



**Integration of Rationale Management with Multi-Criteria
Decision Analysis, Probabilistic Forecasting and Semantics:
Application to the UK Energy Sector**

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St. Edmund Hall

A thesis submitted for the degree of *Doctor of Philosophy*

Department of Engineering Science, University of Oxford

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Abstract

This thesis presents a new integrated tool and decision support framework to approach complex problems resulting from the interaction of many multi-criteria issues. The framework is embedded in an integrated tool called OUTDO (Oxford University Tool for Decision Organisation). OUTDO integrates Multi-Criteria Decision Analysis (MCDA), decision rationale management with a modified Issue-Based Information Systems (IBIS) representation, and probabilistic forecasting to effectively capture the essential reasons why decisions are made and to dynamically re-use the rationale. In doing so, it allows exploration of how changes in external parameters affect complicated and uncertain decision making processes in the present and in the future.

Once the decision maker constructs his or her own decision process, OUTDO checks if the decision process is consistent and coherent and looks for possible ways to improve it using three new semantic-based decision support approaches. For this reason, two ontologies (the Decision Ontology and the Energy Ontology) were integrated into OUTDO to provide it with these semantic capabilities. The Decision Ontology keeps a record of the decision rationale extracted from OUTDO and the Energy Ontology describes the energy generation domain, focusing on the water requirement in thermoelectric power plants.

A case study, with the objective of recommending electricity generation and steam condensation technologies for ten different regions in the UK, is used to verify OUTDO's features and reach conclusions about the overall work.

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Table of Contents

Abstract	i
Acknowledgements	iii
Table of Contents.....	iv
List of Figures	x
List of Tables.....	xiv
List of Abbreviations	xv
List of Nomenclature	xviii
Chapter 1 Introduction	1
1.1 Introduction	1
1.2 Current DSSs and OUTDO	2
1.3 Case Study Background	3
1.4 Research Objectives and Contributions.....	5
1.5 Thesis Structure	8
Chapter 2 Literature Review.....	10
2.1 Introduction	10
2.2 Rationale Management.....	11
2.2.1 Issue-Based Information Systems	13
2.3 Multi-Criteria Decision Analysis	16
2.3.1 Weighted Sum Model.....	19
2.3.2 Weighted Product Model.....	20
2.3.3 ELECTRE III.....	20
2.4 Probabilistic Forecasting	24

2.5	Semantics.....	25
2.5.1	Ontologies.....	26
2.6	Background to OUTDO.....	30
2.7	Other Decision Rationale Capture DSSs.....	34
2.8	Conclusion.....	38
Chapter 3	Decision Support System Framework	40
3.1	Introduction	40
3.2	OUTDO	41
3.2.1	Decision Matrix	42
3.2.2	Global Parameters, Propagation, Sensitivity Analysis and Probabilistic Forecasting.....	45
3.2.3	Goals vs. Criteria matrix and Ontology Dialogue	47
3.2.4	OUTDO Components Summary	48
3.3	Decision Support System Framework.....	50
3.4	The Standardised and Design Decision Process Approaches.....	55
3.4.1	Standardised Decision Process: Bottom-up Approach.....	55
3.4.2	Design Decision Process: Top-Down Approach.....	56
3.5	Previous, Current and Possible Application of OUTDO.....	57
3.6	Conclusion.....	59
Chapter 4	Case Study Description: UK Energy Sector	61
4.1	Introduction	61
4.2	Overview of the UK Energy Sector.....	62
4.3	The Connection Between Energy and Water	65
4.4	Decision Process Goals	68

4.4.1	Energy Goal	69
4.4.2	Environmental Goal	69
4.4.3	Economic Goal	70
4.4.4	Social Goals	71
4.5	Goal vs. Criteria Matrix	72
4.6	Constructing the Decision Process in OUTDO	73
4.7	Conclusion	80
Chapter 5	Solution Development	82
5.1	Introduction	82
5.2	Criteria Creation in OUTDO	83
5.2.1	Criteria for Steam Condensation Issues	84
5.2.2	Criteria for Electricity Generation Issues	86
5.3	Weighting the Criteria	91
5.3.1	Steam Condensation Weight of Criteria	92
5.3.2	Electricity Generation Weight of Criteria	94
5.4	Scoring the Positions	95
5.4.1	External Models (Steam Condensation Technologies Scoring)	96
5.4.2	Electricity Generation Technologies Scoring	101
5.5	Further Analysis: ELECTRE III	106
5.6	Conclusion	109
Chapter 6	Global Parameters	111
6.1	Introduction	111
6.2	Global Parameter Types	112
6.3	Decision Matrix Expressions	116

6.4 Propagation and Sensitivity Analysis	118
6.5 Future Analysis	122
6.5.1 Probabilistic Forecasting Creation.....	126
6.5.2 Future Analysis Results for the Yorkshire and the Humber Region	127
6.5.3 Results for the different locations.....	130
6.6 Decision Hub	134
6.7 Conclusion.....	135
Chapter 7 Decision and Energy Ontology	138
7.1 Introduction	138
7.2 Inclusion of Semantics in OUTDO	139
7.2.1 Ontology Structure	141
7.3 The Decision Ontology.....	144
7.3.1 OUTDO Language	145
7.3.2 Decision Ontology Applications	146
7.4 The Energy Ontology	147
7.4.1 Energy Policy Class.....	148
7.4.2 Technology Class	150
7.4.3 Natural Resource Class.....	151
7.4.4 Location Class	152
7.4.5 Product Class	153
7.4.6 Actor Class	154
7.4.7 Finance Class.....	154
7.4.8 Time Class	155

7.4.9 Axioms	155
7.5 Conclusion.....	157
Chapter 8 Reactive Decision Support.....	158
8.1 Introduction	158
8.2 Consistency Check	159
8.2.1 Goals vs. Criteria Consistency Check	160
8.2.2 Issues vs. Positions Consistency Check	162
8.2.3 Issues Ordering Consistency Check	165
8.3 Automatic Inference	165
8.3.1 Position Node Inference	166
8.3.2 Issue Node Inference	166
8.4 Decision Check.....	169
8.4.1 Retrieval of Important Information	170
8.4.2 Past Experience.....	173
8.4.3 Multiple Qualitative Analyses	176
8.5 Conclusion.....	179
Chapter 9 Discussion, Conclusions and Future Work.....	182
9.1 Introduction	182
9.2 Discussion.....	182
9.2.1 Inclusion of MAUT in OUTDO	182
9.2.2 Case Study Discussion	185
9.2.3 The Future Analysis Feature	186
9.2.4 The Inclusion of Semantics in OUTDO	187
9.3 Thesis Conclusions	189

9.4 Future Work.....	193
Bibliography.....	195
Appendix A Forecasting Equations	220
A.1 Confidence Intervals Equations.....	220
A.2 Future Analysis Equations.....	221
Appendix B Expressions	223
B.1 Wind Turbine Expression	223
B.2 Photovoltaic Cell Expression.....	225
B.3 Biomass Expression.....	225
B.4 Gas Transport Expression.....	226
B.5 CO ₂ Transport Expression	227
B.6 Geothermal Expression.....	227
Appendix C Publications and Other.....	229

List of Figures

Figure 1.1	OUTDO Decision Framework Proposed.	6
Figure 2.1	IBIS representation for the recommendation of engineering artefact positions [34]. [This reference goes in the picture]	15
Figure 3.1	The issue node window with decision matrix in the Formula view...	43
Figure 3.2	The decision matrix in the Values view.....	43
Figure 3.3	The graphical interface of the OUTDO decision process.	44
Figure 3.4	The Global Parameters window.	46
Figure 3.5	The Goals vs. Criteria matrix.	47
Figure 3.6	The decision framework for OUTDO.	52
Figure 4.1	British electricity supply system map in 2011 without wind energy [157].	63
Figure 4.2	Surface water and groundwater available for abstraction in 2008 [160]. There are no data for the areas (CAMS) in grey.	67
Figure 4.3	Goals vs. Criteria matrix used to record and display the decision process intent.	73
Figure 4.4	OUTDO nodes and map nodes used for the selection of electricity generation technology.	76
Figure 4.5	Expansion of the <i>Coal Plant</i> map node showing further details of the coal-based generation technologies [181].	78
Figure 4.6	Expansion of the <i>Biomass Plant</i> map node showing further details of the biomass-based generation technologies [182].	79
Figure 4.7	Expansion of the <i>Gas Plant</i> map node at the top-left [181, 182, 183], <i>Solar Plant</i> at the bottom-left [182, 185] and <i>Nuclear Plant</i> at the right [182, 186].....	79
Figure 5.1	Capacity factors by technology type in the UK [192].	90

Figure 5.2	Using IECM to design wet coolers in thermoelectric plants.....	97
Figure 5.3	Using IECM to design dry coolers in thermoelectric plants.	98
Figure 5.4	Using DEEP to design multiple-effect distillation in thermoelectric plants.	98
Figure 5.5	Simulation of a NGCC CHP plant using Aspen Plus [199].....	99
Figure 5.6	Decision matrix used to find the recommended steam condensation technology, (a) assuming a condensation temperature of 120°C for the CHP position and (b) assuming a condensation temperature of 100°C for the CHP position	100
Figure 5.7	Expansion of the <i>Coal Plant</i> map node for the York and the Humber region, assumed cost of CO ₂ emissions of 0.025 £/kg of CO ₂ [181] and plant start-up in 2040.	103
Figure 5.8	Values view of the main issue node (Yorkshire and the Humber region; CO ₂ emission cost 0.025 £/kg; 2040).	105
Figure 5.9	ELECRE III panel in OUTDO.	108
Figure 6.1	Global Parameters used for the Yorkshire and the Humber region in the decision process.	115
Figure 6.2	Decision matrix values view for the <i>Wind turbine</i> position node analysis.....	117
Figure 6.3	First Global Parameter propagation of CO ₂ emissions cost change from 0.025 to 0.203 £/kg.....	120
Figure 6.4	Second Global Parameters propagation.	121
Figure 6.5	Sensitivity Analysis data input window.....	122
Figure 6.6	Sensitivity Analysis report window showing the changes in recommendations.	122
Figure 6.7	Forecast for <i>Parameter1</i> used to exemplify the Future Analysis feature.	125

Figure 6.8	Forecast plot (above) and Confidence Intervals plot (below) used to exemplify the Future Analysis feature.	125
Figure 6.9	Forecast and Confidence Intervals for CO ₂ emissions costs up to 2050.....	127
Figure 6.10	Future Analysis for the Yorkshire and the Humber region without CCS.....	129
Figure 6.11	Future Analysis for the Yorkshire and the Humber region with CCS.....	130
Figure 6.12	Electricity generation technologies, without CCS, recommended for different regions of the UK from 2010 until 2050.	132
Figure 6.13	Electricity generation technologies, with CCS, recommended for different regions of the UK from 2010 until 2050.....	133
Figure 7.1	Ontology Dialogue window.	140
Figure 7.2	Connection of OUTDO with the semantic-based capabilities.	141
Figure 7.3	(a) Decision Ontology, (b) Example of instances of the Decision Ontology.	145
Figure 7.4	Overall structure of the Energy Ontology.....	148
Figure 7.5	The <i>Energy_Policy</i> , <i>Technology</i> , <i>Natural_Resource</i> and <i>Location</i> subclasses in the Energy Ontology.	150
Figure 7.6	The <i>Product</i> , <i>Actor</i> , <i>Finance</i> and <i>Time</i> subclasses in the Energy Ontology.	153
Figure 8.1	Diagram for Goals vs. Criteria Consistency Check.	161
Figure 8.2	OUTDO message if a goal is not associated with a criterion in the Energy Ontology.....	161
Figure 8.3	Diagram for Issues vs. Positions Consistency Check.	163
Figure 8.4	Warning message for an issue which is not associated with a position.....	164

Figure 8.5	Message corresponding to an ordering of issues that does not correspond to the taxonomy in the Energy Ontology.	165
Figure 8.6	Inference of suggested position nodes.	166
Figure 8.7	Issue Nodes Inference for wind turbines.....	167
Figure 8.8	Representation of Issue Nodes Inference with object properties.	168
Figure 8.9	Inference of issues and positions.	169
Figure 8.10	Decision rationale for the design and construction of nuclear plants in the UK.....	170
Figure 8.11	Engineering process diagram and its Energy Ontology representation.	171
Figure 8.12	Warning message regarding the input to the system (i.e. radioactive material).	172
Figure 8.13	Warning message regarding the output from the system (i.e. radioactive waste).	172
Figure 8.14	Warnings regarding the system itself (i.e. nuclear plant).....	173
Figure 8.15	Advice associated with Past Experience specifications.	175
Figure 8.16	Multiple Qualitative Analyses for the calculation of risk of coal supply.....	179
Figure A.1	Method for the creation confidence intervals.....	221

List of Tables

Table 2.1	Current rationale management tools.....	36
Table 3.1	Summary of OUTDO components, terminologies and features.	48
Table 5.1	Criteria for the selection of steam condensation technology.	85
Table 5.2	Criteria used for electricity generation technology.	87
Table 5.3	Weight selection for the comparison of steam condensation technologies.....	94
Table 5.4	Criteria used for electricity generation technology.	107
Table 6.1	Global Parameters for the 10 different locations.....	131
Table 8.1	Data in the Energy Ontology used in the Multiple Qualitative Analyses feature.	177

List of Abbreviations

AHP	Analytical Hierarchy Process
ASPEN	Advanced System for Process Engineering
API	Application Programming Interface
BOD	Biological Oxygen Demand
BN	Bayesian Network
CAD	Computer-Aided Design
CAMS	Catchment Abstraction Management Strategies
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
CoP	ConocoPhillips
CPF	Carbon Price Floor
DECC	Department of Energy and Climate Change
DEEP	Desalination Economic Evaluation Program
DL	Description Logic
DM	Decision Maker
DR	Decision Rationale
DRAMA	Design Rationale Management System
DRL	Decision Representation Language
DSS	Decision Support Systems
ELECTRE	Elimination and Choice Translating Reality

EPS	Emissions Performance Standard
FiT CfD	Feed-in Tariffs with Contracts for Difference
GEE	General Electric Electricity
GEMIS	Global Emission Model for Integrated Systems
GIS	Geographical Information System
GP	Global Parameters
HC	Hydrocarbon
HHV	High Heat Value
IAEA	International Atomic Energy Agency
IBIS	Issue-Based Information Systems
IECM	Integrated Environmental Control Model
IGCC	Integrated Gasification Combined Cycle
KBDS	Knowledge Based Design System
MAD	Mean Absolute Deviation
MAUT	Multi-Attribute Utility Theory
MCDA	Multi-Criteria Decision Analysis
MWe	Mega Watts of electricity
NETL	National Energy Technology Laboratory
NGCC	Natural Gas Combined Cycle
O&M	Operation and Management
OECD	Organisation for Economic Co-operation and Development
OUTDO	Oxford University Tool for Decision Organisation
OWL	Web Ontology Language
PC	Pulverised Coal

PHI	Procedural Hierarchy of Issues
PM	Particulate Matter
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations
PV	Photovoltaic Cells
QOC	Questions, Options, and Criteria
RDS	Reactive Decision Support
RM	Rationale Management
TOPP	Tropospheric Ozone Precursor Potentials
VOC	Volatile Organic Compounds
WPM	Weighted Product Model
WSM	Weighted Sum Model
XML	Extensible Markup Language

List of Nomenclature

a_{ij}	Score of the j -th position in terms of the i -th criterion
$A_{WSM-SCORE}$	WSM result for position A
$A_{WPM-SCORE}$	WPM result for position A
$C_i(a,b)$	Individual concordance index for the i -th criterion
$C(a,b)$	Concordance index of position a in relation to position b
$Criterion_{value}$	Value of the score used in the WSM method
$C_{p,Betz}$	Rotor power coefficient
$D_i(a,b)$	Individual discordance index for the i -th criterion
e	Forecast error
f	Discrete number of forecast points at time t
F	Total forecast horizon
$GP_{90\%}$	Global Parameter value at the 90% confidence interval line
h	Height for measuring wind speed
I	List of criteria in the decision
J	List of positions in the decision
m	Total number of positions in the decision
MAD	Average difference between the time-series data and the forecast
$MAUT_{score}$	Position vs. criteria score using the MAUT method
N	Total number of criteria in the decision
η	Net plant efficiency
p_i	Preference threshold for the i -th criterion

$p(U)$	Wind speed probability distribution at the speed U
P_w	Average power generated by a wind turbine
Q_{HV}	Combustion heat assuming high heat value (HHV)
q_i	Indifference threshold for the i -th criterion
R	Radius of the wind rotor
r_s	Normalised OECD National Risk Indicator for coal supply country s
$Risk_{uk}$	Indicator of risk supply of steam coal to the UK
ROP_i	Set of recommended positions probabilities
$S(a,b)$	Credibility index of position a in relation to position b
t	Time when the decision is to be made
t_i	Veto threshold for the i -th criterion
v	Total number of supply countries in the supply risk analysis
V	Wind speed
x_s	Fraction of the of steam coal supply from country s to the UK
w_i	Criterion weight for the i -th criterion
W_{in}	Total electricity consumed in the electricity generation process
W_{out}	Total electricity generated from the turbines in a power plant
$z_i(a)$	Score of position a in terms of the i -th criterion
δ	Drive train efficiency
γ	Wind shear
λ_{max}	Maximum value of the credibility index
ρ	Air density

Chapter 1

Introduction

1.1 Introduction

This thesis introduces a new approach to the development of decision support systems (DSSs). Its main contribution is the creation of a methodology (framework) which integrates rationale management, Multi-Criteria Decision Analysis (MCDA), probabilistic forecasting and semantics, resulting in a DSS called OUTDO (Oxford University Tool for Decision Organisation). OUTDO is a new integrated tool to approach complex, long-term problems subject to the interaction of many multi-criteria issues. It is intended to ensure that the analysis of different solutions (here called positions) may be strengthened by using numerical packages (e.g. for simulation and optimisation) and by permitting an uncertainty analysis to be performed through the varying of the prediction of the future values of variables. With the inclusion of semantics in the form of a Decision Ontology and an Energy Ontology, OUTDO gains a level of understanding of the overall process of decision making in the energy area, and is able to provide valuable feedback on the decision process and to check for consistency in the decision rationale¹.

This chapter introduces the research project. Section 1.2 describes the limitations of current DSSs that the work on OUTDO detailed in this thesis will attempt to address. Section 1.3 describes the background of the case study used to verify OUTDO's features. Section 1.4 describes the goals and contributions to the research described in this thesis. Section 1.5 concludes this chapter by outlining the structure of the thesis.

¹ The reasons behind the decisions and the justification for these reasons.

1.2 Current DSSs and OUTDO

DSSs are changing the way decisions are being made. Usually DSSs contain enough information to resolve specific tasks but have a limited scope and require qualified experts to exploit their full potential in real-life situations. Indeed, knowing how to operate a DSS does not mean that it will be used appropriately. To be an expert in a field of knowledge requires familiarity with a vast literature and a corpus of lessons learnt from past experience, and these are not usually incorporated into decision making tools. To help the decision maker reach the best possible decision, it is important to include all relevant information in the decision making process. For example, during the design of a chemical plant, we need to estimate the physical properties, mass and energy balances (using a simulation package such as Aspen Plus [1]), and also other parameters that are essential for a successful plant design. These parameters include: plant safety, the transporting of resources and products, the selection of resource suppliers, customer satisfaction, price fluctuations, market competitors, macroeconomic instabilities, changes in industrial regulations, public acceptability, environmental impacts, climate change, etc. No current DSS is capable of processing this amount of information. Today, the solution for such a problem is to establish a design group with experts from different areas, working in a structured way to produce a plant design.

It can be argued that it is impossible to include in a software system such highly complex questions that involve many systems interacting in different ways [2, 3, 4]. It is, however, possible to take a step back to take a broader view of the problem, and to allow the software to extract the underlying meanings of the concepts that constitute the decision process. If, then, the software has an ‘understanding’ of the subject of the

decision process, it will be able to aid the decision maker in a more accurate and inclusive manner.

At present, one type of DSS is used to capture and record the decision rationale. Another type of DSS is used to support decision making with MCDA. A third type is used to forecast how changing parameters can affect a decision in the future. Other DSSs are starting to attempt to use semantics-based decision support capabilities. However, to our knowledge, there is not one DSS that combines all these tasks in a single and efficient way such as the one proposed in this thesis. The integration of these four methodologies into OUTDO provides robust decision support software that allows consistent and transparent decisions to be made. This is the main contribution of this thesis.

1.3 Case Study Background

Current global trends are driving humanity to a more sustainable world. Developed countries are under political and economic pressure to restructure their energy sector to take into account the need to reduce CO₂ emissions, while still supplying reliable and affordable energy services. In the UK, a provisional solution for the reduction of CO₂ emissions is under-way through the implementation of Natural Gas Combined Cycle (NGCC) power plants. However, a longer-term solution is under discussion, led by the Department of Energy and Climate Change (DECC) [5]. The White Paper on electricity generation released in the summer of 2011 proposes several energy policies to renovate the UK's energy sector and focuses on nuclear power, coal with carbon capture and storage (CCS), and renewable energy generation, especially wind.

However, for the UK to develop a robust and resilient solution for its energy sector, a variety of external factors, some of which are beyond the control of the UK government, have to be thoroughly analysed. These factors include changes in oil prices, CO₂ emissions cost, the availability of water and so on.

In order to resolve such complex questions, all aspects of the problem must be taken into account to find the most appropriate solution. Some of these aspects are trade-offs, including, for example, project costs against the environmental impact or long-term climate changes against immediate social benefits. Therefore, the choice of methodology to manage the influence of these conflicting aspects in the decision process is of paramount importance. No less important than evaluating trade-offs is the capability to include predictions of how the world will behave in the future, long after the decision has been made. It may be the case that, through a change in a parameter value over time (e.g. oil price or CO₂ emissions cost), the recommended solution to a problem may also change. These factors are used to analyse how different future scenarios might change the recommended electricity generation source together with the possible utilisation of the rejected heat from steam condensation.

During the decision process, the decision rationale should be documented. There are many benefits in the documentation of the decision rationale. First, it records the reasons behind the decisions so that the same rationale can be applied to similar problems. It also allows the study of potential effects when the needs regarding an engineering artefact² change. At present, in many cases, the reasons and concepts behind decisions are not formally recorded and are forgotten. Often, when the same

² As understood by Westerberg 2004 [244] and assumed in this report, an artefact is anything created by a human that does not exist in nature, including abstract things such as design and decision processes.

decision process is re-used to obtain a solution for a different place, circumstance or time, the outcome of the decision may be very different from what was decided previously. In addition, the management of knowledge and information is not easy to achieve. Communication between different groups of people working on the same project can be difficult because each person has a different perspective on the project, i.e. one that fits in with their own project activities [6]. Recording the decision rationale addresses these issues by enabling the linking of different sources of project information to further clarify the decision process.

1.4 Research Objectives and Contributions

It is the hypothesis of this research that the integration of rationale management, MCDA, probabilistic forecasting and semantics within a DSS will provide a powerful decision framework to resolve complex and long-term problems resulting from the interaction of many multi-criteria issues. Moreover, the analysis can be dynamically adapted to varying parameters, effectively recorded and improved through semantics-based capabilities.

The need to capture the decision rationale in the resolution of complex problems motivated the development of the proposed DSS. Its main objective is to effectively integrate different methodologies to support the configuration and evaluation of engineering artefacts such as the ones involving energy supply, sustainable development and climate change mitigation.

A graphical representation of the proposed framework structure is shown in Figure 1.1. The main contribution of this framework is to combine the past (by capturing the decision rationale with rationale management), the present (by simplifying

the resolution of complex issues with MCDA methods), and the future (by predicting how parameters that influence the decision process might behave in the future and performing risk analyses³ with probabilistic forecasting). In addition, the framework uses a semantic representation of the energy domain in the Energy Ontology to allow the computer to automatically support the decision process in a generic way. Lastly, this framework facilitates communication between participants, creating a more transparent decision process.

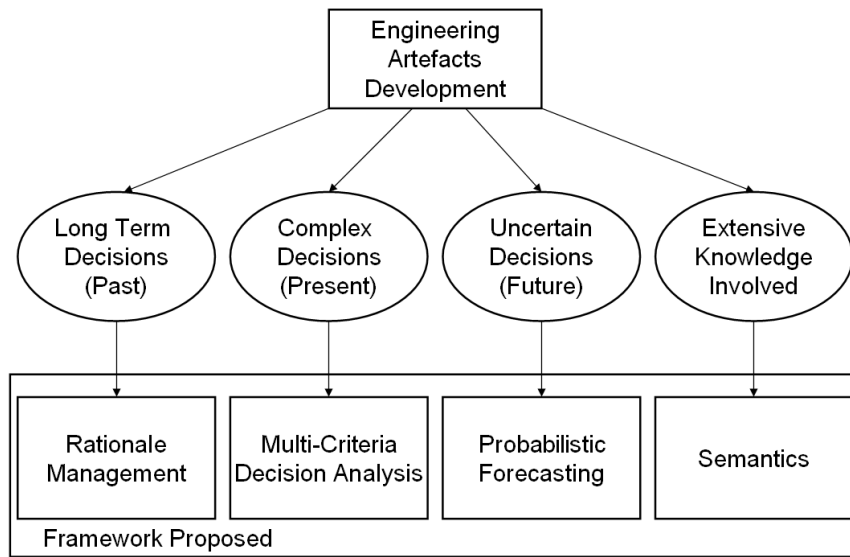


Figure 1.1: OUTDO Decision Framework Proposed.

As stated previously, the main aim of the work is to provide a DSS which allows the recording of the decision rationale, uses MCDA, can propagate future changes to parameter values and includes semantics-based decision support capabilities. This is the main contribution of this thesis. Further contributions which resulted from this research are listed below:

³ According to [245], risk analysis is a quantitative examination of the probability of an event happening over a specified period of time and its related consequences.

- 1) Recording the decision rationale might intervene in the decision process and is very time consuming. This thesis argues that recording the rationale in OUTDO pays off as it provides different approaches to effectively support and re-use decision processes.
- 2) Combining MCDA and probabilistic forecasting, as presented in this thesis, has not been done before. This combination rapidly and dynamically explores in a transparent and simple way how changes in external parameters affect complicated and uncertain decision making processes.
- 3) The case study attempts to standardise decision processes for the selection of electricity generation technologies in the UK. An important concept realised by the author when building the decision process was the importance of selecting the steam condensation technology before the selection of electricity generation technology for a given location. This is because a considerable amount of water is consumed in the generation of electricity from thermoelectric sources and the technology selected considerably affects the selection of electricity generation technology.
- 4) As the decision rationale is recorded for future use, this thesis concludes that the functionalities provided by OUTDO should be used to standardise decision making in the engineering field. As the decision maker evaluates past decisions, he/she can feel reassured that a previous decision can be improved on with certain adjustments. For example, if the extraction of water for electricity generation is negatively affecting the water bodies close to a power plant, then future decisions should increase the importance of water extraction criteria.
- 5) A further major contribution to DSSs in this thesis is the creation of three concepts and mechanisms for the implementation of semantic-based decision support to

engineering problems. These concepts enable OUTDO to provide feedback on the decision process and run consistency checks to evaluate whether the decision rationale components are appropriately linked to each other. It also looks at the lessons learnt from previous decisions and uses them to help reach new decisions, runs multiple qualitative analyses, suggests possible improvements to the decision process and gives valuable information about a specific field to the decision maker.

