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Aggregation of Group Prioritisations for Energy Rationing with an Additive Group Decision Model
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Abstract
The backbone of our industrialised society and economy is electricity. To avoid a catastrophic situation, a plan for how to act during a power shortage is crucial. Previous research shows that decision models provide support to decision makers providing efficient energy rationing during power shortages in the Netherlands, United States and Canada. The existing research needs to be expanded with a group decision model to enable group decisions. This study is conducted with a case study approach where the Swedish emergency preparedness plan in case of power shortage, named Styrel, is explored and used to evaluate properties of a proposed group decision model. The study consist of a qualitative phase and a quantitative phase including a Monte Carlo simulation of group decisions in Styrel evaluated with correlation analysis. The qualitative results show that participants in Styrel experience the group decisions as time-consuming and unstructured. The current decision support is not used in neither of the two counties included in the study, with the motivation that the preferences provided by the decision support are misleading. The proposed group decision model include a measurable value function assigning values to priority classes for electricity users, an additive model to represent preferences of individual decision makers and an additive group decision model to aggregate preferences of several individual decision makers into a group decision. The conducted simulation indicate that the proposed group decision model evaluated in Styrel is sensitive to significant changes and more robust to moderate changes in preference differences between priority classes.

Keywords: Energy rationing, decision analysis, preference aggregation rules, Monte-Carlo simulation, correlation analysis.
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Terminology

Acronyms and Abbreviations

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<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>CI</td>
<td>Critical Infrastructure</td>
</tr>
<tr>
<td>FOI</td>
<td>Swedish Defence Research Agency</td>
</tr>
<tr>
<td>ID</td>
<td>Identifier</td>
</tr>
<tr>
<td>MSB</td>
<td>Swedish Civil Contingencies Agency</td>
</tr>
<tr>
<td>PAR</td>
<td>Preference Aggregation Rule</td>
</tr>
<tr>
<td>SEA</td>
<td>Swedish Energy Agency</td>
</tr>
<tr>
<td>SvK</td>
<td>Svenska Kraftnät</td>
</tr>
<tr>
<td>VSF</td>
<td>Vital Societal Functions</td>
</tr>
<tr>
<td>UNESCO</td>
<td>United Nations Educational, Scientific and Cultural Organization</td>
</tr>
</tbody>
</table>

Notation

- $x > y$  
  Decision maker prefers $x$ over $y$.
- $x \sim y$  
  Decision maker is indifferent between $x$ and $y$.
- $x \succeq y$  
  Decision maker prefers $x$ over $y$ or there is indifference.
- $v(x)$  
  Value function $v$ of alternative $x$.
- $\lambda$  
  Scaling constant.
- $\rho_s$  
  Spearman’s rank correlation coefficient.
- $\tau$  
  Kendall’s rank correlation coefficient.
1 Introduction

The backbone of our industrialised society and economy is electricity. A power blackout could have a significant impact on life and health, vital societal functions and other critical infrastructures. Limited electricity is affecting industrial production and our daily life with heating, water supply, communication and transport. A power blackout lasting for several days would cause a catastrophic situation (Swedish Energy Agency [SEA], 2014).

The electricity supply in Sweden can be limited due to low power production and low possibility to import power from other nations. The situation when the electricity supply is limited and there is not enough electricity to support everyone in society is named power shortage. In case of a power shortage the Swedish national power grid company Svenska Kraftnät (SvK) can command the Swedish power companies to shut down parts of the Swedish power grid (SEA, 2014). According to the Swedish law titled The Electricity Act (1997:857), the shutdown shall be done with respect to prioritised users of electricity to reduce the consequences for human life and health, vital societal functions and critical infrastructure.

To avoid a catastrophic situation with a complete national power blackout, a plan for how to act during power shortage is crucial. Styrel is the name of the Swedish emergency preparedness plan in case of power shortage. Styrel aims to identify and prioritise vital societal functions and critical infrastructure through a planning process with multiple stakeholders. (SEA, 2014)

1.1 Background and problem motivation

The development of society, organisational structures, global networking and modern technology requires strategic decisions based on group preferences instead of a single decision maker’s preferences (Ossadnik, Schinke & Kaspar, 2016). Group decisions need to be structured to preserve rationality and decrease the influence of individual decision makers with higher status (Eisenführ, Weber and Langer, 2010).

Decision analysis aims to support people in making hard and complex decisions. The more complex a decision situation becomes, the better it will be to use procedures and tools to systematically bring forward and
process relevant information (Eisenführ, Weber and Langer, 2010). In emergency preparedness planning the decisions made by government agencies and politicians affect a large number of people. Eisenführ, Weber and Langer (2010) states that these important decisions often lack structure and a systematic process.

The planning process for emergency preparedness in case of power shortage in Sweden, Styrel, started 2004 as a project which involved to prioritise electricity users with societal importance into 8 priority classes. The first national emergency preparedness plan in case of power shortage was completed in 2011 after an extensive collaboration between municipalities, county councils, county administrative boards, Swedish power companies, private sector stakeholders and government authorities. (SEA, 2012)

Wilson (1993) states that a simple way of finding an optimal allocation when the power supply is limited is essentially a rule for rationing which is assigning a priority of service for electricity users in different priority classes. Saaty and Mariano (1979) describes that electricity is easy to ration because it is generated, transmitted and distributed through central locations. The authors states that an important part of energy rationing is priorities. Saaty and Mariano (1979) point out that for short-term energy rationing, the allocation of electricity is efficient following a priorities through a decision analytical objective function.

Reports evaluating Styrel by Veibäck, Sterérus Dover, Fischer and Lindgren (2013) and Lindberg et al. (2014) conclude that the current procedure in group prioritisations for energy rationing sometimes cause an improperly low priority for electricity users with societal importance. A decision analytical approach could support decision makers in the preference aggregation of several stakeholders into group prioritisations for energy rationing.

In the Netherlands, the power grid operator makes the decision regarding the prioritisations for energy rationing according to de Nooij, Lieshout and Koopmans (2008). The authors conducted a study to using decision analysis to reduce the social costs of a power supply interruption through efficient regional rationing of energy. de Nooij et al. (2008) show that social costs are significantly lower when applying efficient rationing as a result of decision making with account to economic and social consequences in different municipalities.
Balson et al. (1992) and Keeney and McDaniels (1992) advocate to use decision analysis to guide decision makers regarding energy rationing in the United States respectively in Canada. Even though the decisions regarding energy rationing should be collective group decisions including several stakeholders such as government authorities, power grid companies, municipalities, county councils, county administrative boards and private sector stakeholders. No group decision model is applied or evaluated yet to compile group prioritisations for energy rationing.

In the decision models evaluated by de Nooij et al. (2008), Balson et al. (1992) and Keeney and McDaniels (1992) the decision makers can for instance account for social costs, environmental impact and, health and safety. Emergency preparedness planning regularly involve these objectives, but they are often presented on a constructed scale (e.g. priority classes) instead of a natural scale (e.g. monetary value).

The research regarding efficient energy rationing to reduce societal impact of power shortages needs to be expanded with a group decision model supporting decision makers in compilation of a regional list of prioritised electricity users based on priority classes.

1.2 Overall aim
The overall aim is to expand the existing research regarding decision analysis for energy rationing which goal is to reduce the societal impact of power shortages. The study focused on proposing and evaluating a group decision model for energy rationing adapted for the Swedish emergency preparedness planning process Styrel. The overall aim with the proposed group decision model is to support decision makers in compiling group prioritisations for energy rationing when the electricity users are divided into priority classes.

1.3 Concrete and verifiable goals
This study aims to answer the following research questions:

- How does participants experience the group decisions in Styrel?
- How does participants in Styrel experience the current decision support for the compilation into a ranked list of prioritised power lines in each county?
- How can preferences of individual decision makers for electricity users in priority classes be represented with a decision model?
1.4 Scope

The focus of this study is to propose a group decision model that can be used as a decision support for energy rationing in a county’s compilation of preferences from several municipalities in a county. No other stakeholders than municipalities and the county administrative boards are considered. Neither are the conditions in any other county than Sweden explored.

The study does not take into account the underlying values which guide decision maker’s opinions and judgement in their decisions regarding energy rationing. These values are of interest because they are influencing the trade-off of statistical lives, statistical monetary values, the objectives and several other factors with importance for decisions in energy rationing.

Another important part of the process of energy rationing is the fact that the stakeholder’s preferences and prioritisations in many cases have a political dimension which can not be ignored. Decision makers in, for example, the municipalities and the county councils are democratically elected by the Swedish people and can therefore be strongly influenced by their political views when identifying and prioritising electricity users. This important topic is however not a part of this study.

The qualitative phase of this study is delimited to analyse the qualitative data produced in two interviews conducted by research colleagues from the Risk and Crisis Research Centre (RCR) at Mid Sweden University. The qualitative data is delimited to transcribed text from the two interviews. The author of this study was not present during the interviews and the summary of findings from the qualitative data in this study is not confirmed by the respondents from the two county administrative boards.

The focus of this study is to propose a group decision model that can be used as a decision support for energy rationing in a county’s compilation
of preferences from municipalities in the county. From the qualitative results, a decision model is developed and evaluated in the quantitative phase. Decision analysis is an area that comprises a lot of decision models. This study focus on representing Styrel decisions with an additive value model for individual decision makers and group decisions. No other decision models are examined nor implemented. The study is additionally delimited to evaluate results in a simulation because no real data from preferences are available due to national security.

1.5 Outline

The first chapter gives the reader an introduction and basic understanding for this study. In Chapter 2 theory and related work is presented. The methodology is described in Chapter 3, this Chapter also includes motivations for the chosen methodology and a method discussion. All results are presented in Chapter 4 and an analysis of the obtained results is available in Chapter 5. Finally, Chapter 6 presents conclusions and suggestions for future research.
2 Theory and related work

This chapter contains previous research and relevant theories for the study. Including an overview of the Swedish power grid, a description of the emergency preparedness planning process Styrel and decision analysis followed by group decision theory regarding how to aggregate individual stakeholder’s preferences and priorities. This chapter also comprises simulation theory, Monte Carlo simulation and correlation analysis.

2.1 Emergency preparedness in case of power shortage

The modern and digital society we live in today creates new challenges, for example our dependence of electricity. The society should function even during disturbances, crises and war. This involves to ensure the ability to prevent, manage and recover from serious disturbances that affect life and health, critical infrastructure and fundamental values. (Swedish Civil Contingencies Agency [MSB], 2014)

Cox (2012) describes that extreme and catastrophic events are challenging to learn from, prepare for, and protect against. Because such events are rare and unfamiliar. The author describes the challenge to traditional decision and risk analysis for catastrophic events as: unpredictability, difficulty of sufficiently describing, envision, or evaluating their consequences, and the struggle of organising effective and coherent responses.

On the topic of power shortages, Sweden have never been forced to shut down parts of the power grid yet. This create difficulties to prepare and protect against the consequences of power shortages. According to Cox (2012) it is a challenge to organise effective and coherent responses for this kind of extreme and catastrophic events. Emergency preparedness planning such as Styrel is an attempt to organise an effective and coherent response in case of power shortage in Sweden. Unfortunately, there is not much information available regarding emergency preparedness planning processes in case of power shortages in other countries. Presumably the lack of information is caused by guaranteeing confidentiality regarding national emergency preparedness plans.

Wilson (1993) states that a simple way of finding an optimal allocation when the power supply is limited is essentially a rule for rationing which is assigning a priority of service for each electricity user. The electricity users are then supplied in order of their priorities until available power supply is exhausted. The author mainly discuss the opportunity of ap-
Applying different electric prices to customers but more importantly the author point out that an implementation of the priority of service need only a few priority classes. Wilson (1993) suggest that not more than 4-5 priority classes should be applied to differentiate electricity users.

De Nooij, Lieshout and Koopmans (2008) explores how to reduce social cost of power shortages through efficient regional rationing in the Netherlands. The authors states that making a manual load shedding in a whole region is technically easier and faster than rationing individual users of electricity or economic sectors. In Netherlands the power grid operator take decisions about which regions that are prioritised based on information on the economic and social effects of shutting down parts of the power grid. The authors point out the importance of supplying the power needed for system stability in all regions, otherwise the power system will shut down and electricity users will be interrupted in an uncontrolled way.

De Nooij et al. (2008) states that the social costs of a power supply interruption are determined by the following factors: Who is affected (e.g. manufacturing plants, offices, public services such as hospitals and private households, the moment the interruption occurs (season, day of the week, time of day), the duration of the interruption and whether a notification prior to the interruption was given.

The result from the study by de Nooij et al. (2008) show that social costs are significantly lower when applying efficient rationing as a result of decision making with account to economic and social consequences in different municipalities. Their result also implies that switching off power supply to manufacturing locations who use a lot of electricity, to the benefit of offices and private households.

2.2 The Swedish power grid

During the last decades the dependency of electricity in society is continually increasing. The electricity production in Sweden consists to 85% of hydropower and nuclear power, and 15% of wind power plants, condensing power plants and combined heat and power (CHP). Swedish power companies import and export electricity daily from and to countries in the Nordic region and Europe. (SEA, 2014)

The Swedish power grid is almost 328 100 miles long and is owned by 160 different power companies. The power grid is structured in a high voltage national grid, a regional grid and a local grid. The national grid is owned
by Svenska Kraftnät (SvK) which deliver electricity to the regional grid through electric transformers that decrease the voltage level. Large users of electricity such as paper mills often receive their electricity direct from the regional grid. The local grid is powered by the regional grid, and provides electricity to industries, household and other users of electricity. (SEA, 2014)

### 2.2.1 Power shortage

Users of electricity can be affected by three different kinds of disruptions of electricity supply: power outages, power deficiency and power shortages. These disruptions have diverse causes and consequences, also they need to be managed in different ways. Unannounced power outages are disruptions caused by external factors, equipment failures or extreme weather conditions. Power deficiency comprise a long-term situation where the total supply of electricity is not enough to support society, this can be caused by damaged nuclear reactors or low water flow. Power shortages occur when the balance in the power system is faulty, consumption of electricity are greater than instantaneous velocity of production and import of electricity. (SEA, 2015)

Svenska Kraftnät, SvK, is responsible for maintaining the balance between production and consumption of electricity as well as preventing and handling power shortages. The risk of power shortages is highest during long and severe cold when the consumption of electricity is larger than normal. To prevent a power shortage SvK can use a disturbance reserve of which consists of gas turbines. As a final action, to avoid a total power blackout, SvK can command a manual load shedding which implies a disconnection of whole or parts of the regional power grid. (SEA, 2014)

### 2.2.2 Manual load shedding

The manual load shedding was introduced in Sweden in the 1980s. This procedure results in a disconnection of whole or parts of the regional power grid (SEA, 2014). Before the emergency preparedness planning process Styrel, the manual load shedding was not conducted to spare certain electricity users. According to a change in 2011 of the Swedish law titled The Electricity Act (1997:857), the manual load shedding shall be done with respect to prioritised users of electricity to reduce the consequences for human life and health, vital societal functions and critical infrastructure.
A manual load shredding has never been required in Sweden so far. However, Sweden has several times been close to face a power shortage. The technical conditions today restricts the manual load shredding to disconnecting power lines and not individual users of electricity. The emergency preparedness planning process Styrel is vital for identifying and prioritising users of societal importance and, due to the technical conditions, determine a ranked order of power lines in all municipalities in Sweden. (SEA, 2014)

2.3 Styrel

Styrel is the name of the Swedish emergency preparedness plan in case of power shortage. Styrel aims to identify and prioritise vital societal users of electricity through a planning process involving municipalities, county councils, county administrative boards, Swedish power companies, private sector stakeholders and government authorities. The prioritises in Styrel are used to conduct a manual load shredding, with respect to users with societal importance, in case of power shortage in Sweden. (SEA, 2014)

The emergency planning process Styrel was initiated by the Swedish Government in 2004. During 2004-2011 the Swedish Energy Agency (SEA) developed Styrel by investigating technical and legal issues, creating a process to support prioritises of electrical users with societal importance, evaluating the proposed model in a municipality and in a county and to educate stakeholders in counties, municipalities and power grid companies. The first national Styrel process was performed in 2011 according to SEA (2014).

