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ANALYTIC HIERARCHY PROCESS IN WIND SITE SELECTION

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Tämän opinnäytetyön tavoitteena oli tutustua analyyttisen hierarkiaprosessin käyttöön ja soveltamiseen tuulivoimapuiston valinnassa. Analyyttinen hierarkiaprosessi on järjestelmällinen päätöksentekomalli, jolla tarkasteluun valitut vaihtoehdot voidaan arvioida ja sijoittaa järjestykseen parhaimmasta huonoimpaan. Opinnäytetyö tehtiin yhteistyössä tuulivoimakonsulttiyhtiö Etha Windin kanssa.

Opinnäytetyössä luotiin prosessin mukainen hierarkia, jonka kriteerit valittiin julkaistujen tutkimusten sekä haastateltavan tuulivoimasiantuntijan perusteella. Tämän lisäksi valittiin kolme tarkasteltavaa tuulipuistoa, joista jokaisen suunnittelu oli käynnissä tämän tutkimuksen aikana.

Lopuksi tulokset varmistettiin ja analysoitiin erillisellä ohjelmalla ja haastattelulla. Tutkimuksen tuloksena saatujen kriteerien järjestys vastasi yleisesti tärkeinä pidettyjen tuulivoimaprojektien lopputulokseen vaikuttavia kriteerejä Suomessa ja valittujen tuulipuistojen järjestys oli loogisesti suhteessa tuulivoimapuiston kokoon. Jatkokehitysideana malli voidaan integroida GIS-ohjelmiston kanssa, jolloin tuloksille luodaan visuaalisempi alusta.

Avainsanat	Analyyttinen hierarkiaprosessi, tuulipuiston valinta, päätöksenteko ja projektin arviointi.

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ABSTRACT

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The aim of this thesis was to apply the analytical hierarchy process in the selection of a wind farm. The analytical hierarchy process is a systematic decision-making model that allows the alternatives selected for consideration to be evaluated and ranked from best to worst. The thesis was done in collaboration with the wind power consulting company Etha Wind.

In the thesis, a hierarchy was created according to the process and the criteria in it were selected based on literature review and interviews of a wind power expert. In addition, three wind farms were considered, each of which was under design during this study.

Finally, the results were verified and analyzed with a separate program and interview. The order of the criteria obtained as a result of the study corresponded to the generally important criteria affecting wind energy project outcome in Finland and the order of the selected wind farms was logically proportional to the size of the wind farm. The value of the result helps decision makers to choose the best alternative in a complex scenario. As a further development idea, the model can be integrated with GIS software to creating a more visual platform for the results.

Keywords Analytic hierarchy process, wind site selection, decision making and project evaluation.

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LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviations

AHP	Analytic Hierarchy Process
TWh	Terawatt-hour
MW	Megawatt
MCDA	Multi Criteria Decision Analysis
MADM	Multiple Attribute Decision Making
MODM	Multiple Objective Decision Making
CI	Consistency Index
CR	Consistency Ratio
TI	Technical Infrastructure
ST	System Technology
WS	Wind Conditions
T&G	Topography and Geology
CC	Capital Cost
O&M	Operation and Maintenance
VC	Value Change
EM	Energy Market
N&V	Noise and Visual
WL&ES	Wildlife and Endangered Species
EP	Energy Policy
PA	Public Acceptance
P	Permissions
EIA	Environmental Impact Assessment

FID	Final Investment Decision
COD	Commissioning Date

Symbols

λ_{max}	Largest Eigenvalue
n	Number of elements
a_{ij}	Element of matrix A
A	Matrix A
S	Sensitivity
P	Sensitivity of a parameter
w	Weight of Pair-wise Comparison

1 INTRODUCTION

Sustainability has been a huge megatrend driver in the energy sector in the 21^{st} century. Wind energy production is growing rapidly around the world to match the increasing energy demand and at the same time moving fossil-based production towards renewable energy sources. Harmful greenhouse gases and particulate emissions produced by fossil-based energy sources results into environmental and health hazards and global warming. Wind energy solves these problems while bringing unlimited, distributed and economically competitive energy to the table.

A limited land area required to build wind energy creates constantly more competitive market for the investors that leads to a desire for competitive advantages in different project planning phases. Trade-offs between competing interests and factors in the project planning conflict with each other, creating uncertainty and complex evaluating processes for the investors. In addition, the fundamental nature of wind energy project comes with a risky high initial cost, which is why it is so important to prioritize objectives and make good decisions in the planning phase that will affect the success of the project and the productivity of the plant.

Decision making itself can be approached from multiple different standpoints and there are many pathways one can take to reach their desired objectives. People practice decision making throughout their lives, yet still manage to make sub-optimal decisions from time to time. That is because decision making gets a little confusing when human elements such as emotions and cognitive and personal biases are involved. In addition, when the stakes get high in the critical moments, it is important to conduct a clear and objective decision-making process that enables practical framework to deal quantitatively with functional relations in a complex network. Analytic Hierarchy Process (AHP) is a powerful organizing tool and a flexible model for establishing priorities by combining judgement and personal values in a logical way.

1.1 Research Objectives and Questions

This thesis consists of two parts: theoretical aspect of Analytic Hierarchy Process and a project implementation with Etha Wind. The purpose of the first part was to understand the background for the thesis and learn to use the mathematical model of Analytic Hierarchy Process to present an easy-to-follow and detailed guide of how to use the AHP framework. Then in the second part in collaboration with Etha Wind, the objective was to apply that framework to create a tool to assess the location of wind farms and see how suitable AHP is in this context. Microsoft Excel was used to carry out the required calculations and they were verified with the AHP software created by SpiceLogic. Three wind sites located in Finland were selected and compared, limiting the impact of this study to the Finnish energy market and regulations. Finally, the results were analyzed to find the most desired alternative and further discussed whether the AHP process would be useful model to support decision making in the future. Based on the above objectives, the research questions are:

- How can AHP be applied to select wind farms?
- What kind of hierarchy needs to be created?
- What is the best wind farm alternative?
- Will AHP provide value for the decision makers in this context?

1.2 Outline of the Study

This chapter briefly describes what each main chapter represents.

1 Introduction: Introduces the reader to the topic of wind energy and the Analytic Hierarchy Process. Research methods, questions and limitations are covered in this chapter.

2 Theoretical Background: Literature that has been reviewed for this thesis was covered in the second chapter. The background of AHP and the basics of wind energy and site selection are explored to gather initial information for the reader.

3 Stages of Analytic Hierarchy Process: Each step of the AHP process is covered in Chapter 3. A step-by-step process prepares the reader to understand the next implementation project.

4 Project Implementation: The process application and interviews were done in the fourth chapter. The project implementation follows the rules of AHP in the wind site selection example and presents each step with result at the end.

5 Conclusions: Summary of the whole study, including all the obtained results, discussion and future thoughts, are covered in the final chapter.

2 THEORETICAL BACKGROUND

This section presents the main literature that has been reviewed for this study. Its purpose is to provide a larger picture of the topics covered in this study. Firstly, the background and applications of AHP are discussed followed by wind energy production and the current way of wind project selection.

2.1 Complex Decision Making

The world is full of complex systems, all interconnected with interdependent factors that interact with each other. Complex systems can be characterized by their dynamic, continually changing nature and interaction with the environment they are in. These interactions make it hard to view the problems in isolation and often require more holistic perspective that gives a better view of the entire system. Complex problems usually have many possible solutions instead of one and each solution might be optimal in certain type of scenario. Unlike decision making in our daily lives that often seems intuitive and almost unnoticeable, as the complexity augments with the amount of information and the number of interactions increases, it is important to know how to prioritize these problems because of our limited resources. However, it is often difficult to identify which solution out weights another. This is where mathematical and computational modeling, analysis and simulations get involved to guide the decision maker to see how these systems are structured and change with time. This approach completes the holistic view that often does not pay much attention to the finer details such as function of the parts. Naturally, complex systems require complex way of thinking, but in a simple way that allows everybody to view the problem in organized and interactable way to help us deepen our understanding of the surrounding world /2,17/.

2.2 Multi-Criteria Decision Making

One way to tackle complex problems is by using multi-criteria decision-making tools (MCDM). MCDM is a branch of operational research and it involves various techniques such as the Analytic Hierarchy Process that deal with finding the optimal result in complex scenarios. Every technique under the MCDM branch has its own its own ideal area of application, drawbacks, and restrictions and some of the widely used techniques are compared in Table 1. MCDM methods have been widely used in agriculture, resource management, immigration, education, transport, investment, environment, defence, and health case. MCDM usually consists of five component process that are goal, decision maker's preferences, alternatives, criteria's, and outcomes. MCDM can be further divided into Multi Attribute Decision Making (MADM) and Multi Objective Decision Making (MODM) based on the number of alternatives under consideration. MODM is best suited for continuous alternatives for which the constraints are predefined in the form of vectors. In MADM the consideration of inherent characteristics is covered leading to fewer number of alternatives and more difficult evaluation and prioritizing. /15/

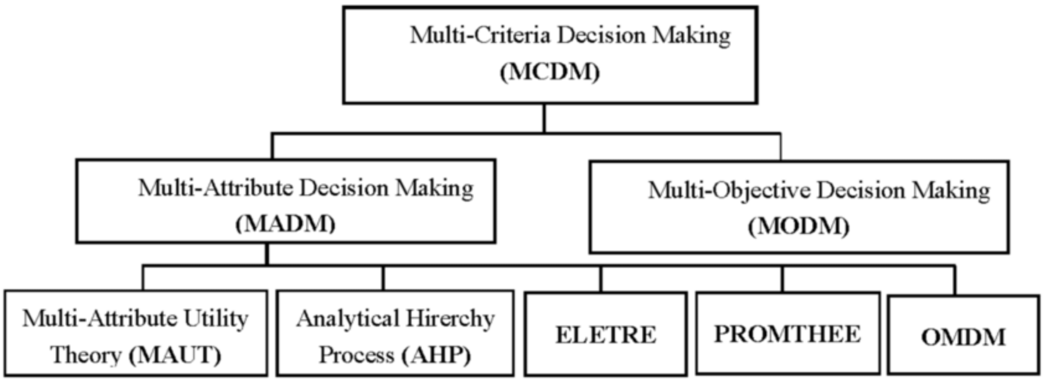

Figure 1. MCDM divided into sub-categories /16/.

Table 1. Comparison of widely used multi criteria decision making methods /14/.