1.5 Thesis Structure

Chapter 2 introduces the reader to the four methodologies integrated in OUTDO, including the new approach for using semantics to support the decision process using the ontological representation of knowledge. The chapter then presents the previous work done leading to this research and finishes by comparing OUTDO to other DSSs. Chapter 3 presents in more detail the features that constitute OUTDO and the decision framework to be used. As the case study implementation in OUTDO is very extensive, it has been broken down into five subsequent chapters. Moreover, it should be noted here that the main focus of the case study is to test and verify the decision framework and not to resolve the UK's energy sector problems. Chapter 4 is the first chapter to test OUTDO with the case study. It attempts to describe the problem within the OUTDO framework, gives a brief description of the UK's energy and water sectors and initiates the development of the decision process in OUTDO. Chapter 5 demonstrates MCDA in the OUTDO framework. Chapter 6 presents the different types of Global Parameters and features such as the Propagation, Sensitivity Analysis and Future Analysis features. These features are then applied to ten different regions in the UK, including the Yorkshire and the Humber region. Chapter 7 explains the benefits of including

semantics into OUTDO and presents the Decision and Energy ontologies. Chapter 8 introduces three different semantic-based mechanisms that make use of the Decision and Energy Ontologies to support the decision process. Chapter 9 discusses the findings resulting from the implementation of the case study in OUTDO, and presents OUTDO's limitations and possible improvements. It then concludes the thesis and case study, and presents the future work recommended for OUTDO.

Chapter 2

Literature Review

2.1 Introduction

This chapter reviews the literature relevant to the research work presented in this thesis. It is intended to provide the reader with an understanding of the main techniques and concepts employed in this project, focusing on their contributions to OUTDO.

Sections 2.2 to 2.5 introduce the methodologies used to support decision making in OUTDO. Specifically, Section 2.2 presents the rationale management representations used to record the decision rationale and helps to explain why Issue-Based Information Systems (IBIS) are the most suitable method to simplify the resolution of decision processes in OUTDO. The section then introduces Compendium, which was used for the development of OUTDO. Section 2.3 explains the benefits of using MCDA to resolve decisions involving multiple criteria and presents some of the different methodologies implemented in OUTDO (i.e. WSM, WPM and ELECTRE III). Section 2.4 introduces probabilistic forecasting, which is used to predict how parameters might vary in the future and to perform risk analyses in the decision process. Section 2.5 presents computational semantics and its capacity to allow the computer to understand and support decision processes. Section 2.6 presents the background on work prior to this thesis. Finally, Section 2.7 discusses other DSSs that attempt to resolve problems with a similar approach to OUTDO and explains how OUTDO's contributions improve the DSS field. Section 2.8 concludes the chapter.

2.2 Rationale Management

Rationale Management is concerned with the explicit representation of decisions and the systematic presentation of the reasons why these decisions were made [7, 8]. Its main objective is to provide a means to record and communicate the reasoning behind decisions [9, 10]. It must therefore include [11]: the reasons behind a decision (goals to be achieved, which in turn define the issues to be resolved); a list of the different alternatives considered (positions); justifications for the selection of one alternative (arguments and/or criteria); and an evaluation of trade-offs. At every step of a decision process, the decision maker has to find the position that best solves an issue. Each issue is a crossroads in which one course of action must be selected out of a variety of different alternatives. Generally, several justifications are required to proceed with one position and to discard the others. These can be related to economic factors, environmental impacts, safety or other factors. The reasons for capturing and recording the decision rationale depends on what the decision rationale will be used for in the present and in the future.

There are several reasons for having a process for documenting the rationale behind an important decision. Firstly, it helps in the quality control of the decision process. Secondly, it preserves the history of the decision process so it can be re-used when the needs for an artefact change. Thirdly, it provides useful information to people who may seek to re-use successful solutions [12, 13, 14, 15]. Design processes (decision processes in engineering projects) carried out by a company represent a significant part of its intellectual capital [16], but it is still often the case that much of the information relevant to decision processes is never documented and is stored only in the memories of the decision makers [17]. If no comprehensive record of the discussions exists, the

context within which key decisions were made may be lost [13]. This means that working groups can repeatedly discuss the same issues that had been resolved earlier, as the justifications for a given decision might not have been clearly understood by all members of the group, or possibly the project group changes over time. Fourthly, a variety of stakeholders involved in decision processes often have different sets of objectives and priorities. Capturing the decision rationale makes the process explicit and supports a consistent view among stakeholders [18]. In addition, other benefits of capturing the decision rationale can be found in [14, 15, 16].

Capturing the decision rationale can either be a dynamic action that creates the assumptions behind the decisions as they are required for a given problem or a passive and fixed description of the decision history [19]. One of the most important reasons for choosing the dynamic model in the context of this thesis is the ability of such systems to look back at a decision and see how a change in parameters might affect the decision and subsequent or interrelated decisions. Certain factors, such as the design requirements, environmental and cost aspects that were involved in the decision, may change over time. It is possible that an appropriately made previous decision may no longer be correct when these factors change. An example would be an unexpected change in the cost of a material. If the cost of a given material used in a manufacturing process increases abruptly, it may need to be substituted. This can have an impact on several subsequent decisions which will need to be reassessed. These subsequent decisions should be re-evaluated to check whether they are still valid. It is therefore highly beneficial for the decision rationale to automatically adapt to different situations.

However, there is a trade-off to be considered between the work involved in recording the design rationale and the value of what is recorded [20, 21, 22]. Therefore,

it is important to select the right representation to capture the decision rationale for each purpose. Different representations have been proposed to support decision rationale such as QOC (Questions, Options, and Criteria) [23], IBIS [24], PHI (Procedural Hierarchy of Issues) [25], DRL (Decision Representation Language) [26], RATSpeak [27], TEAM (Traceability, Exploration and Analysis Model) [28], POE (Problem Oriented Engineering) [29] and ISAL (Issue, Solution and Artifact Layer) [30]. Some of these are discussed in Section 2.7. Among the existing decision rationale methodologies, IBIS have the highest appeal to researchers due to their combination of expressive power and simple formulation [31, 15]. In addition, it is the most common representation used to capture the decision rationale. IBIS suit OUTDO well as they give a quick and clear overview of the decision process and allow the user to efficiently explore an issue in detail with MCDA. Therefore it was included into the OUTDO framework.

2.2.1 Issue-Based Information Systems

IBIS were invented by Kunz and Rittel in 1970 [24] and are used to graphically represent decision processes, support group discussions and capture the reasons behind decisions. The IBIS representation is adequate for the proposed decision framework and software because it effectively transmits the critical reasoning involved in an issue and it has been used to solve “wicked problems”⁴ in several engineering disciplines [15]. The process is as follows. Initially, the problem is described and goals are identified.

⁴ A wicked problem is one that does not have a clearly defined problem or solution [243]. Therefore, there is no right or wrong answer but rather an answer that is “good”, “better”, “good enough” or similar. A tame problem is the opposite of this, meaning that it is generally clear whether or not the problem has been solved.

Then, issues⁵ are brainstormed, and are recorded as questions. Possible solutions to these issues are identified as positions. These positions are associated with arguments, which support them or object to them. The arguments may result in an answer to which all the participants agree. However, if this is not the case, the positions and arguments are then re-examined and turned into new issues, which are treated in the same manner [31]. The outcome of this process is a hierarchy of issues, which allows the user to trace back a decision and analyse its effect on other existing decisions [12]. As IBIS make the decision process ‘transparent’, the decision maker increases the chance that problems, unnoticed by him or her, will be discovered by others. Even though there is no guarantee that a good answer will be discovered, IBIS can disclose solutions for which a compromise can be reached or find aspects of the problem that could be subsequently resolved with other techniques.

IBIS assume that argumentation is sufficient for the selection of the recommended solution [32] but it has been found that, when it comes to the development of engineering artefacts, verbal reasoning alone is not always sufficient to meet a credible recommended solution. For instance, in 2007 Middleton [33] carried out a study which highlighted the fact that IBIS are not equipped to support engineering problems, mainly because an in-depth qualitative comparison of alternatives is required. As an example, the arguments represented by the pros nodes (green nodes with a positive sign) and the cons nodes (red nodes with a negative sign) in Figure 2.1 do not give a clear indication that “*Wind turbine*” should be the selected electricity generation technology for a given location. Therefore, in order to make OUTDO suitable for engineering designs, a new dimension to IBIS had to be created with the inclusion of

⁵ Issues are questions that need to be answered to achieve a set of goals.

MCDA, which allows a systematic and quantitative analysis of multiple criteria problems.

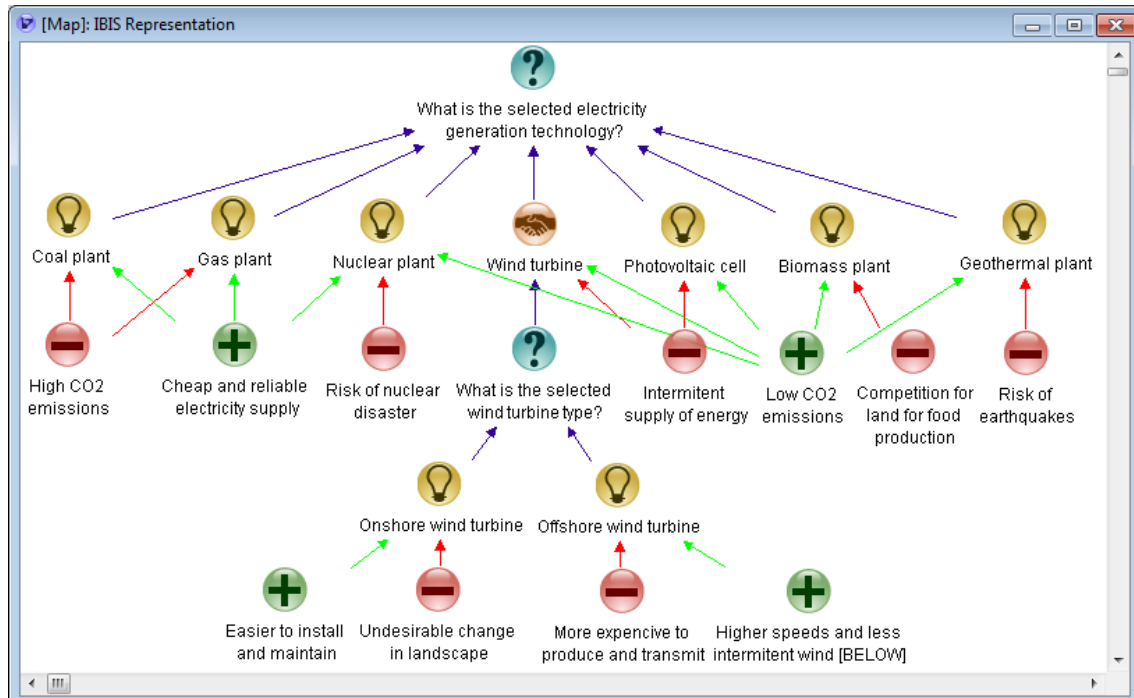


Figure 2.1: IBIS representation for the recommendation of engineering artefact positions [34].

Figure 2.1 was constructed using the Compendium Software (version 1.5.2) [35]. Compendium is an open-source software tool developed in Java [36] that links ideas and information in the form of issues, ideas (positions) and arguments through a visual interface based on the IBIS concept. It was developed out of the experience gained from Questmap [37], which showed that the recording of knowledge needs to have an immediate benefit and not just long-term value [38]. External references such as Word/Excel documents, websites or similar files can be dragged and dropped into Compendium and linked to the various issues, ideas and arguments. Compendium allows a structured formal approach to problem solving combined with sense-making. Sense-making is an unstructured, informal method for allowing a group of people to

understand each other's problem domain and their perspective on that problem [6]. A number of structured analyses and problem solving approaches are supported by Compendium, including dialogue mapping, process modelling, system requirements analysis, strategic planning, environmental planning, business process reengineering, mind mapping, knowledge management, envisioning, presentation, collaborative argumentation, new product design and project management [35, 39]. However, Compendium lacks tools to support an in-depth qualitative evaluation of decision processes. Thus, MCDA methods were integrated with Compendium as part of the research presented in this thesis and to make OUTDO suitable for engineering design problems and policy making.

2.3 Multi-Criteria Decision Analysis

MCDA is a structured methodology which addresses complex problems with multiple and conflicting criteria, i.e. problems containing different forms of incommensurable data, different long-term consequences, high uncertainty, multiplicity of interests and conflicting assessments [40, 41, 42, 43]. It is suitable for decisions involving the presence of environmental and social impacts, which are difficult to translate into monetary terms [40]. Therefore, MCDA methods are broadly used by decision makers in the energy policy formulation and energy management areas, including the environmental performance of energy systems [44, 45]. As many decision makers might be involved in the same decision process, MCDA allows the representation of multiple and possibly conflicting views in the form of different criteria weighting sets, thereby allowing the identification of important conflicts and/or opportunities for compromise [46]. The objective of MCDA is not only to recommend

solutions but also to enable the identification of compromise solutions in a clear way, at the same time promoting a democratic decision making process [45, 47]. MCDA may be applied using a variety of methods, some of which are reviewed in [41, 48, 49].

As mentioned earlier, the methods analysed in detail in this thesis are WSM (Weighted Sum Model), WPM (Weighted Product Model) and ELECTRE III, which are discussed in detail in the next sections. ELECTRE III was chosen after making a careful comparison which included AHP and the PROMETHEE family. Since its introduction, AHP has been accepted to support decisions in various areas in less than a decade [50, 51]. It compares positions using a pairwise approach, produces a ranking of the positions, and presents a summary of the relations between decision components (i.e. positions and criteria) by organising them into hierarchies. It is, however, a complicated and much criticised method. Problems identified are [48]: the high number of pairwise comparisons; the impracticability of the sensitivity analysis; and the fact that the evaluation matrix requires a complex algorithm that might not be understood by the user. Although 42% of the MCDA in the literature used AHP to make decisions on energy [52], AHP is not the best method to implement in OUTDO. This is because OUTDO requires an absolute evaluation for each criterion so that Global Parameters can be used effectively. The Global Parameters concept does not work with AHP as it would require a different equation for each pairwise comparison, thus making it impractical and possibly irrational. This is better explained in chapters 5 and 6.

The ELECTRE method [53, 54] is an ‘Outranking Method’ that evaluates distinct criteria of a quantitative or qualitative nature by making comparisons using a pairwise approach. The outranking approach seeks to find a compromise by balancing the position’s poor and well-performing criteria [55]. For an alternative (position) to

outrank another, the first has to be at least as good as or better than the second alternative. ELECTRE downgrades positions that perform badly in a particular criterion with the aim of making the decision making analysis more similar to the way people make decisions in reality [44]. In the case of ELECTRE I and II, the results are presented in the form of a network of binary outranking relations between the positions. In ELECTRE II and III there are algorithms that create a ranking of alternatives. The PROMETHEE II method [56] belongs to the outranking methods family introduced by Roy in 1968 [54]. It is similar to ELECTRE III but contains preference functions which dictate the importance of the relative differences between the position scores with respect to a given criterion. There are different preference functions and these are detailed in [56]. Outranking does not optimise but rather makes comparisons, making it a flexible, useful model [57].

For this thesis, the MCDA method applied in OUTDO has to solve complex problems involving the development of engineering artefacts and, more importantly, includes the entire set of decisions that dynamically change with the Global Parameters. In other words, the method should easily, effectively, clearly and coherently modify the analysis of an issue to create a new analysis resulting from the Global Parameters changes. As Al-Shemmeri *et al.* [58] points out, selecting the correct MCDA method is a multi-criteria decision on its own. Further analysis to choose the method to be used in this research was based on the approaches of Gilliams *et al.* [59], De Montis *et al.* 2005 [47] and Kowalski *et al.* 2009 [45]. In the end, the main criterion that contributed to the implementation of ELECTRE III in OUTDO instead of PROMETHEE II was the fact that there have been more papers published using ELECTRE III [45]. To find an appropriate MCDA method, many specialists look for similar analyses in the literature

and apply the most popular technique [59]. It would, however, be beneficial to implement other MCDA methods in OUTDO because a comparison of results from different methods would give a better overview of the solutions [60]. In particular, hindsight now shows it would have been wiser to include MAUT [52, 61, 62] in OUTDO as it is more transparent, faster and easier to implement than ELECTRE III and, in common with ELECTRE III, MAUT does not require normalisation factors. The normalisation factors are affected by the changes in Global Parameters and thus affect the whole decision analysis. This is further discussed in Section 9.2.1.

2.3.1 Weighted Sum Model

The Weighted Sum Model (WSM) is possibly the MCDA method most frequently used [48] and is the most important method in OUTDO. However, the results from WSM can be misleading because the selection of normalisation factors considerably affects the analysis, and existing interrelationships between the criteria are not considered [63]. The WSM expression as defined by Fishburn [64] is shown in Equation 2.1:

$$A_{WSM-SCORE} = \max \sum_{i=1}^n a_{ij} w_i \quad \text{for } j = 1, 2, 3, \dots, m \quad \text{Eq. 2.1}$$

where n is the number of decision criteria, m is the number of positions, a_{ij} is the performance (so called score) of the j -th position in terms of the i -th criterion and w_i is the weight of the i -th criterion, which ranges from 0 to 1. To make sure that all the criteria contribute in proportion to their weight, the scores are normalised. The normalisation is performed by multiplying all scores by the inverse of the highest criterion score.

2.3.2 Weighted Product Model

The Weighted Product Model (WPM) has much in common with the WSM except that, instead of adding the scores, the scores are multiplied. WPM has been popular in some MCDA applications, especially in decisions that are measured on a logarithmic scale [48]. Although there are different approaches for this method, Equation 2.2 was introduced into OUTDO because of its ease of implementation [49]:

$$A_{WPM-SCORE} = \max \prod_{i=1}^n (a_{ij})^{w_i} \quad \text{for } j = 1, 2, 3, \dots, m \quad \text{Eq. 2.2}$$

where n is the number of decision criteria, m is the number of positions, a_{ij} is the performance of the j -th position in terms of the i -th criterion and w_i is the weight of the i -th criterion, which ranges from 0 to 1. To make sure that all the criteria contribute in proportion to their weight, the scores are again normalised. The normalisation is performed by multiplying all scores by the inverse of the highest criterion score.

2.3.3 ELECTRE III

ELECTRE III allows inaccurate, imprecise, uncertain and ill-determined data (pseudo-criteria) to be processed [65]. It is particularly appropriate when a small number of criteria are used to compare a large number of positions [41] and is rated highly with respect to criteria completeness and interdependence [47]. However, applying ELECTRE III can be complex and counterintuitive, and the program is rated poorly with respect to transparency and to the applicability of criteria [47]. Different references have their own algorithms for performing ELECTRE III, and for the

implementation of ELECTRE III into OUTDO the methodology was taken from Belton and Stewart [48].

A defining feature of this method is the use of what are termed *concordance* and *discordance* indices. These are designed to measure the levels of support and discordance respectively, using the notion that either a given alternative outranks another or it does not. The concordance index, $C_i(a,b)$, of alternative a outranking alternative b is a number representing the weight of evidence for the assertion that a outperforms b with respect to criterion i . Similarly, $D_i(a,b)$ represents the weight of evidence for the assertion that a does not outrank b . ELECTRE III requires a complex setup involving the definition of extra values for each criterion, the *preference*, *indifference* and *veto* thresholds p_i , q_i and t_i . These are subjectively determined by the decision maker and are used to find the individual concordance and discordance indexes, $C_i(a,b)$ and $D_i(a,b)$, for each criterion as shown in Equation 2.3 and 2.6 respectively.

$$C_i(a,b) = \begin{cases} 1, & \text{if } z_i(a) + q_i(z_i(a)) \geq z_i(b) \\ 0, & \text{if } z_i(a) + p_i(z_i(a)) \leq z_i(b) \end{cases} \quad \text{Eq. 2.3}$$

where $z_i(a)$ is the score of alternative a for the criterion i . If neither condition is satisfied, a linear interpolation is applied to obtain the *individual concordance index* using Equation 2.4:

$$C_i(a,b) = \frac{z_i(a) - z_i(b) + p_i(z_i(a))}{p_i(z_i(a)) - q_i(z_i(a))} \quad \text{Eq. 2.4}$$

These *individual concordance indices* are used to calculate the *concordance index*, shown in Equation 2.5. The concordance indices of all comparisons result in the *Concordance Matrix*.

$$C(a, b) = \frac{\sum_{i=1}^n w_i C_i(a, b)}{\sum_{i=1}^n w_i} \quad \text{Eq. 2.5}$$

where w_i is the weight of criterion i and n is the number of criteria.

Similarly, the *discordance index* is calculated for each criterion as follows:

$$D_i(a, b) = \begin{cases} 0, & \text{if } z_i(b) \leq z_i(a) + p_i(z_i(a)) \\ 1, & \text{if } z_i(b) \geq z_i(a) + t_i(z_i(a)) \end{cases} \quad \text{Eq. 2.6}$$

again, linear interpolation between 0 and 1 is applied if condition 2.6 is not fulfilled.

The *credibility index*, $S(a, b)$, represents the overall degree of credibility that alternative a outranks alternative b and is defined below:

$$S(a, b) = \begin{cases} C(a, b), & \text{if } D_i(a, b) \leq C(a, b) \\ C(a, b) \left[\prod_{i \in J(a, b)} \frac{(1 - D_i(a, b))}{(1 - C(a, b))} \right], & \text{otherwise} \end{cases} \quad \text{Eq. 2.7}$$

where J is a set indexing the set of criteria for which $D_i(a, b) > C(a, b)$.

The *credibility indices* of all comparisons will result in the *Credibility Matrix*. The Credibility Matrix is used to construct ascending and descending ranking orders. This process is called distillation and is described in the sub-section below (Belton and Stewart [48] p. 242).

Descending distillation:

- 1) Determine the maximum value of the credibility index for the alternatives under consideration, such that $\lambda_{max} = \max S(a, b)$
- 2) Set $\lambda^* = \lambda_{max} - (0.3 - 0.15\lambda_{max})$
- 3) For each alternative determine the λ -strength and the λ -weakness. For the comparing alternative (a in Equation 2.8), λ -strength is the number of credibility indices that satisfy conditions 2.8 and 2.9. For the alternative being compared (b in

Equation 2.8), λ -weakness is the number of credibility indices that satisfy conditions 2.8 and 2.9.

- 4) For each alternative, determine its *qualification*, which is the λ -strength minus λ -weakness.
- 5) The set of alternatives with the largest qualification is called the first distillate, D_1 .
- 6) If D_1 has more than one member, repeat the process on the set D_1 until all the alternatives have been classified; then, continue with the original set minus D_1 , repeating until all alternatives have been classified.

To determine the λ -strength, check whether the Credibility index satisfies conditions 2.8 and 2.9:

$$S(a, b) > \lambda^* \quad \text{Eq. 2.8}$$

$$(1 - s) S(a, b) > S(b, a) \quad \text{Eq. 2.9}$$

$$s = (0.3 - 0.15 \lambda_{max}) \quad \text{Eq. 2.10}$$

Ascending distillation:

This is obtained in the same way as the descending distillation except that at step 6, the set of alternatives having the *lowest* qualification forms the first distillate.

Combined Result

The final ranking in ELECTRE III consists of the combination of the rankings resulted from the descending and ascending distillations. This is done by determining points to the ranked positions starting with one point to the least preferred position and increasing a point to the position above. The points for each position in both distillations are added and the new ranking is created. The preferred positions have the highest points and the least preferred position has the lowest points. For example, in Section 5.5, *Coal plant* and *Gas plant* are the preferred positions with the highest points (9).

2.4 Probabilistic Forecasting

Forecasting is an essential skill in the majority of decision making processes because all actions take time to implement and uncontrollable external variables inevitably change [66]. A decision taken today may not be the recommended decision in a month's time, and the ability to anticipate changes or analyse risks is key to empowering people to make better decisions. There is often great uncertainty as to how a variable will behave in the future. Two decades ago, a shift from deterministic forecasts to probabilistic forecasts [67] was seen. The use of probabilistic forecasts (confidence intervals) opens the door for the creation of a range of predicted values and their probabilities, taking uncertainty into account. There is no guaranteed 'correct' method of computing confidence intervals, although some methodologies are assumed appropriate for certain forecasting approaches. Hanbury [68] has established a method for the creation of confidence intervals (see Appendix A). This was implemented in OUTDO as it has the advantage of being applicable to any forecasting technique, and can estimate confidence intervals using the mean error when the forecast is compared with the actual data. This thesis does not focus on how to obtain the probabilistic forecast or on how to analyse its precision, calibration and sharpness. Rather, it intends to present a new approach for risk analysis using a combination of MCDA and probabilistic forecasting.

The concept of combining probabilistic forecasting and MCDA is an important contribution presented in this thesis. A different approach for combining probabilistic forecasting and MCDA applied to a problem presented in the literature was proposed by Szucs and Sallai 2008 [69] where the Analytic Network Process (a generalisation of AHP) was used to find the probability of a fault, and the Bayesian Network to calculate

the overall probability of each fault in the network. To the best of our knowledge, probabilistic forecasting has not been combined with MCDA as it has been done here. The project introduces an innovative methodology for risk analysis⁶ in which the multi-criteria analysis is complemented by the prediction of variables that affect the decision process. The combination of these two methodologies turns the forecast and confidence intervals into the probability of recommendation of each position, thus allowing the decision maker to predict the outcome of the decision and thus make better decisions in the present. This is exemplified in Chapter 6.

2.5 Semantics

Semantics is a rapidly growing field of research that intends to add meaning to information stored in a computer, mainly in text format, and to use this knowledge to improve the interaction between a person and the computer [70, 71]. The main application of semantics in computer science involves the creation of the semantic web. The semantic web intends to create new approaches for enhancing search engines and other applications that would benefit from the computer capability of having a degree of understanding of the user inputs to the World Wide Web [70]. In this thesis, however, the use of semantic-based capabilities looks for ways to support decision making. It does not attempt to simulate an energy generation domain expert who can propose a solution to the user, but instead encourages the decision maker to think for him or herself, utilising the user's creativity in solving the problem. If there are potential mistakes in the decision process, the computer will intervene and warn the user. In other

⁶ In this thesis, risk has the same definition as in [44], whereby the set of different possible outcomes to a problem is known and a probability can be assigned to each outcome.

words, semantics will be used to ‘explain’ to OUTDO the concepts of the energy generation domain in order for the computer to support the decision process and thus to improve the handling of information and knowledge in the framework.

Different knowledge representations can be used to reproduce semantic capabilities. A knowledge representation can be described as a medium of human expression, i.e., language in which we say things about the world [72]. The choice of knowledge representation depends on the type of problem that is to be solved [73]. For example, it is easier to divide numbers represented in Hindu-Arabic (i.e. 205) than in Roman numerals (i.e. CCV), but it can be easier for a non-educated person to add and subtract with Roman numbers. There are various technologies for knowledge representation, but ontologies are becoming the essential representation for domain-specific conceptual knowledge in order to promote semantic capabilities [74, 75, 76]. In addition, there are a number of advantages for the intended implementation of semantics in this work. These advantages are presented throughout chapters 7, 8 and 9.

2.5.1 Ontologies

The original use of the word ‘Ontology’ (with a capital letter) can be traced back to ancient Greece, with Aristotle’s attempts to classify concrete and abstract things and to find ways to systematically resolve the fundamental question of “what is being?” [77]. The more contemporary concept of the word ontology (without a capital letter) has gained popularity among several artificial intelligence research communities since the beginning of the 1990s [78]. Of the many definitions in the literature, the one that is constantly cited and used was suggested by Gruber 1993 [73], which is: “An ontology is an explicit specification of a conceptualisation”. However, the term has been somehow

diluted to become a conceptual database that expresses the domain entities and their relations by means of properties, relations, instances, classes, annotations and axioms (described in Section 7.2.1). In this way, with their flexible data structure, ontologies permit the representation of the design knowledge semantic in a formal way so that the computer can interpret the information contained in them [79].

Due to the need to maintain the formality of ontologies, techniques, standards and languages based on logic have been given the most attention, in particular Description Logics [80, 81]. Description Logics are mature knowledge representation techniques influenced by frame system technology. They represent a class of logic-based knowledge representation formalism that balances expressiveness with decidability. Decidability involves the theoretical issue of whether software can reach a conclusion when processing a description [82]. Description Logics have well-defined formal semantics, which are explained in detail in the Ontology Structure Section (Section 7.2.1). One of the advantages of using Description Logic is that the initial knowledge can expand considerably with logical inferences, thus reducing the efforts for building the knowledge base. An example of an inference is that if an electricity generation technology consumes heat in the process of electricity generation, it can be automatically deduced that this technology is a thermoelectric technology.