2.3.1 Stakeholders

Styrel includes stakeholders (participants) at a local level by municipalities and private stakeholders (companies), at a regional level by county administrative boards and county councils and a national level by government and authorities (SEA, 2014).

Sweden is divided into 290 municipalities and each municipality has responsibility to identify and prioritise vital societal functions and critical infrastructure within their own organisation and in their geographical area according to the Swedish Government (2015). The municipalities need to cooperate with private corporations and additionally the county councils, which are responsible for good health of the population in each county.
At a regional level, Sweden is divided into 21 counties. The county administrative boards are responsible authority at regional level which manage government operations in each county according to the Swedish Government (2015). Additionally, the county administrative boards shall reduce the societal vulnerability, monitor risk, perform emergency preparedness and coordinate activities between municipalities, county councils, authorities and the Swedish government.

At a national level, the Swedish government is responsible to ensure an efficient crisis management and to reduce societal consequences of severe disturbances, crises and accidents (Swedish Government, 2015).

The public authorities’ role and responsibilities for emergency preparedness is regulated in the Swedish regulation named Emergency Management and Heightened Alert Ordinance (2006:942). Authorities with particular responsibility for emergency preparedness are divided into 6 areas of cooperation: financial security, dangerous substances, geographical area responsibilities, technical infrastructure, transport and protection, rescue and care.

2.3.2 Planning process
SEA (2014) describes that Styrel require collaboration between multiple stakeholders and consist of the following steps:

1. Swedish authorities identifies and prioritise users of electricity with societal importance within their responsibility in Planning document no. 1 to relevant county administrative boards.

2. Each county administrative board submit the preferences from all authorities in Planning document no. 1 and send these to each municipality in the county.

3. Each municipality identifies and prioritise users of electricity with societal importance within their geographical area in Planning document no. 1. Each municipality submit prioritises from authorities in their Planning document no. 1 and send this to the relevant power grid company.

4. The power grid companies add information about power line and electricity area for all prioritised users of electricity. These are sent back to the municipalities.
5. Each municipality create a ranking of power lines in their municipality in Planning document no. 2 and send this to respective county administrative board.

6. Each county administrative board create a ranking of power lines in their county in Planning document no. 3. These are sent in Planning document no. 4 to SvK and concerned power companies.

7. The power companies create a plan for manual load shredding based on the Styrel Planning document no. 4.

As described in the last step of Styrel, the result of Styrel are the plans for manual load shredding for each power grid company. An important aspect regarding the plans for manual load shredding are that they give opportunity to switch on users of electricity with societal importance before other users, according to the Styrel ranking of power lines in each county. When the plans for manual load shredding are created at each power grid company, these are sent to SvK and corresponding county administrative boards. (SEA, 2014)

2.3.3 Identifying electricity users with societal importance

The Swedish Civil Contingencies Agency, MSB (2014) has investigated civil contingencies and developed a model to facilitate emergency management. The model describes the core values of the Swedish society: human life and health, the functioning of society, democracy, rules of law and human rights, environment and property, and national sovereignty.

MSB (2014) describes that a subset of the Swedish emergency management are the protection of vital societal functions (VSF) and critical infrastructure (CI). This requires measures and activities to ensure the functionality and continuity of VSF and CI, and thereby the society as a whole. MSB (2014) define the terms societal sector, vital societal function and critical infrastructure as following:

A societal sector refers to the different areas within which vital societal functions (VSF) are present and wherein Critical infrastructure (CI) can be identified.

Activities that maintain a given functionality is called a vital societal function, VSF. Each VSF is included in one of the societal sectors and is maintained by one or more critical infrastructures.
Critical infrastructure (CI) is assets, systems or parts thereof which are essential for the maintenance of vital societal functions, health, safety, security, economic or social wellbeing of people. Disruptions or destruction of CI would have significant impact. Infrastructure can be critical to society at local, regional, national or international level.

The Swedish Energy Agency, SEA (2014) have decided to not give examples of specific vital societal functions, thus examples can implicate too much steering in the local or regional planning process. SEA recommend participants in Styrel to use scenario thinking for disruptions and interruptions in electricity supply. Additionally, SEA refers to the MSB (2011) guidelines to identify vital social functions presented in Table 2.1 below.

Table 2.1: Eleven societal sectors and examples of VSF for each of the sectors (MSB, 2011).

<table>
<thead>
<tr>
<th>Societal sector</th>
<th>Examples of vital societal functions (VSF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy supply</td>
<td>Production and distribution of: electricity, local heating, fuel etc.</td>
</tr>
<tr>
<td>Financial services</td>
<td>Payments, access to cash, central payment system, securities trading etc.</td>
</tr>
<tr>
<td>Trade and industry</td>
<td>Construction, retail, manufacturing etc.</td>
</tr>
<tr>
<td>Health, medical and care services</td>
<td>Emergency medical services, pharmaceutical and equipment supply, disabled and elderly care, primary health care, social services etc.</td>
</tr>
<tr>
<td>Information and communication</td>
<td>Telephony, internet, radio communication, website information, social media etc.</td>
</tr>
<tr>
<td>Municipal technical services</td>
<td>Drinking water supply, sewage treatment, sanitation, road maintenance etc.</td>
</tr>
<tr>
<td>Foodstuffs</td>
<td>Distribution, primary production, inspections and manufacture etc.</td>
</tr>
<tr>
<td>Public administration</td>
<td>Local, regional, national management, diplomatic and consular services etc.</td>
</tr>
<tr>
<td>Protection, safety and security</td>
<td>Military defence, prison service, coastguard, police, fire service, customs, border protection etc.</td>
</tr>
<tr>
<td>Social security</td>
<td>Public pension system, sickness and unemployment insurance etc.</td>
</tr>
<tr>
<td>Transport</td>
<td>Air, rail, maritime, road and public transport etc.</td>
</tr>
</tbody>
</table>

2.3.4 Prioritising electricity users with societal importance

The emergency preparedness planning process Styrel involves dividing electricity user with societal importance into priority classes. In Styrel there are 8 different priority classes, described in Table 2.2.
Electricity users in priority class 8 or other users who are situated on a low ranked power line, can be largely affected during a power shortage. An analysis after the first national Styrel conclude that 73% of the electricity users in priority class 8 are households and vacation homes. (SEA, 2014)

Table 2.2: Styrel priority classes for electricity users (SFS 2011:931).

<table>
<thead>
<tr>
<th>Priority class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Electricity users that in a short time span (hours) have a large impact on life and health.</td>
</tr>
<tr>
<td>2</td>
<td>Electricity users that in a short time span (hours) have a large impact on vital societal functions.</td>
</tr>
<tr>
<td>3</td>
<td>Electricity users that in a longer time span (days) have a large impact on life and health.</td>
</tr>
<tr>
<td>4</td>
<td>Electricity users that in a longer time span (days) have a large impact on vital societal functions.</td>
</tr>
<tr>
<td>5</td>
<td>Electricity users that represents large economic values.</td>
</tr>
<tr>
<td>6</td>
<td>Electricity users that have a major importance for the environment.</td>
</tr>
<tr>
<td>7</td>
<td>Electricity users with importance for societal and cultural values.</td>
</tr>
<tr>
<td>8</td>
<td>All other electricity users.</td>
</tr>
</tbody>
</table>

SEA (2014) point out the importance of a local and regional perspective for identification of electricity users that needs to be prioritised in each county. Some examples of electricity users in each priority class are presented by MSB (2010).

Table 2.3: Styrel priority classes with examples (MSB, 2010).

<table>
<thead>
<tr>
<th>Priority class</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Emergency health care, police, emergency services.</td>
</tr>
<tr>
<td>2</td>
<td>Water, sewage, fuel supply, certain financial systems, radio.</td>
</tr>
<tr>
<td>3</td>
<td>Primary health care, health centres, medical supply.</td>
</tr>
<tr>
<td>4</td>
<td>Transports, food supply.</td>
</tr>
<tr>
<td>5</td>
<td>Pulp and paper mills, refineries, heavy industry.</td>
</tr>
<tr>
<td>6</td>
<td>Garbage disposal, chemical industry.</td>
</tr>
<tr>
<td>7</td>
<td>Archives, museums, objects on UNESCO’s list.</td>
</tr>
<tr>
<td>8</td>
<td>Households, small to medium sized businesses.</td>
</tr>
</tbody>
</table>

To compare the importance of each power line in the municipality and in the county, the electricity user in each priority class represent a score from 1 to 7. The power lines with one user in priority class 1 are assigned with
7 points, power lines with one user in priority class 2 are assigned with 6 points and so on. For power lines with more than one prioritised electricity user get a score representing the sum of the prioritised electricity users. For example, a power line with electricity users in priority class 1, 3 and 5 get the score 7+5+3=15 and a power line with 2 electricity users in priority class 1 get the score 7+7=14. (SEA, 2014)

The scores are transferred to the group decision in the county and of a power line have electricity users in more than one municipality, the scores from each municipality us summarised to a total score according to (SEA, 2014).

2.3.5 Evaluation of Styrel

The work with emergency preparedness regarding power shortage have generated great interest and increased competence, to ensure the functionality of elements with societal importance during crisis and catastrophic situations. In an evaluation report from the Swedish Energy Agency (2012) the authors state that there is a need for further development of Styrel and in particular to create a homogenous interpretations of priority classes to create a continuous and self-enhancing routine.

In a study by Veibäck et al. (2013) the authors argue the need to ensure consistency between priorities and partition into priority classes for different stakeholders. The authors point out that the current planning process for Styrel sometimes cause improperly low prioritises of electricity users with societal importance.

Lindberg et al. (2014) have evaluated Styrel in the Swedish counties Stockholm, Västra Götaland and Skåne during the period September to November 2013. The evaluation consisted of three phases: knowledge enhancement, exercise and collaboration. The purpose of the phases was to improve the ability to manage societal consequences in case of power shortage. Their evaluation shows that the feedback from stakeholders regarding preferences and priority classes is insufficient and this negatively affects the plan for manual load shedding. The authors conclude that the non-existing collaboration between counties about priorities is a risk. Additionally, the authors point out the importance a systematic approach for emergency preparedness to map consequences of executing the plan for manual load shedding.
Although several studies have analysed the planning process Styrel, the current procedure for compiling the prioritised and ranked electricity users at a regional level have not been questioned or discussed at all (Step 6 in Chapter 2.3.2). Various studies conclude that there is a need of a systematic approach for Styrel where the preferences from all stakeholders are preserved and prioritisation at a regional level in Styrel are uniform and structured.

2.4 Decision analysis

The fundamentals of decision analysis were developed in the late 1950s according to Edwards, Miles and von Winterfeldt (2007). The authors state that the first ideas in book format were published in Probability and Statistics for Business Decisions written by Schlaifer (1959). In the 1960s, Howard (1966) named a new discipline “decision analysis” as a result from combining the fields of statistical decision theory and system analysis. Decision analysis is based on the disciplines of mathematics, economics, behavioural psychology and computer science according to Edwards, Miles and von Winterfeldt (2007).

Decision analysis aims to support people in making hard and complex decisions. The more complex a decision situation becomes, the better it will be to use procedures and tools to systematically bring forward and process relevant information. In several areas in our society, there is continually decisions made which affects a large number of people: in politics, agencies, companies, schools and hospitals. These important decision situations often lack structure and systematic analyses. Decision analysis can be helpful in any decision situation, this make it relevant to managers, politicians, sociologists, physicians and engineers. (Eisenführ, Weber and Langer, 2010)

“No model, or results of an analysis, ever makes a decision. The decision makers must make the decision. The analysis informs them about what alternatives might be best and why.” (Keeney, 2009)

Keeney (1982) state an intuitive description of decision analysis, as a formalisation of common sense for decision problems which are too complex for informal use of common sense. Howard (2007) describe that the purpose of decision analysis is to achieve clarity of action. Decision analysis can also be defined in a more technical way as:
Von Winterfeldt and Edwards (2007) argue that structuring decision problems is the most important task of a decision analyst, at the same time this is the least well understood task. The authors state that textbook samples of decision problems are usually neatly structured with, for example, specified objectives and events, but the experience of decision analysts are that in reality the decision problems are unfortunately not as nicely packaged.

### 2.4.1 Structuring decision problems

The basic structure of a decision problem include 4 components according to Eisenführ, Weber and Langer (2010):

1. The *alternatives* (options, actions). The decision maker has a number of alternatives from which to choose.
2. The *uncertainties* which are incidents or states of the world that influences the decision. The decision maker can only form expectations about resolution of uncertainty.
3. The *consequences* of actions and uncertainties. By choosing an alternative and the resolution of uncertainty, the resulting consequences are determined.
4. The *objectives and preferences* of the decision maker with respect to the consequences.

Eisenführ, Weber and Langer (2010) describes how to find relevant alternatives. In some cases, finding alternatives is given in a natural way. While in other cases the alternatives is a result of a search process or a creative process to generate the alternatives. These processes are sometimes limited by time and budget restrictions but they can also be considered involving decisions of its own regarding when the process should be stopped.

To enhance the understanding of structuring a decision problem, von Winterfeldt and Edwards (1986) recommends the following three-step process:
1. **Identify the problem.** In the first step, the following questions are important: What is the nature of the problem? Who is the decision maker? Which groups are affected by the decision?

2. **Select an analytical approach.** In the second step, the appropriate framework is chosen after exploring alternatives. Often the best solution is to combine approaches.

3. **Develop a detailed analysis structure.** In the third step, develop trees, diagrams and networks suitable for the decision problem.

According to Keeney and von Winterfeldt (2007) there are two types of models commonly used in decision analysis: *consequence models* which incorporate judgements, facts, and uncertainties in a decision problem to describe possible consequences of alternatives and *value models* which incorporate the values and risk tolerances to evaluate consequences.

### 2.4.2 Preference logic

The topic of general principles for preferences can be traced back to Book III of Aristotle’s *Topics* according to Hansson (2002). The decision maker’s preferences can be expressed as the attitudes towards alternatives with respect to their consequences. Halldén (1957) proposed the first complete system of preference logic. The author describes the two fundamental value concepts as ”better” for strict preference, “equal in value to” for indifference and “better than or equal in value to” for weak preference. If $X$ represents the set of all possible consequences in a decision situation, Eisenführ, Weber and Langer (2010) presents the following notation for the relations of $x, y \in X$:

- $x \succ y$  
  *x is preferred to y.*
- $x \sim y$  
  *indifference between x and y.*
- $x \succeq y$  
  *x is preferred to y or there is indifference.*

Hansson (2002) states that philosophical tradition create meaning of $x \succ y$ as “y is worse than x” as well as “x is better than y”. The author point out that to use these relations of preferences, the properties of von Neumann and Morgenstern’s axioms must be fulfilled. The two axioms defined by von Neumann and Morgenstern (1953) that need to be fulfilled in case of certainty are completeness and transitivity:

*Completeness* is fulfilled if the decision maker has a preference for any pair of alternatives. For any alternatives $x$ and $y$, exactly one of the following holds: $x \succ y$, $y \succ x$ or $x \sim y$. 

---

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Transitivity is fulfilled if for any three alternatives \(x, y\) and \(z\), the following holds: from \(x > y\) and \(y > z\) follows \(x > z\).

If possible, the decision maker should be able to express preferences with respect to the attribute levels of a subset of objectives, independent of the attribute levels of the remaining objectives according to Eisenführ, Weber and Langer (2010). The authors states that this is called (simple) preferential independence. Let \(a\) and \(b\) be two alternatives that only differ in the \(i\)-th attribute:

\[
a = (a_1, ..., a_{i-1}, a_i, a_{i+1}, ..., a_m)
\]
\[
b = (a_1, ..., a_{i-1}, b_i, a_{i+1}, ..., a_m)
\]

and let \(a'\) and \(b'\) be two alternatives that also only differ in the \(i\)-th attribute:

\[
a' = (a'_1, ..., a'_{i-1}, a'_i, a'_{i+1}, ..., a'_m)
\]
\[
b' = (a'_1, ..., a'_{i-1}, b'_i, a'_{i+1}, ..., a'_m)
\]

Eisenführ, Weber and Langer (2010) describe that an attribute is (simply) preferentially independent of the remaining attributes if it holds for any \(a, b, a', b'\) defined above that:

\[a > b \leftrightarrow a' > b'\]

Additionally, the authors states that the attribute is difference independent if:

\[(a \rightarrow b) \sim (a' \rightarrow b')\]

In prescriptive decision analysis, which aims to identify the best decision to make, decision makers’ preferences are modelled by a mathematical function called a value function. According to Eisenführ, Weber and Langer (2010) a value function will always exist that represents the preference, if a preference is a complete, transitive and the set of consequences \(X\) is countable.

