuring of a value tree representing the objectives of the stakeholders, and an evaluation and analysis of the policy alternatives. The web application was developed in JavaScript, Node.JS, and is supported by a MongoDB-database.

### 4.6.3 Demonstration and Evaluation

The artifact was developed in cooperation with the problem owner with multiple deliveries, to ensure that the software met the expectations of the problem owner. The functionality of the artifact was demonstrated in examples using results from workshops conducted together with the three municipalities of Norrköping, Katrineholm and Filipstad. During the project, the stakeholders described an increased understanding of the decision problem and the issues of conflict. The artifact was demonstrated during a workshop at SKL with representatives from different municipalities.

The artifact was evaluated using informed arguments. The requirements and the evaluation are described in detail in Section 3.3.4. This type of evaluation strategy can be classified as an ex ante evaluation in an artificial environment, enabling a high internal validity. However, the external validity is affected because it is not possible to generalise the results to a real-world setting. The method should, therefore, be evaluated in a real case setting.

### 4.6.4 Research Contributions

The research contributes with POLA, a web-based MCDA application for structuring and analyzing commercial development policy alternatives. A difference between POLA and generic MCDA software is that POLA is designed to fulfill the specific problem context of analyzing commercial development policy in cooperation with stakeholders, which is based on the problem definition and the defined requirements.

### 4.6.5 Author's Contribution

The author reviewed all parts of the paper and co-wrote sections four and five. Jointly with the first author, he carried out the stakeholder workshops and designed the study. He designed and developed the web-application based on discussions with the problem owner.

# 5. Discussion

The overall goal of this thesis has been to develop methods and applications for participatory decision analysis, focusing on the conflict between stakeholders. This research was conducted in the Formas funded project "Multimodal Communication for Participatory Planning and Decision Analysis: Tools and Process Models", and in the Swedish Association of Local Authorities and Regions (SKL) funded project "Decision Support for Municipal Policy". This has enabled this research to find solutions to real-world problems. The developed methods have their roots in MCDA, and more specifically MAVT. The focus has been on how to support decision makers in multi-stakeholder multi-criteria decision problems to model, measure and highlight stakeholder conflicts.

Decision problems within participatory decision analysis are multi-faceted. These problems have multiple stakeholders, often with different opinions regarding the alternatives, and the alternatives are evaluated in terms of multi-criteria. The decision making process in these situations is complex: the decisions may lead to future long-term (costly) conflicts, delaying the decision from being made (see, e.g. (Danielson et al., 2007, 2008; Hansson et al., 2012)). Thus, there is a practical need for the contributed applications and methods that would enable decision makers to model, identify and investigate actions that might lead to future conflicts, and in turn, help the decision makers in making well-informed decisions.

The overall research question guiding this research was: *"How can decision analysis be used as a foundation to evaluate stakeholder conflicts in multi-stakeholder problems?"* To answer this question, the question was divided into two sub-questions.

The first sub-question was: *"How can conflict between stakeholders be modeled and measured in a multi-stakeholder multi-criteria decision problem? And, what are the properties required when eliciting preferences?"*.

To answer this question, we first suggested a prototype method for measuring conflict between stakeholders (Paper I). The method was revised in Paper II to include stakeholder weights, and to consist of two conflict indices, one for measuring conflict within a stakeholder group, and another for measuring conflict between two groups. The main contribution is the development of two conflict indices, which extends the existing research, such as the conflict indicators in (Bana e Costa, 2001) and Ward's method (Rencher, 2003), with an approach for measuring the stakeholder conflict.

The same paper presents the CAR-CE preference elicitation method, which is a prerequisite for measuring conflict. This enables elicitation of positive and negative preferences for an action relative to a “do nothing” alternative, using cardinal ranking. This paper also describes the properties required when eliciting preferences for measuring conflict. The main contribution is to show how CAR method (Danielson and Ekenberg, 2016) can be extended to elicit positive and negative preferences. An implementation of CAR-CE was later used in a web-based questionnaire survey in cooperation with Upplands Väsby municipality. The conflict indices were implemented in XPLOR a web-based application (in Paper V).

To facilitate modeling of stakeholder conflicts, we designed and developed POLA, which is a web-based MCDA application used for structuring and analyzing commercial development policy alternatives. The application was demonstrated using results from workshops conducted together with three municipalities (Paper VI). The main contribution is the development of an application tailored for modelling and analysing stakeholder preferences, to highlight areas of conflict.