Apart from the Semantic Web, the use of ontologies for knowledge representation has gained popularity in biomedical informatics [83, 84, 71], pharmaceutical product development [85], artificial intelligence [86], geographic information systems [87, 88], and social science [89], among other disciplines. There is some development in the engineering domain, for example, in the chemical processing industry [90], however, the great amount of real-time data related to this domain

makes conventional numerical computing techniques more attractive than knowledge-based techniques [91]. In the energy sector, the use of ontologies is new. Recently, Chee Tahir and Bañares-Alcántara 2012 [92] introduced a new approach to the development of optimisation models used for policy evaluation and analysis in the energy sector with the use of ontologies, whilst Keirstead and van Dam 2010 [93] compared an ontology designed for the modelling of socio-technical infrastructure systems with an ontology for modelling urban energy systems [94].

In the realms of decision making, a variety of ontologies have been proposed. For example, Rockwell *et al.* 2010 [95] use a Decision Support Ontology and a Decision Method Ontology to record the decision rationale. In comparison to the Decision Ontology in this report, the Decision Support Ontology allows more aspects of the decision to be captured. However, it does not show how this decision rationale can be effectively used to support decisions. Theissen and Marquardt 2008 [15] uses a Decision Ontology based on the Decision Representation Language (DRL) notation to record the decision rationale. The main aspect of the DRL is that statements (i.e. claims), which may be evaluated or judged, may be included to allow the representation of complex argumentations. Even though the paper mentions that the ontologies presented can be used to support further design processes, it does not give details of how that would be done. By contrast, in OUTDO, the decision rationale is recorded as the decision maker builds his or her decision process. The semantic-based capabilities are then used to automatically support the decision process.

Ontologies can be classified into different types. Application ontologies contain the information required to model a particular domain [96]. Representation ontologies provide representational entities without committing to any particular domain [78]. Task

ontologies are ontologies of methods and tasks with the intent of reusing problem solving knowledge [97]. Domain ontologies intend to describe the knowledge of specific domains. General ontologies intend to describe many domains in one ontology. Naturally, the main difference between Domain and General ontologies is the level of generality. The two ontologies presented in this thesis (the Energy and the Decision ontologies) are Domain ontologies.

In the construction of ontologies, a variety of methodologies have been proposed since the late 1990s [98]. These methodologies originated from early attempts for ontology creation and include, for example, Cyc KB [99], Grüninger and Fox [100], Uschold and King [101], the KACTUS project [102], Sensus [103], and METHONTOLOGY [104]. Of these methods, the one that is mostly similar to the approach used to build the Energy and Decision ontology is Uschold and King's method [101]. It involves identifying the ontology's purposes, building the ontology, evaluating it, and documenting it. It also suggests a bottom-up approach, in which the most detailed concepts are determined and then organised into more general concepts, a top-down approach, in which the most general concepts are determined and then detailed, and a middle-out approach, in which the most important concepts are firstly determined and then detailed and generalised into other concepts. For descriptions, comparisons and evaluations of these and other methodologies for building ontologies, see [105, 98, 106]. To the best of our knowledge, the approaches used to support the decision process have not been explored before, and are presented in Chapter 8.

2.6 Background to OUTDO

Prior research on the use of software for the support and capture of the engineering artefacts-related design decisions that resulted in OUTDO can be traced back to the KBDS (Knowledge Based Design System) [107, 108, 14] tool developed at Edinburgh University. KBDS is based on the IBIS representation and has been applied to the design of chemical processing plants. It captures and records the design alternatives and constraints, giving a description of the design object and how it should be manipulated. As KBDS is based on the IBIS representation, it keeps the choices between alternative design paths and the justifications for the selection of each path. In addition, the system automatically provides specific information about the problem and general information about the domain, and is intended to support the selection of a plan to achieve the goals set. More than just capturing the rationale, KBDS offers functions such as automatic report generation and the propagation of the effects of specification changes [14]. In summary, KBDS captures the design assumptions, goals, issues, justifications and decisions made during the conceptual design of a chemical processing plant [109].

Following the creation of KBDS, DRAMA (Design RAtionale MAnagement) developed by Brice *et al.* [110] is enhanced by the identification and relation of goals to issues, and by using quantitative, instead of qualitative, argumentation [111, 39, 110]. Similarly to OUTDO, DRAMA uses a modified IBIS representation where the decision trees consist only of issues and alternatives (positions) to resolve a particular issue. The justifications for the solutions are contained in a decision matrix⁷ in a way similar to

⁷ A table of positions vs. criteria used to compare positions with some criteria, following the Weighted Sum Model.

OUTDO. These decision matrices can be populated with parameters, which allow the decision maker to measure how changes in these parameters impact the choice of positions. Consistency checking and sensitivity analysis tools are added into DRAMA, which enhances its quantitative argumentation in a similar way to the Propagation feature in OUTDO, as explained in Section 6.4. These warn the designer about which alternatives need to be re-evaluated if criteria weights and parameters change while making a new decision based on the past rationale. DRAMA was successfully used in Vidal *et al.* (2002) [112] to aid the design process of wastewater plants and in the upgrade of the plant reactor safety features of the Dungeness B Nuclear Power Plant [111].

Whilst DRAMA was successful in capturing the essential decision rationale and providing means to dynamically re-use the rationale similarly to OUTDO, it was not well received by its potential users. According to Brice 2010 [113], the reasons why engineers were not interested in recording their design rationale in DRAMA are shown below. Some of these reasons have been addressed in OUTDO.

- 1) The person taking the time to record the rationale is probably not the person getting the benefit from it. Therefore, in OUTDO more decision support tools have been included to support decision making (i.e. MCDA methods, probabilistic forecasting and semantic capabilities), so the user will receive a direct benefit for using the system.
- 2) Recording the design rationale results in extra work for engineers who are already under a lot of time pressure. In OUTDO the support which is given to the decision making process should result in better decisions, which can justify the extra time spent recording the rationale.

- 3) The recording might make it easier for others to question decisions at a later date and hold companies and engineers accountable for mistakes.
- 4) Engineers may consider giving away their knowledge as undermining their job security.
- 5) Problems integrating with other software tools much used in engineering (e.g. AspenPlus [1], CAD packages [114], etc.). To improve this, OUTDO connects to Microsoft Excel [115], which can be connected to CAD packages, AspenPlus through the Simulator Workbook [116] and other tools.
- 6) It is difficult to capture the subtleties of the design process in a structured form. The semantic Consistency Check feature in OUTDO helps with the structuring of the decision process.
- 7) The quantitative argumentation has weaknesses when applied to wicked problems, but it works well for strict, exact, scientific problems [117]. Even though the values can represent quality or quantity measures, they do not express the reason that a particular value was chosen. In wicked problems, the reasons for a given score cannot be easily deduced. In OUTDO, this is addressed as the user is capable of writing the justification for each score in the description of each position node or in the main issue node.

Items 3 and 4 could not be completely addressed through the implementation of OUTDO. These issues have to do with the corporate approach to rewarding the work of its employees with respect to the employee personal results. However, the employee personal results might affect the performance of other employees which in turn might not contribute to the overall improvement of the corporation. Thus, an alternative policy would be for managers to reward those who contribute the most to the corporation in

general, which includes the information that he or she shares with everyone [118]. Compendium, as it stands, could be used to keep track of the information shared by each employee and, thus, be used to evaluate who shared the most information within the corporation and reward the person that contributed the most to the company's success.

In 2006, Middleton carried out a study using Compendium and an Excel spreadsheet to create a decision matrix to aid decision making in his design process [33]. This work highlighted the fact that Compendium in its current form was not equipped for this type of work, mainly because it is not capable of making the kind of in-depth qualitative comparison of positions that is required. This motivated the recent contributions of Bañares-Alcántara and co-workers to extend Compendium, which started with the work of Skrzypczak [119, 120] and Egrot [121]. Skrzypczak made the largest contribution, including an initial decision matrix, Global Parameters, Propagation and Sensitivity Analysis features. Egrot's work focused on the inclusion of ELECTRE I and II in the Compendium code. Recent contributions made by Sapkota [122] included a preliminary connection to extract the goals, criteria and parameters from OUTDO to OWL files using Jena [123]. Hanbury [68] has reviewed methods for the creation of forecasts and created a method to generate confidence intervals, which have been included in OUTDO. The work presented in this thesis has resulted in the most recent changes in the Compendium code, which in turn resulted in the current version of OUTDO.

2.7 Other Decision Rationale Capture DSSs

This section looks at DSSs that were created to solve similar problems to those to be tackled with OUTDO. There are several different areas of knowledge that focus on tools for decision making. These areas have similar objectives, but are given different names, for example decision rationale capture, design decisions, knowledge-based engineering [124, 125] and so on. As mentioned in Blessing and Chakrabarti 2009 [126], there is no well-established, properly organised overview of existing research on design/decision support frameworks. In order to compare OUTDO with other tools in a consistent manner, the scope of the research was limited to a certain area. This section will focus on the tools that explicitly attempt to capture the design/decision rationale and at the same time support the decision process.

A similar study to OUTDO is the Automated Object-Oriented Performance Analysis (AOOPA) [12]. The AOOPA system combines qualitative argumentation (IBIS), quantitative analysis (MCDA) and a collaborative voting approach to decision making [117]. This tool was successfully used to support the collaborative analysis of military performance problems [127]. To achieve this, a decision matrix was used to optimise one solution to a problem from a list of possible alternatives. One of the problems chosen was the high dropout rates on a training course. The decisions and the rejected positions were recorded in the system so that at any time a user of the system would be able to trace back decisions and their rationale to the initial problem. If another course began to show signs of high dropout rates, then the people involved in the course could look at the design rationale to see how the previous course dealt with the problem. AOOPA is similar to OUTDO, but OUTDO goes further and allows the

dynamic change in rationale that Global Parameters provide, foresees how parameters might affect the decision, and provides semantic-based decision support.

A similar approach applied to variability in domain engineering is IVMM (Issue-Based Variability Management Methodology) [128]. IVMM is based on the combination of an extended QOC representation for capturing of decision rationale, which introduces interdependencies between issues in a similar way to IBIS, orthogonal variability modelling and decision matrix (MCDA) [129]. It extends an open source rationale management tool called Sysiphus [130] and is designed for a set of software-intensive systems that share a set of characteristics satisfying the particular requirements of an individual goal developed from a library of components [131]. In comparison to OUTDO, the visualisation of the decision process is not as clear and it does not allow the dynamic adaptation of the rationale with varying parameters, forecasting and semantic decision support.

A detailed study undertaken in 2000 showed a range of different design rationale system prototypes [109]. Out of these, the one that attracted the most attention was IDIS (Integrated Design Information System) [132] which describes chemical plant components and supports the design of chemical plants with the use of a rules-based system. IDIS, together with KBDS, introduces the benefits that, explicitly describing the meaning of plant components, could potentially bring to improving the design of chemical processes. The same concept is used in the introduction of semantics in OUTDO, but this implementation is intended to support decisions in a more generic sense using the meaning of the words.

Current rationale management tools that apply to several other types of problems were reviewed by the author and are displayed in Table 2.1. In addition, the advantages

of integrating participatory methods with analytical tools (such as MCDA) have been extensively recognised. A review of the techniques is shown in Stagl 2007 [44]. However, most of the listed software has not become mainstream. Goosen *et al.* 2007 [133] provides an overview of the pitfalls for decision support development reported in the literature. Of these, the most relevant are matching the original tool requirements to the user's needs, simplicity, transparency, flexibility, reliability and confidence in the results.

Table 2.1: Current rationale management tools.

Acronym	Notation Type	Brief Software Description
ISAL [30]	ISAL	The Issue, Solution and Artefact Layer collects the design rationale from design documents and automatically makes it available in a well-organised manner with the use of ontologies.
Kuaba [134]	Ontology	Kuaba presents a new approach for representing DR improved with a meta-model semantics that describes the artefacts being designed, assigning meaning to the content recorded with the use of ontologies to facilitate the re-use of the decision rationale, which is particularly useful for software design.
SEURAT [27]	RATSpeak	Software Engineering Using RATIONale supports the automatic capture and use of the rationale and searches for problems in both the software system under development (such as bad or inconsistent decisions) and the rationale itself (such as incompleteness or contradictions). This is achieved through the

		use of ontologies with an approach similar to Kuaba.
POE [29]	POE	Problem Oriented Engineering is used when building software to automatically record the rationale.
FBS [19]	Ontology	Function-Behaviour-Structure presents an ontological framework for the construction of different agent-based design rationale and for representing constructive and dynamic design rationale, in addition to features to aid the development of new decisions.
DRed [31] [135]	IBIS	Design Rationale Editor continues work on refining the IBIS methodology.
DREAM [28]	TEAM	The representation extends QOC [23] to suit the traceability of interactive systems.
IMPROVE [15] [136]	Ontology	The Information Technology Support for Collaborative and Distributed Design Processes in Chemical Engineering is a project involving various groups which aims to evaluate, formalise, understand and therefore continuously improve chemical engineering design processes.

On the application side, in the case of the UK, there is a focus on the MARKAL numerical models for the country's electricity generation planning [137, 138]. The problem with such an approach is that the models only oversee the technical aspects of energy systems [139]. There are other issues that might be more difficult to model but which must be included in the decision, such as the extra infrastructure and professional labour required, the impact on the local communities and the environment, etc. OUTDO

can use the MARKAL results to improve its analysis, but at the same time it allows the user to add new criteria which are not included in the MARKAL modules.

The methodologies combined in this study have already been used to support decisions on electricity generation technologies in different countries and therefore have proven their effectiveness in practical applications. Overall, there are various studies of electricity generation technologies planning based on MCDA (e.g. [40, 41, 140, 141]), probabilistic forecasting (e.g. [142, 143]) and rationale management (e.g. [144, 145]). However, to our knowledge, no study includes all methodologies as presented in this project.

2.8 Conclusion

In summary, this chapter has shown the relevant techniques used to support decision making, focusing on assessing their benefits and constraints. It has been shown that the IBIS representation for rationale management has proved to be effective when capturing the most important components of a decision process (issues and positions) and allowing the user to quickly analyse the issues in detail, when resolving wicked problems that cannot be resolved with argumentation alone. Even though recording the decision rationale is time consuming, in OUTDO this process happens simultaneously with the decision process development using MCDA methods, meaning the process is streamlined.

Finally, this chapter presents the previous work from our research group and the work performed by other research groups and concludes that OUTDO stands out because it combines the four methodologies described in this chapter in a very effective way, because of its enhanced capability to dynamically allow the decision rationale to

adapt to new parameters and their predictions and due to the innovative ways in which semantic-based capabilities can be used to support the decision process.

Chapter 3

Decision Support System Framework

3.1 Introduction

This chapter discusses the features added to the Compendium Software and the overall decision framework of the OUTDO decision support software to achieve the objectives outlined in Chapter 1. The OUTDO framework is a result of the combination of the methodologies explained in Chapter 2; its main objectives are to capture and record the decision rationale in a dynamic way for future re-use, to make the decision process clear to all participants, to allow for a detailed analysis of multi-criteria issues and their future predictions, and to provide decision support with the use of semantic capabilities. A case study testing these applications is presented in chapters 4 to 8 of this thesis.

There are many ways in which OUTDO's decision framework can be used to support the decision process. These can be divided into two approaches: the standardised decision process and the design decision process. The standardised decision process is used when the same decision process is to be used frequently and when it is interesting to compare two or more different decisions. The design decision process is used for innovative decisions that will be made only occasionally.

Section 3.2 presents the new features added to Compendium that constitute OUTDO. Section 3.3 explains how a decision maker would approach a problem using OUTDO and its decision framework. Section 3.4 introduces the two different ways to build decision processes with OUTDO, i.e. the standardised decision process and the design decision process. Section 3.5 presents examples in which OUTDO has been used

in the past and present, as well as other possible applications. Section 3.6 concludes the chapter.

3.2 OUTDO

OUTDO is an integrated decision support tool that records and supports the decision process, allowing the decision makers to develop his or her own personalised system for decision making, suitable for their particular interests and context. Its use is suggested for long-term, complex decisions that involve a number of different issues and conflicting criteria. It is based on the constructive approach [146], which consists of building a module to aid decision making [147]. OUTDO is the result of more than 15 years of research [148, 107, 108], firstly at Edinburgh University and later at the University of Oxford in collaboration with Oxford Brookes University. The initial development of OUTDO was made by Skrzypczak (2007) [119, 120]. The features added to Compendium in the current version of OUTDO are shown below and are exemplified with figures throughout the thesis.

OUTDO focuses on decisions involving the design of engineering artefacts. However, the design of an artefact requires a series of decisions. If a tool supports decision making, it consequently supports the creation of engineering designs. Since OUTDO supports decisions related to engineering artefacts, it therefore supports the design of engineering artefacts. Nevertheless, it should be stressed that OUTDO can be used to support decisions in general, meaning a broader audience, including people working in business, finance, health, etc. may be interested in the tool.

3.2.1 Decision Matrix

The addition of the decision matrix to Compendium was an important step in the creation of the OUTDO framework. The decision matrix is accessed through a tab called “Decision Making” in the issue node window (Figure 3.1) and adds the position nodes (solutions to an issue) connected to the issue node automatically in a decision matrix. For example, the position nodes *Position 1*, *Position 2*, *Position 3* (nodes with a light bulb) linked to the *Issue 1* issue node (node with a question mark), in Figure 3.3, correspond to the positions in the decision matrix in Figure 3.1. The decision matrix takes the form of a table with the positions presented along the top row and the criteria listed down the left column, for example, *Criteria 1*, *Criteria 2*, etc. Each criterion can be weighted to reflect its significance in the overall decision; for example, CO₂ emissions are currently a major issue when designing a power plant and would be weighted accordingly to reflect this in any decision made involving electricity supply. The two last columns represent the weights assigned to each criteria and the normalisation factor respectively. The normalisation factor is equal to the inverse of the highest value for the given criterion. For the creation of the scores⁸ and criteria weights, the user can choose to input a single value or an expression that contains Global Parameters as variables. The user can choose to look at these expressions with the Formula view (Figure 3.1) or at the results of these expressions with the Values view (Figure 3.2). Once a position is recommended, the recommended position will have its node changed to a recommendation node (node with a light bulb and a green tick). The user can then choose from a list of MCDA methods to further evaluate the decision. These methods are: WSM, WPM, and ELECTRE I, II and III.

⁸ Scores are the values in the decision matrix that quantify how well a position performs in a criterion.

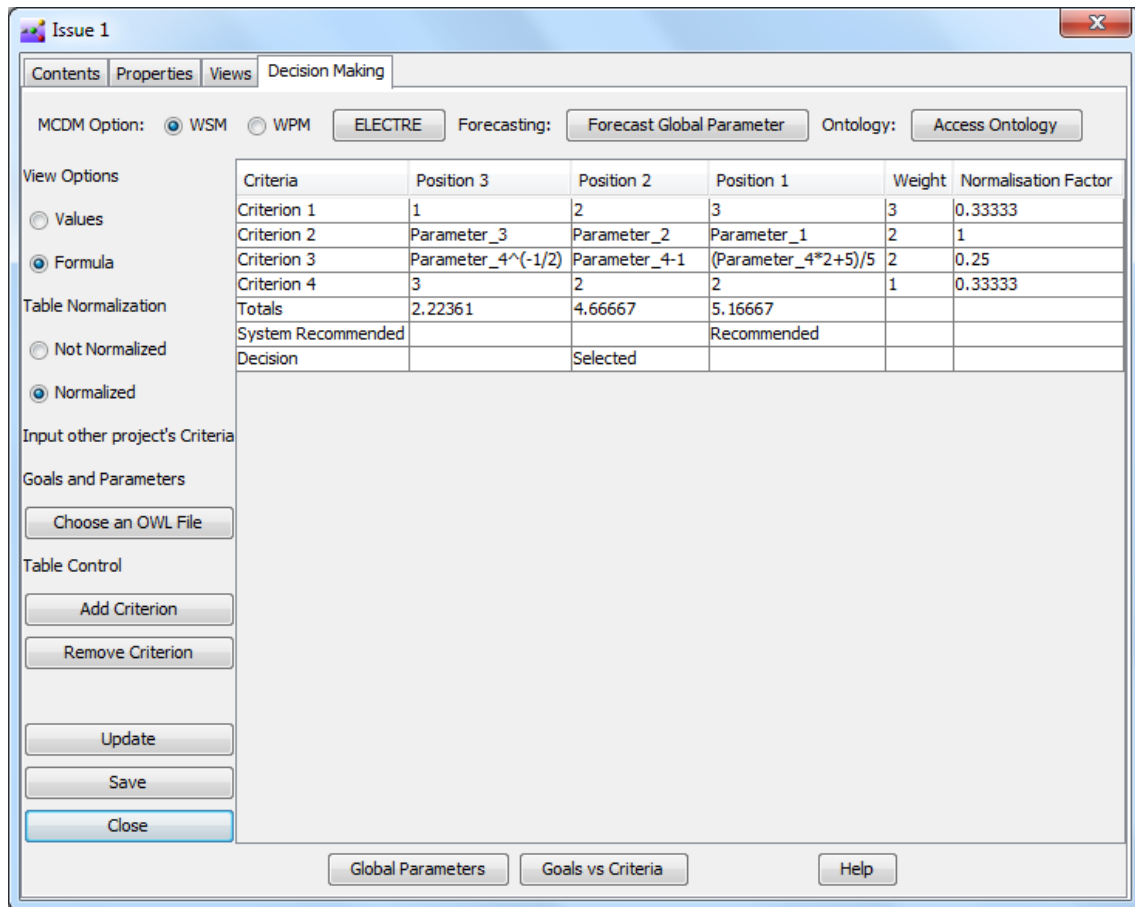


Figure 3.1: The issue node window with decision matrix in the Formula view.

Criteria	Position 3	Position 2	Position 1	Weight	Normalisation Factor
Criterion 1	1	2	3	3	0.33333
Criterion 2	0	0	0	2	1
Criterion 3	0.44721	4	3	2	0.25
Criterion 4	3	2	2	1	0.33333
Totals	2.22361	4.66667	5.16667		
System Recommended			Recommended		
Decision		Selected			

Figure 3.2: The decision matrix in the Values view.

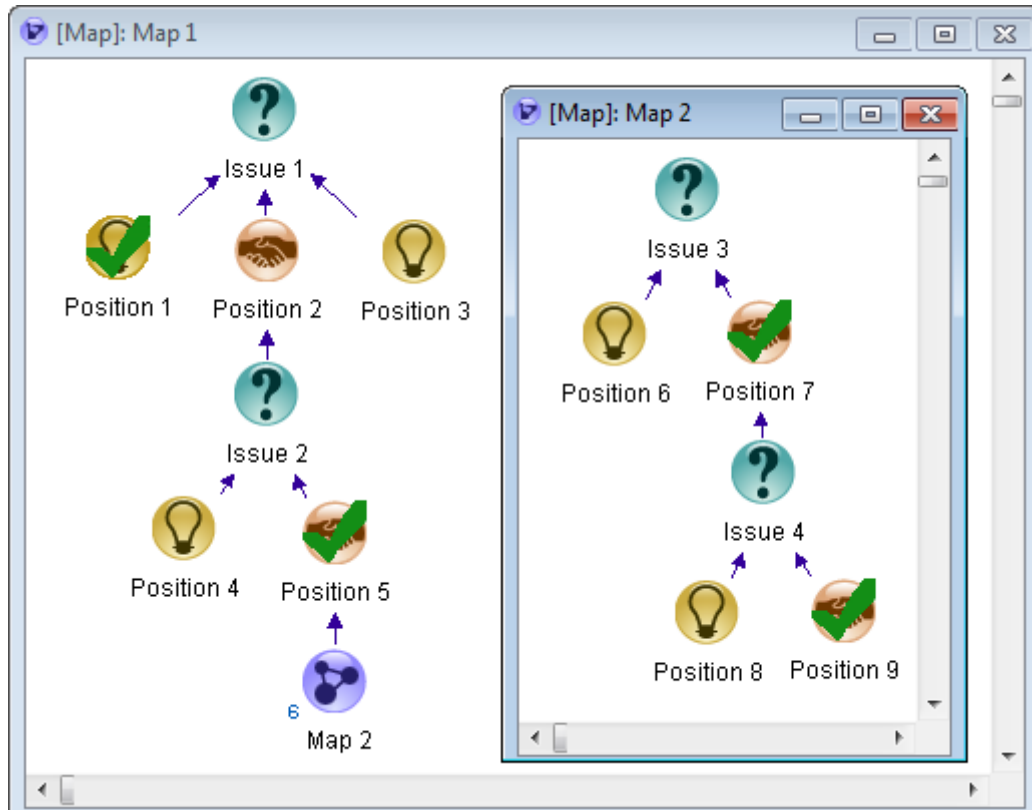


Figure 3.3: The graphical interface of the OUTDO decision process.

Figure 3.3 presents a basic demonstration of a decision process in OUTDO, where issues (e.g. *Issue 1*, *Issue 2*, etc.) are addressed with positions (e.g. *Position 1*, *Position 2*, etc.) and inside each issue node MCDA is applied for a detailed analysis. It is the user, however, who will select the decision regardless of the MCDA recommendations (i.e. where the green tick is placed). To do this, the user will have to manually change the node to the decision node (node with a handshake). If the recommended decision coincides with the user's decision, the node will automatically change to the decision and recommendation node (node with a handshake and a green tick). Following the resolution of one issue, more issues can arise from the selected position, thus starting this cycle again. Map nodes (blue nodes with a network), for example, *Map 2*, can be used to better organise the decision process. They consist of a

node that contains a window with other nodes inside and are used to give further detail on a specific subject.

3.2.2 Global Parameters, Propagation, Sensitivity Analysis and Probabilistic Forecasting

Global Parameters are used to dynamically change the decision process according to changes in input parameters. Currently, the data that can be automatically extracted from external sources are Microsoft Excel spreadsheet cells [115], financial data such as currency exchange rates, commodity prices from <http://finance.yahoo.com/>, and weather data and forecasts from <http://weather.unisys.com/>. These and other types of Global Parameters are described in detail in Chapter 6. The “Update” button in Figure 3.4 re-imports from external sources all the values of the Global Parameters (e.g. *Parameter_1*, *Parameter_2*, etc.) marked as ‘YES’, thus ensuring that updated values are used in the decision making process. The Propagation feature, detailed in Chapter 6, recalculates the recommendations for all the decisions that make use of Global Parameters. In other words, the system evaluates how a change in parameter (e.g. CO₂ emission costs in £/MWh) would affect the decision process as a whole and also reports the changes in the recommendations.

An important feature of OUTDO is that the user has the freedom to choose any decision even if the position is no longer recommended or can investigate the reason for the change to the new position. This means that, before making a definite decision, the user can study how different future scenarios would affect the decision process. For this reason the Sensitivity Analysis feature can be used to analyse how a given percentage variation of the value of a single Global Parameter will affect the decision process. For

example, the Global Parameter that represents the price of oil (*Brent_Crude*) can be varied by $\pm 50\%$ in steps of 10% and the report window can detail the impact of these changes in the whole decision process [149]. In addition, the user is able to create probabilistic forecasts as to how Global Parameters might behave in the future and, by importing these values into the decision matrix, two plots are created showing the probability that the positions will be recommended as the Global Parameters change with time. These plots, as discussed in Chapter 6, can be used to study which is the best position taking into consideration the short, medium and long terms.