2.4.3 Value functions

Dyer and Sarin (1979) states that a preference representation function under certainty is referred to as a value function, and a preference representation function under uncertainty is referred to as a utility function. A value function that may be used to order the differences in the strength of preference between pairs of alternatives or the “preference difference” between the alternatives, is called a measurable value function.
Furthermore, Dyer and Sarin (1979) describes that a value function $v$ assigns a real number to each alternative. The value of an alternative $x$ is greater than the value of alternative $y$ if and only if the decision maker prefers alternative $x$ to alternative $y$:

$$v(x) > v(y) \iff x > y, \ x, y \in X$$

(2.1)

In enhancement, if $w, x, y, z \in X$ and $\succsim$ is defined as a quaternary relation on $X \times X$. The value function $v$ on $X$ exists such that the preference difference between $w$ and $x$ exceeds the preference difference between $y$ and $z$, then $wx \succsim * yz$ if and only if:

$$v(w) - v(x) \geq v(y) - v(z)$$

(2.2)

Dyer and Sarin (1979) states that the value function $v$ is unique up to a positive linear transformation and is therefore a *cardinal function*, this means that $v$ provides an interval scale of measurement. The authors points out that it is important to note that the value function is not on a ratio scale, which means that it is not suitable to conclude things such as, one consequence is twice as good as another. Additionally, if $v'$ also satisfies (2.2), this implies that there are real numbers $\alpha > 0$ and $\beta$ such that:

$$v'(x) = \alpha v(x) + \beta, \quad \text{for all } x \in X$$

(2.3)

Eisenführ, Weber and Langer (2010) describes that value functions are normalised on the interval $[0, 1]$. This means that if all levels lie between $x^-$ which represents the worst level and $x^+$ which represents the best level, and the following holds:

$$v(x^-) = 0 \quad \text{and} \quad v(x^+) = 1$$

(2.4)

A specific functional form of the value model is the additive value function, defined by Krantz et al. (1971) for value functions based on strength of preference as:

$$v(x_1, ..., x_n) = \sum w_i v_i(x_i)$$

(2.5)

Where $v$ is the overall value model, $v_i$ are single attribute value functions and $w_i$ are scaling constants. The additive model requires preference independence and difference independence.
2.4.4 Constructed scales

In some value functions it is not possible to measure the value of an attribute with a natural scale, this results in a need to develop a constructed scale to measure the objective (Keeney and von Winterfeldt, 2007). An example of a natural scale is money, where financial or economic impact follow the nature of the attribute itself. According to Keeney and von Winterfeldt (2007) typically two to ten defined points are represented with a constructed scale. It is important for the value function to assign appropriate relative values to each of those levels.

A constructed scale can, for instance, identify two or more distinct levels of achievement of an objective. This is applied in a decision analysis of national strategies to manage nuclear waste from power plants by Keeney and von Winterfeldt (1994). The objective were to minimise environmental impact and the authors created a constructed scale with attribute level from 0 to 5, where the attribute level 0 represented no impact and level 5 represented major impact to their defined terms aesthetics, endangered species habitat and historical sites.

According to Keeney (2007), once a constructed attribute has been commonly used in practice, people become familiar with it and it takes on properties of an attribute on a natural scale. The author state that the main feature which distinguish a natural attribute from a constructed attribute is the familiarity and the ease of interpreting the attribute levels.

2.5 Group decision theory

The development of society, organisational structures, global networking and technological possibilities requires strategic decisions based on collective decisions instead of a single decision maker according to Ossadnik, Schinke and Kaspar (2016). Very few important decisions are made by individuals on their own as stated by Eisenführ, Weber and Langer (2010).

The complexity of decision problems often requires collaboration between experts from different fields. Additionally, the potential advantages of group decisions are numerous: more ideas, broader amount of information, more knowledge about facts and relationships, less evaluation mistakes and an increased acceptance of the solution (Sims, 2002; Kreigtner and Cassidy, 2011).

Group decision theory is methods for considering several individuals preferences in, for instance, a societal decision. In the decision making
process within groups, the rationality of the process can easily be influenced. If personal interests of members in the group is affected by the upcoming decision, the assessments of the alternatives almost can not be avoided to be influence by those interests according to Eisenführ, Weber and Langer (2010). Furthermore, the authors state that differences in power and status may give unjustified preferences. Members with lower status will often adapt their original preferences to what the higherranked group member prefer.

The potential disadvantages of a group decision has resulted in several studies to create concepts for structured group decisions. Dyer and Sarin (1979) presents a theory for measurable preference aggregation rules (PAR) for a group decision problem. The authors point out that they use the general term preference aggregation rule instead of the often used social welfare function (e.g. Bergson, 1938; Keeney and Kirkwood, 1975) and collective choice rule (e.g. Arrow, 1951; Sen, 1979).

2.5.1 Additive measurable PAR

The additive measurable PAR created by Dyer and Sarin (1979) can be used to guide the decision of a decision maker in a decision that affect the welfare of a group of individuals or as a basis for participatory group decisions by the group itself. The authors’ measurable PAR is for decisions under certainty and require measurable value functions. Their theory is based on theories of PAR for decisions under risk by Harsanyi (1955) and Keeney and Kirkwood (1975) and also PAR for decisions under certainty with ordinal value functions by Fleming (1952).

Dyer and Sarin (1979) states two assumptions for the group decision problems. Firstly, the group contains \( n \geq 3 \) individuals and secondly, the preferences of each individual are essential to the group. The authors’ conditions for the measurable PAR, presented below, are comparable with those presented by Harsanyi (1955) for group decisions under uncertainty.

*Condition 1 (Measurable individual rationality)*: The personal preferences of all individuals satisfy the measurable value function axioms.

*Condition 2 (Measurable group rationality)*: The group preferences satisfy the measurable value function axioms.

*Condition 3 (Exchange independence)*: If all individuals are indifferent between two exchanges, then the group will be indifferent between them.
Condition 1 gives for each individual $i$ in an $n$-person group, the measurable value function $v_i: X \to V_i \subseteq \mathbb{R}$. Dyer and Sarin (1979) states that the impacts of the consequences $x$ on the preferences of the $n$-person group can be represented by the $n$-vector $v(x) = (v_1(x), ..., v_n(x))$ under the assumption that the group preferences are determined by the measurable value functions $v_i$ and that each $v_i$ is known to the group.

For the second condition Dyer and Sarin (1979) point out that to avoid technical difficulties, the set of consequences $X$ is assumed to be suitably rich so that $v: X \to V = \prod_{i=1}^n V_i$. According to the authors, this make it possible to partition $\{1, ..., n\}$ into $I$ and $\bar{I}$, then $V$ can be represented by $V_I \times V_{\bar{I}}$. Condition 2 is then equivalent to the assumption of a group quaternary relation $\succsim^*$ on $X \times X$, and a group measurable value function $W_v$ defined on $X$ satisfying equation (2.2).

From Condition 3 follows that if all individuals are indifferent among all consequences except individual $i$, then the group and individual $i$ will have identical rankings of preferences differences under the condition that group and individual $i$’s preferences are positively related (Dyer & Sarin, 1979).

Dyer and Sarin (1979) present the theorem of the additive measurable PAR for $n \geq 3$ and the authors’ conditions 1, 2 and 3 holds if and only if there exists a group measurable value function $W_v: X \to \mathbb{R}$ such that the following are true:

(i) for any $w, x \in X$, $w \succeq x$ if and only if $W_v(w) \geq W_v(x)$,

(ii) for any $w, x, y, z \in X$, $w, x \succsim^* y, z$ if and only if

$$W_v(w) - W_v(x) \geq W_v(y) - W_v(z),$$

(iii) if $W_v^*$ is another function with the same property, then there exists constants $\alpha > 0$ and $\beta$ such that $W_v^* = \alpha W_v + \beta,$

(iv) $W_v(x) = \sum_{i=1}^n \lambda_i v_i(x)$.

Dyer and Sarin (1979) emphasise that this additive representation also allows negative scaling constants, $\lambda_i < 0$. To ensure that the scaling constants are positive, the additional assumption that group and individual preferences have an ordinal positive relationship could be added.
Baucells and Sarin (2003) presents a further development of the additive measurable PAR for group decisions with multiple criteria.

### 2.5.2 Multiplicative measurable PAR

The additive measurable PAR gives the conditions for the multiplicative measurable PAR also developed by Dyer and Sarin (1979). The authors’ third condition regarding exchange independence is weakened and bounds for each $v_i$ is introduced in the following conditions:

*Condition 4 (Weak exchange independence)*: If all individuals except individual $i$ are indifferent among the consequences associated with two exchanges, then the group will prefer the same exchange as individual $i$. This must be true for any individual $i$.

*Condition 5 (Bounded)*: Suppose all individuals in the group are indifferent among all consequences except for individual $i$. There exists consequences $x_{i*}$ and $x_i^*$ such that individual $i$ considers all other consequences at least as desirable as $x_{i*}$ and none more desirable than $x_i^*$.

Keeney and Kirkwood (1975) stated a condition for the nonlinear PAR under risk which is used by Dyer and Sarin (1979) for the multiplicative measurable PAR:

*Condition 6 (Ordinal independence)*: If any subset $I$ of individuals is indifferent between two consequences, then the group preference is determined only by the preferences of the individuals in subset $I$.

Dyer and Sarin (1979) presents the theorem of the multiplicative measurable PAR for $n \geq 3$ and if the authors’ conditions 1, 2, 4, 5 and 6 hold, then either

$$1 + \lambda W_v(x) = \prod_{i=1}^{n}[1 + \lambda_i v_i(x)] \quad \text{if} \quad \sum_{i=1}^{n} \lambda_i \neq 1$$

or

$$W_v(x) = \sum_{i=1}^{n} \lambda_i v_i(x) \quad \text{if} \quad \sum_{i=1}^{n} \lambda_i = 1$$

where $W_v$ and the $v_i$’s are scaled from 0 to 1, the $\lambda_i$’s are scaling constants $0 < \lambda_i < 1$ for all $I$ and $\lambda > -1$.

### 2.6 Applications of decision analysis and group decision theory within the energy sector

Balson et al. (1992) evaluated the efficiency of decision analysis and risk analysis tools to help structure and develop solutions to complex envi-
ronmental problems in the U.S. The authors describe that the state agencies have started to recommend the use of decision analysis to evaluate decisions and strategies to reduce economic risk. Their conclusion is that techniques for decision- and risk analysis can be used to identify solutions that meet requirements while minimizing costs and future risk exposure.

Keeney and McDaniels (1992) made a decision model to guide the decision makers in strategic decisions regarding power supply in British Columbia, a province on Canada’s Pacific coast. The authors propose a value model and discuss if an additive or multiplicative value model are most suitable for assessing the objectives of economics, environment, health and safety, equity, service and public interest perception. To achieve most of the major objectives an additive model was most suitable in their research, but the economic objective were better modelled by a multiplicative model.

According to Keeney and McDaniels (1992) their model must respond to the interests of a wide variety of stakeholders and will be used to support communication, to clarify differences and build agreement for objectives regarding strategic planning and decisions. The authors’ conclusions are that a value model give regulators and government agencies the opportunity to easy examine the implications of different alternatives. The authors’ value model is already used in various decisions regarding power supply in British Columbia.

2.7 Simulation

Simulation is the imitation of an operation of a real-word process or a system over time (Banks, Carson, Nelson & Nicol, 2001). Simulation is an important tool in solving and understanding numerous and diverse problems according to Sokolowski and Banks (2009). A simulation model is an external and explicit representation of a part of reality (Pidd, 2009). Using a computer simulation creates an opportunity to experiment with different models according to Pidd (2009). The author presents advantages of using a simulation: low cost, not time consuming, ability to replicate, guaranteed legality and security.

There are situations when simulation is not appropriate to use, for example when the problem can be solved by common sense, if the cost of simulating exceeds savings and if system behaviour is too complex. The term simulation comprise different kinds of simulations, for instance the simulation can imitate a discrete event system, particle systems or a differential system. (Banks et al., 2001)
2.7.1 Monte Carlo Simulation

A Monte Carlo Simulation is a simulation of a discrete event system (Banks et al., 2001). Sawilowsky (2003) states that a Monte-Carlo simulation uses repeated random sampling to determine the properties of a behaviour or phenomenon. The author describes that a high-quality Monte-Carlo simulation consist of a pseudo-random generator with a predetermined probabilistic distribution, an appropriate sampling method, a large amount of repetitions to ensure accurate results, a valid algorithm and a realistic simulation model.

Monte Carlo simulation is a widely used technique in different research areas, for instance: engineering systems (Mahadevan, 1997; Yang, Deng, Gao & He, 2016), statistical physics (Binder & Heerman, 2010), modern physics (Jacoboni & Reggiani, 1983; Belotserkovskii & Khlopkov, 2006), mathematics (Jernigan & Turner, 1983; Owen & Tribble, 2005), bioinformatics (Rambaut & Grass, 1996), psychology (Mathieu, Aguinis, Culpepper & Chen, 2012), finance (Detemple, Garcia & Rindisbacher, 2003; Glasserman, 2004), decision analysis (Lee et al. 2008; Tervonen et al. 2013; Betrie et al. 2013) and group decisions (Mateos, Jiménez & Ríos-Insua, 2006; Maloney, Johnson & Zellmer-Bruhn, 2010).

Press, Flannery, Teukolsky and Vetterling (1992) states that any computer program will produce an output that is not truly random, hence it is called a pseudo-random number generator. The authors point out that despite this, the practical computer random number generators are commonly used. Press et al. (1992) argues that from a pragmatic point of view, the randomness is in the eye of the beholder. Thus, what is random enough for one application may not be random enough for another.

Banks et al. (2001) describe that the simulation model takes a set of expressed assumptions, these can be mathematical, logical or symbolic relationship between the entities. Mooney (1997) states that Monte Carlo simulation is a very simple concept but the complicated aspects of the technique are to write the computer code to simulate the conditions desired and to make an interpretation of the sampling distribution.

2.8 Correlation analysis

When analysing data, it is often interesting to measure if the variables are related and how strong the association is between the variables. Rank correlation coefficients are a statistical measure of the similarity between two rankings of different ordinal variables or different rankings of the same
variable (Chen & Popovich, 2002). The most commonly used rank correlation coefficients are Pearson’s (1896) correlation coefficient $r$, Spearman’s (1904) correlation coefficient $\rho_s$, and Kendall’s (1938) correlation coefficient $\tau$. According to Chen and Popovich (2002) one of the differences between these three correlation coefficients are that the Pearson’s coefficient assume that the data is normally distributed while Spearman’s and Kendall’s coefficient do not make any assumptions regarding the distribution of the data.

For ranked lists, the two terms concordant and discordant are essential. These are described by Langville and Meyer (2012) as following: Given two ranked lists, a pair of items appearing in both lists is called concordant if the relative ranking of the two items is the same in both lists and discordant if the relative ranking of the two items does not agree.

Chen and Popovich (2002) point out that Pearson’s coefficient takes into account both the quantity and degree of concordances and discordances, whereas Kendall’s coefficient only reflect the quantity of concordances and discordances and not their degree. The authors states that Spearman’s coefficient only reflects the degree of concordances and discordances on the rank scale.