Sl. No	MCDM Methods	Description	Advantages	Disadvantages
1.	Analytic hierarchy process (AHP)	It also includes pair wise comparison of different alternatives for different criterion.	1. Flexible, intuitive and checks inconsistencies 2. Since problem is constructed into a hierarchical structure, the importance of each element becomes clear. 3. No bias in decision making	1. Irregularities in ranking 2. Additive aggregation is used. So important information may be lost. 3. More number of pair wise comparisons are needed
2	Analytic Network Process(ANP)	AHP builds the decision problem from arrangement of different goals, criteria and alternatives and pair wise comparison of the criteria to obtain the best alternative	1. Independence among elements is not required. 2. Prediction is accurate because priorities are improved by feedback.	1. Time consuming 2. Uncertainty – not supported 3. Hard to convince decision making
3.	Data envelopment analysis (DAE)	DAE is a method where it is used to find the efficiency of combination of multi inputs and multi outputs of the problem.	1. Multiple inputs and outputs can be handled. 2. Relation between inputs and outputs are not necessary. 3. Comparisons are directly against peers 4. Inputs and outputs can have very different units	1. Measurement error can cause significant problems 2. Absolute efficiency cannot be measured. 3. Statistical tests are not applicable. 4. Large problems can be demanding.
4.	Aggregated Indices Randomization method (AIRM)	This method solves the complex problem where uncertainty occurs which has incomplete information for the problem to be solved.	1. Non-numeric, non-exact and non-complete expert information can be used to solve multi criteria decision making problems. 2. Transparent mathematical foundation assures exactness and reliability of results.	It aims only at complex objects multi-criteria estimation under uncertainty.
5.	Weighted Product model(WPM)	Alternatives are being compared with the other by the weights and ratio of one for each criterion.	1. Can remove any unit of measure. 2. Relative values are used rather than actual ones.	No solution with equal weight of DMs
6.	Weighted Sum Model (WSM)	It is used for evaluating a number of alternatives in accordance to the different criteria which are expressed in the same unit.	Strong in a single dimensional problems	Difficulty emerges on multi-dimensional problems
7.	Goal Programming	Goal programming is a division where it has more than one objective which conflicts with each other, and by arranging the goals or target have to be achieved by minimizing the irrelevant information.	1. Handles large numbers of variables, constraints and objectives. 2. Simplicity and ease of use	1. Setting of appropriate weights. 2. Solutions are not pair to efficient.
8.	ELECTRE	It is used to select the best choice with maximum advantage and least conflict in the function of various criteria	Outranking is used	Time consuming
9.	Grey analysis	This methods deal with all incomplete data and to overcome the deficiencies of other methods.	Perfect information has a unique solution	Does not provide optimal solution.

2.3 Analytic Hierarchy Process

The Analytic Hierarchy Process is a mathematical model for decision making. Inventor and theorist Thomas L. Saaty describes AHP as a systematic method for breaking down any problem into hierarchical elements by dividing the problem into smaller constituents and leading the decision makers through documented pairwise comparisons to indicate the relative impact of each element in the hierarchy. AHP has three basic key principles, the first being hierarchical representation, which is breaking the problem down into separate elements. Humans have natural tendency to store detailed information in clusters that contain smaller subcluster and so on. This helps us to integrate a large amount of information and form a more complete pictures of systems. The second key concept is priority setting, which is ranking the elements by relative importance. The relative nature of AHP is not so interested amount the exact measurements of the quantities but rather the proportions between them. Relative measurement theory applies well to the problems where the best alternative must be chosen. The third key concept is logical consistency, which is ensuring that elements are grouped logically and ranked consistently. Logical grouping means that similar objects are grouped into a set, if they share a common trait. Consistency stands for the intensities of relations between objects, that need to be justified in a logical way. The advantages of AHP are: /1,2,6,19/.

- Flexible and easy to understand model for wide range of problems.
- Integrates two fundamental human approaches for analysis, deductive and inductive, and combines them into logical and integrated framework.
- Follows natural human tendency to group systems into levels and elements.
- Provides a scale for measuring intangibles and priorities.
- Tracks logical consistency of judgements.
- Leads to estimate of the desirability of each alternative.
- Considers the relative priorities of factors and enables people to select the best alternative based on their goal.
- Synthesizes representative outcome from diverse judgements.
- Enables people to refine and document their problem and improve their judgement through repetition.

The disadvantages are:

- Like many MCDM methods, AHP is prone to ranking irregularities due to phenomenon called rank reversal. This occurs when a similar alternative is added to the existing list of alternatives that are being evaluated. This causes problems in the interpretation of the criteria weights.

- AHP can be considered a collection of steps, in which important information can be lost by such aggregation. The compensation between good and bad criteria scores can be problematic.

- AHP can be time consuming with all the subsystems needed in the problem reversal, especially when the number of criteria and alternatives is high. I.e., 10 criteria hierarchy requires 45 pairwise comparison calculations from the decision maker to establish the criteria weights.

2.4 Applications of Analytic Hierarchy Process

Analytic Hierarchy Process is most well-known for its versatility and it has been applied to solve countless real-life problems. It can be used in almost any application related to decision making. Due to its intangible properties, the machinery of AHP is best utilized in problems where the criteria and alternatives do not have objective and clear comparisons, for example the aesthetic appeal of the environment. AHP can be used by individuals to make important decisions in their personal lives, such as house selection, job selection, school selection and car selection. AHP has and can be used by groups and organizations across all industries to make significant decisions related to for example projects, risks, budgeting, sourcing, and human resource management. Countries' domestic and foreign political decisions, such as cost containment in health care, optimizing the amount of energy plants and in the promotional strategies of the future are just as viable applications for AHP.

One of the famous examples of AHP is the Sudan transport network project during the 1980's. Sudan is a country located in North Africa. Sudan has a large agricultural potential due to two of river Niles's tributaries, White and Blue Nile, that together irrigate and form fertile and agriculturally important land area. This area of land surrounding the two rivers could feed several hundred million people, which is why funding agencies have focused to develop the area.

The project director and the author of AHP was professor Saaty. The goal of the project was to create transportation network in Sudan to deliver goods from the agriculturally important parts of the country to export outlets such as the city of Port

Sudan at Red Sea. Different parts of the network needed to be prioritized and implemented at different times. The study required data of economic growth rates, natural resources and patterns of production and consumption to estimate movement patterns. It was divided into four different scenarios that were developed over several months by experts and the best alternative was chosen by using AHP. Decisions as complicated as this involve economics, politics and social issues at individual, group and national level and tradeoffs must be made among all dimensions /3,4/.

2.5 Wind Energy Production

Wind energy utilized by the wind turbines is generated from solar energy. Wind generation arises from uneven warming and cooling of the planet's surface. Because the earth is round and due to the mutual position of the sun and the earth, the sun's radiation travels a longer distance in the atmosphere in the polar regions than the equatorial regions, creating temperature differences. These low- and high-pressure areas then form differential hydrostatic pressure forces that try to even each other out, creating global air flows called prevailing winds. Local winds are winds that blow over smaller limited areas. Local winds are affected by many factors such as land-sea temperature fluctuations, terrain, landforms, and terrain coverage. /26/.

The production of electricity occurs when wind turbine converts wind's kinetic energy into electric energy. When the wind reaches certain speed, usually 3-4 m/s, it drives the turbine blades into rotation. The blades spin the generator located in machinery room in the top of the tower called nacelle. This creates electricity that is then converted into grid voltage through transformer and fed into the grid and to the end customers.

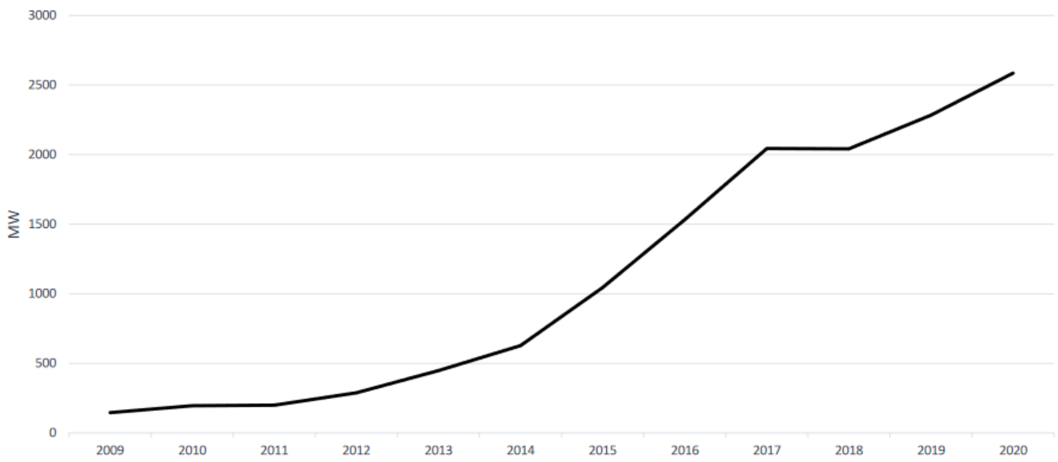

Figure 2. Wind energy production growth (megawatt) in Finland 2009-2020 /25/.

2.5.1 Wind Energy Project Selection and Development

To understand what factors affect the outcome of a wind project, it is important to consider how projects are selected and developed. Projects usually start with a feasibility study aimed at finding a suitable investment site for a wind farm and preliminary assessment of technical, economic, environmental and land use implementation conditions. When choosing a location, trade-offs are usually made between different factors and the windiest locations is not necessarily the best. Operators often use regional surveys for wind, protected areas, endangered animal species, land ownership conditions and property boundaries and distances to roads and settlements to determine the optimal locations for wind farms. Careful planning is the key in this part of the project because the cost of feasibility study is typically less than the loss of income resulting in one month as a result of an error of assessment /27/.

Environmental Impact Assessment (EIA) is applied to wind projects when the number of individual turbines is at least 10 or the total capacity is at least 45 megawatts. The purpose of EIA is to produce information on the environmental impact of the project, to support the decision-making process and to increase citizens' access to information and opportunities to influence the project. EIA consists of two parts, where the first begins when the project operator delivers the EIA documents to the contact authority, which in is the regional Centre for Economic Development, Transport and the Environment in Finland. The documents cover the execution alternatives and what is going to be investigated during the EIA-process. The authority informs the public about the project, gathers the needed statements, and gives their own expert opinion. Agreements and applications deal with the necessary permissions for further project development like landowner agreements, building permits and grid connection application, etc. After this phase, all the required permits are granted, and construction can begin. Maturation phase elaborates the rough source data, providing detailed wind studies, detailed plant design, updated business case analysis and ends with the final investment decision. /28/

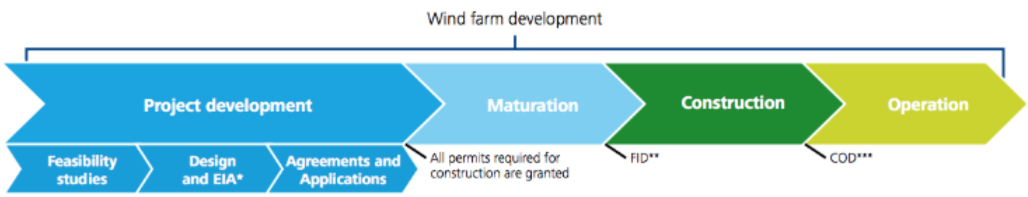

Figure 3. Wind farm development process /24/.

3 STAGES OF ANALYTIC HIERARCHY PROCESS

AHP is an aggregate method that can be decomposed into constituent parts. By following this process step by step, the decision maker can examine complex tasks by combining simple stages into one and arrive at synthesis. The logical overview (Figure 1) guides the decision maker through the whole process. The AHP process can be roughly divided into these following steps:

1. Define the objective.
2. Structure a hierarchy with objective, criteria, and alternatives.
3. Construct a set of pairwise comparisons for criteria and alternatives by using matrixes and the scale of relative importance.
4. Check pairwise comparison consistency.
5. Steps 2-5 are performed for all levels of the hierarchy.
6. Combine weights of the priority vectors into hierarchical synthesis.