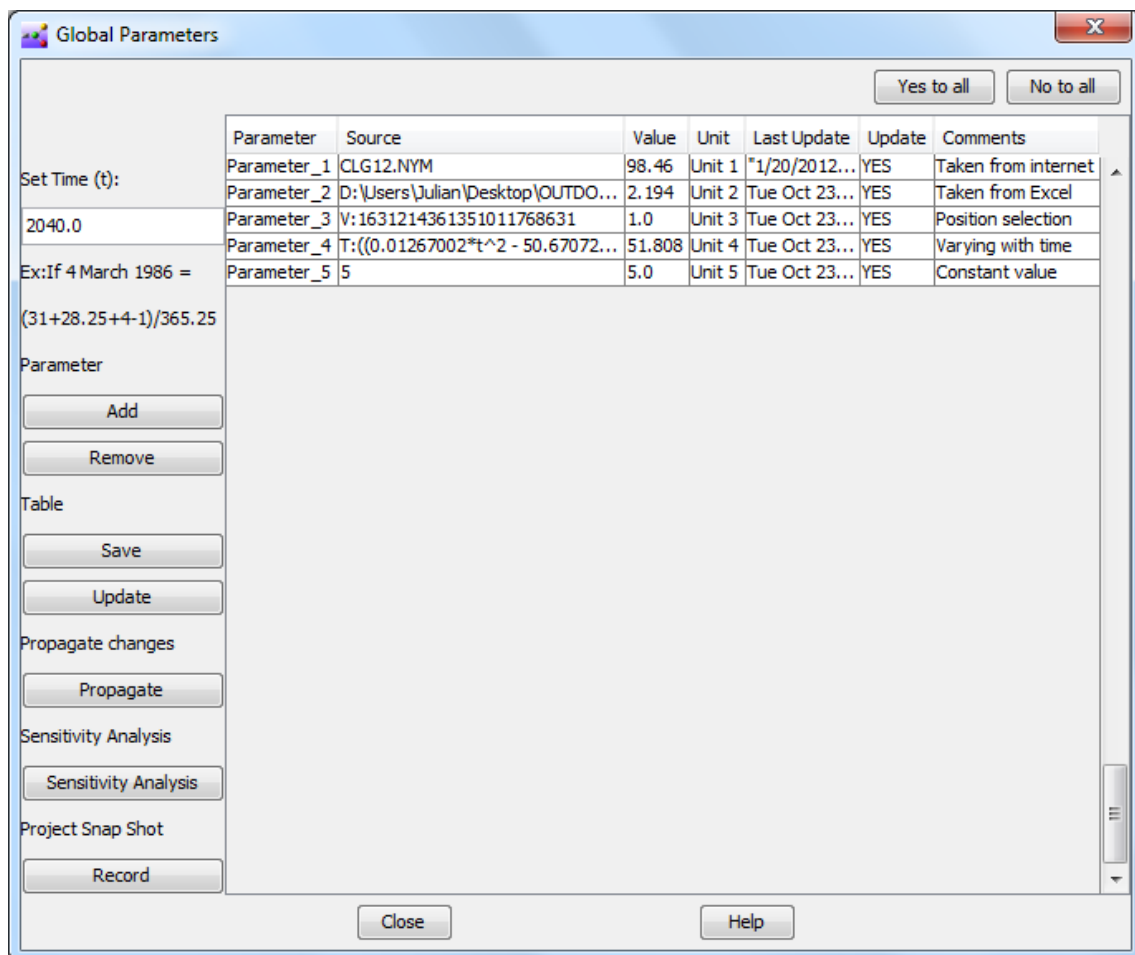


Figure 3.4: The Global Parameters window.

3.2.3 Goals vs. Criteria matrix and Ontology Dialogue

As a more systematic solution can be reached by quantifying the preferences of each goal, through criteria weighting [52], the Goals vs. Criteria matrix, shown in Figure 3.5, allows the user to clarify which criteria relate to each goal in order to record the objectives of the decision process and to clarify them to all participants involved.

Criteria	Goal 1	Goal 2	Goal 3
Criterion 1	☒	☐	☐
Criterion 2	☒	☐	☐
Criterion 3	☐	☒	☐
Criterion 4	☐	☐	☒

Figure 3.5: The Goals vs. Criteria matrix.

The Ontology Dialogue provides a graphical user interface which connects to the semantic-based capabilities in OUTDO, as will be discussed in detail in chapters 7 and 8. The Ontology Dialogue contains all the code required to extract the decision process from OUTDO and to translate it into an ontological format introducing instances into the Decision Ontology. It then connects the Decision Ontology with the

Energy Ontology to provide the semantic-based decision support capabilities which, combined with the other features in OUTDO, results in an exceptionally powerful tool.

3.2.4 OUTDO Components Summary

The OUTDO components are the fundamental elements for constructing a decision process in OUTDO. Table 3.1 presents them and gives a brief description of each OUTDO component and other important terminologies.

Table 3.1: Summary of OUTDO components, terminologies and features.

Component	Description
 Issue nodes	Issue nodes represent the questions to be solved to reach the goals set by the decision maker. They contain a decision matrix which uses criteria and Global Parameters to compare the position nodes connected to them.
 Position nodes	Position nodes are the alternatives being compared to resolve a given issue node.
 Recommended Position nodes	Recommended position nodes are the position nodes that have been recommended to resolve a given issue node by the analysis performed in the decision matrix with the WSM.
 Decision nodes	Decision nodes are the position nodes selected by the decision maker to resolve a given issue node.
 Decision and Recommendation nodes	Decision and recommendation nodes are the position nodes selected by the decision maker that have been recommended

Decision Process

to resolve a given issue node by the analysis performed in the decision matrix with the WSM.

The decision process is the result of using the OUTDO framework on the resolution of a problem. It includes the goals that should be achieved, the issues that have to be resolved with different positions, the criteria that are used to compare the positions, the Global Parameters used to improve the re-use of the decision rationale, and to use the Propagation feature, Sensitivity Analysis feature and probabilistic forecasts.

Decision Rationale

Within the OUTDO framework, decision rationale does not only constitutes of the IBIS structure. It includes the MCDA performed inside each issue node, the Global Parameters and probabilistic forecasts used to enhance the analysis.

Goals

Goals are the intended objectives to be reached by the decision process. They are connected to the criteria in the Goals vs. Criteria matrix to clarify how the goals are represented in the decision process.

Decision Matrix

The decision matrix is where the decision maker compares the possible positions to resolve an issue with different criteria. It can be seen in the Formula view, where the equations can be seen, or the Values view, where the results of the equations can be seen. The automatic result corresponds with the WSM,

	but can be changed to the WPM. In addition, the values in the decision matrix are used when ELECTRE I, II and III are applied.
Global Parameters	Global Parameters are optional variables used to make the decision process dynamic and to improve its analysis with the Propagation, Sensitivity Analysis and probabilistic forecasting features. They are the variable in the equations used for positions vs. criteria scoring in a given issue node decision matrix.
Criteria	Criteria are the components used to compare the position nodes in the decision matrix of an issue node.
Weights of Criteria	Weights of criteria are values used to measure the importance of the criteria in the decision analysis.
Scores	Scores are the values used to measure how positions perform with respect to a given criterion. They can be set as a single value (constant) or they can be an expression that varies with Global Parameters.
Expressions	Expressions are the equations created with Global Parameters. The result of these expressions gives rise to the scores.

3.3 Decision Support System Framework

The DSS that is used in OUTDO is shown in Figure 3.6. This framework supports the creation and analysis of decision processes, while at the same time keeping

a record of decision rationale. The creation of the decision process starts with the *Decision Configuration* block. Its objective is to construct a hierarchy of issues, which describes in detail possible positions to resolve a problem and present them in a transparent and easy-to-follow manner. This block begins with the *Definition of the Problem* task [150, 151] where the stakeholders define the main problem to be resolved (the issue node at the top of the IBIS structure). This includes the problem description, which can be recorded in the issue node window (“Contents” tab in Figure 3.1). After the problem is defined and clarified, the goals intended to be achieved by the decision are defined and added to the “Goals vs. Criteria” window (*Goals Description and Selection* task). The existing barriers to reach the specified goals are expressed as sub-issues of the main issue node, during the *Issues Brainstorming* task. In order to keep track of the hierarchy of issues, this task includes the establishment of the IBIS structure. Finally, positions that address those issues are suggested and the most promising ones are listed and linked to the issue they relate to (*Positions to Reach the Goals Set* task). The positions are mutually exclusive, meaning that only one idea can be accepted as a solution to the question. An example of the *Decision Configuration* block is shown in Chapter 4.

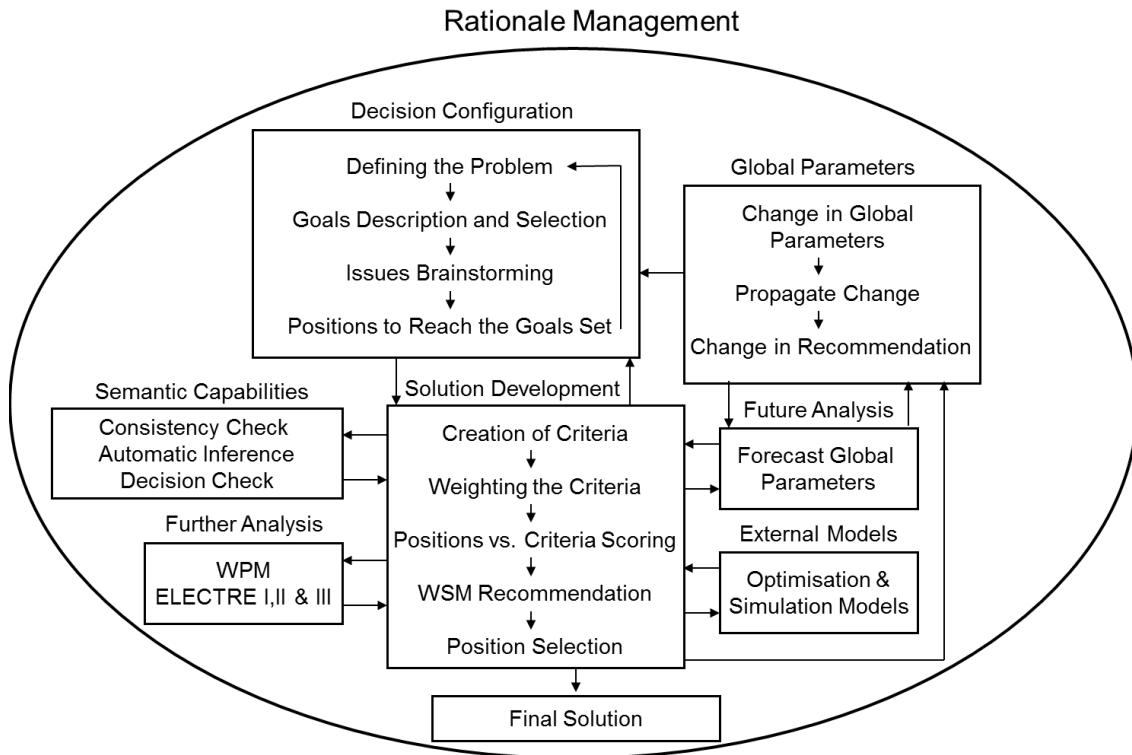


Figure 3.6: The decision framework for OUTDO.

Once a variety of courses of action have been considered, each issue node has to be analysed in detail with MCDA (especially WSM) in order to find the recommended solution. This consists of the *Solution Development* block. The *Solution Development* block is performed within the tab “Decision Making” in the issue node window (Figure 3.1). The *Solution Development* block is defined by filling in the decision matrix cells: the criteria used to compare the potential positions have to be carefully selected (*Criteria Creation* task) and weighted (*Criteria Weighting* task). Finally, the positions are scored (*Positions vs. Criteria Scoring* task) and the recommended position is found (*WSM Recommendation* task).

There are two views of the decision matrix: the Formula view (Figure 3.1), where the user is able to enter values, expressions and Global Parameters, and the Values view (Figure 3.2), which shows the values resulting from evaluating the

expressions in the Formula view. This block captures the justifications for why a position was chosen and others discarded, thus recording the decision rationale. As stakeholders learn more about the decision process, new positions or goals may emerge, allowing for the refining or reformulation of the decision process. If the problem consists of multi-dimensional criteria or if the decision involves inaccurate, imprecise, uncertain or ill-determined data (pseudo-criteria) [65], a more sophisticated MCDA method is applied to allow for a pairwise evaluation of the positions and to contribute to a more robust decision (*Further Analysis* block). The *ELECTRE I, II or III* methods [140, 141] were implemented in OUTDO for this reason. By iterating between requirements elicitation and analysis, a greater confidence in goals and criteria preferences is likely to emerge and the process may then return to the *Decision Configuration* block.

The user can then analyse how a change in the Global Parameters can affect the whole decision process, an analysis which is performed by updating the decision matrix of every issue node in the decision network (*Propagate Change* task). This will update the decision matrices of all issue nodes that make reference to those Global Parameters. The issue nodes whose recommendation changed as a result of the propagation (*Change in Recommendation* report) are reported in a table (discussed in Section 6.4). OUTDO can be used as a hub where the results from different optimisation and simulation models and DSSs are integrated to provide better analysis of the position comparisons and, thus, for improving the decision making process (*External Models* block). In addition, the user can create probabilistic forecasts as to how Global Parameters might behave in the future and, by importing these values into the decision matrix, graphical

plots showing the probability that a given position will be recommended as a function of time can be generated (*Future Analysis* block).

Once the decision maker has selected his or her decision in OUTDO, the decision process can be analysed with the semantic-based decision support capabilities included in the system. There are three ways in which the semantic capabilities support the decision process (*Semantic Capabilities* block). Firstly, the *Semantic Capabilities* block recognises all the OUTDO components and creates links to classes and individuals in the Energy Ontology. If these components are not found in the Energy Ontology or if the component is erroneously linked to another OUTDO component, OUTDO will warn the user. Secondly, the block can suggest position and issue nodes relevant to the decision process. Thirdly, the block looks at the selected positions and checks whether the selection might result in problems that the user is not aware of. At present, OUTDO only supports decisions relating to the energy sector as it is the only domain addressed in the Energy Ontology. If semantic-based capabilities are to be used to support other domains, new ontologies will have to be added to OUTDO.

Out of these blocks, the *Decision Configuration*, *Solution Development*, *Future Analysis*, *External Models*, *Further Analysis* and *Global Parameters* blocks can be applied to engineering design problems as well as to other more generic decision making problems, such as Governmental policy making, business, finance, consultancy and the health sector. The only block which is currently limited to energy decisions is the *Semantic Capabilities* block as it requires the Energy Ontology.

3.4 The Standardised and Design Decision Process Approaches

Before the decision maker starts developing the decision process, he or she should consider whether the same problem needs to be addressed many times with minor variations, or only a few times. The reason for this is that the decision process can be constructed in two different ways: the bottom-up approach and the top-down approach. Both approaches use the framework described in the previous section. The decision process is constructed according to the user's needs to re-use the decision rationale.

3.4.1 Standardised Decision Process: Bottom-up Approach

The standardised or bottom-up decision process approach is to be used when the decision maker wants to create a standard decision process. In other words, the decision process recorded in OUTDO will be used to solve not just a one-off decision but a set of similar decisions, and possibly be used to compare different decisions. This standard decision process can then be adapted to different circumstances, such as a change in intentions (goals) or a change in location, or be used as a basis to make a new decision in the future. For example, if a country wants to invest in renewable energies and needs to make sure that it selects the most appropriate position for each of its regions, the decision maker can create a decision process in OUTDO with all the possible alternatives suitable for the country. In each decision matrix, he or she can include all the parameters that vary with the different locations as Global Parameters. Then, once a decision is made for a given location, the same decision rationale can be re-used to choose the appropriate renewable energy technology for a different location as only

some key parameters will need to be changed. The advantage of using a standard decision process is that the selections of appropriate technologies for each location will be done using the same methodologies and very similar decision rationale, therefore increasing efficiency and possibly reducing inconsistencies in a set of decisions.

For the creation of a bottom-up decision process, the decision maker can include all the positions that might be selected in at least one of the existing scenarios. Once the backbone of the decision process is ready (i.e. a decision process without recommendations or decisions), the decision maker can start to populate the decision matrices from the issue nodes at the bottom of the decision process and move to the issue nodes above until the top, main, issue node is reached. In this way, since all the possible outcomes were analysed in detail, the decision maker will have in hand a better analysis of the final decision than if he or she used the design decision approach outlined below.

3.4.2 Design Decision Process: Top-Down Approach

The design decision or top-down process approach is to be used to deal with novel problems that are not going to be addressed regularly. It takes less time to construct than the bottom-up approach as the decision maker only focuses on the issues resulting from the selected positions, with positions that have not been selected being ignored in this approach. In other words, the decision maker will only focus on the issues that are connected to selected positions and will not waste time with positions that are not going to be considered. For example, if a company is designing a one-off biorefinery and a fermentation process is included, once the decision maker has opted for a continuous fermentation process, the subsequent decisions will not consider the

fermentation batch process as a position. In the top-down approach, as soon as the decision maker creates an issue node, he or she will resolve it using a decision matrix and then move to the lower issues until the decision process is as complete and detailed as the decision maker requires. The advantage of this approach is faster decision making and simplicity. In this approach, it is assumed that the decision maker has a considerable amount of knowledge to build the decision process and find the recommended course of action.

3.5 Previous, Current and Possible Application of OUTDO

Uses of OUTDO to support decision making have been presented in Yeoh 2009 [152], Evans 2011 [153], and Sanchez 2012 [154]. Yeoh used the design decision process approach to evaluate and plan the implementation of the Cquestrate project [155]. This project is a geoengineering project based on an idea originally from Kheshgi [156]. Its main goal is to increase the alkalinity of the ocean in order to allow the ocean to absorb more CO₂ from the atmosphere.

Evans used the standardised decision process approach to assist decision makers in piecing together an effective strategy for the provision of clean drinking water in order to improve the quality of life of those living below the poverty line. Evan's decision process attempts to provide a quick and efficient preliminary evaluation of different types of projects for a given region of interest. The project is customisable both through geographic parameters and through the use of local data to update the unit cost of different water access technologies.

Sanchez is currently using OUTDO's design decision process approach as part of an inter-institutional research project currently underway in Mexico, with the

intention of designing a biorefinery using agro/industrial waste as a feedstock within the context of a mid-size economy. Ten research groups participate in the project, each working on different stages of the biorefinery's design. The use of OUTDO is intended to record the design rationale, support decision making and improve communication between the different participants in the project.

Other examples of how OUTDO could be used to support decision making are listed below:

- A decision process and rationale for one location can be applied to a different location. An example is when a company wishes to find the best energy sources to supply clean and affordable heat and electrical services for a house. As parameters such as solar radiation, wind speed, house size, garden size (with a larger space needed to install a heat pump) and, most importantly, the changing needs of each customer, OUTDO can easily adapt the decision process to the new location and engage the customer in the decision process with his/her particular inputs.
- External parameters relevant to a decision process inevitably change with time. If there is a problem with a solution previously reached using OUTDO, the decision maker can re-use the decision process, trace back to the decision that caused the problem, change the Global Parameters that have changed since the decision was made, and find the up-to-date recommended position. An example is the replacement of a chemical plant reactor. As a result of technical improvements since the plant's construction, the increased cost of energy and new customer requirements, there may be better positions available other than repeating the installation of the previous reactor type [15].

- Before making a final decision, the user can study how different future scenarios can affect the decision process. For this reason, the “Sensitivity Analysis” tool can be used to analyse how a given percentage variation in the value of a single Global Parameter (for example, the cost of oil) can affect the decision process.
- With the inclusion of semantic capabilities, OUTDO can potentially be used as an expert system which supports decisions involving the energy field. However, for this to become reality, the semantic capabilities will have to be expanded, as well as the Energy Ontology. This is further discussed in Section 9.2.4.

3.6 Conclusion

This chapter has presented OUTDO’s features that have been added to the Compendium Software. It gives an overall view of OUTDO’s decision framework and includes a brief explanation of how OUTDO can be used to build decision processes. Two different concepts for the application of OUTDO have been introduced: the standardised decision process and the design decision process. In summary, the steps required to develop the decision process in OUTDO are:

- 1) Select between standardised decision process and design decision process.
- 2) Describe the problem.
- 3) Clarify the goals intended with the project.
- 4) Brainstorm issues preventing these goals being reached.
- 5) Suggest positions that address those issues.
- 6) Apply a MCDA method to the problem.
- 7) Apply other MCDA methods if a clear preference for one position is not found.

- 8) Use Global Parameters, the Propagation feature, the Sensitivity Analysis feature and the Future Analysis feature to analyse the problem in detail, including the effect of parameters which vary with time.
- 9) Apply a semantics check for consistency, to suggest possible issues or positions, and to check whether there are problems with the decisions that have not been considered.

Apart from recording and supporting the decision process, a main contribution of OUTDO is the creation of standard decision processes with the standardised decision process approach. The next chapters attempt to verify OUTDO's features in detail through a case study intended to determine the recommended electricity generation and steam condensation technologies for different areas in the UK, as a function of time, using the standardised decision process approach. The chapters are organised following OUTDO's decision framework presented in Figure 3.1. As a result, Chapter 4 consists of the *Decision Configuration* block in the OUTDO decision framework, Chapter 5 consists of the *Solution Development* and the *Further Analysis* blocks, and Chapter 6 consists of the *Global Parameter*, *External Models* and *Future Analysis* blocks. chapters 7 and 8 describe the *Semantic Capabilities* block. Finally, an evaluation of OUTDO's framework and case study is performed in Chapter 9.

Chapter 4

Case Study Description: UK Energy Sector

4.1 Introduction

The case study chosen to test OUTDO's features has the aim of determining the recommended electricity generation technology for different regions in the UK over the next forty years and the appropriate technology for using or disposing of the heat from a thermoelectric power plant. The application of OUTDO to this project is detailed in chapters 4 to 8, with each of the five focussing on a detailed demonstration of a different OUTDO function.

This chapter introduces the main issues the UK will face in the next decades to replace the nuclear and coal power plants that will be shut down and to provide, at the same time, affordable and low carbon energy. Thus, Section 4.2 gives an overview of the UK's energy sector. It mentions the current challenges faced, the main projects that are currently under development for the implementation of new energy infrastructure and the energy policies used to influence the desired electricity generation technologies. The information in this section will be used to develop the decision processes in the next chapters, for example, when selecting the criteria of comparison and weights of criteria. Section 4.3 introduces the requirements of water for the production of electricity, a problem which has not received sufficient attention, and will become more difficult to solve in the coming years due to the growth in population and climate change. Section 4.3 also describes the alternatives to reduce water consumption and shows the regions most affected by excessive fresh water extraction.

Section 4.4 clarifies the goals intended to be reached in the case study, whilst Section 4.5 shows how a user would start to construct the decision process relevant to this case study in OUTDO. It shows the procedures required and explains how to complete the *Decision Configuration* block shown in Figure 3.6. Thus, having clarified the problem, the user firstly decides between a standardised or design decision process. Secondly, the user clarifies the goals he or she is trying to resolve. Thirdly, the user brainstorms the barriers that might impede the reaching of the goals and turns them into issue nodes. Fourthly, positions (solutions) that resolve the issues found by brainstorming are included in the decision process. Section 4.6 concludes the chapter.

4.2 Overview of the UK Energy Sector

Until now, the infrastructure that supplies energy to consumers in Great Britain (shown in Figure 4.1) has given little cause for concern. The greatest demand for electricity is in southern England, but coal-fired generation in northern England has dominated the generation side. Thus, high voltage transmission lines connect the supply in the North to the demand in the South. In the 1990s, the move from coal to gas-fired generation, which is not so dependent on being close to a mine or a port, helped to ease transmission constraints [157]. Currently, the pressures to decarbonise the electricity generation sector and the decline of UK gas production in the North Sea is creating new challenges to provide affordable energy for the next decades.



Figure 4.1: British electricity supply system map in 2011 without wind energy [158].

The UK has taken on the challenge to achieve 15% renewable energy generation by 2020 and reduce its CO₂ emissions by 80% from 1990 levels by 2050. In addition, the probable electrification of carbon-intensive sectors, such as heat, transport, industry and others, may double the total electricity demand by 2050 [157]. Furthermore, the UK will lose around 20 GW of electricity generation capacity due to the closure of old coal and nuclear plants, threatening its security of supply [5]. If no action is taken now, the reserve generation capacity could be reduced from 14% to only 4% in three years, increasing the likelihood of blackouts [159]. To make things worse, an increase in inflexible⁹ supply sources (such as nuclear) and intermittent supply sources (such as wind) will raise additional challenges to meet demand at all times. Other uncertainties are carbon emission costs which are volatile and hard to predict, CO₂ storage costs, and the costs for future storage and disposal of radioactive waste, which are yet to be resolved in the UK [160]. The rate of investment in electricity supply and transmission may more than double the current amount by 2020, totalling £110 billion. There is a general consensus that current market arrangements will not deliver this [5]. Therefore, the Department of Energy and Climate Change (DECC) proposed a series of energy policies to address these issues in the latest energy planning White Paper 2011 [5].

The UK Government proposed the following strategies to achieve a flexible, diverse and low-carbon electricity generation system with demand responsive to supply fluctuations, electricity storage and interconnections to other countries. 1) Feed-in Tariffs with Contracts for Difference (FiT CfD) to provide long-term, secure subsidies for low-carbon technologies. 2) A Carbon Price Floor (CPF) to set a reasonable price on carbon dioxide, to reduce uncertainty and to encourage investments in low-carbon

⁹ Due to its high capital costs, nuclear power plants are designed to operate at full capacity (more than 90%). Thus, it is an inflexible electricity generation source.

generation. 3) Emissions Performance Standard (EPS) to fix an annual carbon emissions limit equivalent to 450 kg CO₂/MWh at baseload¹⁰ to reinforce the policy that no coal power plant be constructed without co-firing biomass or capturing and storing its carbon emissions. 4) The Green Deal to enhance energy efficiency in homes and businesses [5].

The new UK electricity generation capacity is foreseen to include renewables, carbon capture and storage (CCS) for gas and coal, nuclear power and gas without CCS [5]. However, questions about the generation percentage allocated to each technology, the location of plants, the impact to the environment and surrounding communities, the amount of money that should be invested, and the extent to which the UK should rely on other countries, are crucial and have to be answered now. Not all these aspects are supported by existing optimisation models such as MARKAL [137]. The complexity of these issues makes it an ideal case study to test the operation of OUTDO. OUTDO, applied to the case study problem, can include these aspects to reach a better solution.

Another major feature of the analysis undertaken was the inclusion of water usage as a key factor. Therefore, before embarking on a detailed description of the decision-making process, it is necessary to give some background to this issue in the UK's energy sector.

4.3 The Connection Between Energy and Water

Electricity generation based on the steam cycle (whether nuclear, coal, biomass, combined cycle gas turbine, geothermal or concentrating solar power) requires a considerable amount of water. In the UK, the power sector is one of the largest water

¹⁰ Baseload are the electricity generation technologies that constantly supply the same amount of electricity. They are expensive to construct but cheap to operate (i.e. coal and nuclear).

consumers. However, the connection between electricity generation and water does not normally appear in comparison studies as a major factor.

In 2007, fresh water use for electricity generation accounted for 30% of the total fresh water abstraction in England and Wales [161]. Figure 4.2 shows the Catchment Abstraction Management Strategies (CAMS) used to estimate the water resources available for abstraction. CAMS are areas managed by The Environment Agency responsible for water resources. Each CAMS study the amount of water already licensed for abstraction in each area, the amount of water the environment requires and the quantity of freshwater available. The CAMS are divided into four classes: Water Available (i.e. water is likely to be available at all flows), No Water Available (i.e. no water is available for licensing at low flows), Over-Licensed (i.e. abstraction is such that no water is available for abstraction at low flows), Over-Abstracted (i.e. existing abstraction is causing unacceptable damage to the environment at low flows). This situation may grow worse due to warmer and drier summer conditions in the future [162] added to the population growth in water scarce regions, especially in the South East. The result will be the need for essential infrastructure development in the water supply sector [161]. Apart from damaging the environment, economy and society, water shortages could threaten the availability of electricity generating capacity, as there may be no water available to condense the steam in thermoelectric power plants [157]. Costly sea water membrane desalination has already been implemented for part of the London water supply [163] and it is being considered for Brighton [164]. Forward-looking decisions, however, can reduce the water consumption in the power sector, which would avoid generating a considerable amount of electricity to desalinate water.