### 2.8.1 Spearman's rank correlation coefficient

Pearson’s rank correlation coefficient are assuming a normal distribution, while both Spearman’s rank correlation coefficient and Kendall’s rank correlation coefficient do not make any assumptions about the distribution (Chen and Popovich, 2002). The Spearman rank correlation coefficient for $n$ ranks, where all $n$ ranks are distinct integers can be calculated according to Spearman (1904) as:

$$\rho_s = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)}$$

(2.6)

For a sample of $n$ objects, the $n$ raw scores $X_i$ and $Y_i$ are converted to ranks denoted $rg(X_i)$ and $rg(Y_i)$, then $d_i$ is the difference between the two ranks of corresponding values, $d_i = rg(X_i) - rg(Y_i)$. Spearman (1904) describes how to interpret the results of the rank correlation coefficient, which can vary between -1 and 1. The closer $\rho_s$ is to ±1 the stronger correlation between the samples of objects, an interpretation of the strength of correlation for different values of $\rho_s$ are made by Hinkle, Wiersma and Jurs (2002).
Table 2.4: Strength of correlation for different values of Spearman’s rank correlation coefficient (Hinkle, Wiersma & Jurs, 2002).

| $|\rho_s|$ | Strength of correlation         |
|----------|-------------------------------|
| 0        | No correlation                |
| 0.00 < $|\rho_s|$ < 0.30 | Negligible correlation         |
| 0.30 ≤ $|\rho_s|$ < 0.50 | Low correlation                |
| 0.50 ≤ $|\rho_s|$ < 0.70 | Moderate correlation           |
| 0.70 ≤ $|\rho_s|$ < 0.90 | Strong correlation             |
| 0.90 ≤ $|\rho_s|$ < 1.00 | Very strong correlation        |
| 1.00     | Perfect correlation            |

2.8.2 *Kendall’s rank correlation coefficient*

Kendall’s (1938) rank correlation coefficient $\tau$, evaluates the degree of similarity between two ranked lists reflecting the quantity of concordances and discordances. $\tau_A$ is calculated according as following according to Kendall (1938):

$$
\tau_A = \frac{n_c - n_d}{n(n - 1)/2}
$$

(2.7)

where $n_c$ is the number of concordant pairs, $n_d$ is the number of discordant pairs and $n$ is the number of ranked objects in the list. As for Spearman’s $\rho_s$, all $n$ ranks are distinct for $\tau_A$ but Kendall’s $\tau$ can also be calculated with tied ranks, named $\tau_B$ and $\tau_C$. 
3 Methodology

This chapter presents methodology, approach and chosen methods and tools. The chosen method is exploratory mixed method research with a case study approach and a pragmatic and constructivist worldview. According to Creswell (2014) the combination of both qualitative and quantitative approached in a mixed method approach provides a more complete understanding of the research problem. The author state that the exploratory mixed method begins with a qualitative phase to explore the real phenomenon. The qualitative data are analysed and used to build a model that best fits the sample under study. The results from the qualitative phase forms the following quantitative phase, with appropriate variables and performance measure of the built model (Creswell, 2014).

![Figure 1: Exploratory Sequential Mixed Methods (Creswell, 2014).](image)

3.1 Qualitative phase

The study have initially an inductive approach for the qualitative phase. A literature study is conducted to examine previous work and explore if existing models for decision analysis and preference aggregation can be applied for energy rationing to provide a decision model for Styrel.

The qualitative data are produced by a content analysis on transcribed text from two interviews conducted by research colleagues from the Risk and Crisis Research Centre (RCR) at Mid Sweden University during December 2015 and February 2016. The two respondents are representatives from the county administrative boards in two different Swedish counties. The interviews was performed by research colleagues with a semi-structured methodology to encourage respondents to bring forward unexpected subjects. This study does only include a content analysis of the text from the two transcribed interviews.

The aim of the qualitative phase is to gain knowledge about participants’ experience of group decisions in Styrel and the current group decision support in Styrel. The author was not able to participate during the interviews due to geographical circumstances. Therefore only secondary data is used during the qualitative phase.
The secondary data are two transcribed interviews, planning documents from the Swedish Energy Agency (2015), as well as literature and research articles, which are used for exploring previous knowledge within the areas of for example energy rationing, decision analysis and group decision theory. Literature and research articles are collected by searching in databases such as ScienceDirect®, IEEE Xplore®, Primo™ and Google Scholar™.

The two respondents in the two interviews were selected by research colleagues from the Risk and Crisis Research Centre (RCR) at Mid Sweden University. These county administrative boards were chosen due to the different conditions in each county. The first county, C1, is one of the counties with largest area in Sweden and the total amount of inhabitants are about 130 000 persons. C1 include 8 smaller municipalities with one medium sized city with about 45 000 inhabitants. The second county, C2, include 33 municipalities and the total amount of inhabitants are about 1300 000 persons. C2 include 3 large cities with 82 000-140 000 inhabitants, and one of Sweden’s largest cities with 322 000 inhabitants.

3.1.1 Qualitative data analysis

For the qualitative phase, the data are analysed according to methods of content analysis. According to Hsieh and Shannon (2005) qualitative content analysis is one of numerous methods used to analyse text data. In Scandinavia content analysis have been used in research since the 18th century (Rosengren, 1981). Content analysis were chosen as data analysis method in this study because of the structure this method provide handling a large amount of text data.

The text data can be obtained from surveys, interviews, focus groups or printed media such as articles, books or manuals (Hsieh & Shannon, 2005). The authors states that the content analysis will result in an interpretation of the content of text data through a systematic process where the text is categorised into themes or patterns. This is especially useful for text analysis of data from the two different interviews, to systematically categorise the information into themes.

Creswell (2014) presents a model for analysing qualitative data which are be used for the qualitative content analysis in this study. Creswell’s (2014) model is describes the following six steps with information about how this is applied in this study:
1. Organize and prepare data for analysis. This includes documents, field notes, recorded meetings and interviews. In this step all text data are gathered.

2. Go through all the collected data. In this step the text data are read thoroughly three times at different occasions to make sure that all text are carefully considered. This step should provide a general sense of the information and an impression of the overall depth and credibility of the information.

3. Start coding the data into categories. In this step, several categories will be created based on the content of the qualitative data. The text are organised in chunks and marked by appropriate categories.

4. Use the coding process to generate a description of the setting as well as categories of themes for analysis. In this step, the underlying meaning of content in the interviews are explored. This is repeated for both interviews.

5. Advance how the description and themes will be represented in the qualitative material. In this step, a list of topics are created and similar topics are grouped into more comprehensive topics. The themes are discussed in detail.

6. Make an interpretation of the findings. This interpretation is done through comparing findings with previous research in similar areas and with relevant theories. In this step, the intent is to determine if the qualitative themes can be generalised and used to build a base for the quantitative phase.

### 3.2 Quantitative phase

The quantitative phase start with the recommended three step model presented by von Winterfeldt and Edwards (1986): identify the problem, select an analytical approach and develop a detailed analysis structure (see subchapter 2.4.1).

![Three step model to structure decision problems](von Winterfeldt and Edwards, 1986).

In the first step, identify the problem, the results from the qualitative phase are used to describe and interpret the properties for group decisions for energy rationing. In the second step the appropriate approach is chosen to represent the current decisions in Styrel, both the process of
ranking power lines in each municipality and compiling these preferences into a ranked list of prioritised power lines in each county. In the third step, the detailed decision analysis structure is developed to represent Styrel group decisions with decision analytical properties.

Only the additive measurable PAR is applied for group decision in Styrel and not the multiplicative measurable PAR even though the group decision fulfils all 6 conditions stated by Dyer and Sarin (1979). The main reason for applying the additive measurable PAR is that this group decision model is similar to the current procedure of summing scores. The additive decision model are also intuitive and easy to understand according to Eisenfür, Weber and Langer (2010).

Howard (2007) states that an important ethical aspect when using decision analysis is that the decision model can easily justify any course of action if the elements of analysis is manipulated. The additive measurable PAR is applied for group decision for energy rationing because this model can be easily be understood even by people inexperienced using decision models.

Normalisation is an arithmetic process to rescale the attribute values into a specified range, typically from 0 to 1 or from 0 to 100. The normalisation is preserving the proportionality between the scores given from the current Styrel process so these can be used in the decision model. If the scores are denoted by $s_1, ..., s_8$ then the value function $v(P_x)$ is given by:

$$v(P_x) = \frac{s_x}{\text{max } s}$$

The developed detailed analysis structure, is henceforth referred to as the decision model. Due to national security, no real data produced in the Styrel planning process are accessible. Confidentiality regarding energy rationing is important for all municipalities, county administrative boards and power grid companies, to ensure protection against external threats. To evaluate the group decision model for energy rationing, a simulation is necessary to imitate group decisions in Styrel. The simulation consist of a simulation model and a simulation experiment, conducted based on the Styrel process for energy rationing in Sweden.
The group decision setting in Styrel are indeed complex, but this is handled by the delimiting the simulation to only include the Styrel group decision where the preferences of several municipalities are compiled into a county group decision.

The simulation for Styrel group decisions consists of a simulation model and a simulation experiment, developed with the programming language Java. In April 2016, Java is the most popular programming language according to the TIOBE index (TIOBE Software, 2016) and the Popularity of Programming Language index, PYPL index (Carbonnelle, 2016).

3.2.1 Simulation model

In this study, the simulation are conducted in order to predict the effects in the resulting group decision for changes in the group decision model.

The group decision in Styrel are represented in the simulation model with the key characteristics: multiple municipalities, power lines, electricity users and priority classes 1-7 for electricity users. To generate different scenarios for the group decision in the simulation model, the pseudo-random number generator Random (Oracle, 2016) is used with a uniform distribution and sampling with replacement. For the simulation of group decisions in Styrel, the demands on randomness is not especially high because the main point is to explore the effect of changes in the decision model.

The pseudo-random number generator implemented in Java is implemented in several parts of the simulation model to generate as many different group decision scenarios as possible. The pseudo-random number generator is throughout the study set to a uniform distribution because no information regarding the real distribution is known to the author.

The pseudo-random generator in the simulation model use sampling with replacement and as already mentioned, a uniform distribution. For real group decisions in Styrel, the distribution of for example the amount
of electricity users in each priority class is not likely represented by a uniform distribution. The simulation aims to explore effects in the group decision when changing the preference differences between priority classes. Therefore, the simulation is not depending on the quotient of electricity users in each priority class since the 4 value functions are applied for each scenario.

The simulation model and simulation experiment are built with and delimited by a set of assumptions. One of these assumptions is that the group decision is not affected by the preferences of the county administrative board itself.

Several assumptions are made in the simulation model for Styrel: The resulting group decision is determined by the output of the decision model and the preferences of all municipalities are equally important. More than 3 municipalities are located in a county and each municipality have prioritised electricity users and power lines. A power line must be located in one or more municipalities and must have one or more prioritised electricity users. A prioritised electricity user must be located in one municipality, on one power line and belong to one priority class.
The simulation model is presented with algorithms and pseudocode to describe how it is implemented in Java. With information about the amount of municipalities, power lines and prioritised electricity users in a county, the simulation model generate municipalities according to Figure 3.5 assigning the input parameters with unique identifiers (ID).

**Algorithm for creating municipalities**

1. Create a list of unique ID's for municipalities.
2. Create a list of unique ID's for users.
3. Create a list of unique ID's for power lines.
4. Unique power line ID's are randomly assigned to the municipalities. Each municipality gets at least one power line.
5. Unique user ID's are randomly assigned to each municipality such that all power lines in all municipalities will have at least one user.
6. For each municipality:
   6.1. Get a subset of random power lines that is not assigned to the current municipality. If the municipality have enough users to assign to these power lines, add power lines to the municipality.
   6.2. Assign a random priority class 1-7 to each user, where priority one is the highest priority.
   6.3. Assign users to power lines.
7. All municipalities have been created.

**Figure 3.5: Algorithm for creating municipalities with power lines and electricity users.**

The algorithm generate all municipalities in a county with power lines located in each municipality and the prioritised electricity users with priority classes and located at each power line. The procedure of creating a county with municipalities, power lines and electricity users in priority classes is additionally described in more detail in pseudocode, a high-level description of the operating principle of the simulation model.

**Pseudocode – Creating municipalities**

```plaintext
function createCounty(n, m, k)
  Input: Three integers n, m and k, where n ≥ 1, m ≥ 1, k ≥ 3, n ≥ m, k ≤ m.
  Output: Set of municipalities containing both unique and shared power lines with prioritised users.

  M ← Set of k municipalities.
```

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\[ L \leftarrow \text{Set of } m \text{ power lines.} \]
\[ U \leftarrow \text{Set of } n \text{ users.} \]

\textbf{for each municipality } M_i \text{ in } M \textbf{ do}

\hspace{1em} \text{if } i \neq k \text{ then}

\hspace{2em} L_i \leftarrow \text{unique subset of } L \text{ such that } \{\text{non-assigned power lines in } L\} \geq M_i

\hspace{2em} U_i \leftarrow \text{unique subset of } U \text{ such that } \{\text{non-assigned users in } U\} \geq L_i \text{ and } U_i \geq L_i

\hspace{1em} \text{else}

\hspace{2em} L_i \leftarrow \text{remaining unique subset of } L

\hspace{2em} U_i \leftarrow \text{remaining unique subset of } U

\hspace{1em} \text{end if}

\[ L_{\text{random}} \leftarrow \text{random power lines subset of } c \text{ percentage of } L \]

\hspace{1em} \text{if } U_i > L_i + L_{\text{random}} \text{ then}

\hspace{2em} L_i \leftarrow L_{\text{random}}

\hspace{1em} \text{end if}

\textbf{for each user } U_{i,j} \text{ in } U_i \textbf{ do}

\hspace{2em} U_{i,j}.\text{priorityClass} \leftarrow \text{random priority class between 1-7}

\hspace{1em} \text{end for}

\textbf{for each power line } L_{i,j} \text{ in } L_i \textbf{ do}

\hspace{2em} L_{i,j}.\text{users} \leftarrow \text{unique subset } U_{i,j} \text{ of } U_i \text{ such that } \{\text{non-assigned users in } U_i\} \geq L_i

\hspace{1em} \text{end for}

\hspace{1em} \text{end for}

\hspace{1em} \text{return } M

M = \text{Set of all municipalities}
L = \text{Set of all power lines}
U = \text{Set of all users}
c = \text{percentage of shared power lines}
L_i = \text{Power lines in municipality } i
U_i = \text{Users in municipality } i
U_{i,j} = \text{Users located on power line } j \text{ in municipality } i

Figure 3.6: Pseudocode for creating municipalities with power lines and electricity users.

When the conditions in the county are set, the preferences of each municipality is computed with the additive model to determine the value function of each power line. The group decision is compiled with the additive measurable PAR and the group preferences, are ordered with the most important power line in the county first, resulting in a ranked list power lines in the county. The scaling constants \( \lambda_p \) and \( \lambda_c \) are set to be equal for all priority classes and all municipalities.
The decision makers in Styrel are assumed to be indifferent between power lines if their value functions are equal in value. The group is consequently indifferent between group value functions of power lines if their value functions are equal in value. The simulation model handles the indifference by randomly assigning these power lines in consecutive ranks.

**Algorithm generating a ranked list of power lines**

1. Create a list for all power lines in the county.
2. Retrieve the value functions of power lines in each municipality. Append the ranked list with the value function of each power line multiplied by the group scaling constant. If there already is a power line with the same ID in the ranked list, then calculate the sum of the group scaling constant multiplied by the power line’s value functions.
3. Rank the list of power line ID’s in descending order based on group value functions. If more than one power line have the same value, then randomly put these power lines in consecutive ranks.

**Figure 3.7: Algorithm for generating group decision and a list of ranked power lines.**

This part of the simulation model is also described in pseudocode in Figure 3.8.

**Pseudocode - Rank power lines**

```plaintext
function rankPowerLines(userValueFunction)  
Input: User value function for user priority class 1-7.  
Output: A ranked list of power lines in descending order, highest prioritised first.

for each municipality M_i in M do
  for power line L_{j,i} in M_i do
    if R contains a power line R_l equal to L_{j,i} then
      R_l.value += L_{j,i}.valueFunction( userValueFunction )
    else
      R_l = L_{j,i}.valueFunction( userValueFunction )
    end if
  end for
end for
R.sortDescending( )
return R
```

M = Set of all municipalities
M_i = Municipality with ID i
The simulation model is used in the simulation experiment to evaluate the sensitivity of preference differences in the group decision model, applying the current value function for Styrel and 3 proposed value functions.