The second sub-question was: *“How can portfolio decision analysis, including sensitivity analysis, be utilised in the context of conflicting stakeholders?”*.

To answer this question, we first proposed an approach to solving a Knapsack problem, which uses a conflict-based budget as the constraining resource, instead of using a traditional monetary budget (Paper I). The idea was to show how a change in conflict affects the portfolio composition. This approach was later revised in Paper III to include counter-productive (negative) portfolios. Paper III presents the DANCE framework for conflict evaluations which utilises three novel methods: i) CAR-CE for eliciting preferences (Paper II), ii) the two conflict indices for measuring conflict (Paper II) and iii) an approach to portfolio generation and robustness analysis (Paper III). The main contribution is that the framework enables preference elicitation, measuring and analysis of the conflict related to a group of stakeholders preferences regarding a set of actions.

In paper V, we present XPLOR a web-based visualisation tool for exploring stakeholder preferences and conflicts. XPLOR implements the conflict indices, and a Knapsack optimisation approach similar to the one presented in Paper I. The application could be used by both municipality representatives and general citizens to explore the preferences and conflicts of others. The main contribution is the development of an application to visualise stakeholder conflicts.

Furthermore, Paper IV presents a method enabling an embedded form of sensitivity analysis of portfolios. The method was based on the DELTA method's embedded form of sensitivity analysis, which was originally used for the sensitivity analysis of alternatives. This paper presents approaches for using this type of sensitivity analysis in both a priori and a posteriori sensitivity analyses of portfolios of alternatives. The main contribution of this paper is to show how the DELTA method's embedded form of sensitivity analysis (Danielson and Ekenberg, 1998) of actions could be used for portfolios.

To answer the overall research question, this thesis presented: 1) DANCE a framework which utilised the following three novel methods: i) CAR-CE an application of the CAR method used to elicit positive and negative preferences relative to a "do nothing" alternative ii) two conflict indices for measuring conflict between and within stakeholder groups, iii) conflict constrained portfolios of actions including robustness analyses of portfolios; 2) two web-applications, i) POLA which supports modeling stakeholder objectives and values (which can be sources of conflict), and ii) XPLOR used for visualising and analyzing stakeholder conflicts in land use planning; and 3) SENS a method for sensitivity analysis of portfolios of alternatives.

This thesis shows how decision analysis be used as a foundation for evaluating stakeholder conflicts in multi-stakeholder problems. The novelty of this research is that it extends the existing boundaries of decision analysis with methods for measuring and analysing stakeholder conflicts, and with software for modelling and visualisation of stakeholder preferences. In addition, these methods and software also contribute to a practice and to practitioners, in the modelling, investigation and analysis of stakeholder conflicts. In this thesis, the focus has been on problems and practitioners in land use planning, which has guided the research in a certain direction. For example, the XPLOR application was tailored to solve a specific problem, visualising stakeholder conflicts in Upplands Väsby municipality. The other artifacts, the DANCE framework, SENS, and POLA are more general and can be applied in other contexts. The contributed methods and software were evaluated using an ex ante strategy in an artificial environment. This choice has implications for the validity of the research, with benefits such as providing a means for high internal validity because the evaluation is conducted in a controlled environment. However a general drawback is that the external validity cannot be proven because the results cannot be generalised to other settings. Therefore, the methods and software should in the future be evaluated in a real case setting.

## 5.1 Future Research

A future direction of research is to use the DANCE framework and the web-based application XPLOR in a new case study. This would enable an evaluation of the artifact together with other stakeholders and municipalities, enabling a thorough evaluation of the tool and methods. Another approach is to use the conflict indices with data from other surveys using a similar type of preference information. In addition, XPLOR could be extended by a preference elicitation module, to make it into an integrated application, instead of eliciting preferences using an external questionnaire. Another possible direction is to evaluate the method for sensitivity analysis presented in Paper IV, by applying it in a real case setting. Regarding the portfolio optimisation, one direction of further research is to investigate different optimisation approaches for generating portfolios with different characteristics regarding consensus or conflict. The slider implementation of the CAR-CE method used in the questionnaire presented in Paper II could be described in a separate evaluation of its usability and other aspects of the user interaction with the slider.

The web-application POLA could be further evaluated, by using it in cooperation with other municipalities. Further development could be to enable elicitation of preferences using CAR-CE and then apply the conflict indices to investigate any potential conflict.

The methods presented in the thesis could also be applied in contexts other than participatory decision making, which would show their generality.

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