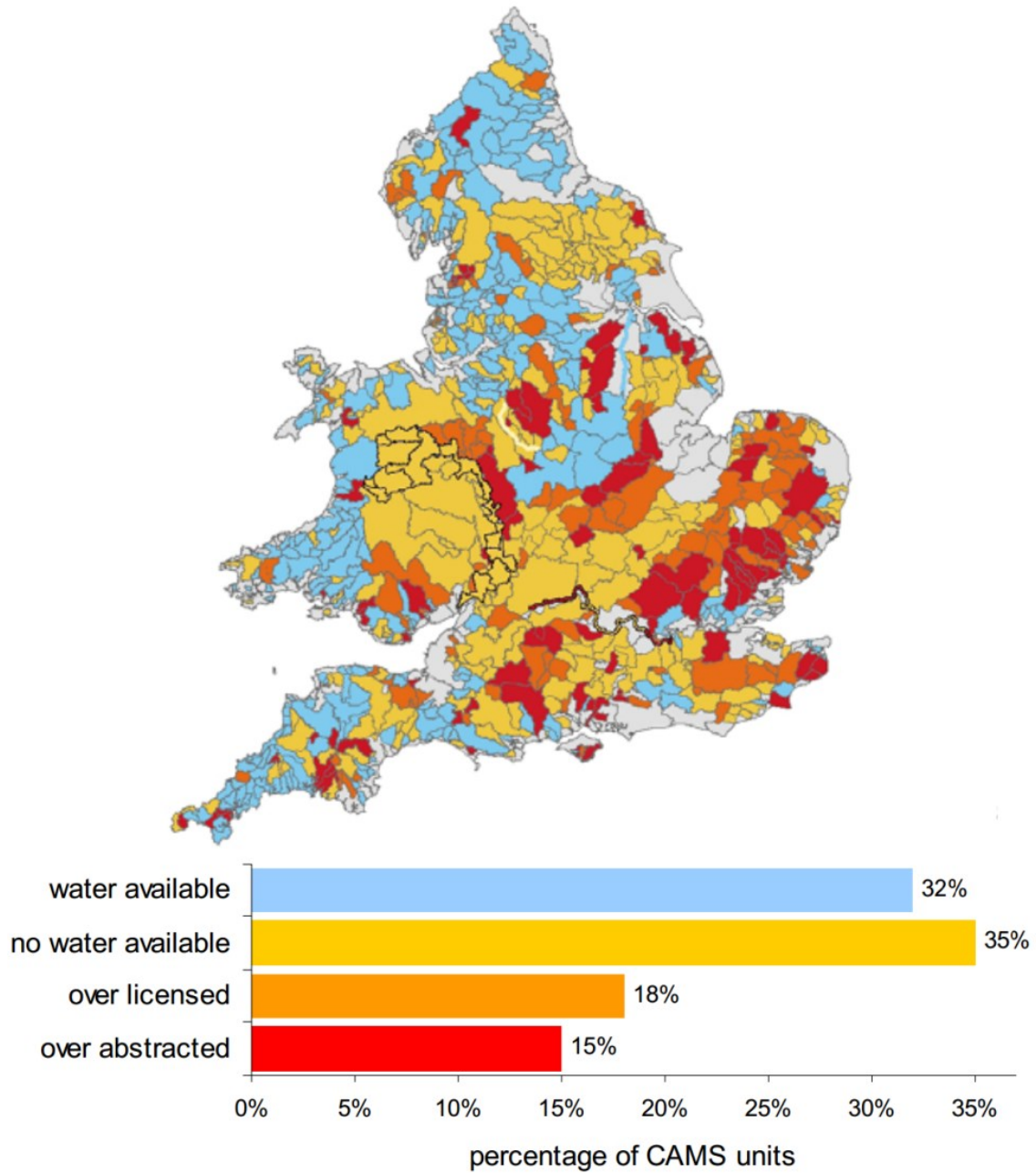


Figure 4.2: Surface water and groundwater available for abstraction in 2008 [161].

There are no data for the areas (CAMS) in grey.

The issue of water consumption in steam-based power generation using wet cooling towers could be mitigated with sea water once-through coolers (as long as the plant is near the sea), dry coolers and cogeneration plants. Fresh water once-through coolers are the best cooling position as it returns the water extracted from the water

body, and the heat exchangers suffer less corrosion than in the case of salt-water cooling. However, fresh water coolers are not suitable for UK generation plants as the water bodies available do not have sufficient volume or flow rates to operate without damaging the environment. Sea water once-through coolers are convenient as they use freely available sea water. However, due to the need to economically develop the countryside, to reduce transmission costs, or due to the location of geological carbon storage sites, it may be necessary to establish plants too far from the coast to allow sea water cooling. Dry cooling does not require water, but can increase the cooling system capital costs threefold and reduce the overall efficiency of the plant by around 4% compared to the use of cooling tower technology [165]. Although cogeneration has the potential to considerably reduce the amount of water used in the generation of energy from thermoelectric sources, it reduces the amount of electricity produced and, depending on the power plant's location, can considerably increase generation costs. Another water saving alternative is to use the waste heat generated to desalinate sea water through distillation. This technology has proven to be efficient and is in use in China [166] and Israel [167]. Ultimately, water consumption could be reduced by the implementation of non-thermoelectric generation technologies such as wind or photovoltaic cells.

4.4 Decision Process Goals

Given the current state of the energy and water sector in the UK and the future prospects for the sector, the selection of electricity generation and steam condensation technologies for each region of the UK should aim at specific goals. These goals are organised into energy, environmental, economic and social goals which are explained

below. The criteria resulting from these goals will be discussed in the next chapter together with the scoring and weighting of these criteria.

4.4.1 Energy Goals

The reliable supply of electricity is essential for the well-being of the population and the UK economy. The energy goal intends to provide long-term energy price stability and energy supply security. Generally, the consumption of coal and natural gas increases a country's exposure to energy price instability as fossil fuel prices have become more unpredictable. These fluctuations are caused by issues such as natural disasters, unstable geopolitics and national politics, and increasing demand from developing countries [41, 150, 168, 169, 170]. Furthermore, renewable energies can affect a country's energy stability, especially with wind and solar technologies, due to their electricity generation unpredictability and intermittency [171, 172]. Two possible solutions for these issues are to diversify the sources of electricity generation [170, 150] and to implement high peak-load response¹¹ technologies [173].

4.4.2 Environmental Goals

When planning for the implementation of electricity generation power plants in the UK, a detailed environmental impact assessment is performed. However, previous experience can be used for a quick comparison between different positions. This case study focuses on the reduction of gaseous emissions such as CO₂ [174], SO₂,

¹¹ Peak-load response criterion measures the technology's ability to quickly react to variations in demand.

Particulates, and TOPP¹² [150, 170, 175], water usage [176], water pollution BOD¹³ [177] and land requirements [178]. To the extent that it is necessary and possible, the environmental costs of electricity production, including the provision of technologies to reduce these impacts are reflected in the electricity costs. Other environmental impacts that are not directly included in this study are: emissions of hydrocarbons (HCs), arsenic, fluorine, volatile organic compounds (VOC), carbon monoxide, heavy metals, especially lead (Pb) and mercury (Hg), solid waste disposal, radioactive waste storage, acoustic emissions, electromagnetic interferences, unpleasant odours, microclimatic changes, etc. [178].

4.4.3 Economic Goals

The economic goal involves the money required to produce a given amount of electricity, heat or desalinated water, and the prospects for developing local and national economy and industry. The investment cost criterion is frequently applied to compare energy systems [150]. It consists of the costs involving the extraction of natural resources, construction of roads and connections to the national grid, engineering services, technological installations, purchase of equipment, and other incidental construction work [150]. Investment cost includes the technical maturity, safety, service life, etc. of the designed technology. This facilitates the decision process and avoids redundancies when making the decision. Operation and maintenance costs are divided into fixed and variable costs and consist of employees' wages, water, chemicals, other

¹² Tropospheric Ozone Precursor Potential (TOPP) represents the potential formation of near ground (tropospheric) ozone which can cause summer photochemical smog.

¹³ Biological Oxygen Demand (BOD) is a parameter frequently applied to measure the concentration of organic compounds in water that can be decomposed by bacteria.

services, and maintenance costs to extend the life cycle of the plant and prevent faults that may result in the interruption of operations [150]. Fuel cost refers to the supply of resources to be consumed by the plant, for example, enriched uranium for nuclear power plants [150].

An important aspect that is not considered here is the value added to a contracted UK engineering company that could sell technology and services abroad. This factor has not been included in the analysis as all power generation technologies can contribute to this to a certain extent and the added value is difficult to quantify. For example, China is currently the main producer of photovoltaic cells. A country that wishes to invest in photovoltaic cells would have to invest a large amount of money in the sector in order to compete with the Chinese production base [179]. The local economic development will be addressed in the section on social goals and is related to the amount of jobs created directly and indirectly resulting from the given electricity generation technology [150, 178].

4.4.4 Social Goals

The social goals intend to improve the quality of life or to reduce the impact on individuals and communities that will be affected by the project. Energy supply systems employ many people for the construction, operation and decommissioning phases and, thus, are contributors to the development and prosperity of communities [150]. Out of the positions considered in this study, biomass has the greatest job intensity due to plantation, fuel processing and biomass transportation [150]. There are several ways in which energy systems affect society. One factor that should be given more attention and which is included in this study is the risk of fatalities from each technology [173]. A

social goal that has not been included in this study is public acceptance, which concerns visual amenity and noise generation, and which have been key in preventing the development of a number of onshore wind projects [157].

4.5 Goal vs. Criteria Matrix

Before the decision maker starts building the decision process, the goals that he or she wants to achieve need to be clarified. The Goals vs. Criteria matrix in OUTDO allows the user to add criteria and goals to the decision process. Check box columns are used to clarify which criteria are related to which goals to record the decision process intent and clarify it to all participants involved, as shown in Figure 4.3. Each of the main goals described above (i.e. *Energy*, *Environmental*, *Economic* and *Social* goals) is connected to its respective criteria for a quick review of the decision analysis. Following, the more detailed goals are introduced manually by the user through the “Goals vs. Criteria Matrix” as shown in Figure 4.3 and are connected to its specific criteria. For example, the *Increase Energy Price Stability* goal (a sub-goal of the *Energy* goal) is connected to the criterion *Diversity of supply*. Apart from making the project goals explicit for all participants, the Goals vs. Criteria matrix plays an important role with respect to the semantic capabilities, by providing consistency checks to the decision process, as will be explained in chapters 7 and 8.

Criteria	Economic	Environmental	Social	Energy	Increase Energy Price Stability	Reduce Cost	Reduce Global Warming Effect	Increase Employment
Cost (£/MWh)	☒	☐	☐	☐	☐	☒	☐	☐
Cost (£/KW)	☒	☐	☐	☐	☐	☒	☐	☐
Capital cost (£/MWh)	☒	☐	☐	☐	☐	☒	☐	☐
O&M cost (£/MWh)	☒	☐	☐	☐	☐	☒	☐	☐
Fuel cost (£/MWh)	☒	☐	☐	☐	☐	☒	☐	☐
CCS installation Cost (£/MWh)	☒	☐	☐	☐	☐	☒	☐	☐
Low grade heat demand	☒	☒	☐	☐	☐	☐	☐	☐
Water usage (kg/MWh)	☐	☒	☐	☐	☐	☐	☐	☐
Water production (kg/MWh)	☐	☒	☐	☐	☐	☐	☐	☐
Availability of water	☐	☒	☐	☐	☐	☐	☐	☐
Proximity to sea (boolean)	☐	☐	☐	☐	☐	☐	☐	☐
Quality of water	☐	☒	☐	☐	☐	☐	☐	☐
COD (g/MWh)	☐	☒	☐	☐	☐	☐	☐	☐
N (g/MWh)	☐	☒	☐	☐	☐	☐	☐	☐
CO2 equivalent (kg/MWh)	☐	☒	☐	☐	☐	☐	☒	☐
SO2 equivalent (kg/MWh)	☐	☒	☒	☐	☐	☐	☐	☐
Particulates equivalent (kg/MWh)	☐	☒	☐	☐	☐	☐	☐	☐
TOPP equivalent (kg/MWh)	☐	☒	☒	☐	☐	☐	☐	☐
Land requirement (m2/MWh)	☒	☒	☐	☐	☐	☐	☐	☐
Direct employment (People/TWh)	☐	☐	☒	☐	☐	☐	☐	☒
Total employment (People/TWh)	☐	☐	☒	☐	☐	☐	☐	☒
Net plant efficiency	☒	☐	☐	☐	☐	☐	☐	☐
Diversity of supply	☐	☐	☐	☒	☒	☐	☐	☐
Peak load response	☐	☐	☐	☒	☐	☐	☐	☐
Risk aversion	☐	☐	☒	☐	☐	☐	☐	☐

Figure 4.3: Goals vs. Criteria matrix used to record and display the decision process intent.

4.6 Constructing the Decision Process in OUTDO

This section presents the *Issues Brainstorming* and *Positions to Reach the Goals Set* tasks in the OUTDO decision framework. It consists of the IBIS structure development and is the beginning of the construction of the decision process. Firstly, as explained in Section 3.4, the user needs to decide the intention of recording the decision rationale and choose between the standardised decision and the design decision process approaches. The aim of the case study is to find a recommended electricity generation technology for ten different locations in the UK for the construction of a new 700 MW power plant (or the equivalent to 700 MW capacity in solar PV or onshore wind projects) at a selected location. These locations are London, South West England, South East England, Yorkshire and the Humber, East England, North West England, South

Wales, North Wales, Oxfordshire and Scotland. Northern Ireland was not included in this study. As the decision process will be used several times for different locations and possibly in the future, the standardised decision process approach is the best one to use.

The construction of the decision process begins with brainstorming on the main issue to be resolved, which is “*What is the selected electricity generation technology?*” as shown in Figure 4.4. In this figure, the list of electricity generation technologies that are considered viable for the UK are included as position nodes (i.e. *Nuclear plant*, *Natural gas plant*, *Biomass plant*, *Photovoltaic cell*, *Coal plant*, *Geothermal plant* and *Wind turbine*) and are linked to the main issue node. Some types of electricity generation technologies were not included in the list. Hydropower was not included because its theoretical generation capacity can provide only 3% of the country’s 2020 renewable energy electricity needs and, due to environmental impacts and other restrictions, the real available capacity would be considerably less [180]. Wave and tidal stream technologies were not included as they are yet to become mature technologies and there are very few operating commercial systems [181]. Tidal range power was not included as it would not work well with the OUTDO standardised decision process approach, in particular this case study, because it is limited to specific sites [181]. Pumped storage would contribute to a more flexible electricity grid management, but it is not an electricity generation technology, it is an alternative for electricity storage.

Some of the technologies are analysed in further detail. For instance, *the Wind turbine position node* is connected to another issue node called “*What is the selected wind turbine?*”, which is used to choose between offshore and onshore wind turbines. The map nodes in the third row of nodes from top to bottom in Figure 4.4 are used to expand the description of the technologies the node is named after. For example, the

window displayed in Figure 4.5 corresponds to the map node called *Coal Plant* in Figure 4.4. The arrows pointing from the map nodes to the position nodes have no significance to the decision matrices; they are only used to indicate that the map node expands the position node's concept. Similarly, the arrows connecting the issue node "*What is the selected cooling system?*" to the map nodes are only used to show that the map nodes have an issue in common. The reason why they have an issue in common is because the map nodes involve thermoelectric technologies that need cooling system in their steam cycles. Note the *Solar Plant* map node includes nodes describing both thermoelectric (concentrating solar power) and non-thermoelectric (photovoltaic) technologies. The number on the bottom left of the map nodes shows how many nodes are inside that map node, the number on the bottom right, for example in the *Nuclear Plant* map node, shows that this node appears in more than one map node. The star symbol, in the top right of some nodes, implies that the nodes contain a written description inside them.

The issue node "*What is the selected electricity generation technology?*" will be analysed in detail in Chapter 5 to find the recommended electricity generation technology in the Yorkshire and the Humber region and will be re-used to find the recommended technologies for nine other UK regions in Chapter 6.

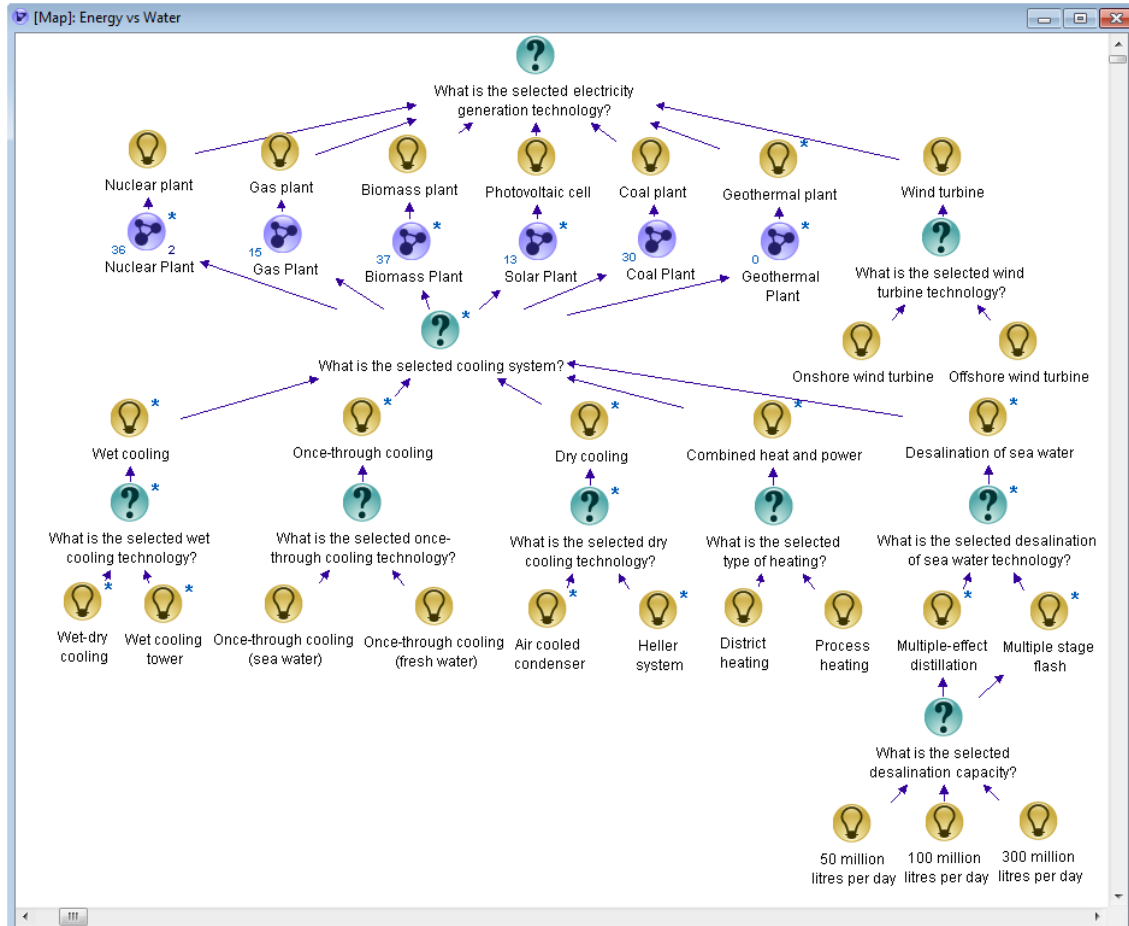


Figure 4.4: OUTDO nodes and map nodes used for the selection of electricity generation technology.

The issue node “*What is the selected cooling system?*” represents a detailed study of possible ways to use the waste heat from a thermal power plant. In a coal power station, usually 60% of the energy from the combustion of coal is dispersed to the environment [182] through *Wet cooling* (*Wet-dry cooling* or *Wet cooling tower*), *Once-through cooling* (which could use sea or fresh water), or *Dry cooling* (*Air cooled condenser* or *Heller system*). Instead of wasting 60% of the energy to the environment as heat, the plant could produce 3-8% less electricity and make use of this energy that would have been wasted as low temperature steam (70°C-180°C) using *Combined heat*

and power for District heating or Process heating, or produce water with Desalination of sea water (Multiple-effect distillation or Multiple stage flash).

Another relevant question is “*What is the selected desalination capacity?*”. The capacities considered in the study were *50 million litres per day, 100 million litres per day or 300 million litres per day*. Note, however, that *Combined heat and power* and *Desalination of sea water* are not cooling systems and, thus, should not be connected to the issue node “*What is the selected cooling system?*”. The reason for this purposely erroneous connection is to test the consistency check semantic capability presented in Section 8.2.2.

For the selection of coal technology, Figure 4.5 starts comparing an Integrated Gasification Combined Cycle (*IGCC coal*) [182] with *Pulverised coal* (PC) [182] and conventional *Steam turbine coal* technologies [183]. Three different IGCC plant designs, (a) the General Electric Energy gasifier in the radiant only configuration (*GEE radiant only coal*), (b) the ConocoPhillips gasifier technology (*CoP E-Gas coal*) and (c) the Shell gasifier technology (*Shell coal*) are compared, as well as, two PC designs, *Supercritical PC* and *Subcritical PC* [182].

Another relevant question related to the main question is “*What is the selected steam coal supplier to the UK?*” and the positions considered three current suppliers: *South Africa, Colombia and Russia* [184]. The last issue is to decide whether CCS should be included or not; an example of this is “*What is the selected carbon capture technology for IGCC (GEE)?*”. This is a major decision and will considerably influence the main issue in Figure 4.4. In the case of IGCC designs, which use pre-combustion technology, carbon capture is performed with *Selexol 2nd stage* technology. In the case of *Pulverised coal*, which uses post-combustion technology, carbon capture is achieved

with *Amine absorber* technology. Carbon storage is not mentioned here but it assumes a deep, saline aquifer for geological capture. More detail on the CCS technology used in this study is presented in Chapter 5.

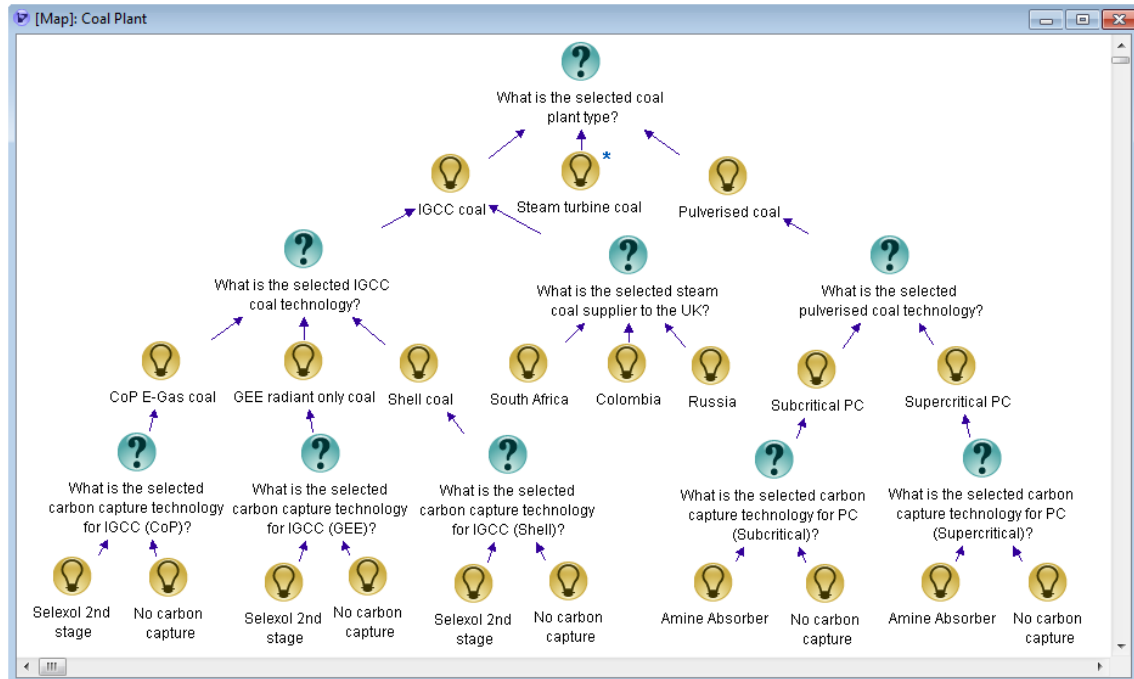


Figure 4.5: Expansion of the *Coal Plant* map node showing further details of the coal-based generation technologies [182].

The other map nodes in Figure 4.4, are the *Biomass Plant* shown in figure 4.6, and *Nuclear Plant*, *Gas Plant* and *Solar Plant* as shown in Figure 4.7. The *Geothermal Plant* map node does not have further information because its technology selection is site specific, thus the deep binary organic Rankine cycle was the only technology assumed in this work, due to its flexibility. The technology can operate at temperatures as low as 80°C, but it is usually implemented in the range of 125-165°C [185].

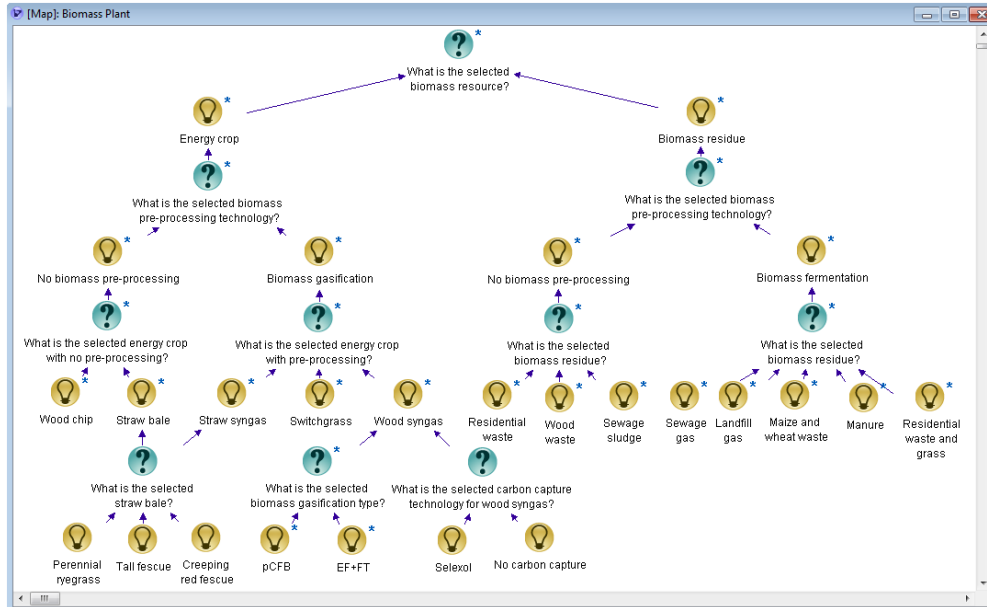


Figure 4.6: Expansion of the *Biomass Plant* map node showing further details of the biomass-based generation technologies [183].