### 3.2.2 Simulation experiment

In the simulation experiment, the developed simulation model is used in a Monte-Carlo simulation to evaluate the effects in the resulting group decision when changing the preference differences between priority classes for electricity users in the decision model.

The simulation experiment consists of 1000 repetitions generating various group decisions scenarios for Styrel. Each scenario is generated by pseudo-random input parameters within a specified range for quantity of users, power lines and municipalities in a county. A uniform distribution is applied for the pseudo-random number generators and sampling with replacement is applied. For each scenario a correlation analysis is conducted between the resulting group decisions based on 4 different value functions, named Current, Double, Recursive and Extreme.

For each scenario, a random quantity of electricity users, power lines and municipalities in a county are selected. The ranges can be altered but are set for this simulation experiment to 100-200 electricity users, 50-100 power lines and 5-10 municipalities in the county. The additive model for municipality preferences and the additive measurable PAR are based on the 4 different value functions presented in Chapter 4.3. The scaling constants are set as equal for all priority classes and equal for all municipalities. The algorithm for one scenario is presented in Figure 3.9.

The assumptions made in the simulation experiment regarding the ranges for the input parameters are not based on facts from the real Styrel group decisions, real conditions for the amount of prioritised electricity users located on the same power line or real conditions for the amount of power lines located in more than one municipality. However, it is certain that all input parameters varies since the conditions are different in all Swedish counties. The ranges for the input parameters are set with the underlying assumptions that the amount of electricity users is more or
equal to the amount of power lines, and that the amount of power lines are between 5 and 10 times the amount of municipalities.

**Algorithm generating a scenario**

1. Generate a random number between 100 and 200, as the number of unique electricity users in the county.
2. Generate a random number between 50 and 100, as the number of unique power lines in the county.
3. Generate a random number between 5 and 10, as the number of unique municipalities in the county.
4. Create a county based on the generated input parameters.
5. For each value function \( v_C(P_x) \), \( v_D(P_x) \), \( v_R(P_x) \) and \( v_E(P_x) \), apply it to the county and retrieve a ranked list of power lines for the county.
6. Calculate Spearman’s rank correlation coefficient between the ranked lists of power lines.
7. Calculate Kendall’s rank correlation coefficient between the ranked lists of power lines.

**Figure 3.9: Algorithm for an iteration of the simulation experiment.**

**Figure 3.10: Flow chart for simulation experiment.**
3.2.3 Correlation analysis

Rank correlation coefficients are a suitable measurement to analyse how similar the group prioritisations based on different value functions are. The simulation model and simulation experiment use a uniform distribution for the pseudo-random number generator. This means that according to Chen and Popovich (2002) Pearson’s rank correlation coefficient can not be applied, therefore both Spearman’s and Kendall’s rank correlation coefficients are implemented in the simulation model. The reason for using both of these rank correlation coefficients is that they measure different aspects of similarities for group prioritisations.

The used version of Kendall’s rank correlation coefficient is $\tau_A$, because for energy rationing it is necessary to use distinct ranks because the ranked list of power lines needs to be straightforward with a unique rank for each power line in order to perform a manual load shredding prioritising certain power lines.

The correlation analysis is conducted 6 times per scenario in the simulation experiment calculating Spearman’s and Kendall’s rank correlation coefficient pairwise for group prioritisations based on the 4 value functions. The different combinations for the simulation experiment are: Current and Double, Current and Recursive, Current and Extreme, Double and Recursive, Double and Extreme, and, Recursive and Extreme.

To make sure that the interpretation of the strength of correlation is objective instead of subjective, the intervals presented by Hinkle, Wiersma and Jurs (2002) in Table 2.4 is applied in the analysis of the results.

3.3 Method discussion

Tree measurements to ensure the study’s credibility are reliability, validity and objectivity described by Björklund and Paulsson (2012): Reliability represent the extent to which you can achieve the same results if the study is repeated. Validity represents the extent to which you actually measure what you intend to measure. Objectivity represents the extent to which personal beliefs and values impacts the study. For scientific studies many researchers argue that these three aspects must be considered.
3.3.1 Reliability

The reliability can be increased by verifying the results several times according to Björklund and Paulsson (2012). The reliability of the qualitative phase could be questioned in this perspective because the interviews are not repeated with respondents from the county administrative boards. Björklund and Paulsson (2012) point out that the aspects of reliability must be balanced against the amount of available resources. The number of interviews are small, which gives an increased risk of producing different results if the study is repeated with other respondents.

The simulation model and simulation experiment is built in Java to increase the reliability, constructing the simulation with the single purpose of imitating a specific Styrel decision. The ranges for the pseudo-random number generator set for the input parameters in the simulation experiment will increase the reliability as well because the variation of possible scenarios will be countable.

3.3.2 Validity

Björklund and Paulsson (2012) states that the validity can be increased by considering various perspectives, this enhances the ability to generalise findings. The exploratory mixed method increases the validity of the study with the combination of strengths for qualitative and quantitative research methods. The study will describe in depth and with rich detail the process Styrel decisions regarding prioritisations in the qualitative phase. The simulation in the quantitative phase will help to generalise research findings and evaluate proposed group decision model for energy rationing. However, since the proposed group decision model is only evaluated by a simulation the validity of the quantitative phase can be questioned.

The simulation experiment apply both Spearman’s and Kendall’s rank correlation coefficients to increase the validity of the study, ensuring that the rank correlation measures show similar strength of correlation between group prioritisations. The validity is also increased by evaluating with rank correlation coefficient which do not make any assumptions about the distribution of the generated pseudo-random numbers.
3.3.3 Objectivity

Björklund and Paulsson (2012) describes that in qualitative interviews it is important to reproduce facts objectively and avoid using emotionally charged words. Since the respondents are interviewed in Swedish, the objectivity is decreased by not using quotes from respondents in the results. The objectivity is on the other hand increased by minimising the impact of personal beliefs and values during interviews as the qualitative data consists of transcribed interviews. The information stated by respondents are not described using emotionally charged words. The objectivity can be increased by clarifying and motivating choices made in the study to give the reader opportunity to reflect on the results (Björklund & Paulsson, 2012). The decision analytical approach is described in detail and additionally compared to the current Styrel scores to clarify that the group prioritisations are equal. The simulation model and simulation experiment are described in detail with motivated choices such as the uniform distribution for generating pseudo-random numbers and predetermined ranges for input parameters. The strength of correlation is analysed with the intervals presented by Hinkle, Wiersma and Jurs (2002) instead of a subjective interpretation.

3.4 Societal and ethical considerations

A societal aspect of the study is the fact that it concerns public safety. With a plan for power shortage, Sweden can avoid a catastrophic situation if the electricity supply is lower than the electricity consumption. The importance of improving the planning process for power shortage is a societal matter. The extended knowledge about the dependencies of electricity is interesting on a societal level as well, because of our vulnerability in case of damage to the power grid. The societal dependencies of electricity is increasing, this point toward that the importance of a decision model for energy rationing is increasing as well.

To apply a decision model to energy rationing requires a consideration of the ethical aspects. Howard (2007) describes decision analysis as amoral and just like any other powerful tool people can use decision analysis for good or bad. The author states that a decision model can justify any course of action if someone is manipulating the elements of analysis: the information, alternatives, and preferences. This ethical problem is of course present when using a decision model for energy rationing. Some or all of the decision makers could be inexperienced using decision models which could result in unnoticed manipulation of alternatives, information or preferences.
Ethics is of big concern to decision analysts as well as to doctors and lawyers (Howard, 1980). The scale of the problems that decision analysts work on, could make the consequences of their activities more extensive than they are in the medical and legal cases. For energy rationing the consequences of a decision can be wide-ranging, especially if an electricity user with societal importance is improperly low prioritised.

Howard (1980) describes that the decision facing decision analysts are potentially complicated and could be affecting human life and the environment. Particularly decision analysis in social decisions, the course of action can be interpreted as “scientifically based” rather than a consequence of the preference and information inputs of the decision maker. According to Howard (1980) the most serious moral responsibility arise when decision analysis is applied in the public arena. Using a decision model for energy rationing as a support for decision makers when compiling the preferences of multiple stakeholders need to be seen as consequences of preferences.

One of the ethical considerations for this study is to not reveal sensitive information regarding the Styrel procedure or the manual load shredding plan. In the hands of foreign powers this plan can show weaknesses of the Swedish power grid. Additionally, if a potential attacker knows the plan to avoid a catastrophic situation in case of power shortage, this can be used to create a catastrophe instead. No real data regarding preferences of municipalities or real conditions in counties are accessed or exposed.
4 Results

This chapter presents the results of the study. The disposition of this chapter is: Summary of findings in qualitative data, the proposed decision model for energy rationing and results from the simulation.

4.1 Summary of findings in qualitative data

The qualitative text data are coded into relevant themes and the summary of the findings in qualitative data are presented according to these themes. The respondents are anonymised and referred to as C1 and C2 (see Chapter 3.1 for description of the conditions in the counties).

4.1.1 Participants

The respondent from the county administrative board in county C1 have responsibility for risk- and vulnerability assessments and emergency preparedness. The participants in Styrel in county C1 are security coordinators in each of their 8 municipalities. The respondent from the county administrative board in county C2 have responsibility for emergency preparedness. The participants in Styrel from the 33 municipalities in C2 has a variety of responsibilities, typically participants are security coordinators and emergency coordinators but they can also be working in emergency services or be responsible for the energy sector.

Both respondents agree on that the Styrel process are satisfactory. Both county administrative boards and their municipalities consider Styrel as a simple and clear process which is easy to follow. C2 argues that they all are familiar with the Styrel process now, and they do not want any larger changes of the current process.

4.1.2 Identification

During the Styrel process, C1 have gathered their municipalities in meetings to discuss what functions in the county that could be considered vital societal functions (VSF) and critical infrastructure (CI). C1 points out that these meetings are possible for them with 8 (smaller) municipalities but could easily become too complex in a county with many municipalities. The smaller municipalities also have fewer resources to work with Styrel, C1 argues that available resources are a key issue regarding Styrel and identification of electricity users.

C2 confirms C1’s reasoning with the opinion that the larger municipalities in county C2 engaged more in the Styrel process compared to the
smaller municipalities. C2 have divided their 33 municipalities into 5 local regional councils to work with emergency preparedness, these councils was used also during Styrel. The county administrative board and the 5 local regional councils gathered in meetings to create a list of examples of VSF and CI in different priority classes. C2 argues that this created a rather homogeneous view of how to identify and prioritise electricity users in each municipality.

4.1.3 Prioritisation
C2 explains that even though they together created lists with examples of electricity users in each priority class, they had different opinions regarding the belonging of electricity users in many situations. The municipality with one of Sweden’s largest cities was leading and influential during meetings and discussions regarding prioritisations and priority classes. C2 argues that the group of county administrative board and the 5 local regional councils attempted to reach compromises but some participants persisted on their preferences. According to C2, the largest municipality influenced the others in their identification and prioritisation of electricity users.

In C1 the county administrative board and municipalities were more united in the identification and prioritisation of electricity users. In the county of C1, there are few electricity users that represents large economic value and few electricity users with cultural values. C1 argues that one of the most important VSF’s are present in the societal sectors Information and communication and Health, medical and care services.

4.1.4 Ranking and group decision process
When the individual preferences of all municipalities was about to be compiled into a regional ranked list of power lines, the county administrative board in C1 gathered all 8 municipalities and the county council in a meeting. The meeting started with a discussion about which electricity users that are the most important in the county. The top 20 power lines were agreed upon during this meeting and were ranked highest in the county. First thereafter the county administrative board considered the submitted lists of ranked power lines in each municipality.

C1 states that they had a very good discussion between all participants during the compiling of a ranked list of power lines for the county. According to C1, there was a lot of fair compromises made between the municipalities. All participants agreed on a 10% system, where all municipalities were allowed to submit a specific number of power lines each
round, depending on how many power lines the municipality had prioritised in total. For example, one of the municipalities had a total of 70 prioritised power lines and another municipality had a total of 20 prioritised power lines. During each round, the first municipality was allowed to submit 7 power lines and the second municipality was allowed to submit 2 power lines to the county’s ranked list of power lines. After a few rounds, the county’s ranked list of power lines is completed.

C1 points out that the discussion regarding the ranking of power lines was based on the ranking of power lines in each municipality, not the scores for each power line. The score for a power line were often misleading because it could be important and high ranked in a municipality along with a low score.

C2 states that the compilation into a ranked list of power lines for the county were time consuming and that they would benefit from extra resources, a consultant or any other support in the compilation into a group decision. The ranking of power lines in county C2 were aggregated by ranking the power lines holding users in priority class 1 highest and so on. The ranking regarding scores for each power line were considered in the county’s ranked list. The individual preferences of the 33 municipalities were submitted first in the later part of compilation a ranked list of power lines for the county.

4.2 Decision model for energy rationing

This chapter presents the proposed group decision model for energy rationing which is suitable when the electricity users with societal importance is divided into several priority classes.

In Styrel, all electricity users in the same priority class are equally important. No differentiation are present between different types of electricity users within each priority class. For example, an emergency health care location with priority class 1 are equally important as a police station with priority class 1. Nor is there any differentiation between priority classes in different municipalities, an electricity user in priority class 5 in one municipality is equally important as an electricity user in priority class 5 in another municipality.
The priority classes in Styrel are a constructed scale. If the 7 highest priority classes 1-7 (see Table 2.2) are represented by $P_x$, where $x \in [1, 2, 3, 4, 5, 6, 7]$. Then priority class 1 is represented by $P_1$, priority class 2 is represented by $P_2$, priority class 3 is represented by $P_3$, and so on.

Each county consists of several municipalities. For the group decisions in Styrel, the county administrative boards compile the preferences of the municipalities in the county. Prioritised electricity users in priority class $x$ in municipality $y$ are denoted $P_{x,y}$, where $y \in \mathbb{N}$ and $x \in X$ if $X$ is the set of priority classes $X = [1, 2, 3, 4, 5, 6, 7]$. If the county consists of 4 municipalities then $y \in [1, 2, 3, 4]$. Prioritised electricity users in priority class $x$, in municipality 1 are denoted $P_{x,1}$, prioritised electricity users in priority class $x$, in municipality 2 are denoted $P_{x,2}$, and so on.

The prioritised electricity users are located on local power lines. A prioritised power line must be located in at least one of the municipalities and must hold prioritised electricity users. A power line can be shared by several municipalities within the county. Power lines in Sweden are usually denoted by an alphabetical code, but in this representation of Styrel the notation $L_i$ will be used, where $i \in [1,2,...n]$ in a county with $n$ prioritised power lines.

4.2.1 Preference logic

Given the above notation of priority class $x$ of a prioritised electricity user in municipality $y$, $P_{x,y}$. The following preference logic holds:

$$P_{x,y} > P_{x',y} \quad \text{if and only if} \quad x < x' \quad \text{(4.1)}$$

$$x, x' \in X, \quad X = [1, 2, 3, 4, 5, 6, 7]$$

A prioritised electricity user of a higher priority class $x$, are preferred over an electricity user of a lower priority class, $x'$. For instance, an electricity user classified as priority class 1 by municipality 1 is denoted $P_{1,1}$ and an electricity user classified as priority class 2 by municipality 1 is denoted $P_{2,1}$. The electricity user in priority class 1 is always preferred over the user in priority class 2, and $1 < 2$, therefore: $P_{1,1} > P_{2,1}$.

The preference relation where the decision maker is indifferent between two alternatives holds:

$$P_{x,y} \sim P_{x',y} \quad \text{if and only if} \quad x = x' \quad \text{(4.2)}$$
where $x, x' \in X$ and $y, y' \in \mathbb{N}$. This means that the decision maker are indifferent between prioritised electricity users if and only if they belong to the same priority class.