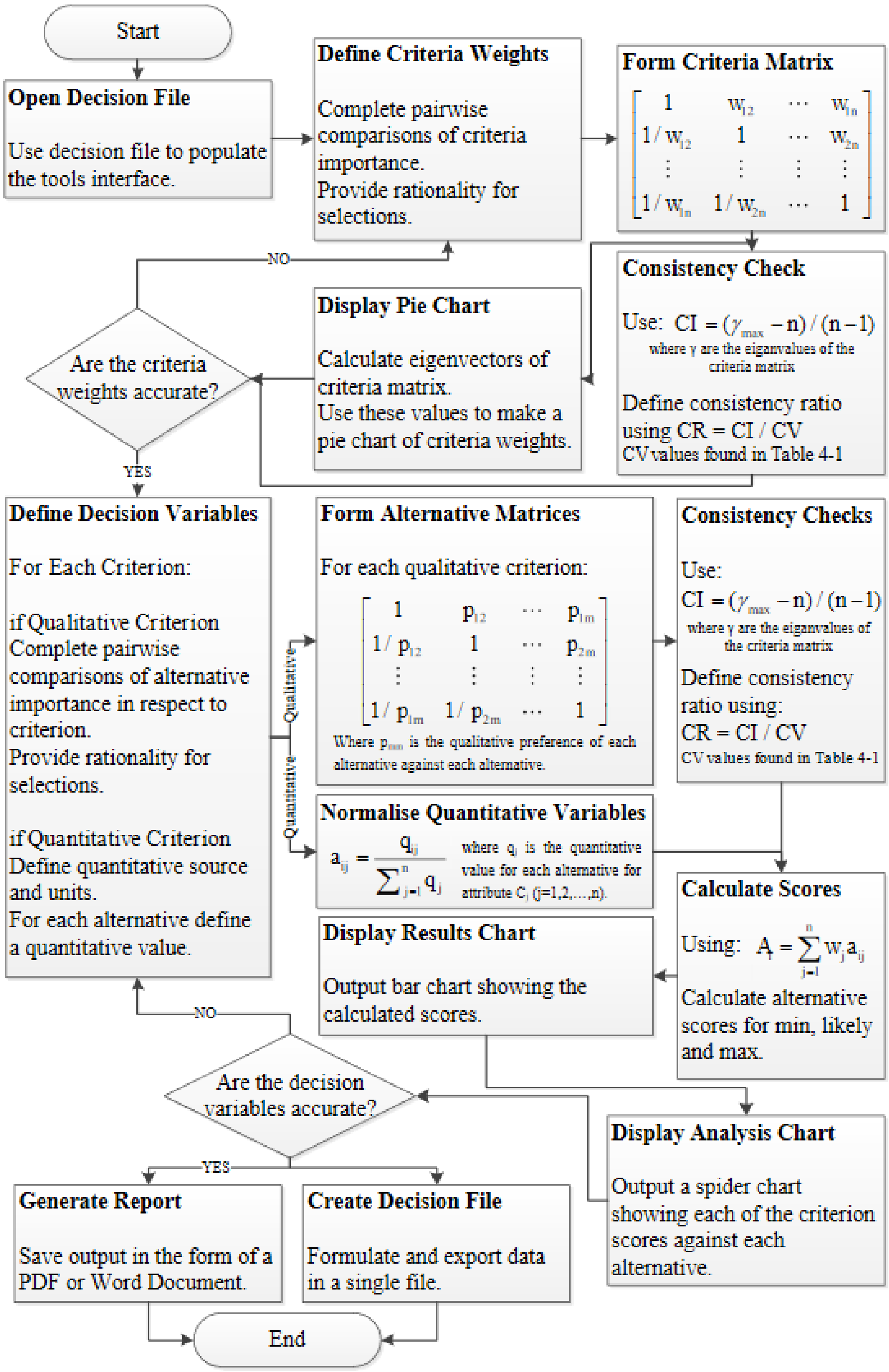

Figure 1. Overview of the steps of analytic hierarchy process /18/.

3.1 Defining the Objective

Every decision-making methodology starts with defining the objective. It is the first, the most important, and the most difficult step in the process. Objective planning can be approached by considering the factors of the present state which can be worked into some sensible outcome. Alternatively, the desired objective can be starting point which then works backwards to identify the needed factors required to reach that objective. Defining the overall objective should reflect the assumptions regarding to the cause of the problem and not just its manifestations. For example, low productivity in the manufacturing facility is not the problem the decision maker should focus on, it is the manifestation of larger problem. They should rather focus on what makes the low productivity happen (e.g., poor management, interruptions in workflows or process inefficiencies.)/1/.

3.2 Developing a Hierarchical Structure

As the complexity of the system increases, it is harder for people to grasp distinct pieces of information. A hierarchy is type of system which is based on identities that can be grouped into sets with one group affecting only one other group. The elements of each level of hierarchy are assumably independent. An example of simplified hierarchy (Figure 2) can give a basic idea of hierarchy that is scalable with identities, groups, and levels. It is also worth noticing, even though the goal of the hierarchy affects the criteria, the goal is also affected by the criteria. This feedback can be calculated into the hierarchy but will not be used in this AHP calculation example. The experience has shown that even when it is ignored, a correctly build hierarchy can still be a good model of reality. /4/.

The second step of AHP is to structure problem hierarchically. In the most basic form, a hierarchy is composed of three levels. The top level is the objective which is the problem the hierarchy is trying to solve. This objective flows through intermediate level of criteria to the lowest level of alternatives. The criteria level can be further divided into a sub-criteria level that is placed level above the alternatives. A hierarchy is complete when every element of a level functions as a criterion for all the elements of a level below. An element is described as an object within a level /1/.

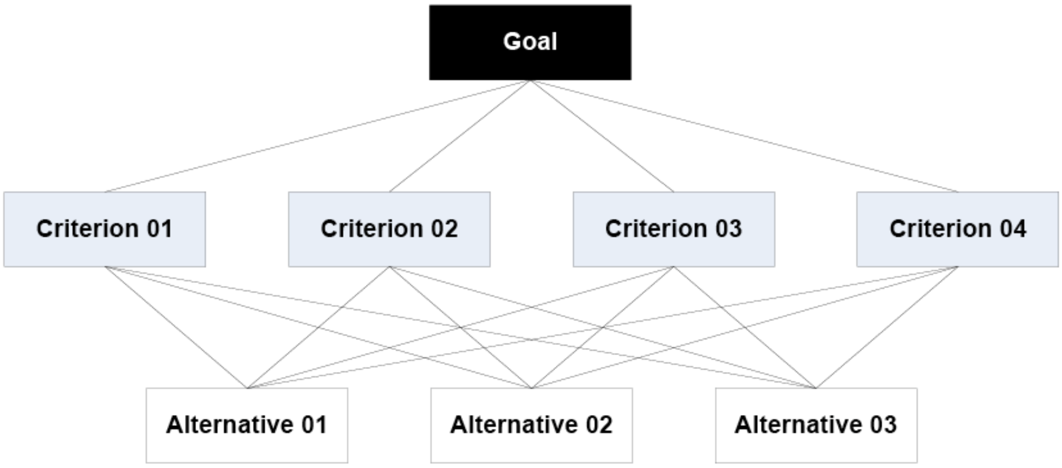

Figure 2. The most elementary form of hierarchy /5/.

The advantage of using this kind of hierarchy is that it shows how changes in the upper levels affect the lower levels. Hierarchy gives a good overview of information and structure of the system. Hierarchy composed of modules evolves naturally more efficiently compared to a system that is assembled as a whole. They are also stable in a sense that small actions have small consequences and flexible because of their resistance to disruptions. The disadvantage is that hierarchies tend to understand the highest levels by seeking information of the interactions of the levels rather than directly from the elements. /4/.

It is important that the hierarchy is developed by or with the participants of the project. Discussion about the range of preferences is needed to make sure that everybody is committed to the chosen criteria and alternatives. The strength of the criteria can be later estimated by each member of the project to create consensus for moving forward. However, it is crucial that the team members agree on the project objective since this will affect all the later decisions /1/.

But hierarchy by itself is not very useful in problem solving and decision making. There is a need to figure a method to find out the impact one level of the hierarchy has to elements in the higher levels. This way we could calculate the strength of the impact of the elements in the lower levels to the overall hierarchy. The most elementary aspect of the process, matrixes, are covered in the chapter 3.3 /4/.

3.3 Deriving Weights for the Criteria

Once the hierarchical representations have been established, the priorities of the criteria must be weighted to perform pairwise comparison. If the weights are not known, the elements are subjectively estimated from the scale of relative importance /1/.

3.3.1 The Scale of Relative Importance

The scale of relative importance is used for comparing weights of the criteria. It is a numerical scale from 1 to 9, where 1 is the equal importance and 9 is the extremely importance of the compared criteria. The scale has been proven effective in many applications and in theoretical comparison between other scales. Other scales can and have been used, such as the balanced scale, provided the scale represents people's differences in feelings during comparisons. The scale should also not extend as far as possible and so that the subject is aware of all graduations. Through experimental comparisons it becomes clear that around seven objects are ideal for the consistency and accuracy of the judgements. Usually, certain types of question appear during the weighting process. For example, which criteria is more important, which criteria is more likely and which criteria is more preferred compared to the others /1/.

Table 2. Saaty's scale of relative importance /5/.

SCALE	NUMERICAL RATING	RECIPROCAL
Extremely Preferred	**9**	**1/9**
Very strong to extremely	8	1/8
Very strongly preferred	**7**	**1/7**
Strongly to very strongly	6	1/6
Strongly preferred	**5**	**1/5**
Moderately to strongly	4	¼
Moderately preferred	**3**	**1/3**
Equally to moderately	2	½
Equally preferred	**1**	**1**

When people are weighting the criteria, their decisions should be based on data or a reason. The individual making judgements should have access to information about the criteria and alternatives to be able to set numerical values for the weights in the matrix. In the case of disagreement where multiple different numerical ratings are chosen for the weight, the geometric mean (Equation 1) of decisions is selected as the final weight of the criteria. In the case of strong disagreements, each case can be calculated separately and the most consistent is usually selected /1/.

$$\left(\prod_{i=1}^{n} x_i\right)^{\frac{1}{n}} = \sqrt[n]{x_1 x_2 \cdots x_n} \qquad (1)$$

3.4 Pair-Wise Comparison Matrix

A matrix is an arrangement of numbers into horizontal rows and vertical columns. The individual items in a matrix are called its elements. Matrixes can be applied in solving systems of linear equations, transforming coordinates in geometry, and representing graphs /12/. Pairwise comparison is the process of comparing elements in pairs to determine which of each element is preferred. When comparing two elements, the decision maker assigns numerical value from the scale of relative importance to any pair representing the element. For pairwise comparison, the matrix is the preferred form, because it offers simple, well-established framework for testing consistency, obtaining information through comparisons, and analyzing the sensitivity of overall judgements /2/.

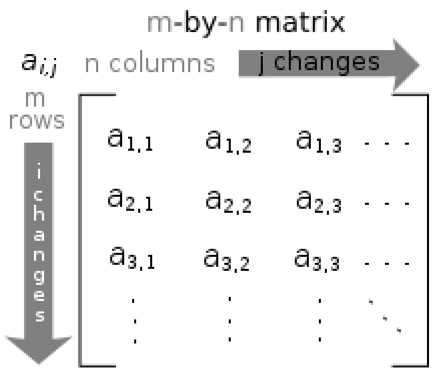

Figure 4. Matrix dimensions with elements and two variable subscripts /12/.