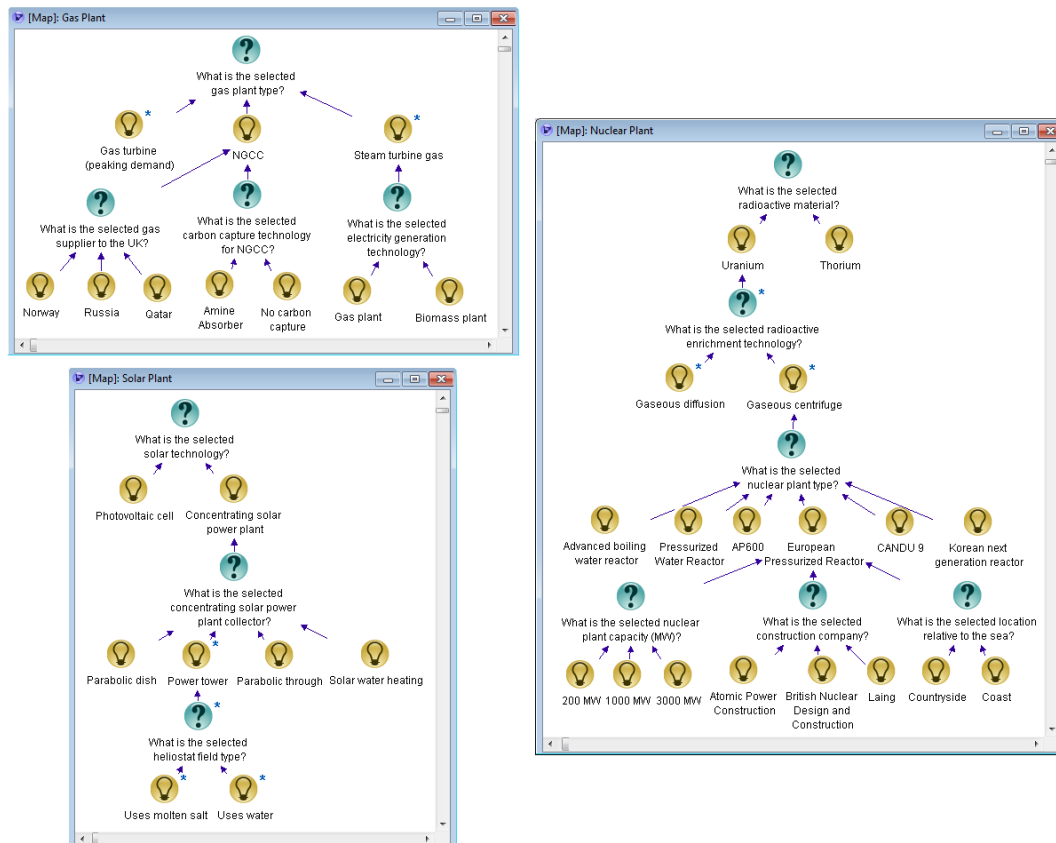


Figure 4.7: Expansion of the *Gas Plant* map node at the top-left [182, 183, 184], *Solar Plant* at the bottom-left [183, 186] and *Nuclear Plant* at the right [183, 187].

4.7 Conclusion

This chapter introduced the main issues the UK will face in the next decades to replace the nuclear and coal power plants that will be shut down and to provide, at the same time, affordable and low carbon emissions energy. In addition, this chapter discusses the considerable amount of water required for producing energy in thermoelectric power plants and the resulting problems, and presents cooling technologies that consume less or no water. One important example of the hierarchy of issues created in this chapter is that the decision maker should first select the steam condensation technology before he or she selects the electricity generation technology. Other issues that could have been included in this decision process involve waste water treatment, SO₂ removal technologies, wind turbine drive-trains, CO₂ storage technologies and so on.

Having clarified the problem the user first decides between a standardised or design decision process. Here the standardised decision approach was adopted as the same decision process is to be applied in different locations. Secondly, the user clarifies the goals he or she is trying to resolve. Thirdly, the user brainstorms the barriers that might impede the reaching of the goals and turns them into issue nodes. Fourthly, positions (solutions) that resolve the issues found by brainstorming are included in the decision process. The decision maker should repeat the second, third and fourth steps until the decision process reaches the required level of detail.

This chapter focused on the rationale management methodology in OUTDO without the selection of the positions and justifications for their selections. At this point, the decision rationale only allows the participants to have an overall idea of the decision process as the hierarchy of issues has been established. This process is time consuming

and requires considerable knowledge from the decision maker. As argued in Chapter 2, if OUTDO's features stopped at this point, recording the decision rationale would not be justified. This is because, the arguments and the qualitative analysis of the selection of the position are not included and thus the benefits for using OUTDO (effective rationale re-use) would not surpass its costs (time required to build the rationale). The next chapter presents and exemplifies a detailed analysis of the main issue nodes presented in this chapter using MCDA methods.

Chapter 5

Solution Development

5.1 Introduction

The decision maker has selected the goals that he or she wants to achieve with the decision process, carried out a preliminary study of the issues and possible positions to resolve the problem faced. Now it is time to start the detailed analysis using MCDA methods. This process, which consists of the *Solution Development* block in Figure 3.6, is explained in this chapter and is tested using the case study.

To populate the decision matrices belonging to each issue node, the user follows the steps that make up the different sections of this chapter. Section 5.2 gives details on how to select the criteria for MCDA problems. It then shows examples for two issue nodes, the “*What is the selected cooling system?*” and the “*What is the selected electricity generation technology?*” nodes. Section 5.3 presents the different methods for selecting weights of criteria and applies the Simos’ method [41] to the steam condensation problem. Section 5.4 shows the sources of the scores used to compare the positions. It presents the external models used to estimate the costs, water consumption and net plant efficiency of the steam condensation technologies and the databases used to compare different electricity generation technologies in the ten different regions of the UK. Section 5.5 presents ELECTRE III and shows that it is beneficial to apply more than one MCDA to a problem. Section 5.6 concludes the chapter.

5.2 Criteria Creation in OUTDO

Comparing positions to solve an issue is challenging. Every position has its positive and negative characteristics. The MCDA approach makes use of criteria as yardsticks to check how the positions perform with regard to particular aspects; for example, coal is a cheap source for electricity generation but it has high CO₂ emissions. The principles for the appropriate selection of criteria used in energy planning follow a set of rules. Firstly, the criteria chosen and the criteria weights have to represent the project goals. Secondly, the criteria have to reproduce the critical characteristics and the overall performance of the positions being considered, while avoiding redundancies. Thirdly, every position has to be represented by each criterion; for example, even though a *CHP plant* is an electricity generation technology, the criterion *Heat production* (where the higher the steam condensation temperature the better) can be used to compare different *CHP plant* designs but cannot be used to compare a *CHP plant* with other sources of electricity generation. Fourthly, the criteria should be quantifiable preferably in terms of units (e.g. £/MWh) or indices (e.g. sustainable indices). If this is not possible, the criteria should be expressed qualitatively if necessary represented by scores, for example, from 0 to 5. Finally, the clearer the analysis, the more rational the decision maker's result will be [41]. Some methods for criteria selection are the Delphi method, the least mean square method, the Minmax deviation method and the correlation coefficient method [41]. Due to the high number of papers in electricity generation decision making, the criteria selection for this type of issue was based on the literature, this is presented in the Criteria for Electricity Generation section. The criteria used to compare steam condensation technologies are presented and explained in the next section.

In OUTDO, a series of decisions are required to find the recommended course of action. To maintain the integrity and cohesion in the decision process, issues that address similar problems must have similar or identical criteria and criteria weights. For example, the decision maker could exclude the water consumption criterion when selecting to burn an energy crop¹⁴ or biomass residue¹⁵ in a thermoelectric power plant. In our case, the energy crop position is selected and the biomass residue position is rejected. When biomass is compared with coal, nuclear and gas power plants, it could be the case that the energy crop position is not selected due to the high consumption of water, but if the biomass residue position was the position being compared, it would have been the selected position. If water availability is of considerable concern, it should then be included as one of the criteria in all relevant issue nodes, assuming the same weight of criteria. However, one cannot generalise and assume that every issue must have the same criteria because different technologies have particular characteristics. The same applies to the criteria weights. For example, if nuclear reactor technologies are being compared, safety criteria will receive a higher weight than in choosing between boiler technologies for a coal fired power station.

5.2.1 Criteria for Steam Condensation Issues

It seems logical that a decision maker will firstly select the electricity generation technologies before looking at steam condensation issues. However, the results of the analysis of the selection of steam condensation technology will directly influence the

¹⁴ Energy crop is the intentional plantation of a low-cost, low-maintenance harvest for the production of biofuels (e.g. ethanol) or biomass for the incineration in a power plant (e.g. willow or poplar tree).

¹⁵ Biomass residue is the plant matter that is not used for food production or composting and, therefore, can be used to generate electricity in thermoelectric power plants.

electricity generation technology comparison and should be assessed before a decision on electricity generation technology is made. The reason is because there might be local demand for low grade heat from a cogeneration plant, a need for water desalination from a hybrid power plant or the lack of available fresh water which could impede the operation of cooling towers during the summer. The criteria used to compare the steam condensation technologies are focused on the local societal and environmental needs as well as on costs and technical aspects. Table 5.1 explains in detail the rationale behind each criterion.

Table 5.1: Criteria for the selection of steam condensation technology.

Criteria	Criteria Description
a) Capital cost (£/MWh)	Capital cost represents the money required for the construction and startup of the system. Note that in this comparison capital and O&M costs are considered separately. This is because it is advantageous to the decision maker to have both costs stated clearly. The levelised ¹⁶ capital cost is an estimated value, as it varies with the interest rate during the plant's life cycle. It should be noted, however, that the multiplication of the criterion weight and the normalisation factor should be the same for the capital and O&M cost criteria as they share the same units.
b) O&M Cost (£/MWh)	This criterion measures the operation and management costs of steam condensation systems. It is a very important factor especially when comparing dry cooling systems as a considerable amount of energy is consumed to run the system.

¹⁶ Levelised cost combines the capital, fuel, operating and maintenance costs into one value [190]. The levelised cost does not include future replacement, degradation costs, discount rates or financial costs, etc. which should be added for a more precise study. However, it includes the service life designed for the power plant and the risk of investment (technical maturity) of the plant into the decision process.

c) Water usage (kg/MWh)	This criterion measures the amount of water required in the steam condensation system operation.
d) Net plant efficiency, HHV (%)	The net plant efficiency criterion displays the overall efficiency of a NGCC plant with different steam condensation technologies. It indirectly shows the energy consumed to run the cooling systems or the thermal energy that was not used for electricity generation in hybrid plants.
e) Low grade heat demand (Boolean)	This criterion describes whether a location has a demand for low grade heat (from 70°C to 180°C). It takes either the value 1 if the local areas have high demand for low grade heat or 0 if it does not.
f) Proximity to the sea (Boolean)	This criterion is used to specify if the plant is going to be built on the coast or inland. This is important as desalination and sea water once-through systems are only feasible on the coast. It takes either the value 1 if by the coast or 0 if inland.

5.2.2 Criteria for Electricity Generation Issues

To maintain coherence throughout the decision process, the criteria and criteria weights chosen to compare the positions were the same for electricity generation related issues, with a few exceptions such as, for example, the inclusion of the *Diversity of supply*, *Peak load response* [173] and *Risk aversion* [173] criteria that are only relevant for the most general issue node (“*What is the selected electricity generation technology?*”). Table 5.2 presents these criteria and explains how some positions are scored. These criteria were based on the goals proposed in Chapter 4. It should be noted that these criteria scores consider the entire technology’s life cycle. Other potential

criteria for the selection of energy systems can be found in [45, 41, 140, 173, 178, 188, 189, 190, 191].

Table 5.2: Criteria used for electricity generation technology.

Criteria	Criteria Description
a) Cost (£/MWh)	This is the main criterion used to compare electricity technologies in this study. This criterion represents the levelised electricity costs including capital, fuel and O&M costs [192]. Global Parameters are used to adapt the cost of generation to different locations and interest rates. Most data were taken from GEMIS 4.6 [183] and [182]. The expressions used in this criterion are shown in detail in Appendix B.
b) Water usage (kg/MWh)	This criterion measures the amount of water required through the process life cycle. Normally, thermoelectric technologies consume the most water due to the need to condense steam. There are cases in which the water usage criterion has a negative sign. This is the case when desalination is selected to produce fresh water using the waste heat. The data were taken from GEMIS 4.6 and [182].
c) BOD (g/MWh)	This criterion determines the amount of biodegradable material introduced into water bodies. This increases bacterial cultures in the water body and, thus, reduces the dissolved oxygen, affecting the local aquatic environment [177]. The criterion scores were taken from GEMIS 4.6.

d) N (g/MWh)	The increase in nitrogen concentration in a water body stimulates the growth of photosynthesising algae cultures. Bacteria respiration and decomposition of the algae consume the dissolved oxygen and can cause eutrophication¹⁷ [177]. The criterion scores were taken from GEMIS 4.6.
e) CO₂ equivalent (kg/MWh)	CO₂ is associated with global warming and the reduction of its emission has been the focus of many governments, academics, and researchers [174]. The criterion scores were taken from GEMIS 4.6 and [182].
f) SO₂ equivalent (kg/MWh)	SO₂ is a harmful gaseous emission resulting mainly from coal and oil combustion; the emissions from natural gas technologies are usually smaller [193]. Its possible health effects are eye irritation, lung damage, infections, and cancer [170]. In addition, it can cause acid rain. The criterion scores were taken from GEMIS 4.6 and [182].
h) TOPP equivalent (kg/MWh)	The Tropospheric Ozone Precursor Potential represents the potential formation of near ground (tropospheric) ozone which can cause summer photochemical smog. It represents a regional impact that evaluates the photochemical ozone formation (smog) caused by the degradation of volatile organic compounds (VOC) in the presence of light and nitrogen oxides (NO_x) [175]. The criterion scores were taken from GEMIS 4.6.
i) Particulates (kg/MWh)	Particulate matter results from the incomplete burning of fossil fuels and of biomass or through the agglomeration of SO₄⁻² with other substances. It is toxic and can cause altered immunological response, systematic toxicity, decreased pulmonary function and heart stress [170]. The criterion scores were taken from GEMIS 4.6 and [182].

¹⁷ Eutrophication happens when organic decomposition and bacterial respiration consume the oxygen dissolved in a body of water, reducing the oxygen available for fish and invertebrates in the water [177].

j) Land requirements (m²/MWh)	Land requirement is a major source of concern, especially for biomass energy crops. This is because land that could be used for the production of food is used to produce fuel [178]. The data were taken from GEMIS 4.6.
k) Direct employment (People/TWh)	The energy sector is very important for the distribution of wealth in a country. In the UK it employs at present 173,000 people [193]. To increase this figure, which would be beneficial to society, the new technology employed should have a high rate of employment. The data were taken from GEMIS 4.6.
l) Indirect employment (People/TWh)	This criterion is similar to the one above but addresses the indirect job creation resulting from the implementation of the technology. The data were taken from GEMIS 4.6.
m) Diversity of supply (%)	The diversity of supply criteria intends to reduce the effects that fuel price fluctuation (energy security) and renewable energy intermittent supply of energy (energy stability) would have in the National Grid. The data were taken from MacLeay <i>et al.</i> 2012 [158]. This criterion is measured by the percentage of supply from each technology.
n) Risk aversion (Qualitative)	Maximum credible number of fatalities per accident is used here as a surrogate for risk aversion. The extent of the consequences of hypothetical extreme accidents, the largest being in the case of nuclear. The criterion was taken from Hirschberg <i>et al.</i> 2006 [173].
o) Peak load response (Qualitative)	Energy demand varies considerably throughout the day and the year. It is very important not to allow the demand to overtake the supply. Thus, the easier it is to control the supply of energy, the better the technology is. The criterion was taken from Hirschberg <i>et al.</i> 2006 [173].

There are two different units that the above criteria can be compared with; these are MW and MWh. The installed capacity (MW) measures the maximum electricity supply that can be generated at one time. Different technologies have different capacity factors¹⁸; for example, one MW from a nuclear power produces considerably more electricity than one MW from a wind turbines because a wind turbine only generates electricity when the wind is blowing. MWh, however, represents the actual electricity being produced and, thus, were used to compare the criteria. Figure 5.1 shows the capacity factor of different electricity generation technologies in the UK.

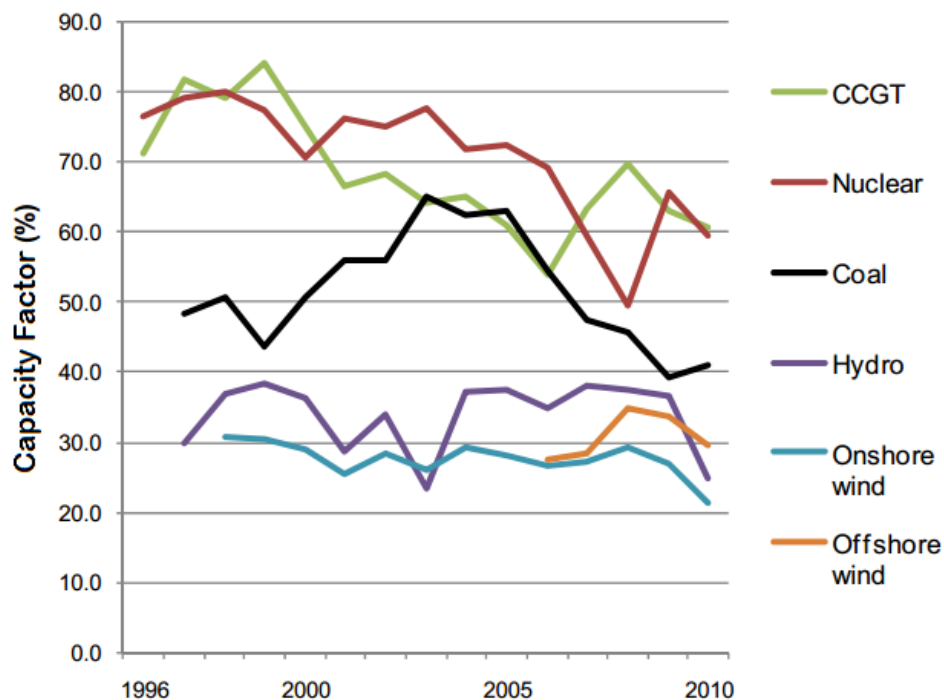


Figure 5.1: Capacity factors by technology type in the UK [193].

¹⁸ Capacity factor is the amount of electricity generated by a device in a year divided by the electricity generated by the same device in a year, assuming it produces electricity at its maximum capacity all the time (in other words, its capacity times a year).

5.3 Weighting the Criteria

Each criterion have its own contribution to the decision analysis. The weight of criteria is the coefficient that dictates the relative importance of a criterion in the decision [41]. In most cases, the larger the weighting value, the more relevant the criterion is to the problem. Different criteria weights will lead to different evaluation results. It is usually interesting to vary the weight of criteria to check how confident the decision maker is with regards to the final decision. The selection of the criteria weights has to be studied in the evaluation process [194]. This can be achieved by assigning equal weights or rank-order weights [41]. The equal weights method does not need any input from the decision maker. It has been criticised because, by assuming all criteria have equal weight, the relative importance among the criteria is ignored [41]. The rank-order weights method is divided into three approaches: the subjective, objective and combination weighting methods.

In the subjective weighting method, the decision makers directly express their preferences regarding the criteria. For example, in the subjective weighting methodologies, Simos, Swing-weighting, pair-wise comparisons are the most used [41]. The Simos method [195] is used in this thesis and is described in the next section. The Swing-weighting method is similar to the Simos method, but explicitly requires the decision makers to create a fictitious bad alternative in all criteria, so that the decision makers, knowing how bad their decisions can potentially be, would be more realistic when setting the weights [52]. The pair-wise method can use the AHP methodology, where each criterion is compared with the other criteria in a scale that ranges from one (not dominant) to nine (much more dominant) [52]. It is impractical to use AHP in OUTDO due to the usage of Global Parameters as explained in Chapter 2. However, it

could be beneficial to use this approach for weighting the criteria. The objective weights are obtained by mathematical methods which intend to take the score's variability and the interdependency of the criteria into account. The combination method can be applied to determine the integration of two or more methods. A good review of methods and tools used for the selection of criteria weights is shown in [41].

Another important issue when using the WSM and the WPM is that the user should be constantly aware of the normalisation factor. OUTDO includes only one alternative to calculate the normalisation factor, which is the inverse of the highest score of each criteria. It could be the case that with the variation of Global Parameters a criterion normalisation factor would vary. This would directly affect the comparison of all the positions as the normalisation factor would change the effective weight of the criteria relative to the overall decision process. For instance, as the average wind speed changes considerably with the location, the price of wind energy could increase, for example, more than tenfold. As the normalisation factor is the inverse of the highest score, the normalisation factor might decrease as well. Therefore, the relevance of the cost criteria, for the comparison of, for example, gas and coal, will reduce in the overall decision process. This is highly undesirable as the same decision process is to be used several times in different situations. A change in the normalisation factor might not be realised by the decision maker and result in an unwanted solution. A possible solution to this problem is suggested in Section 9.2.1 with the use of MAUT.

5.3.1 Steam Condensation Weight of Criteria

No Multi-Criteria Decision Analysis study comparing steam condensation technologies has been found in the literature. Thus, the Simos method [196] was used in

the selection of the weight of criteria for steam condensation technologies, and this is presented in Table 5.3. In this method, a card is used to represent each criterion and to create a rank in which the top card (criterion) is the most important in the decision and the bottom card (criterion) is the least important. In addition, white cards can be placed between criteria to further increase the importance of the criteria above the white card and reduce the importance of the criteria below the white card.

In the example given in Table 5.3, the letter of the criteria is the same as that used in Table 5.1. As the Yorkshire and the Humber region has an over-abstraction of fresh water [161] and has considerable demand for industrial heat [197], *Water usage (kg/MWh)* and the *Low grade heat demand* criteria have been positioned at the top together with *Net plant efficiency (HHV)*, which is the main criterion for the operation of the plant. Assuming a low electricity generation cost of 60 £/MWh, the cost of steam condensation is between 2-8% of a NGCC plant, thus was placed at the bottom of the rank with two white cards in between. As there are seven cards, they have points from 1 to 7, the card with the lowest point is given to the least important criteria. For each level of the ranked criteria the points are summed and divided per the number of criteria in each level, thus the weight of criteria is found.

The criterion *Proximity to the sea* was not included in the Simos method because this criterion is not intended to compare the positions. It is used as a requirement for the positions *Desalination of sea water* and *Once-through cooling* to be included in the analysis. If the location is not close to the sea, the score for *Desalination of sea water* and *Once-through cooling* will be -1 and, as the *Proximity to the sea* criterion has the weight of 21, these positions will not be recommended. The Simos methodology is

intended to be used in group decision making to facilitate the selection of criteria as agreeing on the ordering of cards can be simpler than selecting the weights directly.

Table 5.3: Weight selection for the comparison of steam condensation technologies.

Ranking	Criteria	Cards	Points	Average Weights
1	c, d, e	3	5, 6, 7	$(5+6+7)/3 = 6$
2	White Card	1	(4)	-
3	White Card	1	(3)	-
4	a, b	2	1, 2	$(1+2)/2 = 1.5$
Sum	5	7	21 ¹⁹	

5.3.2 Electricity Generation Weight of Criteria

An extensive search for MCDA studies applied to electricity generation planning in the UK was performed to find appropriate criteria weights for this thesis. Unfortunately, such a study has not been published in the literature or performed by the UK Government. The paper from the literature that most closely resembles the weights of criteria used to compare the electricity generation positions in this research are found in [173]. This study was performed in Germany, but its weights have been applied to the situation in the UK. The weights of criteria in this thesis assume the economy-centred case as given in [173] and have been modified as some criteria in [173] were not included in the case study and the case study has some criteria that [173] does not include. The financial requirement criterion in the paper is assumed to be the cost criteria, which equals 56%. The peak load response takes the same value of 4.8%.

¹⁹ Sum of points excluding the values in parenthesis.

Diversity of Supply has been included and is given a score of 3.2%. The weights of economic related criteria add up to 64%, two thirds of the 36% remaining has been directed to environmental related criteria (24%) and the remaining third has been assigned to the social related criteria (12%). The 12% for social related criteria is divided between direct employment (4%), risk aversion (6%), following the ratio in the paper, and indirect employment receiving half of the direct employment weight (2%). From the 24% given to the environmental related criteria, because water is an important issue in this thesis, and [173] does not address this topic, the water usage criterion is included and given a weight of 7%. CO₂ emissions and land requirement weights follow the same proportion as given in [173] and receive 6% and 4.5% respectively. The five criteria left (COD, N, SO₂ equivalent, TOPP equivalent, Particles equivalent) share the remaining weight which results in 1.3% for each criterion.

5.4 Scoring the Positions

In this case study, the positions vs. criteria scoring follows the WSM, because it is more frequently used, allows for a simpler analysis and is more transparent than WPM and ELECTRE III. The benefits of using WSM are that, firstly, the scores can be the quantitative value of the criteria, for example, for the *Cost* criteria the score will be the cost of that position (i.e. 71.9 £/MWh for nuclear power plants), making the analysis more transparent to the decision makers. Secondly, Global Parameters can be added to the equations to directly include the changes in parameters into the scores. The problems of using WSM are discussed in Section 9.2.1. Regarding the base case analysis to be applied in the other locations in the case study, the Yorkshire and the Humber region was selected because in the North Lincolnshire unitary authority area in

particular, water is over-abstracted. (current extraction is resulting in intolerable harm to the environment at low river flows [161]) and there is a demand for combined heat and power for district heating and industry. An example of a cogeneration (electricity and heating) plant in this area is the Immingham Power Station, which is the biggest cogeneration plant in Europe with a capacity of 730MWe [197].

5.4.1 External Models (Steam Condensation Technologies Scoring)

OUTDO is to be used as an integrated assessment tool where the analysis of different positions may be strengthened with different numerical simulation packages and optimisation models. These models are not part of OUTDO, for this reason they are called external models. Four external models were used in the analysis of the issue node “*What is the selected cooling system?*” in Figure 4.4. The models calculate the capital costs, operation and management costs, water usage and net plant efficiency of the different positions attached to the issue node. In order to keep the technologies comparison coherent, a NGCC plant was assumed producing 550 MWe. The net plant efficiency is calculated using Equation 5.1.

$$\eta = \frac{W_{out} - W_{in}}{Q_{HHV}} \quad \text{Eq. 5.1}$$

where η is the net plant efficiency, W_{out} is the electricity generated from the turbines, W_{in} is the electricity consumed in the process and Q_{HHV} is the gas combustion heat (assuming high heat value (HHV)).

The Integrated Environmental Control Model (IECM) version 6.2.4 [198] was used to find the scores for *Wet cooling tower* (Figure 5.2) and *Air cooled condenser* (Figure 5.3). The IECM was developed by the NETL in collaboration with Carnegie

Mellon University and is freely available. The environmental conditions assumed for the cooling system designed maximum capacity were 80% humidity and 32°C ambient temperature. The scores from the cooling tower were used to find the values for *Once-through (sea water)* using [165]. The Desalination Economic Evaluation Program (DEEP) version 4 [199] was used to find the score for *Multiple-effect distillation* (Figure 5.4), which is the selected *Desalination of sea water* position. DEEP is a free, Excel based model created by the IAEA for performance and cost analysis of hybrid sea water desalination power plants.

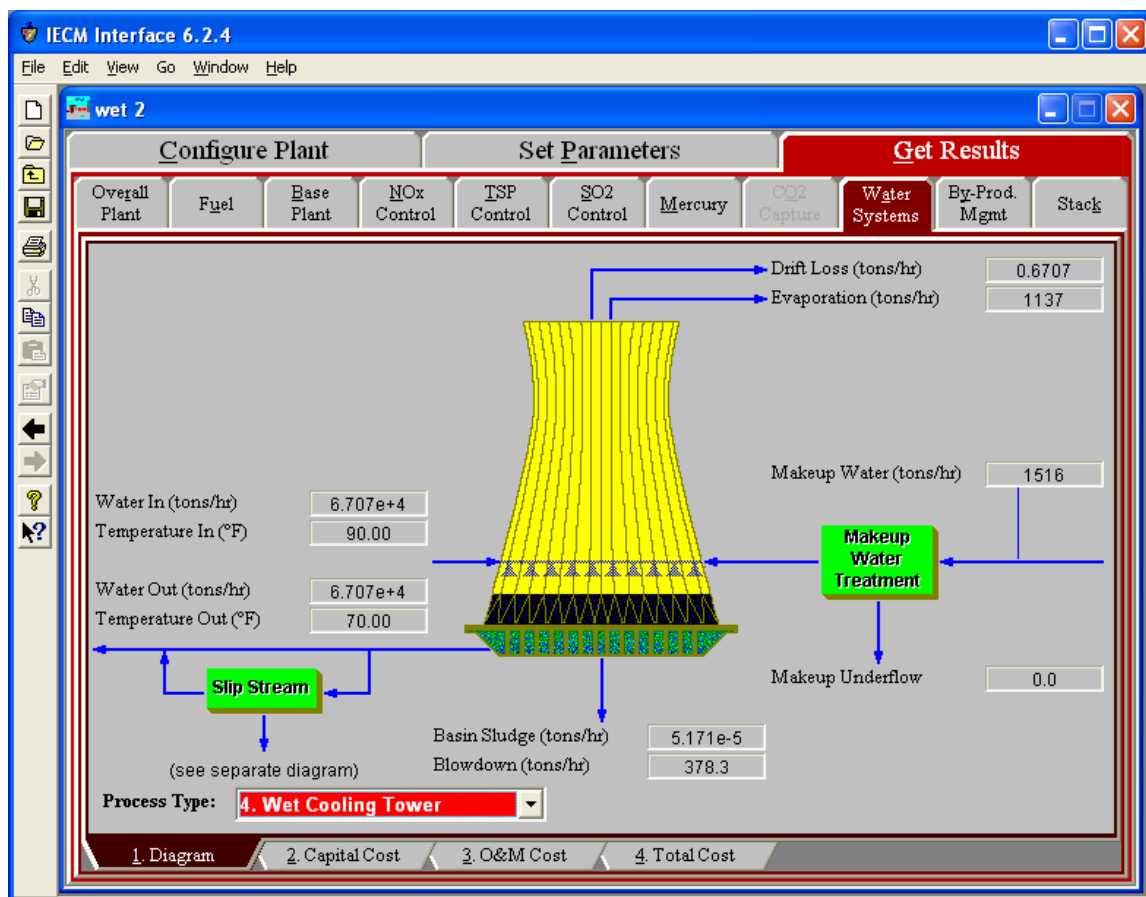


Figure 5.2: Using IECM to design wet coolers in thermoelectric plants.