### 4.2.2 Rationality

The following properties for the decision analytical approach of Styrel holds:

**Completeness:** For any prioritised users $P_x, P_{x'}$, exactly one of the following holds:

$$P_x > P_{x'} \text{ or } P_x \sim P_{x'} \text{ for } x \leq x'$$

(4.4)

If $x < x'$ then $P_x$ is preferred over $P_{x'}$ and if $x = x'$ then the decision maker is indifferent between $P_x$ and $P_{x'}$.

**Transitivity:** The preferences are consistent for any three alternatives:

$$\text{if } P_x > P_{x'} \text{ and } P_{x'} > P_{x''} \text{ then } P_x > P_{x''}$$

(4.5)

where $x < x' < x''$ and $x, x', x'' \in X$.

For the priority classes 1-8 in Styrel the following holds:

$$P_1 > P_2 > P_3 > P_4 > P_5 > P_6 > P_7 > P_8$$

(4.6)

### 4.2.3 Value functions

For Styrel, the value function $v$ assigns a real number to each priority class. The value of a priority class $x$ is greater than the value of priority class $x'$ if and only if the decision maker prefers priority class $x$ over priority class $x'$:

$$v(P_x) > v(P_{x'}) \iff P_x > P_{x'}$$

(4.7)

for $x < x'$ and $x, x' \in X$ where $X$ is the set of priority classes $X = \{1, 2, 3, 4, 5, 6, 7\}$. For example the value of priority class 1 are larger than the value of priority class 2, $P_1 > P_2 \iff v(P_1) > v(P_2)$. The value function of prioritised users in the same priority class are equal, if $x = x', x, x' \in X$ then:

$$v(P_x) = v(P_{x'}) \iff P_x \sim P_{x'}$$

(4.8)
Henceforth, if $x, x', x''$ and $x''' \in X$ and $\succeq^*$ is defined as a quaternary relation on $X \times X$. The value function $v$ on $X$ represents the preference difference between $P_x$ and $P_{x'}$ exceeds or equals the preference difference between $P_{x''}$ and $P_{x'''}$, then $P_x \succeq^* P_{x''} \succ P_{x'''}$ if and only if:

$$v(P_x) - v(P_{x'}) \geq v(P_{x''}) - v(P_{x'''})$$  \hspace{1cm} (4.9)

The current process in Styrel involve assigned scores from 1-7 for electricity users in each priority class, presented in Table 4.1. The normalised values representing the scores in Styrel gives $v(P_8) = 0$ and $v(P_1) = 1$.

Table 4.1: Styrel priority classes with scores (SEA, 2014), with normalised scores represented as a value function.

<table>
<thead>
<tr>
<th>Priority class $x$</th>
<th>Score $s_x$</th>
<th>Value function $v(P_x)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>6/7</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>5/7</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>4/7</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>3/7</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>2/7</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1/7</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

As stated in Chapter 2.4 a value function is measurable if it can be used to order the differences in the strength of preference between pairs of alternatives. Styrel decision model can be represented by a measurable value function because the following is true:

$$v(P_1) > v(P_2) > v(P_3) > v(P_4) > v(P_5) > v(P_6) > v(P_7) > v(P_8)$$  \hspace{1cm} (4.11)

An decision analytical interpretation of the scores are that the preference difference between $P_x$ and $P_{x+1}$ equals the preference difference between $P_{x'}$ and $P_{x'+1}$:

$$v(P_x) - v(P_{x+1}) = v(P_{x'}) - v(P_{x'+1})$$  \hspace{1cm} (4.12)

where $x, x' \in X = [1, 2, 3, 4, 5, 6, 7]$. The current preference difference in Styrel can be derived from Equation (4.6) and (4.7):

$$v(P_1) - v(P_2) = v(P_2) - v(P_3) = v(P_3) - v(P_4) = v(P_4) - v(P_5) = v(P_5) - v(P_6) = v(P_6) - v(P_7) = v(P_7) - v(P_8)$$  \hspace{1cm} (4.13)
4.2.4 Additive model

The current score system in Styrel can only be represented by a decision analytical approach with an additive model if the scaling constant \( \lambda_p \) is equal for all priority classes, and \( v(P_x) \) is the measurable value function \( v(P_1) = 1, v(P_2) = \frac{6}{7}, ..., v(P_7) = \frac{1}{7}, v(P_8) = 0 \). In Appendix B, this additive model of Styrel decisions is compared to the score system that is used in reality.

For the current decisions in Styrel, the score of a power line is the sum of the scores from the electricity users in each priority class which is located on the power line. Hence, the value function \( v \) assigns a real number to each power line \( L_i \) determined by the priority classes for prioritised electricity users located on the power line, \( P_{x,i} \), and the scaling constant \( \lambda_p \).

\[
v(L_i) = \sum \lambda_p v(P_{x,i})
\]  

The value function for each power line \( v(L_i) \) can be represented by an additive model. Additionally, the value function for each power line is a measurable value function which can order power lines based on the strength of preference. The value function of a power line \( L_i \) is greater than the value function of power line \( L_j \) if and only if the decision maker prefers priority class \( x \) over priority class \( x' \), and \( P_x \) belongs to \( L_i \) and \( P_{x'} \) belongs to \( L_j \):

\[
v(L_i) > v(L_j) \iff L_i \succ L_j \text{ if } v(L_i) = \lambda_p v(P_x) \text{ and } v(L_j) = \lambda_p v(P_{x'})
\]  

for \( x < x' \) and \( x, x' \in X \) where \( X \) is the set of priority classes \( X = [1, 2, 3, 4, 5, 6, 7] \). For example the value function of a user of priority class 1 are larger than the value function of a user of priority class 2, \( L_i \succ L_j \iff v(L_i) > v(L_j) \) if \( v(L_i) = \lambda_p v(P_1) \) and \( v(L_j) = \lambda_p v(P_2) \). The value functions of power lines with equivalent users in equal priority classes are equal, if \( x = x' \), \( x, x' \in X \) then:

\[
v(L_i) = v(L_j) \iff L_i \sim L_j
\]  

\[
if v(L_i) = \lambda_p v(P_x) \text{ and } v(L_j) = \lambda_p v(P_{x'})
\]
For the ranking of power lines according to value functions, the property of preference logic regarding indifference in (4.16) will be problematic because all power lines need to have distinct ranks to enable a manual load shredding. At the same time, this problem is logically solved by the preference logic of indifference where the decision maker is indifferent also of which power line \( L_i, L_j \) that is ranked highest considering consecutive ranks.

Henceforth, if \( x, x', x'' \) and \( x''' \in X \) and \( \succeq \) is defined as a quaternary relation on \( X \times X \). The measurable value function \( v \) represents the preference difference between \( L_i \) and \( L_j \) exceeds or equals the preference difference between \( L_k \) and \( L_i \), then \( L_i L_j \succeq L_k L_i \) if and only if:

\[
v(L_i) - v(L_j) \geq v(L_k) - v(L_i)
\]

\[
\text{if } v(L_i) = \lambda_p v(P_x), \quad v(L_j) = \lambda_p v(P_{x'})
\]

\[
\text{if } v(L_k) = \lambda_p v(P_{x''}), \quad v(L_i) = \lambda_p v(P_{x'''})
\]

In a municipality there are indifference between an electricity user in priority class \( x \) located at power line \( L_i \) and an electricity user in the same priority class \( x \) located at power line \( L_j \), these must be equally important as described in the preference logic of electricity users and power lines. Let \( L_i \) and \( L_j \) be two power lines that only differ in the \( i \)-th electricity user.

\[
L_i = (P_1, \ldots, P_{i-1}, P_i, P_{i+1}, \ldots, P_m)
\]

\[
L_j = (P_1, \ldots, P_{i-1}, P_i^*, P_{i+1}, \ldots, P_m)
\]

and let \( L_i' \) and \( L_j' \) be two power lines that also only differ in the \( i \)-th electricity user:

\[
L_i' = (P'_1, \ldots, P'_{i-1}, P'_i, P'_{i+1}, \ldots, P'_m)
\]

\[
L_j' = (P'_1, \ldots, P'_{i-1}, P''_i, P'_{i+1}, \ldots, P'_m)
\]

The power lines are (simply) preferentially independent of the remaining prioritised if it holds for any \( L_i, L_j, L_i', L_j' \):

\[
L_i \succ L_j \iff L_i' \succ L_j'
\]

Additionally, the power lines is difference independent if:

\[
(L_i \rightarrow L_j) \sim (L_i' \rightarrow L_j')
\]
An example of the additive model presented in (4.14) is the value function \( v \) of a power line \( L_i \), \( v(L_i) \), with \( \lambda_p = \frac{1}{7} \) and one prioritised electricity user in each of the priority classes 1, 3 and 7 is represented by:

\[
v(L_i) = \sum \lambda_p v(P_x) = \lambda_p v(P_1) + \lambda_p v(P_3) + \lambda_p v(P_7) =
\]

\[
\frac{1}{7} \cdot 1 + \frac{1}{7} \cdot \frac{5}{7} + \frac{1}{7} \cdot \frac{1}{7} = 0.28
\]

4.2.5 Group decision model

In the Styrel group decisions, value functions for power lines from each municipality are compiled into a group decision with ranked power lines in the county.

The group preferences are determined only by measurable value functions and each value function are known to the group. These assumptions are true for Styrel group decision process if the current score system are determining the value functions and ranks of the power lines in each municipality and similarly in the county. In Styrel, each value function are known to the group since the value function of users in each of the 7 priority classes are set.

The group decision in Styrel result in a ranked list of power lines where the value function of each power line can be used to order the power lines according to strength of preference comparing pairs of power lines (equal to the individual order of power lines described in Equation (4.17)). The preference logic for \( v(L_i) \) is presented in Chapter 4.2.4 which shows that \( v \) is a measurable value function. The additive measurable PAR for group decisions in Styrel can be represented by:

\[
v_G(L_i) = \sum \lambda_G v(L_i)
\]

(4.18)

Where \( v_G(L_i) \) is the group value function for power line \( L_i \), \( \lambda_G \) is the group scaling constant and \( v(L_i) \) is the value function or value functions for power line \( L_i \) from municipalities where \( L_i \) is located and have prioritised electricity users. In a group decision there are indifference between an electricity user in priority class \( x \) located in municipality \( y \) and an electricity user in the same priority class \( x \) located in municipality \( y' \), these must be equally important.

To use the additive measurable PAR for group decisions for Styrel according to Equation (4.18), the three conditions (1-3) presented in Chapter
2.5.1 need to be fulfilled. To apply the multiplicative measurable PAR, these conditions are expanded with three additional conditions (4-6) presented in Chapter 2.5.2.

**Condition 1 (Measurable individual rationality):** The personal preferences of all individuals are measurable value functions, according to Equation (2.1), (2.2), (4.11), (4.13), (4.15) and (4.17).

**Condition 2 (Measurable group rationality):** The group preferences are represented by measurable value functions, according to Equation (2.1), (2.2), (4.11), (4.13), (4.15), (4.17) and (4.18).

**Condition 3 (Exchange independence):** Both municipalities and the group (county) will always be indifferent between power lines with value functions of equal value. As discussed regarding indifference between two power lines in Equation (4.8) and (4.16).

**Condition 4 (Weak exchange independence):** If a number of power lines are located in only one municipality $i$, then the other municipalities in the county are indifferent between the exchanges of ranks of these power lines. The group will then prefer the same exchange as municipality $i$.

**Condition 5 (Bounded):** Suppose all municipalities in the county are indifferent among all power lines except for municipality $i$. There exists power lines $L_i^*$ and $L_i^{*'}$ such that municipality $i$ considers all other power lines at least as important as $L_i^*$ and none more important than $L_i^{*'}$.

**Condition 6 (Ordinal independence):** If any subset $I$ of municipalities in a county is indifferent between two power lines, then the group preference is determined only by the preferences of the municipalities in subset $I$.

The group decisions in Styrel fulfil all 6 conditions with the interpretations above.

### 4.3 Proposed value functions

To explore if the resulting group decision is affected by changing preference differences, three additional preference differences are proposed creating 3 new Styrel value functions.

The first new relation for the strength of preference is increasing with a factor 2 for each preference difference, this is henceforth referred to as *Double* and $v_D(P_x)$:
\[ v_D(P_2) = 2(v_D(P_2) - v_D(P_3)) = 4(v_D(P_4) - v_D(P_5)) = 8(v_D(P_4) - v_D(P_5)) = 16(v_D(P_5) - v_D(P_6)) = 32(v_D(P_6) - v_D(P_7)) \]

The next new relation for the strength of preference is referred to as Recursive and \(v_R(P_n)\). The preference differences have a recursive relationship meaning that a subsequent preference difference are given by the previous. The recursive preference difference can be represented by \(F_n = F_{n-1}\) where \(n = 5, 4, 3, 2, 1\). The recursive preference differences are:

\[ v_R(P_1) - v_R(P_2) = \left(\frac{6}{5}\right)^2(v_R(P_2) - v_R(P_3)) = \left(\frac{6}{5}\right)^2(v_R(P_3) - v_R(P_4)) = \left(\frac{6}{5}\right)^2(v_R(P_4) - v_R(P_5)) = \left(\frac{6}{5}\right)^2(v_R(P_5) - v_R(P_6)) = \left(\frac{6}{5}\right)^2(v_R(P_6) - v_R(P_7)) \]

The recursive preference difference can also be written as:

\[ v_R(P_1) - v_R(P_2) = 7.2(v_R(P_2) - v_R(P_3)) = 45(v_R(P_3) - v_R(P_4)) = 240(v_R(P_4) - v_R(P_5)) = 1080(v_R(P_5) - v_R(P_6)) = 4320(v_R(P_6) - v_R(P_7)) \]

The third new relation for strength of preference is referred to as Extreme and \(v_E(P_n)\). The preference difference is increasing by a factor 200:

\[ v_E(P_1) - v_E(P_2) = 200(v_E(P_2) - v_E(P_3)) = 200^2(v_E(P_3) - v_E(P_4)) = 200^3(v_E(P_4) - v_E(P_5)) = 200^4(v_E(P_5) - v_E(P_6)) = 200^5(v_E(P_6) - v_E(P_7)) \]

<table>
<thead>
<tr>
<th>Priority class (P_n)</th>
<th>Current (v_C(P_n))</th>
<th>Double (v_D(P_n))</th>
<th>Recursive (v_R(P_n))</th>
<th>Extreme (v_E(P_n))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 (7/7)</td>
<td>1</td>
<td>1/7</td>
<td>5.0 \times 10^{-3} (1/200)</td>
</tr>
<tr>
<td>2</td>
<td>0.85 (6/7)</td>
<td>0.5 (32/64)</td>
<td>0.14 (1/7)</td>
<td>2.5 \times 10^{-5} (1/200^2)</td>
</tr>
<tr>
<td>3</td>
<td>0.71 (5/7)</td>
<td>0.25 (16/64)</td>
<td>0.024 (1/42)</td>
<td>1.3 \times 10^{-7} (1/200^3)</td>
</tr>
<tr>
<td>4</td>
<td>0.57 (4/7)</td>
<td>0.13 (8/64)</td>
<td>0.0048 (1/210)</td>
<td>6.3 \times 10^{-10} (1/200^4)</td>
</tr>
<tr>
<td>5</td>
<td>0.43 (3/7)</td>
<td>0.063 (4/64)</td>
<td>0.0012 (1/840)</td>
<td>3.1 \times 10^{-12} (1/200^5)</td>
</tr>
<tr>
<td>6</td>
<td>0.29 (2/7)</td>
<td>0.031 (2/64)</td>
<td>0.0004 (1/2520)</td>
<td>1.6 \times 10^{-14} (1/200^6)</td>
</tr>
<tr>
<td>7</td>
<td>0.14 (1/7)</td>
<td>0.016 (1/64)</td>
<td>0.0002 (1/5040)</td>
<td></td>
</tr>
</tbody>
</table>
In Table 4.3, a small example of the resulting ranked list of power lines is created to visualise that the 4 different value functions can produce the different rankings due to the altered strength of preference.