When two sets of criteria or alternatives are compared, one is placed in the horizontal row section and the other is placed in the vertical column section of the matrix to form a square matrix (Figure 4). This square matrix has an equal number of rows and columns and other useful properties, such as eigenvectors and eigenvalues.

These will later indicate the importance of factors the problem solver should focus on /1/.

Matrixes have a reciprocal property (Equation 2), if activity *i* has one of the preceding numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*.

$$a_{ij} = \frac{1}{a_{ji}}, a_{ij} \neq 0 \tag{2}$$

Hence, giving the matrix form:

$$\begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \tag{3}$$

The main diagonal line will always be 1, because criteria *n* relative importance to criteria *n* is always equally importance, thus giving the numerical rating of 1. It is also worth noticing that the matrix has *n* (equation 4) number of weight judgements, where *n* is the number of criteria per matrix, because the reciprocals are automatically assigned /1/.

$$Number\ of\ comparisons = \frac{n(n-1)}{2} \tag{4}$$

Next, the second level of hierarchy or criteria are compared with each other. The comparison of weights is always an activity appearing in the column on the left against an activity appearing in the row on top. If we examine the element a_{12}in the previous matrix (Figure 4), we should ask “what is the importance of criteria 1 on the left related to criteria 2 on top”. If the importance would be “strongly preferred”, we can see from the scale of relative importance that its numerical rating is 5. Therefore, the weight 5 is entered to the equivalent cell and the weight 1/5 reciprocal is entered to the reverse comparison. This is then repeated for each element of the matrix. In this case, the relation between weights w_i and judgements a_{ij} are simply: /1,4/.

$$a_{ij} = w_i/w_j \tag{5}$$

And:

$$\begin{bmatrix} w_1/w_1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \vdots & \vdots & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \dots & w_n/w_n \end{bmatrix} \tag{6}$$

The second level Excel table comparing the criteria looks like this (Table 3.).

Table 3. The comparison of weights in the second level of hierarchy /1/.

Objective	Criteria 1	Criteria 2	Criteria 3	...	Criteria n
Criteria 1	-	-	-		-
Criteria 2	-	-	-		-
Criteria 3	-	-	-		-
...					
Criteria n	-	-	-		-
Total ∑					

After the second level pairwise comparison between the criteria is done, the same comparison will be done to the third level alternatives (Table 4). The third level Excel table looks like the second level table, except the criteria is replaced by alternatives that are relatively compared to each criterion.

Table 4. The comparison of weights in the third level of hierarchy /1/.

Criteria	Alt. 1	Alt. 2	Alt. 3	...	Alt. n
Alt. 1	-	-	-		-
Alt. 2	-	-	-		-
Alt. 3	-	-	-		-
...					
Alt. n	-	-	-		-
Total ∑					

The sum of the columns is calculated in both the second and third levels and used later in the consistency calculations (Equation 7).

$$\sum_{i=1}^{n} a_{ij} \tag{7}$$

3.4.1 Eigenvector and Priority Vector Calculation

According to Thomas L. Saaty, there are four ways to calculate the eigenvectors and their vector of priorities. These calculations give a crude estimation of the eigenvector and the vector of priorities, and the fastest and most precise way of calculation would be to use a computer with the AHP software /4/.

(1) To sum the elements in each row for every row of the matrix. Then sum the gained results together to the total of all sums. The vector of priorities is the sum of the row divided with the total.
(2) Calculate the sum of each column and form the reciprocals of these sums. Normalize by dividing each reciprocal with the sums of the reciprocals.
(3) Calculate the sum of each column and divide each element with that column sum. Then add the elements in each row and divide by the number of elements in the row.
(4) Multiply the elements in each row, take the nth root to get the eigenvector. Normalize by calculating the total sum of eigenvectors and divide with each eigenvector to get the priority vector.

All these four ways of calculation give slightly different results, and each one is useable in the further calculations. If we compare the results in each case, the accuracy and complexity of calculation improves from 1 to 2 to 3 to 4, last one being the best approximation. Let us use the method 4 in the further calculations.

The way to calculate eigenvectors of the weights is to use the geometric mean (Equation 1) or method 4 described earlier. It is done by multiplying every element of the row and taking the nth root which is the number of the elements in the row. /1/.

$$Row\ n \rightarrow \sqrt[n]{\frac{w_n}{w_1} * \frac{w_n}{w_2} *\cdot \frac{w_n}{w_3} * \cdots \frac{w_n}{w_n}} = Eigenvector\ a, b, c, \dots n \qquad (8)$$

Weights are multiplied and nth root is taken to get the eigenvector for the respected row. Once all the eigenvectors' *a, b, c, …n* have been developed for every row of the matrix, the eigenvectors are added together to get the total sum of eigenvectors (equation 6).

$$a + b + c + \cdots n = Total \qquad (9)$$

The vector of priorities x_1, x_2, x_3, ...x_n (Equation 10) is calculated by normalizing the result of eigenvector for the respected row /1/.

$$\frac{n}{Total} = Vector\ of\ Priority\ x \qquad (10)$$

In mathematical terms, the eigenvector becomes the vector of priorities after it has been normalized. With these results we should be able to rank the criteria from best-to-worst and the relative desirability for each criteria /1,4/.

The weights of eigenvectors have a physical meaning in AHP. They determine the participation of that criterion relative to the total result of the goal. For example, if the one of the eigenvector values is 0,05, this factor contributes four times less than eigenvector with value of 0,2 /5/.

When the matrix is at this point, we can see that *x1, x2, x3…xn* are just *w1, w2, w3…wn*, respectively. These eigenvectors are approximations of the exact eigen-vectors, but they are still used to simplify the calculation process /5/. At this point the matrix data is generally inconsistent and it needs to be checked.

3.5 Calculating the Consistency

The next step is to determine whether the decision makers have been consistent in their weight approximation. The inconsistency calculations are based on maximum eigenvalue λ_{max} that needs to be solved (Equation 11) from the matrix A'. The result of the inconsistency check is either to re-examine the weights in the construction phase or to confirm that the matrix in consistent /1,5/.

$$A'w' = \lambda_{max}\, w', A' = (a_{ij}) \qquad (11)$$

3.5.1 Maximum Eigenvalue

To calculate the maximum eigenvalue λ_{max}, first take the pairwise comparison matrix (Table 3) and then calculate the sum of each of the columns one by one. Then using the eigenvector *x* of each row, calculate the estimate of maximum eigenvalue of the matrix as follows (equation 9):

$$\lambda_{max} = (x_1 * \sum_{i=1}^{n} a_{i_1}) + (x_2 * \sum_{i=1}^{n} a_{i_2}) + \cdots (x_n * \sum_{i=1}^{n} a_{i_n}) \quad (12)$$

The closer λ_{max} is to the number of activities in the matrix, the more consistent is the result /1,4/.

3.5.2 Consistency Index

The maximum eigenvalue λ_{max} is then applied to the consistency index formula (Equation 13) where *n* is the number of elements in the matrix. The consistency index tells us the deviation of consistency /1,4/.

$$CI = \frac{\lambda\, max - n}{n-1} \quad (13)$$

3.5.3 Random Index

The random index scale is fixed and based on the number of evaluated criteria (Table 5). It is based on the average random index for the matrix of order using a sample size of 100. As the size of the matrix increases, the random index increases as well. The letter *N* describes the size of the matrix and *RI* is the corresponding random index value /1,4/.

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 5. Random index table /5/.

3.5.4 Consistency Ratio

The final step of consistency ratio is the ratio between the consistency index and the random index. The consistency ratio indicates how much the transitivity rule has been violated. When the consistency 100% in the preferences, the deviation will be 0. The higher consistency is, the more inconsistent the evaluations are. The consistency ratio is calculated with the following equation (Equation 14):

$$CR = \frac{CI}{RI} < 0{,}1 \sim 10\% \qquad (14)$$

Generally, the matrix is considered consistent if the ratio is around 10% or less. In some specific cases with relatively large matrices (i.e. 7 to 9 elements) it is often hard to achieve high level of consistency and less than 20% consistency ratio can be acceptable. If the matrix is not consistent, the weighting of the criteria should be reviewed. If this keeps failing, the problem is most likely inaccurately structured hierarchy. One way to solve the problem is to group similar criteria and then subdivide them into sub-criteria /1,5/.

3.6 Synthesis of Priorities

The principle of synthesis is now applied, and all levels of hierarchy are tied together. The question is now how obtained priorities are interpreted. The pairwise matrixes are reintroduced. The solution matrix (Table 6) compares the relative desirability of the alternatives with respect to the criteria. With this matrix we can observe that the largest vector of priority is the most wanted alternative in each criterion category. Note that some criterion might be favoring some of the alternatives.

Finally, calculate the global priority to find out the most desirable alternative. The previously calculated criterion and alternative eigenvectors are multiplied and then added together (Equation 15).

$$Solution\ A\ = \sum_{j=1}^{n} x_j a_{ij} \qquad (15)$$

Table 6. Pairwise comparison matrix with global priorities /1/.

Solution	Criteria 1 x_1	Criteria 2 x_2	Criteria 3 x_3	…	Criteria n x_n	Solution
Alt. 1	-	-	-		-	A
Alt. 2	-	-	-		-	B
Alt. 3	-	-	-		-	C
…						
Alt. n	-	-	-		-	N
Total ∑						

3.6.1 Sensitivity Analysis

Sensitivity analysis can be used to check the outcome of an evaluation. It tells how much the priorities of the alternatives change if the criterion priorities are changed. For example, once the results have been obtained and we would like to change the wind condition criteria from strongly more important to extremely more important, would the alternative ranking change and by how much? It also visualizes the changes of the analysis and shows possible rank reversal points, at which point the alternative ranking changes take place.

Sensitivity can be calculated with the following formula (16), where *P* is the sensitivity of a parameter and *x* is the input variable:

$$S = \frac{\frac{\partial x}{x}}{\frac{\delta P}{P}} \tag{16}$$

4 PROJECT IMPLEMENTATION

The project part of this thesis was done in collaboration with Etha Wind. Etha Wind is the largest wind power consultant in Finland established in 2003. They focus on providing services supporting sustainable development /23/. The goal of the project was to apply the AHP framework in a wind farm site comparison context to select the most preferred alternative. Initially four interview sessions, about 4 hours in total were planned with Etha Wind's employee, where the employee would be introduced to the topic and provide the necessary information about the alternatives and wind power in general. The thesis and the hierarchy would be introduced in the first session, the criteria and the alternatives would be compared in the last three sessions. The results would be discussed in one additional meeting.

4.1 Hierarchy Structure

The example of a wind farm site selection ended up being four level hierarchy that was divided into four sub-criteria: technical, economic, environmental, and socio-political. The sub-criteria were not taken into consideration in the calculations and were placed just to make the hierarchy easier to grasp. In addition, 13 criteria were selected based on previous AHP studies in renewable energy evaluations /30, 24,11/ and interviewee's input.