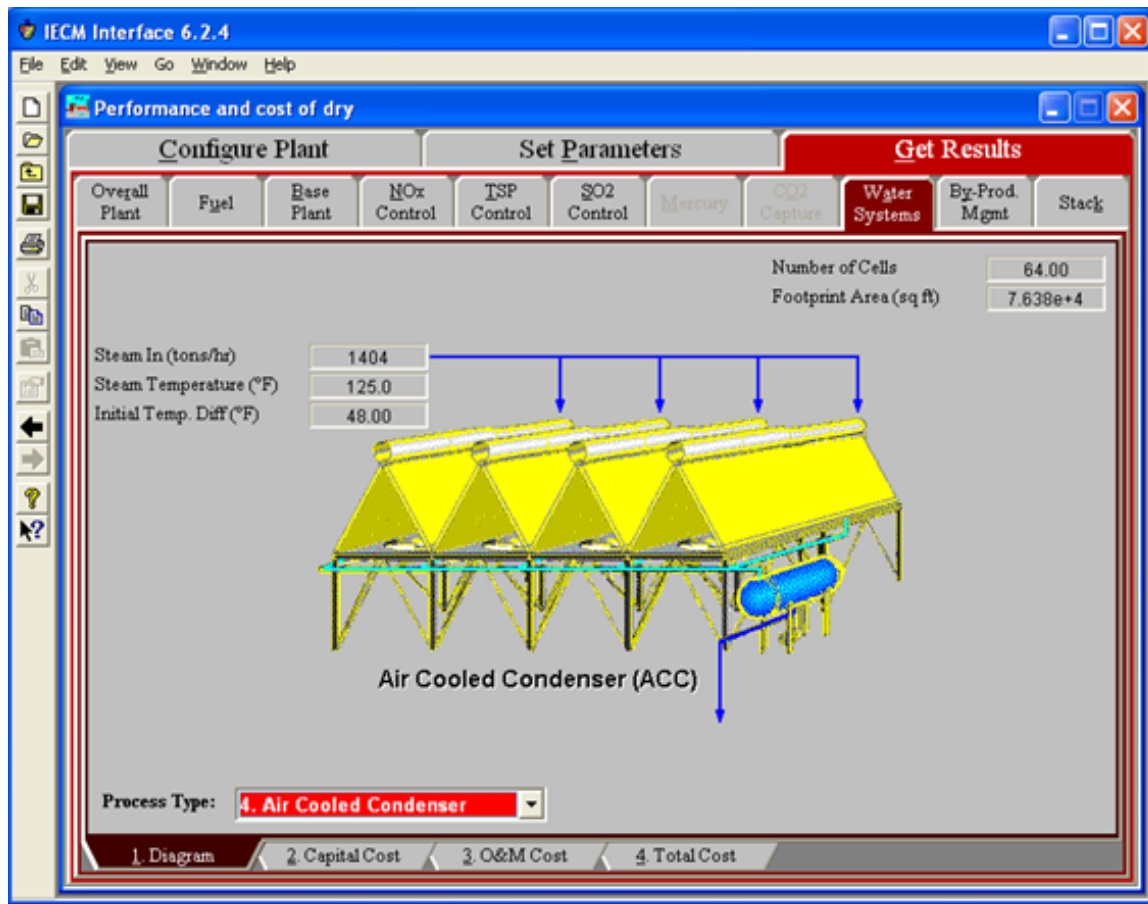


Figure 5.3: Using IECM to design dry coolers in thermoelectric plants.

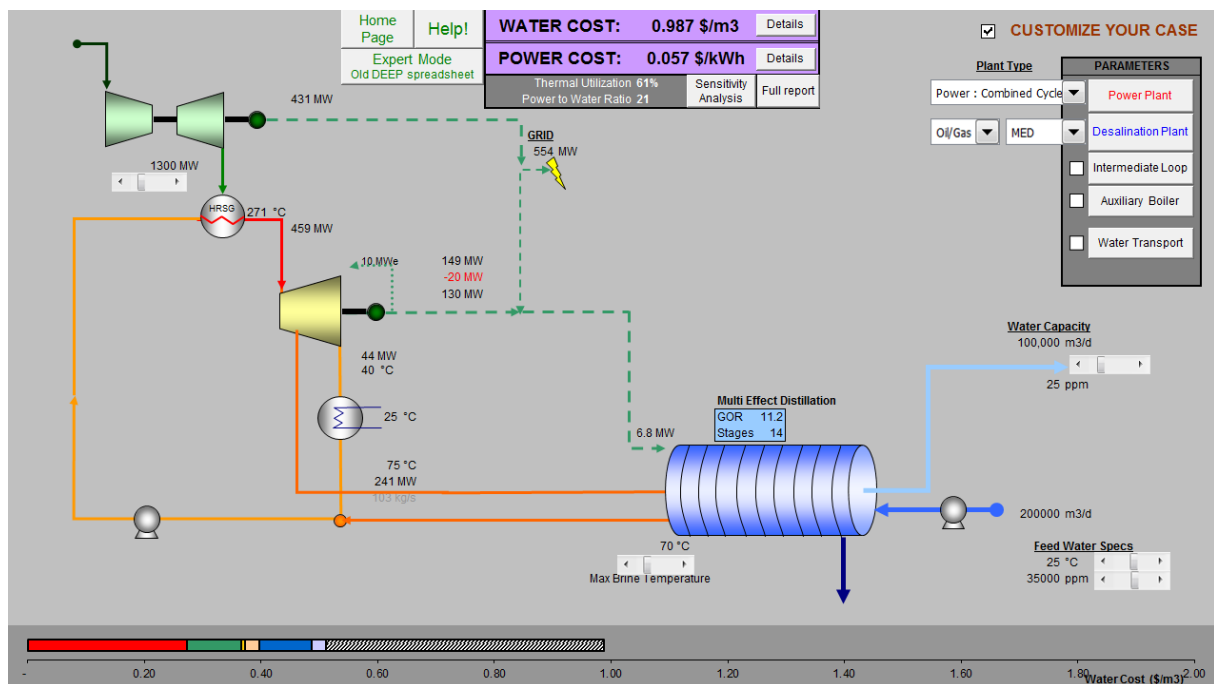


Figure 5.4: Using DEEP to design multiple-effect distillation in thermoelectric plants.

A simulation model of an IGCC power plant in Aspen Plus taken from [200] was adapted to represent a NGCC CHP plant shown in Figure 5.5. This simulation was used to calculate how a change in condensation temperature (stream 25 in the diagram) affects the net plant efficiency. The lower the temperature of the stream 25, the more electricity can be generated from the “LP” (low pressure) turbine in the diagram. However, if the condensation temperature is too low (close to ambient temperature), the heat from the steam condensation would be wasted. If the condensation temperature is relatively high (70-180°C), the heat can be used for district heating, for industrial purposes or to desalinate sea water. For desalination, the condensation temperature in DEEP was assumed to be 70°C and resulted in a net plant efficiency of 47.3%. Two condensation temperatures of 100°C and 120°C were used in the simulation shown in Figure 5.5 and their respective net plant efficiencies were found to be 44.59% and 43.36%.

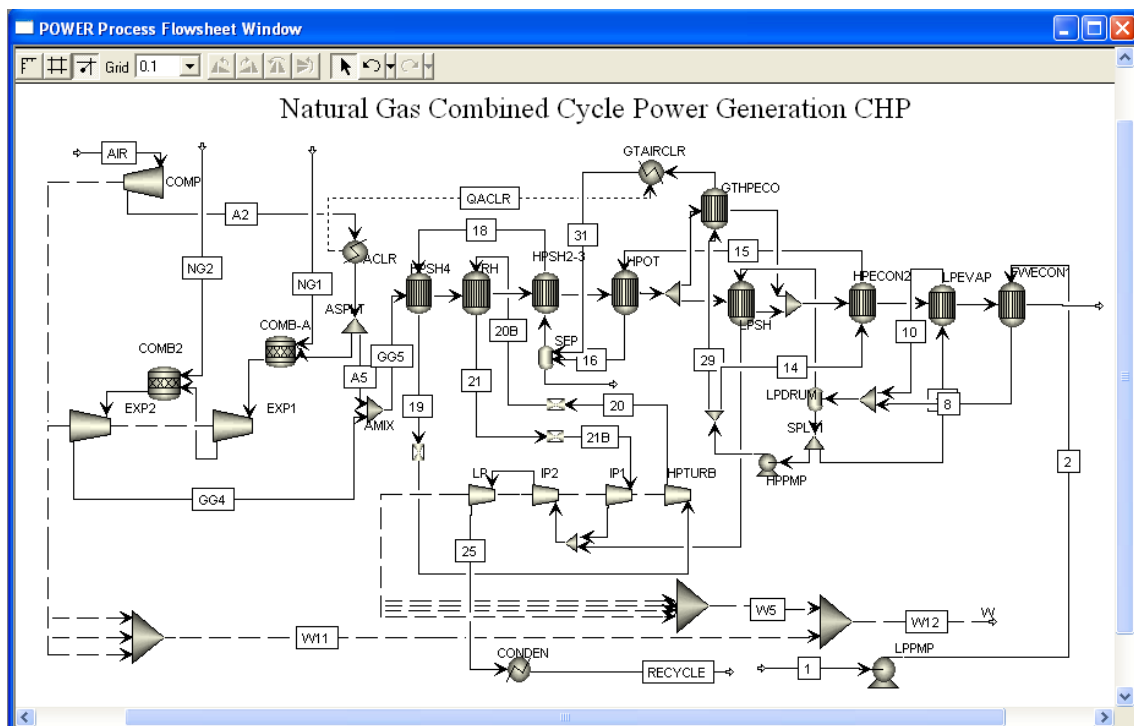


Figure 5.5: Simulation of a NGCC CHP plant using Aspen Plus [200].

Criteria	Combined heat and power	Desalination of sea water	Wet cooling	Dry cooling	Once through cooling	Weight	Normalisation Factor
Capital cost (£/MWh)	2.04	2.043	0.643	1.435	0.5864	-1.55	0.48948
O&M cost (£/MWh)	1.279	2.194	0.604	0.726	0.5811	-1.45	0.45579
Water usage (kg/MWh)	20.882	-7176.729	1124.865	0	0	-6	0.00014
Net plant efficiency (HHV)	44.585	47.307	49.255	48.4	49.56	6	0.0277
Proximity to sea	0	0	0	0	0	10	1
Low grade heat demand	1	0	0	0	0	6	1
Totals	10.99978	10.86266	6.35898	6.4758	7.40818		
System Recommended	Recommended						
Decision		Selected					

(a)

Criteria	Combined heat and power	Desalination of sea water	Wet cooling	Dry cooling	Once through cooling	Weight	Normalisation Factor
Capital cost (£/MWh)	2.098	2.043	0.643	1.435	0.5864	-1.55	0.47664
O&M cost (£/MWh)	1.315	2.194	0.604	0.726	0.5811	-1.45	0.45579
Water usage (kg/MWh)	21.478	-7176.729	1124.865	0	0	-6	0.00014
Net plant efficiency (HHV)	43.36	47.307	49.255	48.4	49.56	6	0.0277
Proximity to sea	0	0	0	0	0	10	1
Low grade heat demand	1	0	0	0	0	6	1
Totals	10.76962	10.90329	6.37177	6.50434	7.41984		
System Recommended		Recommended					
Decision		Selected					

(b)

Figure 5.6: Decision matrix used to find the recommended steam condensation technology, (a) assuming a condensation temperature of 120°C for the CHP position and (b) assuming a condensation temperature of 100°C for the CHP position

Figure 5.6 shows the results from the external models used in the decision matrix for the “*What is the selected cooling system?*” issue node. The criteria weights for the criteria involving costs share the same units (£/MWh), thus the criteria weights for *Capital cost* and *O&M cost* times the normalisation factor should be equal for both criteria, so that 1 £/MWh for *Capital cost* contribute the same as 1 £/MWh for *O&M cost* in the WSM analysis. Thus, *Capital cost* received a weight of 1.55 and *O&M cost* a weight of 1.45 to add up to 3 as presented in Table 5.3. It should be noted, however, that the weight of the cost criterion is negative because the lower the cost of the technology, the more interesting it is for the decision maker. Assuming a condensation temperature of 120°C (net plant efficiency of 43.4%), the decision matrix recommends *Desalination of sea water* as shown in Figure 5.6 (b). However, if the condensation temperature is reduced to 100°C, which would result in an increase of the *Net plant efficiency (HHV)*

to 44.6% and assuming that a reduction of 20°C in the steam condensation temperature does not affect the *Low graded heat demand* criterion weight, the new recommended option would be *Combined heat and power*, as shown in Figure 5.6 (a).

5.4.2 Electricity Generation Technologies Scoring

The sources used to score the criteria in the issue nodes involving electricity generation technologies are shown in Table 5.2 and mainly come from the Global Emission Model for Integrated Systems (GEMIS) v.4.6 database [183] and a publication from the U.S. National Energy Technology Laboratory (NETL) [182]. GEMIS v.4.6 is a freely available database that was previously hosted by the Öko-Institut, and is now hosted by the International Institute for Sustainability Analysis and Strategy (IINAS) [201]. The GEMIS v.4.6 database includes more than a thousand products such as electricity, heat, oil, gasoline, coal, wood and ten thousand processes such as coal plant, refinery, coal extraction and wind farms. These data include the complete process life cycle (i.e., construction, operation and decommissioning of all processes from the natural resource extraction to product delivery). There are some exceptions, for example, the decommissioning of nuclear power plants and storage of nuclear waste is not included and had to be manually included. Most data come from Germany. As Germany and the UK have similar levels of development, the data have been adapted for use in the UK. The conversion factor used to convert EUR to GBP is 0.8258 (1st July 2010). The NETL publication [182] assumes values from the U.S. and gives a very good description of costs, gaseous emissions and water consumption of IGCC, PC and NGCC power plants with and without CCS. However, this source does not include all the life cycle costs and emissions; it only focuses on the electricity generation process in

the power plant. Similarly to GEMIS, the data from NETL was adjusted for use in the UK. The conversion factor to convert USD to GBP is 0.6644 (1st July 2010).

The positions compared in the main issue node (“*What is the selected electricity generation technology?*” in Figure 4.4) are the positions selected in the map nodes in Figures 4.5, 4.6 and 4.7. All the issue nodes in all the map nodes in the case study have a decision matrix suggesting a recommended position. However, due to space limitation, the only map node, apart from the *Energy vs. Water* map node (Figure 4.4), that has its issue nodes explained is the *Coal Plant* map node (Figure 4.5). The *Coal Plant* map node is important because, as well as selecting the coal plant technology to be used, it dictates whether CCS should be included or not in the coal plant being compared in the main issue node in Figure 4.4.

Figure 5.7 compares the coal plant technologies; the comparison is bottom up. Firstly, the issue nodes at the bottom of the figure have to be decided, for example, “*What is the selected carbon capture technology for IGCC (GEE)?*”. For this analysis, the year of the project to start operation is 2040²⁰, the location is Yorkshire and the Humber and the CO₂ emission cost is 0.025 £/kg of CO₂. This is not the value assumed by the DECC in 2040 [202], but it is used to showcase the Propagation feature (Section 6.4). In the case of IGCC designs, CCS is recommended for the *GEE radiant only coal* design using a pre-combustion technology for carbon capture technology based on *Selexol 2nd stage*, but it is not recommended for the *CoP E-Gas coal* and *Shell* designs. Selexol is a solvent (mixture of dimethyl ethers) used to absorb CO₂ and SO₂. Note that in the case of PC, which uses post-combustion technology for carbon capture (*Amine*

²⁰ The date the decision is to be implemented is important because it will alter the decision analysis. For example, in this study, gas prices are set to rise and capital costs for photovoltaic cells and wind turbines are set to fall with time. It is, however, important to know the recommended decisions in the future to make a better decision in the present.

absorber), CCS is not recommended. Secondly, the second row of issue nodes from the bottom, for example, the “*What is the selected IGCC technology?*” issue node will automatically compare the positions selected in the issue nodes below, i.e. assuming CCS for GEE technology and no CCS for Shell technology. This is good because it could be the case that CoP or Shell designs without CCS might still be better than GEE with CCS assuming the given set of criteria weights. Finally, the issue node at the top (“*What is the selected coal plant type?*”) compares the *IGCC* (GEE) with CCS, *Pulverised coal* (Supercritical), without CCS and conventional *Steam turbine coal* without CCS. It should be noted that the criteria and weights are the same for every issue node in this map node. Global Parameters are used to automatically change the analysis of the issue node above regarding the resolution of the issue nodes below in the decision process. This is explained in Section 6.2.

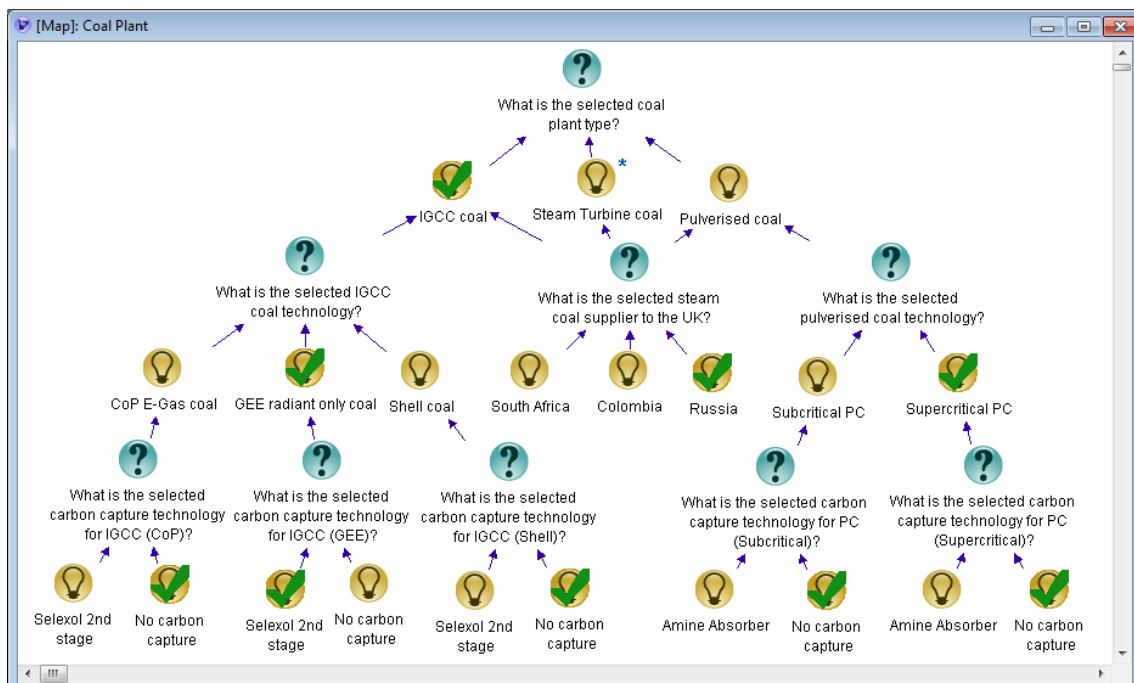


Figure 5.7: Expansion of the *Coal Plant* map node for the York and the Humber region, assumed cost of CO₂ emissions of 0.025 £/kg of CO₂ [182] and plant start-up in 2040.

Assuming Yorkshire and the Humber region, in 2040, with a CO₂ emission cost of 0.025 £/kg of CO₂, Figure 5.8 compares the following positions. *Nuclear plant* assuming the European Pressurised Reactor design (EPR), *Wind turbine* assuming onshore turbines, *Photovoltaic*, assuming conventional silicon-based technology, *Geothermal plant*, assuming deep binary organic Rankine cycle, *Coal plant* assuming IGCC with second stage Selexol for carbon capture and deep, saline aquifer for geological carbon storage (hence the low CO₂ emissions equivalent), *Gas plant* assuming NGCC without CCS, *Biomass plant* assuming wood syngas and energy crop, without CCS.

Figure 5.8 shows the Values view of the decision matrix for the issue node “*What is the selected electricity generation technology?*”. Each value is the result of the operations of the expressions in terms of the constants and Global Parameters in the Formula view. The cost criterion is a special case, it includes expressions where parameters such as solar radiation, wind speed, biomass plantation yield have been used to adapt the decision analysis to different regions of the UK, see Chapter 6. For some criteria (e.g. *CO₂ equivalent (kg/MWh)*), the larger the score, the worse it is for the position being compared. In these cases, the weights of criteria have a negative value. As it can be seen, for the case of the Yorkshire and the Humber region, Coal with CCS is the recommended position to be considered in 2040, assuming a CO₂ emission cost of 0.025 £/kg, the Global Parameter values shown in Figure 6.1 and the given criteria weights. Some important things to notice are, firstly, that the *Water usage (kg/MWh)* criterion has some scores with negative values. This is because water is not consumed, but is being produced as *Desalination of sea water* is the recommended position for the “*What is the selected cooling system?*” issue node. Secondly, with the assumed CO₂

emissions cost, Gas does not include CCS (this decision is made in the Gas Map node, which is not shown) leading to higher CO₂ emissions than Coal with CCS. Thirdly, the cost metrics utilised in this study provide an estimate for capturing, transporting, storing and monitoring carbon dioxide for a relatively simple project. The cost can vary considerably as a function of the reservoir characteristics, type of land and purchasing of sub-surface rights of the properties where the pipeline is to be built. For more detail on the uncertainties regarding the cost of CCS see [182].

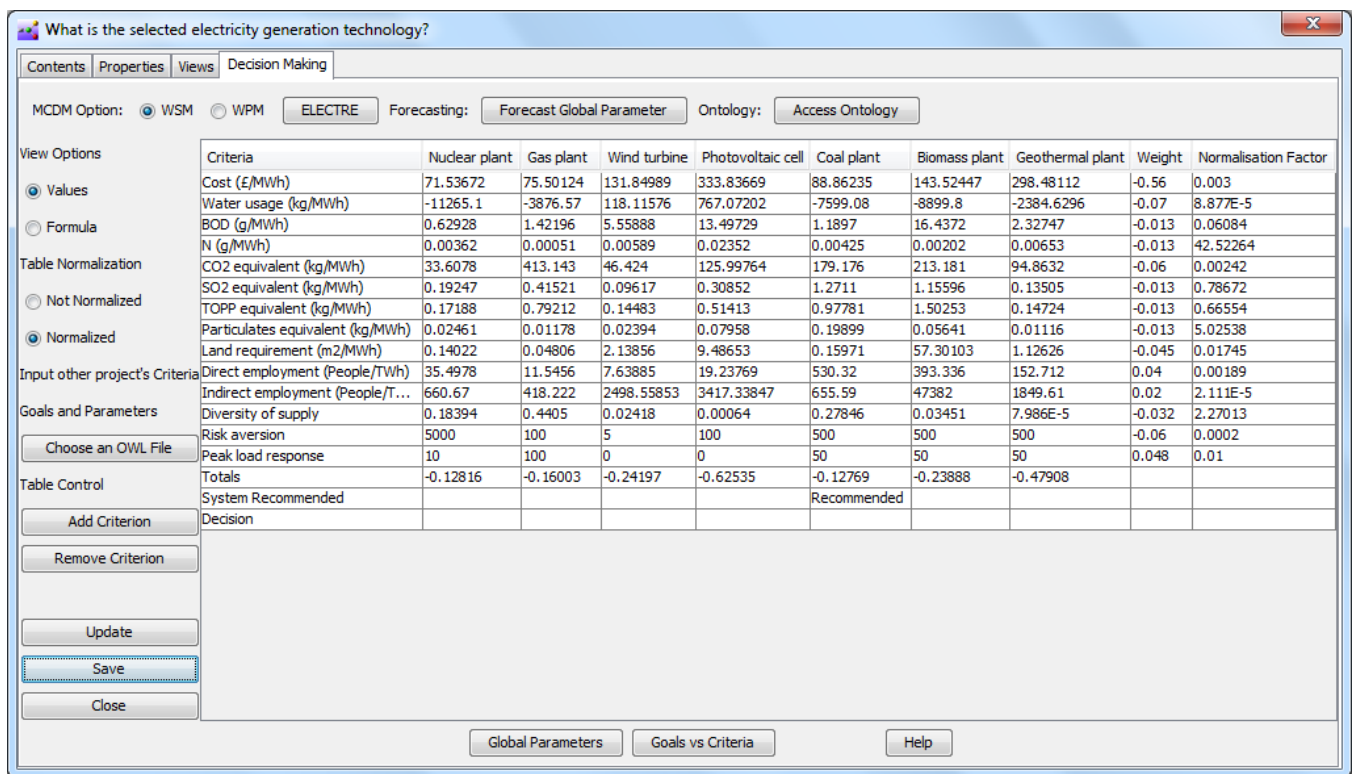


Figure 5.8: Values view of the main issue node (Yorkshire and the Humber region; CO₂ emission cost 0.025 £/kg; 2040).

Alternatively, instead of using data from the GEMIS v.4.6 database, the data in Figure 5.8 could have been taken from MARKAL modules or similar systems. This would contribute to a more precise analysis as the data will be specific to the UK. The

results from the MARKAL models would be extracted to the decision matrix through the use of Global Parameters.

5.5 Further Analysis: ELECTRE III

As it can be seen, the WSM total value of the analysis in Figure 5.8 for *Coal plant* and *Nuclear plant* are very similar. In order to certify that *Coal plant* is the recommended position and because this problem involves multi-dimensional criteria, including inaccurate, imprecise or uncertain data (pseudo-criteria) [65], a more sophisticated MCDA method can be applied to allow for a pairwise evaluation of the positions and contribute to a more robust decision. ELECTRE I, II or III methods were implemented within OUTDO for this reason. The distinctive characteristics of ELECTRE III are its capability to deal with a high degree of uncertainty in the input data and its ability to be less influenced by data variations [203]. ELECTRE III was, therefore, applied to the decision matrix in Figure 5.8.

However, there are no precise rules for defining veto, preference and indifference thresholds, explained in Section 2.3.7. The establishment of thresholds comprises the assessment of errors in the scores, rules of procedure and considerable subjective input from the decision maker, but the overriding approach is the use of “common sense” [203]. The thresholds in the case study, as shown in Table 5.4, were set relatively high to avoid vetoing some positions and to result in a relatively well distributed concordance and credibility matrices. It should be noted that for the implementation of ELECTRE III, the weights of criteria have to be positive in the decision matrix. In this case, the user has to select between ascending (ASC) and

descending (DEC) for each criteria in Figure 5.9 regarding the criterion performance and score values.

Table 5.4: Criteria used for electricity generation technology.