In the example, 10 power lines in a municipality is ranked according to the additive decision model (Equation (4.14)) with the 4 different value functions: Current, $v_C(L_i)$, Double, $v_D(L_i)$, Recursive $v_R(L_i)$, and, Extreme $v_E(L_i)$.

<table>
<thead>
<tr>
<th>Power line $L_i$</th>
<th>Rank $v_C(L_i)$</th>
<th>Rank $v_D(L_i)$</th>
<th>Rank $v_R(L_i)$</th>
<th>Rank $v_E(L_i)$</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>8</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_2$</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_3$</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_4$</td>
<td>5</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>1</td>
<td>6</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_5$</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_6$</td>
<td>9</td>
<td>10</td>
<td>7</td>
<td>7</td>
<td>1</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_7$</td>
<td>10</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_8$</td>
<td>3</td>
<td>6</td>
<td>8</td>
<td>8</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_9$</td>
<td>2</td>
<td>7</td>
<td>9</td>
<td>9</td>
<td>1</td>
<td>6</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_{10}$</td>
<td>1</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>8</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Aggregation of Group Prioritisations for Energy Rationing with an Additive Group Decision Model
Rebecca Petersen

The current value function set the highest rank for power line $L_{10}$, even though this power line only include prioritised electricity users in the lowest priority classes, 6 and 7. All the 3 proposed value functions rank power line $L_{10}$ as rank 9 or 10 of the 10 power lines. Additionally, the current value function rank power line $L_{7}$ as the least important although this power line include an electricity user in the highest priority class.

This small example confirms that with the decision support of the current value function could rank electricity users with a high priority class improperly low as stated by respondents in the interviews and previous evaluation reports. The example also indicates that the 3 proposed value functions could provide the decision maker with better decision support. However, no general conclusions about the value functions can be made without further evaluation in various situations at group decision level.

4.4 Simulation example

An example of the results from a scenario in the simulation experiment is presented in Appendix C, Table 4.4 and Table 4.5. This specific example include a total of 169 electricity users, a total of 57 power lines and 10 municipalities in a county.

Table 4.4: The top 10 ranked power lines in the example county according to group decision based on 4 different value functions (see the complete table in Appendix C).

<table>
<thead>
<tr>
<th>Rank of power lines ID acc. Current</th>
<th>Rank of power lines ID acc. Double</th>
<th>Rank of power lines ID acc. Recursive</th>
<th>Rank of power lines ID acc. Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>29</td>
<td>29</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>24</td>
<td>23</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>23</td>
<td>15</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>15</td>
<td>40</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>40</td>
<td>8</td>
<td>26</td>
<td>26</td>
</tr>
</tbody>
</table>

From the top 10 ranked power lines in Table 4.4 it is clear that in this example the value functions produce different group prioritisations and rankings of power lines. The correlation analysis for this example will further compare the similarity between the resulting ranked lists derived from group decisions with the 4 value functions.
Table 4.5: Correlation analysis for the example scenario.

<table>
<thead>
<tr>
<th>Value functions</th>
<th>Spearman’s $\rho_s$</th>
<th>Kendall’s $\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current &amp; Double</td>
<td>0.21519315530204816</td>
<td>0.17418546365914786</td>
</tr>
<tr>
<td>Current &amp; Recursive</td>
<td>0.13987555094633145</td>
<td>0.10776942355889724</td>
</tr>
<tr>
<td>Current &amp; Extreme</td>
<td>0.13987555094633145</td>
<td>0.10776942355889724</td>
</tr>
<tr>
<td>Double &amp; Recursive</td>
<td>0.39318122893440477</td>
<td>0.30952380952380953</td>
</tr>
<tr>
<td>Double &amp; Extreme</td>
<td>0.39318122893440477</td>
<td>0.30952380952380953</td>
</tr>
<tr>
<td>Recursive &amp; Extreme</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

The perfect correlation between the Recursive value function and the Extreme value function which means that $\rho_s = 1.0$ and $\tau = 1.0$, gives the conclusion that the ranked lists power lines and the group preferences for these value functions are equal.

The correlation are negligible between the group prioritisations based on the Current value function and the 3 proposed value functions Double, Recursive and Extreme according to Hinkle, Wiersma and Jurs’ (2002) ranges for strength of correlation. This implies that the current value function only have a small similarity to all the proposed value functions with increased preference differences. Note that this is only the rank correlation results from one scenario and no general conclusion should be made based on this.

4.5 Simulation results

The simulation results from 1000 scenarios in the simulation are presented separately for Spearman’s rank correlation coefficient and Kendall’s rank correlation coefficient. The correlation analysis between the group prioritisations based on the current value model and the 3 proposed value models is presented first and then correlation analysis for the group prioritisation of the 3 proposed decision models.

4.5.1 Current value function and proposed value functions

In the visualisation with two scatter plots for each comparison, the average of the rank correlation coefficient is marked. The average as well as the maximum and minimum rank correlation are presented in a table.

Current and Double

The results of the evaluation of the ranked lists of power lines according to the Current value function and the Double value function presented in a table and scatter plots.
Figure 4.2: Spearman’s rank correlation coefficient $\rho_s$ for 1000 scenarios with average, comparing the group prioritisations based on the value functions Current and Double.

Figure 4.3: Kendall’s rank correlation coefficient $\tau$ for 1000 scenarios with average, comparing the group prioritisations based on the value functions Current and Double.

Table 4.6: Correlation analysis for group prioritisations based on the value functions Current and Double.

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spearman’s $\rho_s$</td>
<td>0.47103</td>
<td>0.926651</td>
<td>0.000428</td>
</tr>
<tr>
<td>Kendall’s $\tau$</td>
<td>0.397758</td>
<td>0.871239</td>
<td>0.023797</td>
</tr>
</tbody>
</table>
According to Hinkle, Wiersma and Jurs’ (2002) strength of correlation for different values of $\rho_s$, the group prioritisations based on the Current value function and the Double value function have an average $\rho_s$ in the range $0.30 \leq \rho_s < 0.50$, which represents a low correlation. The maximum $\rho_s$ represents a very strong correlation and the minimum $\rho_s$ represents a negligible correlation between the resulting group prioritisations.

**Current and Recursive**

The results of the evaluation of the ranked lists of power lines according to the Current value function and the Recursive value function presented in a table and scatter plots.

![Figure 4.4: Spearman’s rank correlation coefficient $\rho_s$ for 1000 scenarios with average, comparing the group prioritisations based on the value functions Current and Recursive.](image-url)
Figure 4.5: Kendall’s rank correlation coefficient $\tau$ for 1000 scenarios with average, comparing the group prioritisations based on the value functions Current and Recursive.

The average $\rho_s$ for the Current and Recursive value function is within the range $0.30 \leq \rho_s < 0.50$, which represents a low correlation between the resulting group prioritisations according to Hinkle, Wiersma and Jurs (2002). The maximum $\rho_s$ represents a very strong correlation and the minimum $\rho_s$ represents a negligible correlation.

**Current and Extreme**

The results of the evaluation of the ranked lists of power lines according to the Current value function and the Extreme value function presented in a table and scatter plots.
Figure 4.6: Spearman’s rank correlation coefficient $\rho_s$ for 1000 scenarios with average, comparing the group prioritisations based on the value functions Current and Extreme.

Figure 4.7: Kendall’s rank correlation coefficient $\tau$ for 1000 scenarios with average, comparing the group prioritisations based on the value functions Current and Extreme.
Table 4.8: Correlation analysis for group prioritisations based on the value functions Current and Extreme.

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spearman’s ρₚₛ</td>
<td>0.417559</td>
<td>0.871979</td>
<td>-0.0442</td>
</tr>
<tr>
<td>Kendall’s τ</td>
<td>0.347693</td>
<td>0.836314</td>
<td>-0.02557</td>
</tr>
</tbody>
</table>

The average ρₛ for the group prioritisations based on the value functions Current and Extreme is within the range $0.30 \leq \rho_s < 0.50$, which represents a low correlation between the group prioritisations according to Hinkle, Wiersma and Jurs (2002). The maximum ρₛ represents a strong correlation and the minimum ρₛ represents a negligible correlation.

This subchapter include an overview of the average ρₛ and τ for group prioritisations based on all 3 proposed value functions and the Current value function.

Table 4.9: Overview of average rank correlation coefficient comparing group prioritisations based on the value functions Current, Double, Recursive and Extreme.

<table>
<thead>
<tr>
<th>Value functions</th>
<th>Spearman’s ρₛ</th>
<th>Kendall’s τ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>Double</td>
<td>0.47103</td>
</tr>
<tr>
<td>Current</td>
<td>Recursive</td>
<td>0.425486</td>
</tr>
<tr>
<td>Current</td>
<td>Extreme</td>
<td>0.417559</td>
</tr>
</tbody>
</table>

4.5.2 Proposed value functions

The 3 proposed value functions Double, Recursive and Extreme resulting ranked lists of power lines are compared with the rank correlation coefficients Spearman’s ρₛ and Kendall’s τ. First, the correlation between group prioritisations based on the value functions Double and Recursive is calculated for all 1000 iterations in the simulation experiment.

Table 4.10: Correlation analysis for group prioritisations based on the value functions Double and Recursive.

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spearman’s ρₛ</td>
<td>0.813864</td>
<td>1.0</td>
<td>0.230043</td>
</tr>
<tr>
<td>Kendall’s τ</td>
<td>0.764425</td>
<td>1.0</td>
<td>0.224505</td>
</tr>
</tbody>
</table>

The average ρₛ for the group prioritisations based on the value functions Double and Recursive is within the range $0.70 \leq \rho_s < 0.90$, which represents a strong correlation according to Hinkle, Wiersma and Jurs (2002). The maximum ρₛ represents a perfect correlation and the minimum ρₛ represents a negligible correlation.
Figure 4.8: Spearman’s rank correlation coefficient \( \rho_s \) for 1000 iterations with average, comparing group prioritisations based on the value functions Double and Recursive.

Figure 4.9: Kendall’s rank correlation coefficient \( \tau \) for 1000 iterations with average, comparing group prioritisations based on the value functions Double and Recursive.

The correlation between the group prioritisations based on value functions Double and Extreme is calculated for all 1000 scenarios in the simulation experiment.
Table 4.11: Correlation analysis for group prioritisations based on the value functions Double and Extreme.

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spearman’s $\rho_s$</td>
<td>0.804617</td>
<td>1.0</td>
<td>0.274595</td>
</tr>
<tr>
<td>Kendall’s $\tau$</td>
<td>0.752374</td>
<td>1.0</td>
<td>0.25045</td>
</tr>
</tbody>
</table>

The average $\rho_s$ for the group prioritisations based on the value functions Double and Extreme is within the range $0.70 \leq \rho_s < 0.90$, which represents a strong correlation according to Hinkle, Wiersma and Jurs (2002). The maximum $\rho_s$ represents a perfect correlation and the minimum $\rho_s$ represents a negligible correlation.

Figure 4.10: Spearman’s rank correlation coefficient $\rho_s$ for 1000 scenarios with average, comparing group prioritisations based on the value functions Double and Extreme.
Figure 4.11: Kendall’s rank correlation coefficient $\tau$ for 1000 scenarios with average, comparing group prioritisations based on the value functions Double and Extreme.

The correlation between the group prioritisations based on value functions Recursive and Extreme is calculated for all 1000 scenarios in the simulation experiment.

Table 4.12: Correlation analysis for group prioritisations based on the value functions Recursive and Extreme.

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spearman’s $\rho_s$</td>
<td>0.989612</td>
<td>1.0</td>
<td>0.803328</td>
</tr>
<tr>
<td>Kendall’s $\tau$</td>
<td>0.984083</td>
<td>1.0</td>
<td>0.729323</td>
</tr>
</tbody>
</table>

The average $\rho_s$ for the group prioritisations based on the value functions Recursive and Extreme is within the range $0.90 \leq \rho_s < 1.00$, which represents a very strong correlation according to Hinkle, Wiersma and Jurs (2002). The maximum $\rho_s$ represents a perfect correlation and the minimum $\rho_s$ represents a strong correlation.
Figure 4.12: Spearman’s rank correlation coefficient $\rho_s$ for 1000 scenarios with average, comparing group prioritisations based on the value functions Recursive and Extreme.

Figure 4.13: Kendall’s rank correlation coefficient $\tau$ for 1000 scenarios with average, comparing group prioritisations based on the value functions Recursive and Extreme.
Table 4.13: Overview of average rank correlation coefficient for the group prioritisations based on the 3 proposed value functions Double, Recursive and Extreme.

<table>
<thead>
<tr>
<th>Value functions</th>
<th>Spearman’s $\rho_S$</th>
<th>Kendall’s $\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Recursive</td>
<td>0.813864</td>
<td>0.752374</td>
</tr>
<tr>
<td>Double Extreme</td>
<td>0.804617</td>
<td>0.752374</td>
</tr>
<tr>
<td>Recursive Extreme</td>
<td>0.989612</td>
<td>0.984083</td>
</tr>
</tbody>
</table>

The average correlation between group prioritisations for the 3 proposed value functions are very strong. The average correlation between the group prioritisations based on the value functions Recursive and Extreme is almost a perfect correlation, this means that the ranked lists of power lines in the county are almost always equal.
5 Analysis

This chapter consists of an analysis of the results from the qualitative phase and the quantitative phase.

5.1 Participants’ experience of Styrel

C2 states in the interview that stakeholders have different preferences regarding which electricity user that belong to the different priority classes. This indicates that the constructed scale with 7 priority classes in Styrel have not yet taken on properties similar to a natural scale, such as monetary value. Keeney (2007) describe that once a constructed attribute has been commonly used in practice, people become familiar with it and it takes on properties of an attribute on a natural scale.

Group decisions regarding emergency preparedness (including Styrel) in the larger county C2 are conducted with 5 local regional councils instead of all 33 municipalities. This indicates that group decisions are experienced as difficult to accomplish with multiple municipalities and point toward that a group decision model for Styrel is needed to support the compilation of preferences for all municipalities in a county, especially in a counties with many municipalities.

Eisenführ, Weber and Langer (2010) describes that differences in power and status may give unjustified preferences because members with lower status will often adapt their original preferences to what the higher-ranked group member prefer. C2 confirm this issue stating that 1 of the 33 municipalities with conceivably higher status and power, influenced the other municipalities to adapt their original preferences regarding electricity users in priority classes as well as prioritisations of power lines in the county. This results also indicate that the scaling constant for different municipalities are not equal for larger municipalities and smaller municipalities.

The compilation of the group decisions are conducted differently in the two counties C1 and C2. The score system that should be supporting the group decision is not used by C1 with the motivation that the compiled scores are misleading, frequently giving low ranks to electricity users in high priority classes. The current decision support with sum of scores can be represented by a decision analytical approach which will produce results as a consequence of preference as stated by Howard (1980). Because C1 perceive the compiled scores as misleading, they are probably not representing the preferences of municipalities nor the county administrative
board. This confirm the results in the evaluation reports by the Swedish Defence Research Agency (FOI) by Veibäck et al. (2013) and the evaluation report from three county administrative boards by Lindberg et al. (2014).

C2 states that the compilation of a ranked list of power lines in the county was time consuming, this can be interpreted as that the current decision support with scores did not facilitate the compilation of the municipalities’ preferences into a group decision. C2 aggregated a ranked list of power lines in the county by ordering power lines with electricity users in the highest priority class first and so on. This procedure can be compared with the preference differences in the value function Extreme, \( v_E(P_x) \) applied in the simulation experiment. The Extreme value function produce a group decision ranking power lines with the highest priority class first, and so on. This indicates that the preferences of C2 is not represented by the preference difference present in the Current value function \( v_C(P_x) \).

### 5.2 Decision model for energy rationing

The proposed decision model for energy rationing is built on information about the current Styrel procedure with 7 priority classes and prioritisation by summing scores for power lines based on the priority classes of the electricity users located on the power line.

Chapter 4.2 shows that the proposed decision model fulfils the preference logic presented by Halldén (1957), the properties of von Neumann and Morgenstern’s (1953) rationality axioms and Dyer and Sarin’s (1979) conditions for measurable PAR for group decisions.