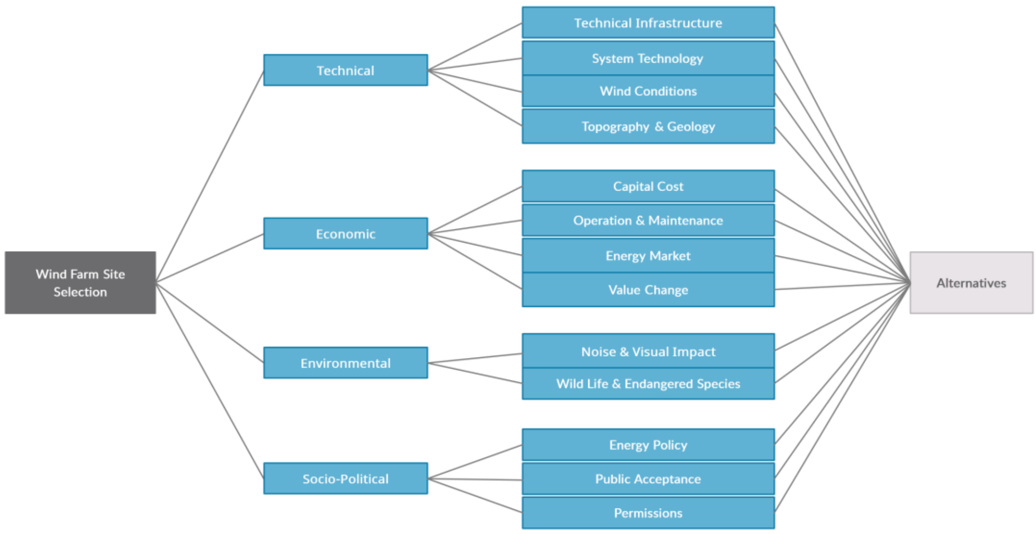

Figure 5. Step 1: Hierarchy development for wind farm site selection.

4.1.1 Criteria Definition

The 13 selected criteria were defined as follows:

- Technical Infrastructure (TI): The project alternatives have different technical demands, such as substation distance, transmission cables and road availability and suitability that are needed to be considered to realize energy production and distribution.
- Wind Conditions (WC): The viability of required wind speed is vitally important for the project. It is the main factor that determines the energy obtained from the wind energy system and the return on investment. Wind mapping data must be recorded for at least 1 year to have the average wind speed of the site.
- System Technology (ST): The rapidly increased demand for wind turbines in the last decade has led to the development of more powerful and efficient equipment. System technology selection has a large impact on annual energy production and the cost of installation.
- Land Topography & Geology (T&G): Topography determines the placement and spacing of the turbines. Topography affects the wind conditions and generally flat areas generate better wind flows whereas more rugged land interferes with the wind flow. Land geology including soil stability, bedrock, erosion, and drainage that affect foundation requirements could also be included in this criterion.
- Capital Cost (CC): The financing of the project comes with high initial cost that covers all the planning, construction, component, and management costs. Turbine costs, construction and electrical infrastructure are the major capital expenditures.
- Operation & Maintenance (O&M): Operation and maintenance costs are long-term costs in the project that include maintenance and repair costs, operational costs, and possible deconstruction of the wind turbines.

- Energy Market (EM): The existing energy market demand and energy price affects the evaluation of the project.
- Value Change (VC): Value change is a long-term criterion that should be considered in the economic calculations.
- Noise & Visual Impact (N&V): A wind project should be planned so that noise pollution from the turbine blades and rotor machinery and shadows and flickering do not affect the residential areas. Electromagnetic interference caused by the rotation of the blades that interrupts the performance of electrical equipment and could be considered environmental criteria as well.
- Wildlife & Endangered Species (WL&ES): Wind farms mostly affect birds through collision with the turbines but also some habitat loss and soil and water habitat changes occur. Long-term monitoring of the area should be done beforehand.
- Energy Policy (EPO): There are national and international regulation that affect the investment decisions. Some nations might offer renewable energy incentives such as tax cuts or feed-in-tariffs to encourage investments. On the other hands, there are restrictions related to construction and operation of the plant.
- Public Acceptance (PA): Public relations is an important part of stakeholder management in a project. Public needs to be informed about the project and they can share their opinions about it. Generally, wind farms are accepted but strong opposition might cause delays or even abolishment of the project. There is some evidence, that with greater residential distance from the wind farm the public acceptance grows /29/.
- Permissions (P): The project needs to be executed within rule and regulation framework of the local and national government. Permissions consist of more impactful permissions that might bring down the whole project and less impactful permissions that might be just a slight inconvenience.

4.1.2 Alternative Input Data

Three selected alternatives were selected for the project. All the projects were on-going during the time of writing this thesis and were selected based on the recommendations of Etha Wind employee and on their suitability for the comparison.

- Juthskogen, Maalahti: Located in South Ostrobothnia, Finland, around 13km from the coast of Gulf of Bothnia. The initial project planning of environmental impact assessment (EIA) started in spring 2019 and the goal was to erect 19 to 22 wind turbines with total height of 275 to 300 meters.

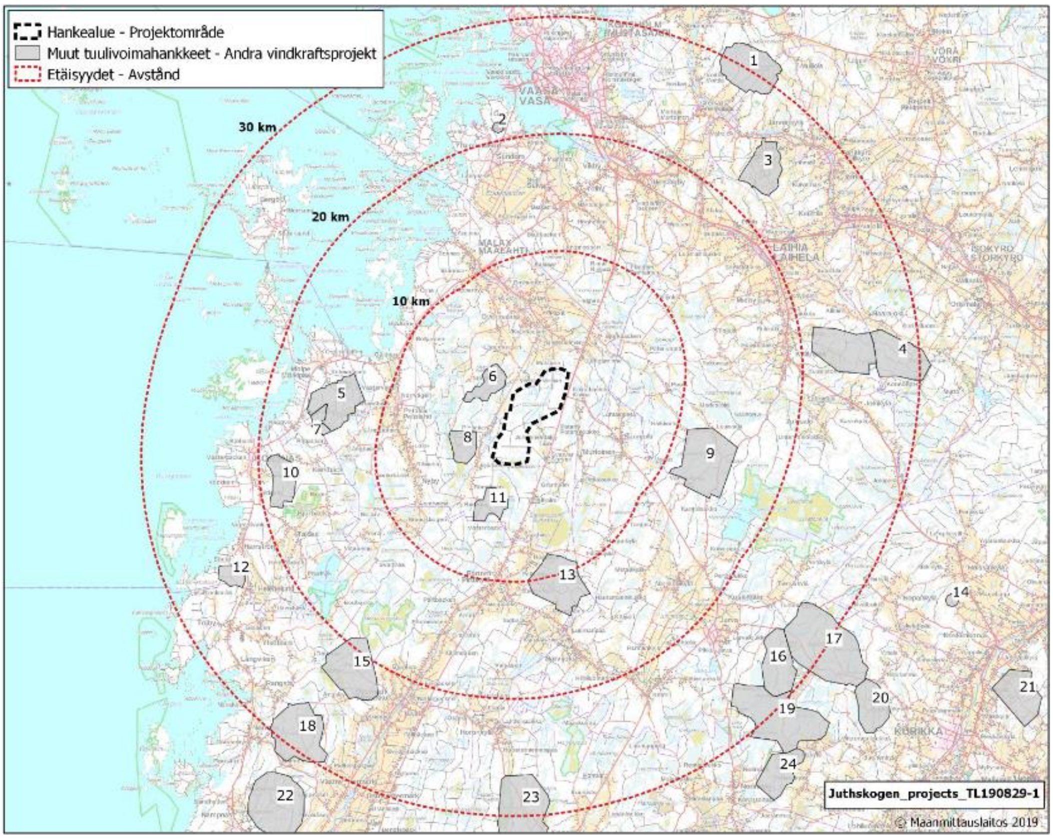

Figure 6. Juthskogen project area with other wind projects within 30km range /20/.

- Salola, Jyväskylä: Located in Central Finland, around 30km South of Jyväskylä. The goal was to erect 8 to 10 wind turbines with the total height of 275 to 290 meters. The project feasibility planning was started in 2019 with the goal to start production in 2023.

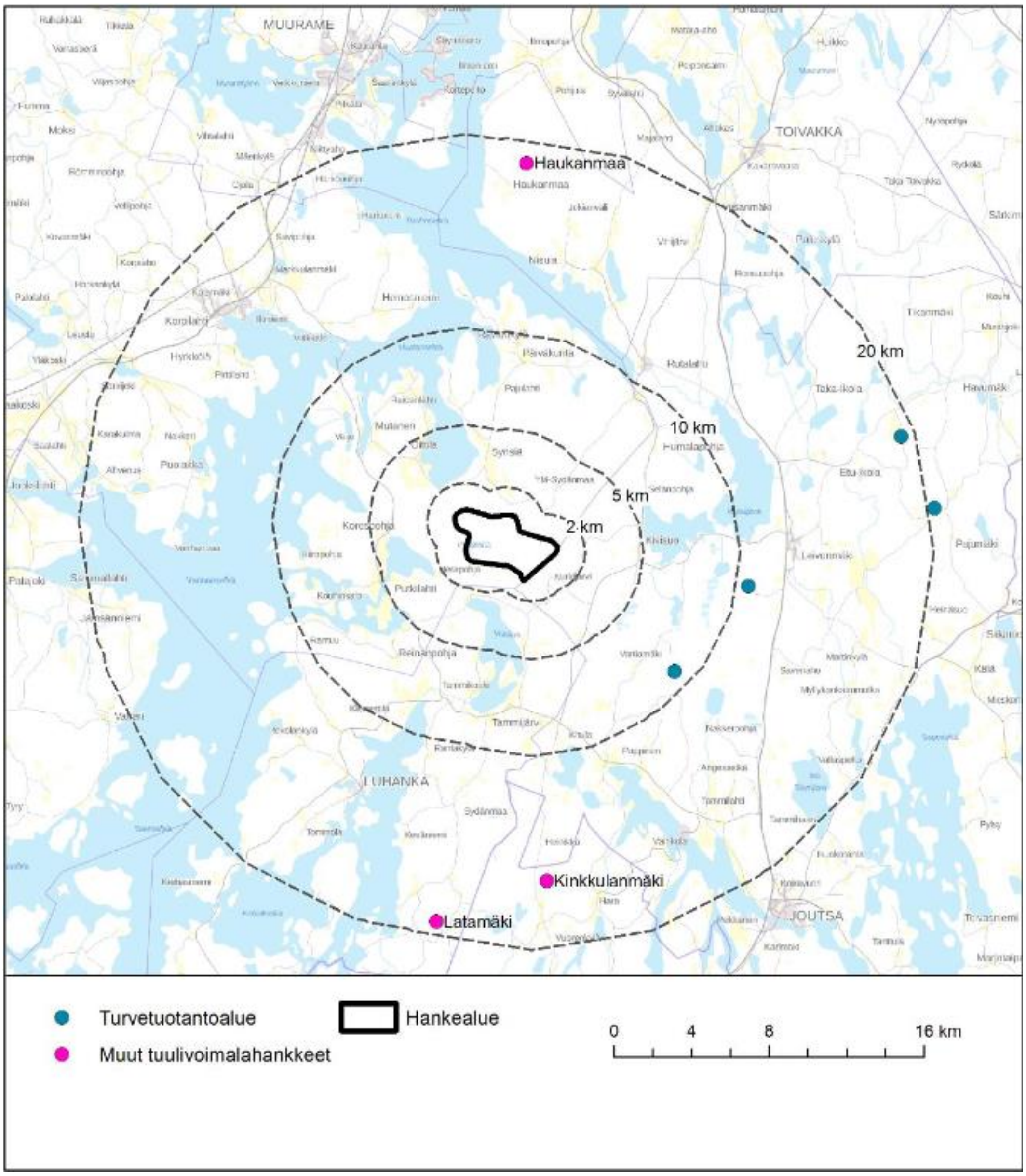

Figure 7. Salola project area with other wind projects marked with pink dots and peat production areas marked with blue dots /21/.

- Nikara, Multia: Located in Central Finland, around 15km northeast from Multia. The project environmental impact assessment (EIA) started in April 2020. The goal was to erect 20 to 29 wind turbines with the height of 250 meters.

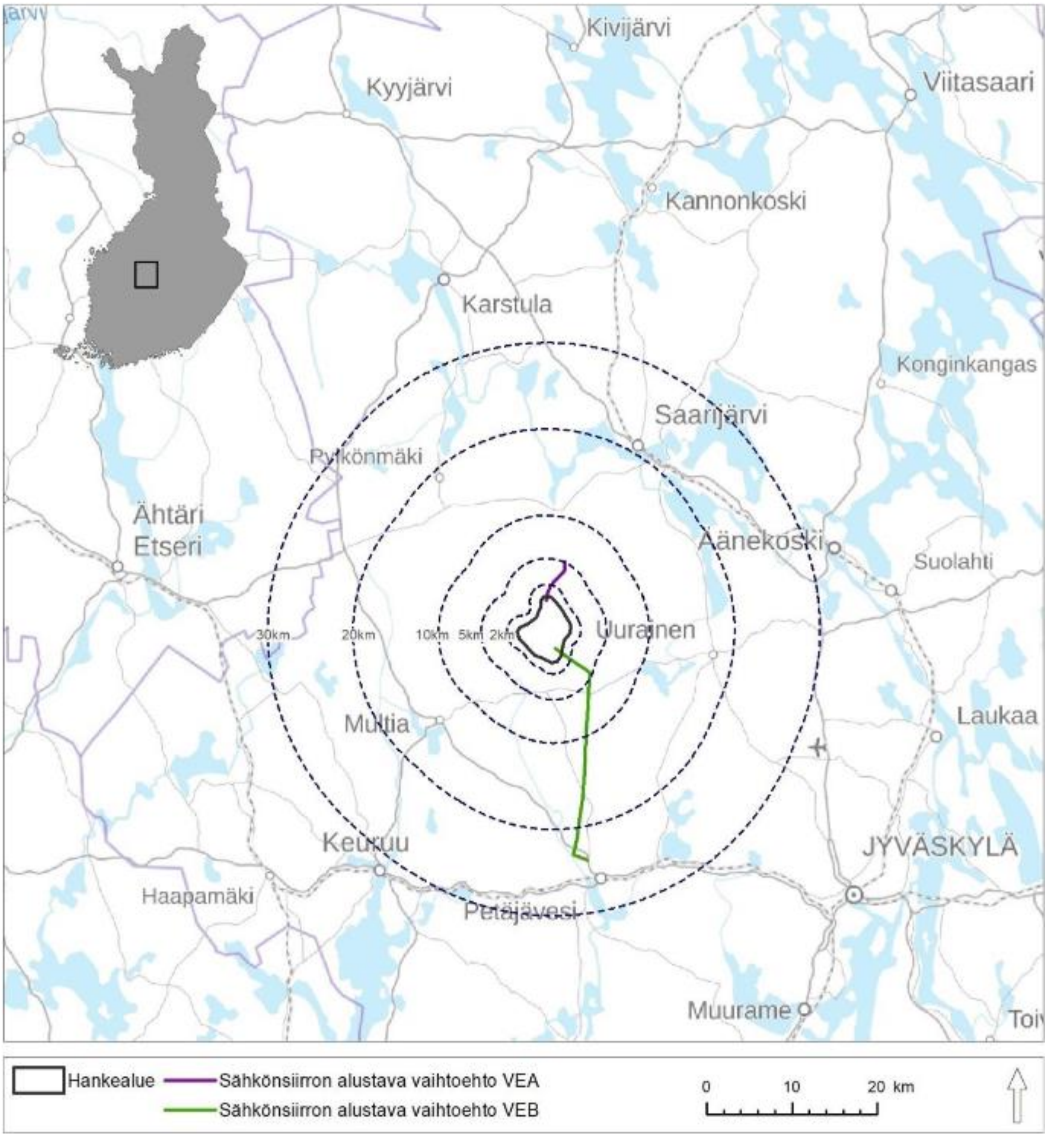

Figure 8. Nikara project area with two electric grid alternatives /22/.

The alternative input tables were created to provide quantifiable reference points for the comparisons. In some of the cases where estimate information was provided on other project and available information on other, the estimates were selected as reference points for the comparisons.

Table 7. Alternative input data for all the selected alternatives.

Juthskogen, Maalahti	Information (YVA 28.1.2020)
Technical Infrastructure	23km grid work or 8km with new transformer station
System Technology	Single unit power 6-8 MW with total height 275-300m
Wind Conditions	Average 7,7 m/s at 190m
Topography & Geology	Area is managed commercial forest, bedrock paragneiss, soil siltmoraine, no groundwater areas
Capital Finance	19-22 turbines (288 million), construction cost and electric infrastructure
Operation & Maintenance	7,2 million dollars in 10 years, maintenance 2-4 times a year according to the maintenance plan
Value Change	Value change of 19-22 turbines during 25 years
Energy Market	Energy price and demand in Finland
Noise & Visual Impact	Total height 275-300m and nearest residential building 1km (No exceedings in noice and flickering modellings)
Wild Life Impact	Area important bird migration route with some impact migratory bird collisions, no endangered squirrels, bats or frogs
Energy Policy	No feed-in tariffs and no tax help
Public Acceptance	Nearest residential building 1km and nearest village with around 50 residents 3-4km and nearest urban area 6-10km
Permissions	Required permits mentioned in the YVA

Salola, Jyväskylä	Information (Osayleiskaava 14.9.2020)
Technical Infrastructure	32km grid work; 22km landcable to old transformer station and earthcable for 10km to transformer station
System Technology	Single unit power 8-10 MW with total height 275-290m
Wind Conditions	Average 7,5 m/s at 200m
Topography & Geology	Area is hilly and mostly managed commercial forest, bedrock granite and no important bedrock areas , soil mixed, no groundwater areas
Capital Finance	8-10 turbines (115-180 million), construction cost and electric infrastructure
Operation & Maintenance	2,8-4,5 million in 10 years, 1-2 maintenance plan visits and 1-2 unpredictable maintenance visits
Value Change	Value change of 10 turbines during 25 years
Energy Market	Energy price and demand in Finland
Noise & Visual Impact	Total height 275-290m and nearest residential building 1km and holiday building 1,5 km
Wild Life Impact	Unimportant bird area that locates in bird migration route, no endangered squirrels, bats or frogs (laji.fi)
Energy Policy	No feed-in tariffs and no tax help
Public Acceptance	Nearest residential building 1km and holiday building 1,5 km and 146-157 residential buildings in 5km radius
Permissions	Required permits mentioned in the master plan

Nikara, Multia	Information (Osayleiskaava 7.4.2020)
Technical Infrastructure	30km cable to old transformer station or new transformer station
System Technology	Single unit power 4-10 MW with total height 250m
Wind Conditions	Average 7,8 m/s at 200m
Topography & Geology	Area is mainly open swamps and closed forests, bedrock porfyric granite and granidiorite, soil mixed, two classified ground water areas
Capital Finance	20-29 turbines (144-522 million), construction cost and electric infrastructure
Operation & Maintenance	3,6-13 million in 10 years, 1-2 maintenance plan visits and 1-2 unpredictable maintenance visits
Value Change	Value change of 20-29 turbines during 25 years
Energy Market	Energy price and demand in Finland
Noise & Visual Impact	Total height 250m and nearest residential building 1,1-1,3 km
Wild Life Impact	Unimportant bird areas, no endangered squirrels, bats or frogs
Energy Policy	No feed-in tariffs and no tax help
Public Acceptance	Nearest residential building 1,1-1,3 km and 56-123 residential buildings in 5km radius
Permissions	Required permits meantioned in the master plan

4.2 Criteria Comparison

The criteria were compared pairwise by using the 1 to 9 scale of relative importance. The interviewee was informed how the judgements are done and they provided their expert knowledge about the comparisons. The question was to find what criteria are the most important when selecting a wind farm site and since all the alternatives were in Finland, the whole study was restricted to Finland. The top three most important factors in Excel were Permissions (0,153), Wind Conditions (0,140) and Public Acceptance (0,131). The least important factors were evaluated to be Technical Infrastructure (0,020), Value Change (0,021) and Energy Policy (0,026).

The consistency of the criteria evaluation ended up being 18,6% and based on Saaty’s rule, consistency should be below 10% to be valid. However, in comparisons where the number of criteria is large and exceeds 9, it is sometimes acceptable to have consistency ratio below 20%. In this case, with 13 criteria the consistency should still be passable. The criteria consistency could be lowered by revisiting the comparisons or by removing unnecessary criteria from the hierarchy.

Table 8. Step 2: Eigenvector and priority vector calculation in wind farm site selection in Excel.

Level 2	TI	WC	ST	T&G	CC	O&M	EM	VC	N&V	WL&ES	EPO	PA	P	Eigenvector	Priority V.
TI	1,000	0,111	0,167	0,250	0,500	1,000	0,111	3,000	0,143	0,200	1,000	0,125	0,167	0,325	0,020
WC	9,000	1,000	3,000	1,000	1,000	7,000	4,000	8,000	0,500	1,000	8,000	1,000	2,000	2,293	0,140
ST	6,000	0,333	1,000	4,000	1,000	1,000	2,000	1,000	1,000	4,000	3,000	1,000	0,333	1,377	0,084
T&G	4,000	1,000	0,250	1,000	0,250	2,000	0,143	4,000	0,167	1,000	0,250	0,200	0,250	0,565	0,034
CC	2,000	1,000	1,000	4,000	1,000	0,500	3,000	1,000	3,000	1,000	6,000	1,000	0,333	1,390	0,085
O&M	1,000	0,143	1,000	0,500	2,000	1,000	0,167	2,000	0,125	0,333	4,000	0,167	0,167	0,523	0,032
VC	0,333	0,125	1,000	0,250	1,000	0,500	0,125	1,000	0,200	0,250	1,000	0,250	0,143	0,350	0,021
EM	9,000	0,250	0,500	7,000	0,333	6,000	1,000	8,000	0,333	0,333	1,000	0,333	0,167	0,981	0,060
N&V	7,000	2,000	1,000	6,000	0,333	8,000	3,000	5,000	1,000	1,000	3,000	1,000	1,000	2,032	0,124
WL&ES	5,000	1,000	0,250	1,000	1,000	3,000	3,000	4,000	1,000	1,000	4,000	1,000	1,000	1,491	0,091
EPO	1,000	0,125	0,333	4,000	0,167	0,250	1,000	1,000	0,333	0,250	1,000	0,143	0,167	0,423	0,026
PA	8,000	1,000	1,000	5,000	1,000	6,000	3,000	4,000	1,000	1,000	7,000	1,000	1,000	2,143	0,131
P	6,000	0,500	3,000	4,000	3,000	6,000	6,000	7,000	1,000	1,000	6,000	1,000	1,000	2,518	0,153
Total	59,333	8,587	13,500	38,000	12,583	42,250	26,546	49,000	9,801	12,367	45,250	8,218	7,726	16,410	1,000

Table 9. Step 3: Consistency calculation for criteria in wind farm site selection in Excel.