Eisenführ, Weber and Langer (2010) states that a value function will always exist that represent the preferences, if a preference is a complete, transitive and the set of alternatives is countable. This suggests that a value function for energy rationing can always be derived if the identified electricity users can be prioritised into priority classes and fulfils the demands of completeness and transitivity.

Regarding preference logic, the constructed scale with priority classes demands strict preference between priority classes and that all electricity users in the same priority class are equally important. The decision model do not give decision makers the ability to prefer certain electricity users before other electricity users within a priority class. This is also true for
the group decisions regarding preferences of power lines according to Condition 3 for Exchange independence.

If the constructed scale were expanded to hold preference differences not only between the priority classes but also within a priority class, the preferences in the decision model for energy rationing may possibly be more accurate and the group decision will perhaps also result in fewer power lines with equal value.

5.3 Proposed value functions

The interview results indicate that the preferences of municipalities and group preferences are not represented by the value function referred to as Current, derived from the Styrel scores for each priority class. This result is used to suggest 3 value functions to investigate the importance of the preference differences between priority classes.

The small example in Chapter 4.3 of a ranked list of power lines in a municipality based on the 4 different value functions indicate the effect in the resulting group decision when changing the preference differences between priority classes. Dyer and Sarin (1979) point out that an assumption of the additive measurable PAR is that the group preferences are determined only by measurable value functions. Hence, the right preference differences between priority classes are essential to use this decision model.

The preference difference of the Current value function give equal importance of 1 power line with 1 electricity user in priority class 1 as for instance a power line with: 1 electricity user in priority class 2 and 1 electricity user in priority class 7, or, 7 electricity user in priority class 7. The example in Chapter 4.3 shows that the ranking based on Current return the lowest rank to a power line with an electricity user in priority class 1 and the highest rank to a power line with many electricity users in low priority classes. However, the example show that the preference differences do matter in the municipalities’ rankings of power lines which is forwarded into the county’s ranking of power lines.

The preference difference of the Double value function give equal importance of 1 power line with 1 electricity user in priority class 1 as for a power line with 2 electricity users in priority class 2. Similarly, the Recursive value function propose that the decision maker is indifferent between a power line with 1 electricity user in priority class 1 and a power line
with 7 electricity users in priority class 2. The Extreme value function propose that the decision maker is indifferent between a power line with 1 electricity user in priority class 1 and a power line with 200 electricity users in priority class 2.

5.4 Simulation

The scatter plots comparing the resulting group prioritisations for current value function and the 3 proposed value functions show that the correlation are varying for different scenarios. The rank correlation coefficients are 1 for equal group prioritisations and 0 for completely different group prioritisations. The Monte-Carlo simulation aims to evaluate the similarity between group prioritisations based on different value functions with enough repetitions to find accurate mean values for the rank correlation coefficients $\rho_s$ and $\tau$.

The group prioritisations, ranked lists of power lines for the county, are centred around the mean value but can be rather similar in some scenarios and very different in other scenarios. For the group prioritisations based on Current and Double, Current and Recursive and Current and Extreme, this is shown in the scatter plots and in the maximum and minimum values of $\rho_s$ and $\tau$. The mean value of $\rho_s$ when comparing Current with each of the proposed value functions result in a low correlation ($\rho_s < 0.50$) according to Hinkle, Wiersma and Jurs’ (2002) interpretation of the strength of correlation. The simulation results show that the group prioritisation based on the Current value function are very different from the group prioritisation based on the proposed value functions. Consequently, the group prioritisations are sensitive to changes in preference differences regarding priority classes for prioritised electricity users in Styrel.

Kendall’s rank correlation coefficient $\tau$ are constantly slightly smaller than Spearman’s rank correlation coefficient $\rho_s$ for all scenarios. The group prioritisations based on the value function Double are the most similar to the group prioritisations based on Current, this could be due to that the preference differences are more similar for these two value functions compared to Current and Recursive and Current and Extreme.

The correlation between the group prioritisation with the 3 different proposed value functions show that the group prioritisations based on Double and Recursive and Double and Extreme has a mean correlation $\rho_s$ value representing a strong correlation while Recursive and Extreme have a mean correlation $\rho_s$ value representing a very strong correlation.
The 3 proposed models could result in group prioritisations with lower correlation if the county consists of an increased amount of power lines and electricity users than applied in the simulation experiment. The simulation indicates that the group prioritisations produced in the decision model is not sensitive to moderate changes in preference differences.
6 Conclusions

This chapter presents the conclusions of the study, first answering the research questions and afterwards presenting suggestions for further research.

- The two interviewed participants in Styrel experience the group decisions as time-consuming and unstructured. These participants are at the same time satisfied with the Styrel process and they do not want any major changes in the overall process of identifying and prioritising electricity users.

- The two interviewed participants in Styrel experience the current decision support as misleading. The conclusion is that preferences of these two decision makers are not represented by the applied preference differences between Styrel’s priority classes in the current decision support.

- The proposed decision model for energy rationing is based on a measurable value function for electricity users with societal importance divided into priority classes. Preferences of power lines for individual decision makers are determined by an additive decision model based on the measurable value functions for electricity users located on the power line. The proposed additive decision model is applied and discussed for energy rationing according to the Swedish emergency preparedness planning process Styrel.

- The proposed group decision model is an expansion of the decision model for individual decision makers presented above. The proposed group decision model is based on the additive measurable PAR. The proposed group decision model is applied for group decisions in Styrel where the preferences of several individual decision makers are compiled into a group prioritisation.

- The results from the Monte Carlo simulation indicate that the group prioritisations are sensitive to significant changes in preference differences between priority classes but not as sensitive to moderate changes in preference differences between priority classes. The proposed group decision model is therefore usable even if the individual decision maker’s preference differences are slightly different.
6.1 Suggestions for further research

The proposed group decision model need to be further evaluated in real settings, preferably in both Sweden and in other countries. More information is required regarding preference differences and scaling constants for decisions of individual decision makers and for group decisions to apply the proposed group decision model. Further research should additionally evaluate other group decision models presented in Chapter 2.5, the multiplicative measurable PAR and the multi-attribute additive group decision model.

It is also necessary to evaluate the societal impact if only a subset of the power lines in the group prioritisations are provided with electricity. This could be done by expanding the simulation model and simulation experiment created in this study with ability to evaluate which priority class the electricity users belong to if only providing electricity to the first 50% of power lines in the list of group prioritisations for energy rationing. As seen in the example of a Swedish municipality with 10 power lines in Chapter 4.3, just shutting down 10% (one power line) will impact an electricity user in priority class 1 following the preferences of individual decision makers derived from the current Styrel procedure. An expansion of the simulation would hopefully provide a more complete understanding of the potential societal impacts of proposed group decision model when changing the preference differences between priority classes.

The simulation of group decisions in Styrel should be further adapted to the real conditions in Swedish counties, imitating the real decisions in Styrel in the municipalities as well as the group decisions generating group prioritisations. This require further research exploring, for example, the approximate amount of shared power lines in municipalities, the approximate amount of prioritised electricity users in each municipality, the approximate amount of prioritised electricity users located on a power line and the distribution of prioritised electricity users in each priority class. More information about the real conditions will provide a better simulation evaluating the proposed group decision model for energy rationing.

The priority classes for electricity users with societal importance can be enhanced with the opportunity to prefer certain electricity users to other electricity users within a priority class. The group prioritisations applying this could then be compared to the group prioritisations using fewer priority classes. The group prioritisation could additionally be provided
with information about the societal sector, VSF or CI that each prioritised electricity user belong to supporting the decision maker to further decrease the impact of power shortages.
References


Aggregation of Group Prioritisations for Energy Rationing with an Additive Group Decision Model
Rebecca Petersen


Appendix A: Interview guide

The interviews are conducted in Swedish, therefore the interview questions are presented here in their original format.

Målet med intervjun är att identifiera vilka avvägningar, värderingar och preferenser som har gjorts och hur dessa förklaras.

Bakgrundsfrågor
- Namn, kön, yrke/position
- Erfarenhet och roll i organisationen? (Hur länge har du arbetat för xx organisation, vilka är dina arbetsuppgifter och ansvaret i organisationen? Vilken är din utbildning?)

Processen
- Hur organiserade ni arbetet?
- Hur uppfattar du din roll som samordnare, vilket ansvar/uppgift har du i processen?
- Var det enkelt att följa den processmodell som föreskrivs i Styrel?
- Om ni avvikit från modellen, varför gjordes detta, på vems initiativ, vilka konsekvenser fick detta utifrån ditt förmenande?
- Har ni haft några extra resurser – specialistkunskaper för att genomföra det här arbetet (vilka)?
- Finns ytterligare aktörer i den här processen som ni haft kontakt med? När kom de in? På vems initiativ?
- Skulle ni göra något annorlunda, om ni gjorde om processen nu?

Information
- Vilken information hade du och vem bistod med den informationen?
- Upplevde du att det fanns aktörer som inte undanhöll information (påverkade det senare prioriteringar?)
- Fanns motstridig information och hur prioriterade du mellan olika typer av information, var några informationskällor viktigare än andra?
- Saknade du någon information inför arbetet?
- Var det någon information eller utsaga som försvann under processens gång?
Värderingar
- Hur arbetade ni med att värdera behoven av el och prioriterade ledningar?

Prioriteringar
- Hur gjordes prioriteringarna/avvägningar med kommunen?
- I vilken utsträckning har ni följt modellen med poängsättning och rangordning av elledningar?
- Vad hade ni för känsla rörande den resulterande rangordningen av elledningar?
- Vilka argument har vägt tungt i de slutgiltiga prioriteringarna?
Appendix B: Styrel additive model

The current score system in Styrel which aims to guide decision makers in ranking of power lines is equal to the representation of Styrel by an additive decision model.

In the example below, one municipality is ranking power lines according to scores and according to the additive decision model for Styrel. \( L_i \) represents the power line with index \( i = 1, 2, 3, 4, 5 \), PX is the number of electricity users of priority class X on each power line, \( X = [1, 2, 3, 4, 5, 6, 7] \), \( v_c(L_i) \) is the rank of each power line according to the additive decision model with \( \lambda_p = \frac{1}{7} \), the scores \( S(L_i) \) are a sum of the scores \( s_x \) ranging from 1-7 where electricity users in priority class 1 get 7 points, class 2 get 6 points and so on (see Table 4.1).

### Table B.1: Example of ranked power lines in one municipality according to score system \( S(L_i) \) and value model \( v_c(L_i) \).

<table>
<thead>
<tr>
<th>Power line ( L_i )</th>
<th>Rank ( v_c(L_i) )</th>
<th>Rank ( S(L_i) )</th>
<th>Scores ( S(L_i) )</th>
<th>( v_C(L_i) )</th>
<th>P ( 1 )</th>
<th>P ( 2 )</th>
<th>P ( 3 )</th>
<th>P ( 4 )</th>
<th>P ( 5 )</th>
<th>P ( 6 )</th>
<th>P ( 7 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>5</td>
<td>5</td>
<td>13</td>
<td>0,28</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2</td>
<td>3</td>
<td>3</td>
<td>18</td>
<td>0,37</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L3</td>
<td>1</td>
<td>1</td>
<td>20</td>
<td>0,41</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4</td>
<td>2</td>
<td>2</td>
<td>19</td>
<td>0,39</td>
<td></td>
<td></td>
<td>1</td>
<td>6</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L5</td>
<td>4</td>
<td>4</td>
<td>17</td>
<td>0,34</td>
<td></td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

The calculations of \( v_c(L_i) \) and \( S(L_i) \) are according to the following formulas:

\[
v(L_i) = \sum \lambda_p v(P_x) \quad \text{and} \quad S(L_i) = \sum S(P_x)
\]

For power line with index 1, \( L_1 \) the value function \( v_c(L_1) \) and score \( S(L_1) \) are:

\[
v_c(L_1) = \lambda_p v_c(P_1) + \lambda_p v_c(P_3) + \lambda_p v_c(P_7) = \frac{1}{7} \ast 1 + \frac{1}{7} \ast \frac{5}{7} + \frac{1}{7} \ast \frac{1}{7} = 0,28
\]

\[
S(L_1) = S(P_1) + S(P_3) + S(P_7) = 7 + 5 + 1 = 13
\]

With equal scaling constant for all priority classes, \( \lambda_p = \frac{1}{7} \), the current score system in Styrel can be represented by an additive model.
Appendix C: Simulation example

This is an example of the output from an iteration of the simulation experiment.

Users: 169
Power Lines: 57
Municipalities: 10

*** Correlations using Spearman ***
Current & Double: 0.21519315530204816
Current & Recursive: 0.1398755094633145
Current & Extreme: 0.1398755094633145
Double & Recursive: 0.39318122893440477
Double & Extreme: 0.39318122893440477
Recursive & Extreme: 1.0

*** Correlations using Kendall ***
Current & Double: 0.17418546365914786
Current & Recursive: 0.10776942355889724
Current & Extreme: 0.10776942355889724
Double & Recursive: 0.30952380952380953
Double & Extreme: 0.30952380952380953
Recursive & Extreme: 1.0

Table C.1: Ranked power lines in a county according to 4 different value functions.

<table>
<thead>
<tr>
<th>Rank of power lines ID acc. Current</th>
<th>Rank of power lines ID acc. Double</th>
<th>Rank of power lines ID acc. Recursive</th>
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All municipalities  
*** Municipality 1 ***
User | Priority
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Power line 1

User 1 | CLASS_4
User 2 | CLASS_2
User 3 | CLASS_4
User 4 | CLASS_5
User 5 | CLASS_3
User 6 | CLASS_4
User 7 | CLASS_2
User 8 | CLASS_7
User 9 | CLASS_1
User 10 | CLASS_3
User 11 | CLASS_5
User 12 | CLASS_7
User 13 | CLASS_2
User 14 | CLASS_6
User 15 | CLASS_2
User 16 | CLASS_2
User 17 | CLASS_5
User 18 | CLASS_4
User 19 | CLASS_2
User 20 | CLASS_3
Power line 2
User 21 | CLASS_3
User 22 | CLASS_3
Power line 3
User 23 | CLASS_5
User 24 | CLASS_7
User 25 | CLASS_4
Power line 4
User 26 | CLASS_6
User 27 | CLASS_5
Power line 5
User 28 | CLASS_2
Power line 6
User 29 | CLASS_7
Power line 7
User 30 | CLASS_1
Power line 8
User 31 | CLASS_2
Power line 9
User 32 | CLASS_7
Power line 10
User 33 | CLASS_5
Power line 19
User 34 | CLASS_4
User 36 | CLASS_6

------------------
*** Municipality 2 ***
User | Priority
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Power line 11
User 36 | CLASS_1
User 37 | CLASS_2
### Aggregation of Group Prioritisations for Energy Rationing with an Additive Group Decision Model

**Rebecca Petersen**

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User 85  CLASS_7
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User 104 CLASS_3
User 105 CLASS_5
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User 107 CLASS_1
User 108 CLASS_2
Power line 22
User 109 CLASS_5
User 110 CLASS_6
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User 112 CLASS_6
Power line 23
User 113 CLASS_5
User 114 CLASS_3
User 115 CLASS_1
Power line 24
User 116 CLASS_5
User 117 CLASS_3
User 118   CLASS_4
User 119   CLASS_4
Power line 25
User 120   CLASS_3
Power line 26
User 121   CLASS_1
Power line 27
User 122   CLASS_3
Power line 40
User 123   CLASS_7
User 124   CLASS_6

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User   Priority
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Power line 29
User 126   CLASS_2
Power line 30
User 127   CLASS_6
Power line 31
User 128   CLASS_6
Power line 32
User 129   CLASS_7
Power line 33
User 130   CLASS_3
Power line 34
User 131   CLASS_7
Power line 40
User 132   CLASS_1
Power line 8
User 133   CLASS_2
User 134   CLASS_7

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*** Municipality 5 ***
User   Priority
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User 136   CLASS_5
Power line 36
User 137   CLASS_4
Power line 37
User 138   CLASS_1
Power line 38
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