λmax	16,486	Maximum Eigenvalue
C.I.	0,290	Consistency Index
C.R.	0,186	Consistency Ratio

Consistency Ratio = 18.90%

Figure 9. Consistency calculation for criteria in wind farm site selection in SpiceLogic.

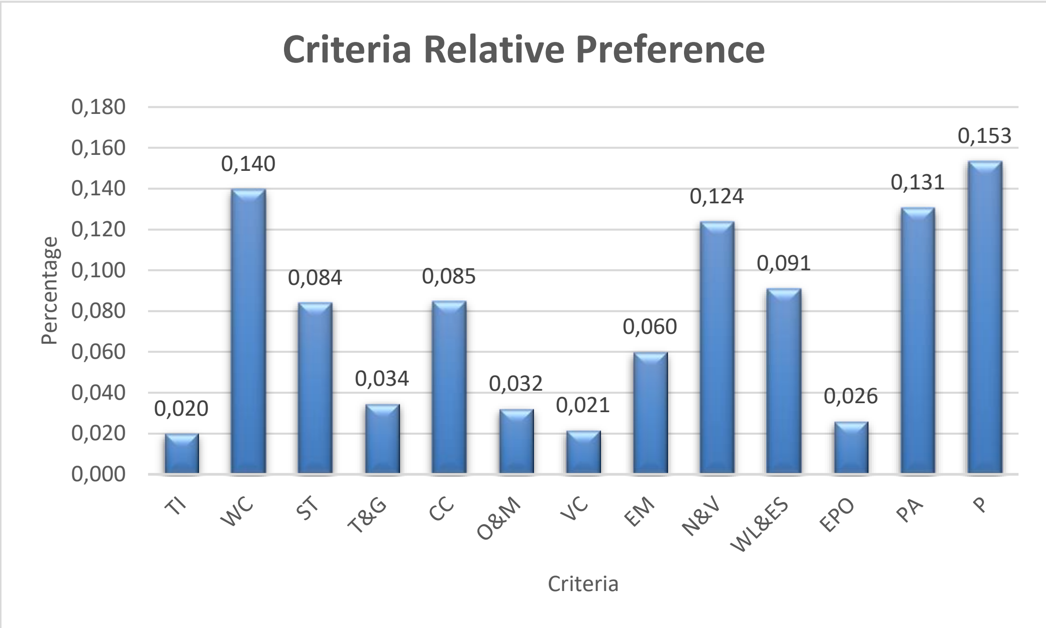

Figure 10. Criteria relative preference in wind farm site selection example in Excel.

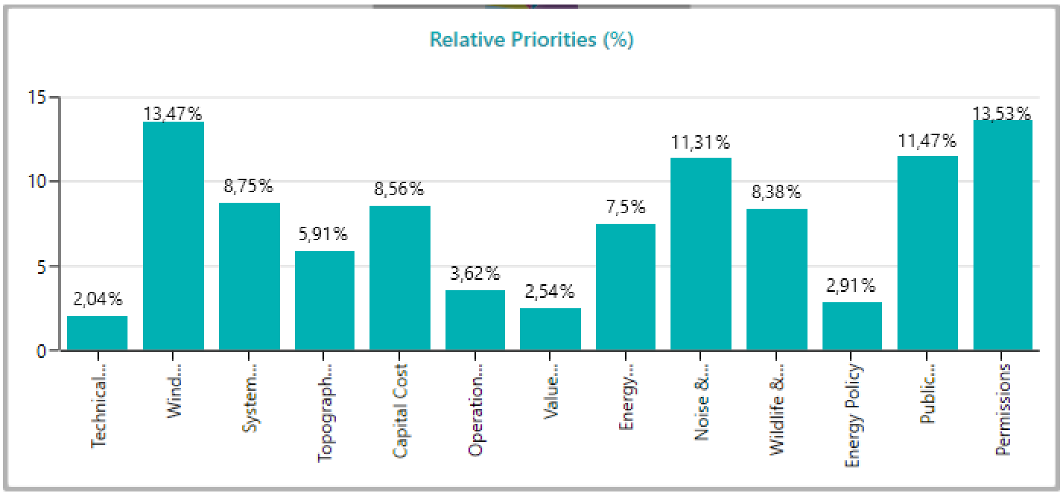

Figure 11. Criteria relative priorities in wind farm site selection example in SpiceLogic software.

4.3 Alternative Comparison

The three selected alternatives were compared similarly using pairwise comparisons, the 1 to 9 scale of relative importance and the interviewee's expertise. The alternative input data was used as a reference point for the comparisons.

Table 10. Step 4: Pairwise comparisons and consistency calculations for alternatives in wind farm site selection in Excel.

Technical Infra.	Juthskogen	Salola	Nikara	Eigenvector	Priority Vector	Consistency	Value
Juthskogen	1,000	0,500	5,000	1,357	0,352	λmax	3,054
Salola	2,000	1,000	5,000	2,154	0,559	C.I.	0,027
Nikara	0,200	0,200	1,000	0,342	0,089	C.R.	0,046
Total	3,200	1,700	11,00	3,854	1,000		

Wind Conditions	Juthskogen	Salola	Nikara	Eigenvector	Priority Vector	Consistency	Value
Juthskogen	1,000	3,000	1,000	1,442	0,429	λmax	3,000
Salola	0,333	1,000	0,333	0,481	0,143	C.I.	0,000
Nikara	1,000	3,000	1,000	1,442	0,429	C.R.	0,000
Total	2,333	7,000	2,333	3,365	1,000		

Land Topography	Juthskogen	Salola	Nikara	Eigenvector	Priority Vector	Consistency	Value
Juthskogen	1,000	0,333	5,000	1,186	0,287	λmax	3,094
Salola	3,000	1,000	6,000	2,621	0,635	C.I.	0,047
Nikara	0,200	0,167	1,000	0,322	0,078	C.R.	0,081
Total	4,200	1,500	12,000	4,128	1,000		

System Tech.	Juthskogen	Salola	Nikara	Eigenvector	Priority Vector	Consistency	Value
Juthskogen	1,000	0,333	4,000	1,101	0,280	λmax	3,086
Salola	3,000	1,000	5,000	2,466	0,627	C.I.	0,043
Nikara	0,250	0,200	1,000	0,368	0,094	C.R.	0,074
Total	4,250	1,533	10,00	3,935	1,000		

Capital Cost	Juthskogen	Salola	Nikara	Eigenvector	Priority Vector	Consistency	Value
Juthskogen	1,000	5,000	0,333	1,186	0,279	λmax	3,065
Salola	0,200	1,000	0,143	0,306	0,072	C.I.	0,032
Nikara	3,000	7,000	1,000	2,759	0,649	C.R.	0,056
Total	4,200	13,000	1,48	4,250	1,000		

Operation & Main	Juthskogen	Salola	Nikara	Eigenvector	Priority Vector	Consistency	Value
Juthskogen	1,000	5,000	0,333	1,186	0,279	λmax	3,065
Salola	0,200	1,000	0,143	0,306	0,072	C.I.	0,032
Nikara	3,000	7,000	1,000	2,759	0,649	C.R.	0,056
Total	4,200	13,000	1,476	4,250	1,000		

Energy Market	Juthskogen	Salola	Nikara	Eigenvector	Priority Vector	Consistency	Value
Juthskogen	1,000	1,000	1,000	1,000	0,279	λmax	3,000
Salola	1,000	1,000	1,000	1,000	0,072	C.I.	0,000
Nikara	1,000	1,000	1,000	1,000	0,649	C.R.	0,000
Total	3,000	3,000	3,000	3,000	1,000		

Value Change	Juthskogen	Salola	Nikara	Eigenvector	Priority Vector	Consistency	Value
Juthskogen	1,000	5,000	0,333	1,186	0,279	λmax	3,065
Salola	0,200	1,000	0,143	0,306	0,072	C.I.	0,032
Nikara	3,000	7,000	1,000	2,759	0,649	C.R.	0,056
Total	4,200	13,000	1,476	4,250	1,000		

Noise & Visual	Juthskogen	Salola	Nikara	Eigenvector	Priority Vector	Consistency	Value
Juthskogen	1,000	0,500	0,200	0,464	0,117	λmax	3,025
Salola	2,000	1,000	0,250	0,794	0,200	C.I.	0,012
Nikara	5,000	4,000	1,000	2,714	0,683	C.R.	0,021
Total	8,000	5,500	1,450	3,972	1,000		

Wild Life	Juthskogen	Salola	Nikara	Eigenvector	Priority Vector	Consistency	Value
Juthskogen	1,000	0,250	0,250	0,397	0,109	λmax	3,054
Salola	4,000	1,000	0,500	1,260	0,345	C.I.	0,027
Nikara	4,000	2,000	1,000	2,000	0,547	C.R.	0,046
Total	9,000	3,250	1,75	3,657	1,000		

Energy Policy	Juthskogen	Salola	Nikara	Eigenvector	Priority Vector	Consistency	Value
Juthskogen	1,000	1,000	1,000	1,000	0,333	λmax	3,000
Salola	1,000	1,000	1,000	1,000	0,333	C.I.	0,000
Nikara	1,000	1,000	1,000	1,000	0,333	C.R.	0,000
Total	3,000	3,000	3,00	3,000	1,000		

Public Accept.	Juthskogen	Salola	Nikara	Eigenvector	Priority Vector	Consistency	Value
Juthskogen	1,000	3,000	2,000	1,817	0,517	λmax	3,108
Salola	0,333	1,000	0,250	0,437	0,124	C.I.	0,054
Nikara	0,500	4,000	1,000	1,260	0,359	C.R.	0,093
Total	1,833	8,000	3,25	3,514	1,000		

Permissions	Juthskogen	Salola	Nikara	Eigenvector	Priority Vector	Consistency	Value
Juthskogen	1,000	2,000	2,000	1,587	0,500	λmax	3,000
Salola	0,500	1,000	1,000	0,794	0,250	C.I.	0,000
Nikara	0,500	1,000	1,000	0,794	0,250	C.R.	0,000
Total	2,000	4,000	4,00	3,175	1,000		

4.4 Results

Finally, the values of priorities of criteria comparisons and alternative comparisons are brought together. Separate software called Analytic Hierarchy Process Software created by SpiceLogic was used to verify the Excel calculations and visualize the sensitivity analysis. The obtained output defines the values for the wind project alternative in Excel as 0,429, 0,333 and 0,239, respectively. These results match the

SpiceLogic software values, 41,92, 32,49 and 25,54, which makes Nikara the most preferred alternative followed by Juthskogen and Salola.

In the sensitivity analysis there were 117 variables altogether. All the variables were insensitive, meaning that none of them would change the ranking order of the first alternative. Some variables had rank reversal points between the second and the third most preferred alternatives, but those did not change the first alternative position.

Table 11. Step 5: Synthesis of priorities to get the composite in wind farm site selection in Excel.

Solution	TI	WC	ST	T&G	CC	O&M	EM	VC	N&V	WL&ES	EPO	PA	P	Solution
	0,020	0,140	0,084	0,034	0,085	0,032	0,021	0,060	0,124	0,091	0,026	0,131	0,153	
Juthskogen	0,352	0,429	0,280	0,287	0,279	0,279	0,279	0,279	0,117	0,109	0,333	0,517	0,500	0,333
Salola	0,559	0,143	0,627	0,635	0,072	0,072	0,072	0,072	0,200	0,345	0,333	0,124	0,250	0,239
Nikara	0,089	0,429	0,094	0,078	0,649	0,649	0,649	0,649	0,683	0,547	0,333	0,359	0,250	0,429
Total														1,000

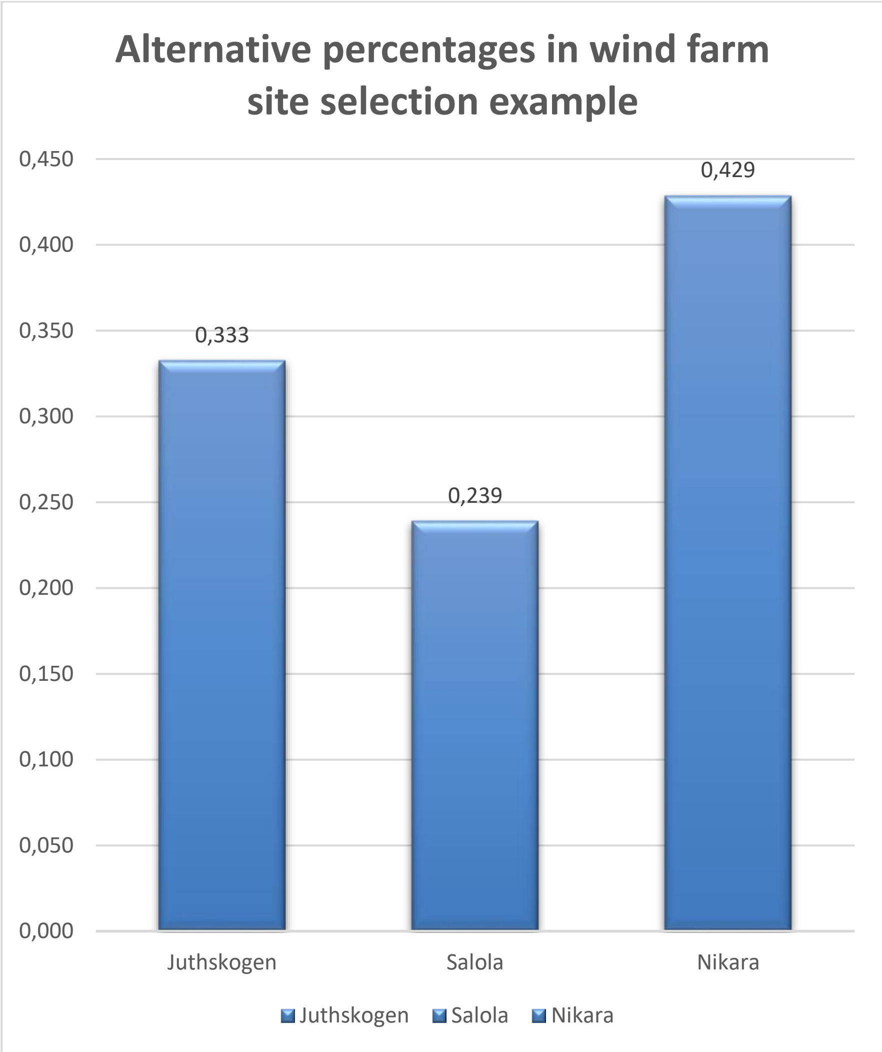

Figure 12. Alternative percentages in wind farm site selection example in Excel.

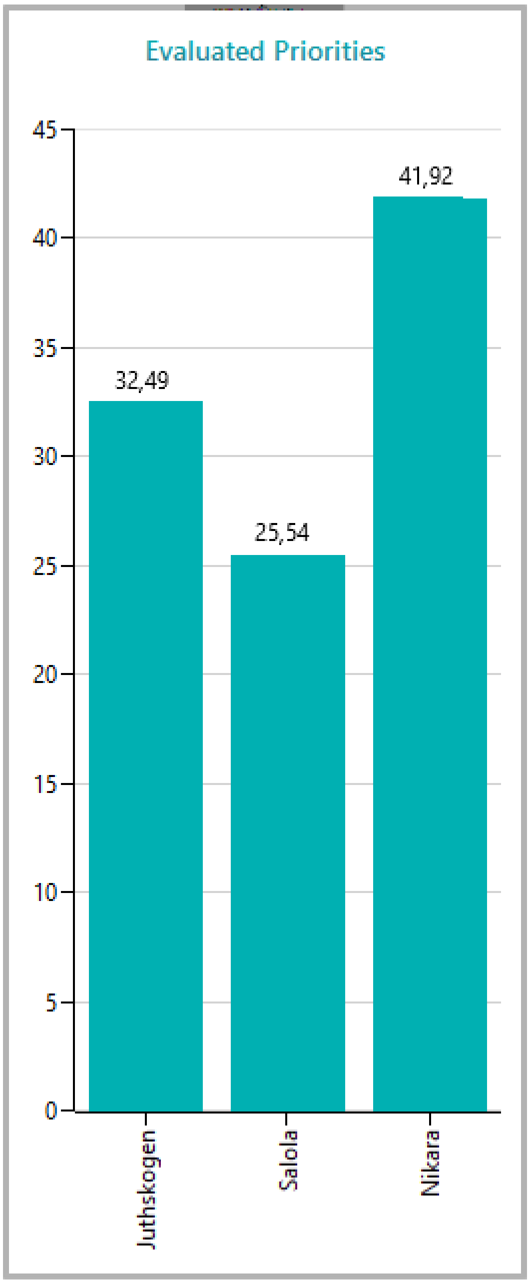

Figure 13. Alternative priorities evaluated in SpiceLogic software.

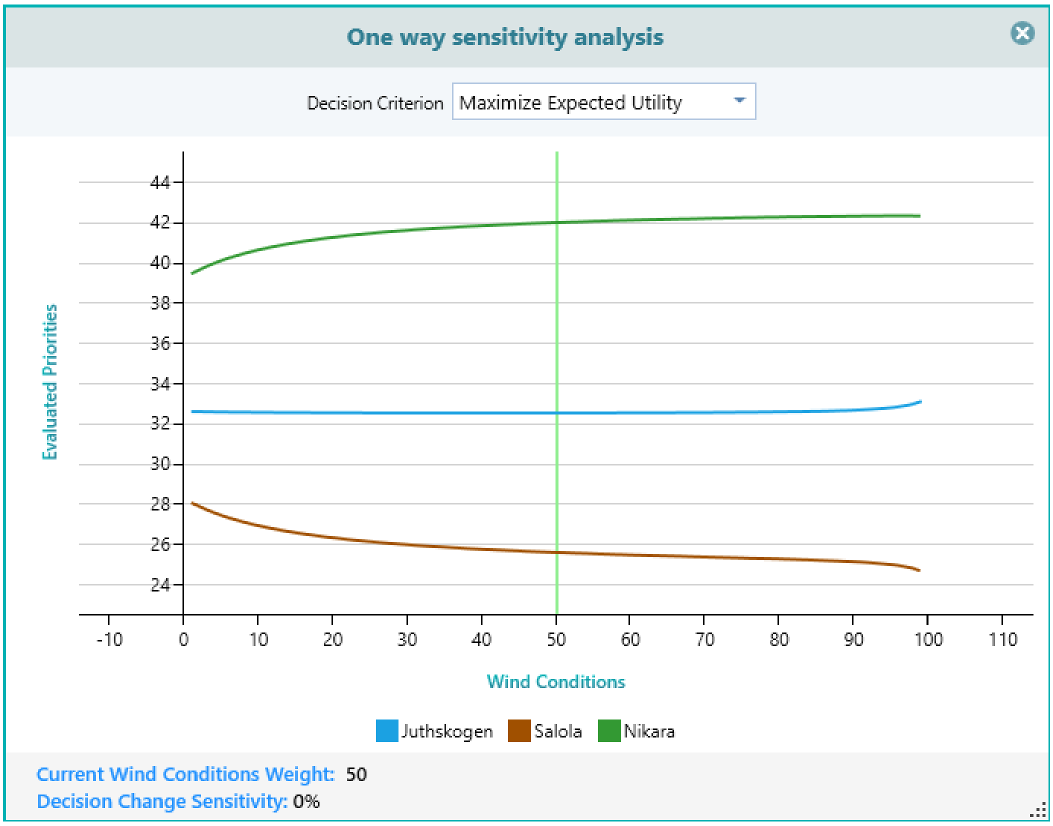

Figure 14. One way sensitivity analysis of wind conditions in SpiceLogic.

5 CONCLUSIONS

This thesis aimed to study how analytic hierarchy process could be applied to wind site selection to choose the best alternative out of selected group. Criteria and alternatives were both evaluated with numerical and linguistic values by guided a wind energy expert. The evaluations were based on the knowledge and experience of the expert, which brings a certain amount of uncertainty that was checked after the evaluations.

The hierarchy used in the process was created based on previous renewable energy site selection studies and the expert's knowledge. Because of the selected alternatives were all located in Finland, the results of this study are limited to Finland. The evaluations of the criteria and alternatives were converted into pair-wise comparison matrixes that were used to calculate the eigenvectors and vector of priorities to get the overall global priority. The consistency of the comparisons was checked and the whole process was verified with AHP software. The project with the highest global priority was selected as the best option.

According to this study, the most preferred criteria were permissions (0,153), wind conditions (0,140), and public acceptance (0,131), while the least preferred were technical infrastructure (0,020), value change (0,021), and energy policy (0,026). The verified software result values and order matched the Excel calculations. Out of the three selected alternatives, Nikara (0,429) was the most preferred followed by Juthskogen (0,333) and Salola (0,239). The obtained values match the generally important monetary and regulative factors influencing the outcome of a wind project in Finland. The biggest factor influencing the revenue is wind resources and the regional permits are required for further project development. The largest CAPEX of the main project components are the wind turbines followed by civil works, grid connectivity and project planning, which makes matches the system technology preference /24/. This study also points out the relative preferences of tangible criteria like technical infrastructure and intangible criteria, such as noise and visual impact, which is usually difficult to quantify without some sort of discrete system.

In the future it might be worth exploring the integration of the AHP and GIS software to provide better data gathering and to feature a more visual platform for the received data. This way the AHP process could prove useful in context of decision making for a wind farm feasibility study, but further case study might be needed. Another idea would be to implement a broader hierarchy with factors, such as intrinsic company objectives (market share, payout ratio, sales, earnings), investor objectives (profit, control, security) and risks (low, medium, and high-risk scenarios) to create a more useful tool for portfolio management. Since the model is working, it is scalable with more alternatives if needed. The execution of these kinds of projects would be very time consuming, especially in the comparison phase where the number of comparisons would probably increase many times over, and this kind of implementation would probably require team of researchers and multiple experts to gather information from.

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