Criteria	Highest Score	Veto	Indifference	Preference	Order
a) Cost (£/MWh)	333.84	300	0	70	DEC
b) Water usage (kg/MWh)	11265.1	20000	0	7000	DEC
c) BOD (g/MWh)	16.43	40	0	14	DEC
d) N (g/MWh)	0.0235	0.03	0	0.02	DEC
e) CO₂ equivalent (kg/MWh)	413.143	2000	0	700	DEC
f) SO₂ equivalent (kg/MWh)	1.2711	3	0	0.7	DEC
h) TOPP equivalent (kg/MWh)	1.5025	3	0	0.7	DEC
i) Particulates (kg/MWh)	0.1990	0.3	0	0.2	DEC
j) Land requirements (m²/MWh)	57.30	100	0	14	DEC
k) Direct employment (People/TWh)	530.32	1000	0	350	ASC
l) Indirect employment (People/TWh)	47382	1000000	0	40000	ASC
m) Diversity of supply (%)	0.4405	2	0	0.7	DEC
n) Risk aversion (Qualitative)	5000	8000	0	3500	DEC
o) Peak load response (Qualitative)	100	300	0	70	ASC

Click to chose the Threshold or enter the value on the tables below

Define Veto Thresholds

C...	Wat...	B...	N...	CO...	S...	T...	P...	L...	Dir...	Indir...	D...	Ris...	P...
300.0	20000.0	40.0	0.03	2000.0	3.0	3.0	0.3	100.0	1000.0	1000000.0	2.0	8000.0	300.0
SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM
DEC	DEC	DEC	DEC	DEC	DEC	DEC	DEC	DEC	ASC	ASC	DEC	DEC	ASC

Preference Threshold

C...	Wa...	B...	N...	C...	S...	T...	P...	L...	Dir...	Indir...	D...	Ris...	Peak l...
70.0	7000.0	14.0	0.02	700.0	0.7	0.7	0.2	14.0	350.0	40000.0	0.7	3500.0	70.0
SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM

Indifference Threshold

C...	W...	B...	N...	C...	S...	T...	Pa...	La...	Di...	In...	Di...	Ri...	Pe...
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM

Ascending Order

Concordance Table

PARAMETERS

outranking model: Electre III

Veto Thresholds: Cost (£/MWh)=300.0 Water usage (kg

Ascending Order shown below:

[Nuclear plant] [Gas plant] [Coal plant]

[Wind turbine] [Biomass plant]

[Geothermal plant]

[Photovoltaic cell]

PARAMETERS

outranking model: Electre III

Veto Thresholds: Cost (£/MWh)=300.0 Water usage (kg

Descending Order shown below:

[Gas plant] [Coal plant]

[Nuclear plant]

[Wind turbine] [Biomass plant]

[Geothermal plant]

[Photovoltaic cell]

III

Save Report

Close Save Help

Figure 5.9: ELECURE III panel in OUTDO.

Figure 5.9 shows the ELECTRE III panel in OUTDO. The text area on the right displays the positions order of preference for the ascending and descending distillations, where the positions at the top are better than the positions at the bottom. The algorithms used in both distillations are explained in Section 2.3.7. The final ranking is the combination of the ascending and descending distillations, shown in Section 2.3.7. This corresponds to *Coal plant* and *Gas plant* as the recommended positions, *Nuclear plant* as the second recommended position, *Wind turbine* and *Biomass plant* as the third recommended positions, *Geothermal plant* as the fourth recommended position and *Photovoltaic cell* as the fifth recommended position. Combining the results from WSP and ELECTRE III analysis strengthens the recommendation of *Coal plant* as the solution for this particular decision matrix.

Even though ELECTRE III can be shown to be useful to support a single decision making process, it does not seem to work very efficiently in OUTDO. This is because the Global Parameters, one of the important features in OUTDO, constantly

change to adapt the decision analysis of different scenarios. ELECTRE III does not suit this purpose well because each decision requires a considerable amount of time and effort to select the right threshold for each different analysis. This question is further discussed in Section 9.2.1.

5.6 Conclusion

This chapter demonstrated how to apply Multi-Criteria Decision Analysis to a decision process in OUTDO. This application consists of the selection of criteria and their corresponding weights, the scoring of positions vs. criteria and the problems involving MCDA methods. Criteria and their weights are used to express the importance of the goals that have to be achieved with the decision process. Different methods for the selection of criteria and their weights have been presented. Once these are chosen, the decision maker has to ensure that they are the same in all issue nodes as far as it is applicable, to keep the decision process coherent. However, in some cases, new criteria have to be created to compare the different set of positions. For instance, issues involving electricity generation will include criteria that are not relevant to the comparison of steam generation technologies and vice versa.

A variety of external packages were used to calculate the cost, water consumption and plant efficiency for the comparison of steam condensation technologies (i.e. DEEP, IECM and Aspen Plus). External packages are used to better analyse the positions and thus contribute to a better decision process. It was argued that the steam condensation technology should be selected before the electricity generation technology as water availability is becoming a major issue, the waste heat from thermoelectric power plants could be used for heating purposes or for desalinating

water, and the selection of steam condensation technology would directly affect the comparison of electricity generation technologies.

The second stage of the standardised decision process approach was also introduced in this chapter. It consists of finding the recommendation for an issue node and using this recommendation in the comparison of the subsequent issue. For example, the GEE design is the recommended IGCC technology. Therefore, the GEE design will be used in the comparison of the different types of coal plants (i.e. IGCC, PC and conventional steam cycle). Furthermore, it was demonstrated that if the user is not sure about a specific decision, he or she can apply other MCDA methods to improve the analysis.

The next chapter will use the MCDA studies presented in this chapter and apply different OUTDO features to improve the analysis. These features include the variation and forecasting of Global Parameters. In addition, the recommended positions will be determined for different areas in the UK. Finally, the author will conclude the case study by presenting the selected positions in the decision process.

Chapter 6

Global Parameters

6.1 Introduction

This chapter explores in detail how Global Parameters and the features related to them support decision making in OUTDO. They are represented by the *Global Parameters*, *Future Analysis* and *External Models* blocks in Figure 3.6. Global Parameters consist of the variables in expressions in the decision matrices. The parameters relevant to the problem may vary with time, location or circumstance. Global Parameters empower the decision maker to explore the impact of changes of parameters on each decision matrix. As the recommendations coming from one issue might influence the analysis of other issues, Global Parameters can change the result of the analysis of one issue node which affects the resolution of other issue nodes, thus making the decision rationale re-use more dynamic and efficient. There are different types of Global Parameters; some are related to the source from which the parameters are taken and some concern the way in which they are calculated. Global Parameters are arguably the most important feature in OUTDO and therefore a whole chapter is dedicated to them.

Section 6.2 presents the different types of Global Parameters and some of the Global Parameters used in the case study. Section 6.3 presents the main Global Parameters used in Chapter 5, and shows how they were calculated or where they were taken from, and presents the main expressions used in the case study. Section 6.4 presents and exemplifies the Propagation and Sensitivity Analysis features. Section 6.5 presents the Future Analysis feature, shows some examples of its implementation and

finalises the case study with the prediction of the recommended electricity generation technologies, with and without CCS, for ten different regions in the UK. Section 6.6 explains that the Global Parameters feature can be used as a hub where information from other DSSs, optimisation and simulation packages can be appropriately combined to improve the scoring of the positions in the decision process. Section 6.7 concludes the chapter.

6.2 Global Parameter Types

There are several different mechanisms to assign a value to a Global Parameter, as listed below.

- Manually fixed by the user. This is the most straightforward way to set a Global Parameter value and should be used if a quick change in parameter is needed, without further analysis. An example is *CO2_Emissions_Cost* (cost of CO₂ emissions in GBP per kg CO₂); see Figure 6.1.
- Imported from the web. OUTDO allows parameters to be imported from web databases, e.g. financial data such as stocks, currencies and commodity prices from <http://finance.yahoo.com>, or weather data and forecasts from <http://weather.unisys.com>, etc. A good example of this functionality is when a stock trader wants to decide which stocks or commodities to buy or sell. As the trader's personalised decision rationale is already recorded, he or she would only have to update the stock or commodity prices to obtain a new recommendation. Another example of this functionality is when an old decision rationale needs to be re-evaluated. In this case, the update of Global Parameters might considerably change the final decision. It should be noted, however, that this feature might not be

appropriate for long-term decisions, as daily fluctuation of the parameters might lead to wrong estimates of future trends. Probabilistic forecasting should be used in this case. An example of this Global Parameter type is *Oil_Price* (price of crude oil in USD per barrel); see Figure 6.1.

- Imported from Excel. The user can import a Global Parameter value from a cell in an Excel file. This allows the user to create his or her own models in Excel to improve the data used for comparing different positions. An example is *Desalination_Capital_Cost* shown in Figure 6.1. This is the capital cost of desalinating 100 million litres of water per day calculated with DEEP 4, an Excel based application [199]. Some external models can be connected to OUTDO through Excel (e.g. Aspen Plus [1]). OUTDO is to be used as an integrated assessment tool where the analysis may be strengthened with different numerical simulation packages and optimisation models. OUTDO offers a means by which scattered information from different sources can be brought together in a meaningful and organised way. This will allow the decision maker to consider different aspects of the problem in detail, resulting in better decisions. An example is *CHP_Efficiency* in Figure 6.1. This is the efficiency from a simulation of a cogeneration NGCC plant in Aspen Plus [1] (explained in the External Models section in Chapter 5).
- Varying with respect to time. A parameter t is available in the Global Parameters window to represent time. The user can create parameters that are time dependent expressions. An example is *Gas_Fuel_Cost* as shown in Figure 6.1. It represents the fuel cost of a NGCC plant according to future predictions as in [183] and is equal to

$0.003528 t^2 - 14.192 t + 14285.2$, where t is the year when the decision will be made.

- Associated with the resolution of an issue. A change in recommendation for one issue node might affect the resolution of another issue node. An example is *Selexol_IGCC_GEE_Selected* in Figure 6.1. This parameter will be equal to 1 if CCS is recommended for coal based generation and 0 if not.

Global Parameters can create different scenarios which can result in different outcomes from the decision process. Scenarios are internally consistent stories about one way in which the future could unfold. The Global Parameters in Figure 6.1 consist of the scenario used in the creation of the decision process for the Yorkshire and the Humber region in 2040.

Global Parameters

Global Parameters							Yes to all	No to all
	Parameter	Source	Value	Unit	Last Up...	Update	Comments	
Set Time (t):	Total_Electricity_Generation_Capacity	375.665	375.665	GW	Tue Oct ...	NO	UK total electricity generation capacity	
	Gas_Electricity_Generation_Capacity	165.482	165.482	GW	Tue Oct ...	NO	UK gas combustion electricity generation capacity	
2040.0	Coal_Electricity_Generation_Capacity	104.608	104.608	GW	Wed Nov ...	NO	UK coal combustion electricity generation capacity	
	Nuclear_Electricity_Generation_Capacity	69.098	69.098	GW	Tue Oct ...	NO	UK thermo nuclear electricity generation capacity	
Ex: If 4 March 1986 =	Biomass_Electricity_Generation_Capacity	12.964	12.964	GW	Tue Oct ...	NO	UK biomass combustion electricity generation capacity	
	Wind_Electricity_Generation_Capacity	9.082	9.082	GW	Tue Oct ...	NO	UK wind electricity generation capacity	
(31+28.25+4+1)/365.25	Hydro_Electricity_Generation_Capacity	5.262	5.262	GW	Tue Oct ...	NO	UK hydro electricity generation capacity	
	Solar_Electricity_Generation_Capacity	0.242	0.242	GW	Tue Oct ...	NO	UK solar electricity generation capacity	
Parameter	Geothermal_Electricity_Generation_Capa...	0.03	0.03	GW	Fri Jun 2...	NO	UK geothermal electricity generation capacity	
Add	Interest_Rate	0.08	0.08	Percent	Fri Jun 2...	NO	Interest rate	
	Water_Price	1.9047E-4	1.9047E-4	£/kg	Fri Jun 2...	NO	Water price for electricity production	
Remove	Gasoline_Price	1.7	1.7	£/kg	Fri Jun 2...	NO	Gasoline price for transport	
Table	CO2_Emissions_Cost	0.025	0.2	£/kg	Mon Nov ...	YES	Price for emitting CO2 (this is analysed in more details with a probabilistic fo...	
	Wind_Capital_Cost	T:((5.663...	489583586.75	£	Mon Nov ...	YES	Wind capital cost varying with time (from 2010 until 2050)	
Save	Wind_O&M_Cost	T:((0.000...	27.587	£/MWh	Mon Nov ...	YES	Wind operation and management cost varying with time (from 2010 until 20...	
	Gas_Fuel_Cost	T:((0.012...	63.304	£/MWh	Mon Nov ...	YES	Gas fuel cost varying with time (from 2010 until 2050)	
Update	Coal_Capital_Cost	T:((-0.90...	1289001516	£	Mon Nov ...	YES	Coal without CCS capital cost varying with time (from 2010 until 2050)	
	Coal_Fuel_Cost	T:((0.0035...	16.125	£/MWh	Mon Nov ...	YES	Coal fuel cost varying with time (from 2010 until 2050)	
Propagate changes	Coal_With_CCS_Capital_Cost	T:((-1.22...	1755341904	£	Mon Nov ...	YES	Coal with CCS capital cost varying with time (from 2010 until 2050)	
Propagate	Desalination_Capital_Cost	EXCEL:EX...	2.043	£/MWh	Tue Oct ...	NO	Import value from Excel file for desalination capital cost	
	Desalination_O&M_Cost	D:\Users\...	2.194	£/MWh	Tue Oct ...	NO	Import value from Excel file for desalination operational and management cost	
Sensitivity Analysis	Desalination_Efficiency	V:163111...	47.307	Percent	Fri Jun 2...	NO	Import value from Excel file for desalination efficiency	
	Desalination_Water_Production	D:\Users\...	-7176.729	kg/MWh	Fri Jun 2...	NO	Import value from Excel file for desalination water production	
Sensitivity Analysis	CHP_Capital_Cost	D:\Users\...	2.098	£/MWh	Mon Nov ...	YES	Import value from Excel file for combined heat and power capital cost	
	CHP_O&M_Cost	D:\Users\...	1.315	£/MWh	Mon Nov ...	YES	Import value from Excel file for combined heat and power operational and ...	
Project Snap Shot	CHP_Efficiency	D:\Users\...	43.36	P	Mon Nov ...	YES	Import value from Excel file for combined heat and power efficiency	
	CHP_Water_Usage	D:\Users\...	21.478	kg/MWh	Mon Nov ...	YES	Import value from Excel file for combined heat and power water usage	
Record	Wet_Cooling_Capital_Cost	D:\Users\...	0.643	£/MWh	Fri Jun 2...	NO	Import value from Excel file for wet cooling capital cost	
	Wet_Cooling_O&M_Cost	D:\Users\...	0.604	£/MWh	Wed Jan ...	NO	Import value from Excel file for wet cooling operational and management cost	
	Wet_Cooling_Efficiency	C:\Julian\...	49.255	P	Wed Jan ...	NO	Import value from Excel file for wet cooling efficiency	
	Wet_Cooling_Water_Usage	C:\Julian\...	1124.865	kg/MWh	Wed Jan ...	NO	Import value from Excel file for wet cooling water usage	
	Wind_Speed	6.5	6.5	m/s	Mon Nov ...	YES	Local wind speed at 45m above ground	
	Biomass_Yield	9	9.0	ODT/ha/year	Mon Nov ...	YES	Local biomass yield based on poplar and willow short-rotation coppice	
	Net_Land_Use	50	50.0	%	Mon Nov ...	YES	Local ratio of available land for biomass cultivation on a diameter of 10 km	
	Solar_Irradiation	847	847.0	kWh/m2	Mon Nov ...	YES	Local yearly solar irradiation	
	Geothermal_Temperature	80	80.0	C	Mon Nov ...	YES	Local geothermal temperature at 2000 meters below sea level	
	Gas_Pipeline_Length	31.92	31.92	km	Mon Nov ...	YES	Gas pipeline length required to supply gas to selected location	
	Coal_Rail_Transport_Distance	25	25.0	km	Mon Nov ...	YES	Rail length required to supply coal to selected location	
	Coal_Shipping_Distance	1050	1050.0	km	Mon Nov ...	YES	Ship length required to supply coal to selected location	
	CO2_Pipeline_Length1	0	0.0	km	Mon Nov ...	YES	CO2 pipeline length required to store CO2 from selected location (assuming...	
	CO2_Pipeline_Length2	0	0.0	km	Mon Nov ...	YES	CO2 pipeline length required to store CO2 from selected location (assuming...	
	CO2_Pipeline_Length3	31.92	31.92	km	Mon Nov ...	YES	CO2 pipeline length required to store CO2 from selected location (assuming...	
	CO2_Offshore_Pipeline_Length	61.81	61.81	km	Mon Nov ...	YES	CO2 pipeline length required to store CO2 from selected location (assuming...	
	Local_Heat_Demand	1	1.0	boolean	Mon Nov ...	YES	Equal to 1 if there is heat demand close to the power plant. 0 if not	
	Located_By_The_Coast	1	1.0	boolean	Mon Nov ...	YES	Equal to 1 if there is by the coast. 0 if not	
	Water_Availability	-6	-6.0	Weight	Mon Nov ...	YES	Criterion weight for Water usage (kg/MWh) in "What is the selected source...	
	Ambient_Temperature	32	32.0	C	Fri Jun 2...	NO	Local ambient temperature	
	Humidity	80	80.0	P	Fri Jun 2...	NO	Local humidity	
	Cost_Weight	-0.56	-0.56	Weight	Mon Nov ...	YES	Criterion weight for Cost (£/MWh)	
	Water_Usage_Weight	-0.07	-0.07	Weight	Mon Nov ...	YES	Criterion weight for Water usage (kg/MWh) in "What is the selected source...	
	BOD_Weight	-0.013	-0.013	Weight	Mon Nov ...	YES	Criterion weight for BOD (g/MWh)	
	N_Weight	-0.013	-0.013	Weight	Mon Nov ...	YES	Criterion weight for N (g/MWh)	
	CO2_Emissions_Weight	-0.06	-0.06	Weight	Mon Nov ...	YES	Criterion weight for CO2 equivalent (kg/MWh)	
	SO2_Emissions_Weight	-0.013	-0.013	Weight	Mon Nov ...	YES	Criterion weight for SO2 equivalent (kg/MWh)	
	NO2_Emissions_Weight	-0.013	-0.013	Weight	Mon Nov ...	YES	Criterion weight for NOx equivalent (kg/MWh)	
	TOPP_Emissions_Weight	-0.013	-0.013	Weight	Mon Nov ...	YES	Criterion weight for TOPP equivalent (kg/MWh)	
	PM_Emissions_Weight	-0.013	-0.013	Weight	Mon Nov ...	YES	Criterion weight for Particulates equivalent (kg/MWh)	
	Land_Requirement_Weight	-0.045	-0.045	Weight	Mon Nov ...	YES	Criterion weight for Land requirement (m2/MWh)	
	Direct_Employment_Weight	0.040	0.04	Weight	Mon Nov ...	YES	Criterion weight for Direct employment (Persons/(MWh 10^6))	
	Total_Employment_Weight	0.020	0.02	Weight	Mon Nov ...	YES	Criterion weight for Total employment (Persons/(MWh 10^6))	
	Diversity_Of_Supply_Weight	-0.032	-0.032	Weight	Mon Nov ...	YES	Criterion weight for Diversity of Supply	
	Risk_Aversion_Weight	-0.060	-0.06	Weight	Mon Nov ...	YES	Criterion weight for Risk Aversion	
	Peak_Load_Response_Weight	0.048	0.048	Weight	Mon Nov ...	YES	Criterion weight for Peak load response	
	O&M_Cost_Weight	-0.132	-0.132	Weight	Mon Nov ...	YES	Criterion weight for O&M cost (£/MWh)	
	Capital_Cost_Weight	-0.132	-0.132	Weight	Mon Nov ...	YES	Criterion weight for Capital cost (£/MWh)	
	Oil_Price	CLG12.NYM	98.46	\$/bbl	"1/20/20...	NO	Import value from the internet for oil price	
	Wet_Cooling_Selected	V:163111...	0.0	boolean	Mon Nov ...	YES	Equal to 1 if node is selected or recommended. 0 if not	
	Desalination_Selected	V:163111...	0.0	boolean	Mon Nov ...	YES	Equal to 1 if node is selected or recommended. 0 if not	
	CHP_Selected	V:163111...	0.0	boolean	Mon Nov ...	YES	Equal to 1 if node is selected or recommended. 0 if not	
	Once_Through_Cooling_Selected	V:163111...	1.0	boolean	Mon Nov ...	YES	Equal to 1 if node is selected or recommended. 0 if not	
	Dry_Cooling_Selected	V:163111...	0.0	boolean	Mon Nov ...	YES	Equal to 1 if node is selected or recommended. 0 if not	
	Selextol_IGCC_GEE_Selected	V:163111...	1.0	boolean	Mon Nov ...	YES	Equal to 1 if node is selected or recommended. 0 if not	
	No_CCS_IGCC_GEE_Selected	V:163111...	0.0	boolean	Mon Nov ...	YES	Equal to 1 if node is selected or recommended. 0 if not	
	Selextol_IGCC_CoP_Selected	V:163111...	1.0	boolean	Mon Nov ...	YES	Equal to 1 if node is selected or recommended. 0 if not	
	No_CCS_IGCC_CoP_Selected	V:163111...	0.0	boolean	Mon Nov ...	YES	Equal to 1 if node is selected or recommended. 0 if not	
							Close	Help

Figure 6.1: Global Parameters used for the Yorkshire and the Humber region in the decision process.

6.3 Decision Matrix Expressions

The expressions (equations) used for the comparison of the positions are a major step in building a dynamic decision rationale. A considerable amount of effort is required to include these parameters, as every score must be studied in detail to include possible parameters that might vary and affect the position's analysis. In the case study, every parameter that affects the amount of MWh produced is included in all criteria scores that relates to this unit. For example, the wind speed of the location considered for the implementation of a wind turbine will directly influence the amount of electricity generated by that turbine and, thus, most criteria analysis (scores) will be influenced by the average wind speed. Figure 6.2 shows the equations for the selection of *Wind turbine*. As the data used was taken from the GEMIS [183] database and it assumed an annual generation of 3600 MWh per turbine, the analysis was multiplied by 3600 and divided by the amount of electricity generated in each new location in the UK. The equation $140.06 \text{ Wind_Speed}^2 - 712.75 \text{ Wind_Speed} + 487.09$ is used to calculate the electricity generation for each location and, thus, adjust the costs, CO₂ emissions, etc. to the average wind speed of the location. On the other hand, the *Risk aversion* and *Diversity of supply* criteria does not vary with the wind speed. A detailed study for the creation of the expressions used to compare the positions is shown in Appendix B.

Criteria	Wind turbine
Cost (£/MWh)	$((\text{Wind_Capital_Cost} * (\text{Interest_Rate} * ((1 + \text{Interest_Rate})^{20}) / (((1 + \text{Interest_Rate})^{20}) - 1))) / (2000 * 700) + \text{Wind_O\&M_Cost} + \text{CO2_Emissions_Cost} * 22.8477 + \text{Water_Price} * 58.131) * 3600 / (48 \dots)$
Water usage (kg/MWh)	$(58.131 * 3600 / (487.09 + 140.06 * (\text{Wind_Speed}^2) - 712.75 * \text{Wind_Speed}))$
BOD (g/MWh)	$(2.73582 * 3600 / (487.09 + 140.06 * (\text{Wind_Speed}^2) - 712.75 * \text{Wind_Speed}))$
N (g/MWh)	$(0.002901024 * 3600 / (487.09 + 140.06 * (\text{Wind_Speed}^2) - 712.75 * \text{Wind_Speed}))$
CO2 equivalent (kg/MWh)	$(22.8477 * 3600 / (487.09 + 140.06 * (\text{Wind_Speed}^2) - 712.75 * \text{Wind_Speed}))$
SO2 equivalent (kg/MWh)	$(0.047329409 * 3600 / (487.09 + 140.06 * (\text{Wind_Speed}^2) - 712.75 * \text{Wind_Speed}))$
TOPP equivalent (kg/MWh)	$(0.071278945 * 3600 / (487.09 + 140.06 * (\text{Wind_Speed}^2) - 712.75 * \text{Wind_Speed}))$
Particulates equivalent (kg/MWh)	$(0.011780813 * 3600 / (487.09 + 140.06 * (\text{Wind_Speed}^2) - 712.75 * \text{Wind_Speed}))$
Land requirement (m2/MWh)	$(1.052496 * 3600 / (487.09 + 140.06 * (\text{Wind_Speed}^2) - 712.75 * \text{Wind_Speed}))$
Direct employment (People/TWh)	$3.75948 * 3600 / (487.09 + 140.06 * (\text{Wind_Speed}^2) - 712.75 * \text{Wind_Speed})$
Indirect employment (People/TWh)	$1229.67252 * 3600 / (487.09 + 140.06 * (\text{Wind_Speed}^2) - 712.75 * \text{Wind_Speed})$
Diversity of supply	$\text{Wind_Electricity_Generation_Capacity} / \text{Total_Electricity_Generation_Capacity}$
Risk aversion	5
Peak load response	0
Totals	-0.08048

Figure 6.2: Decision matrix values view for the *Wind turbine* position node analysis.

Another interesting example of an expression taken from the *Cost (£/MWh)* criterion as applied to the *Gas plant* position is shown in Equation 6.1. This expression is broken down into different types of costs to allow different interest rates, CO₂ emissions costs, the inclusion or not of CCS and technologies used for steam condensation to be compared. A brief explanation of the variables (e.g. *Interest_Rate*, *CO2_Emissions_Cost*, *Wet_Cooling_Selected*, etc.) is shown in Figure 6.1.

$$\begin{aligned}
 &(\text{No_CCS_NGCC_Selected} * ((277814869.6 * (\text{Interest_Rate} * ((1 + \text{Interest_Rate})^{15}) / (((1 + \text{Interest_Rate})^{15}) - 1))) / (6000 * 700)) + (0.0137 * \text{Gas_Pipeline_Length} - 0.0442) + 3.290 + \text{CO2_Emissions_Cost} * 413.14 + \text{Water_Price} * 775.89 + \text{Gas_Fuel_Cost} + (\text{Wet_Cooling_Selected} * (0)) + (\text{Once-Through_Cooling_Selected} * (-0.276)) + (\text{Dry_Cooling_Selected} * (0.584)) + (\text{CHP_Selected} * (1.279)) + (\text{Desalination_Selected} * (1.806))) \\
 &+
 \end{aligned}
 \tag{a}$$

$$\begin{aligned}
 &\text{Amine_Absorber_NGCC_Selected} * ((613393226.9 * (\text{Interest_Rate} * ((1 + \text{Interest_Rate})^{15}) / (((1 + \text{Interest_Rate})^{15}) - 1))) / (6000 * 700)) + (0.0161 * \text{Gas_Pipeline_Length} - 0.0519) + 8.8 + \text{CO2_Emissions_Cost} * 91.12 \\
 &+ \text{Water_Price} * 1456.62 + \text{Gas_Fuel_Cost} * 1.172 + (\text{Wet_Cooling_Selected} * (0)) + (\text{Once-Through_Cooling_Selected} * (-0.276)) + (\text{Dry_Cooling_Selected} * (0.584)) + (\text{CHP_Selected} * (1.279)) + (\text{Desalination_Selected} * (1.806)) + (((0.008067 * \text{CO2_Pipeline_Length1} + 0.02151) * 5.7 * 1 + (0.003944 * \text{CO2_Pipeline_Length2} + 0.02151) * 14.3 * 0.4 + (0.002761 * \text{CO2_Pipeline_Length3} + 0.02151) * 28.4 * 0.2 + (0.002115 * \text{CO2_Offshore_Pipe_line_Length} + 0.02151) * 56.8 * 1.558 * 0.1 + 5.7 * 4.837) * 1000000 / 12000000))) \\
 &
 \end{aligned}
 \tag{b}$$

Eq. 6.1

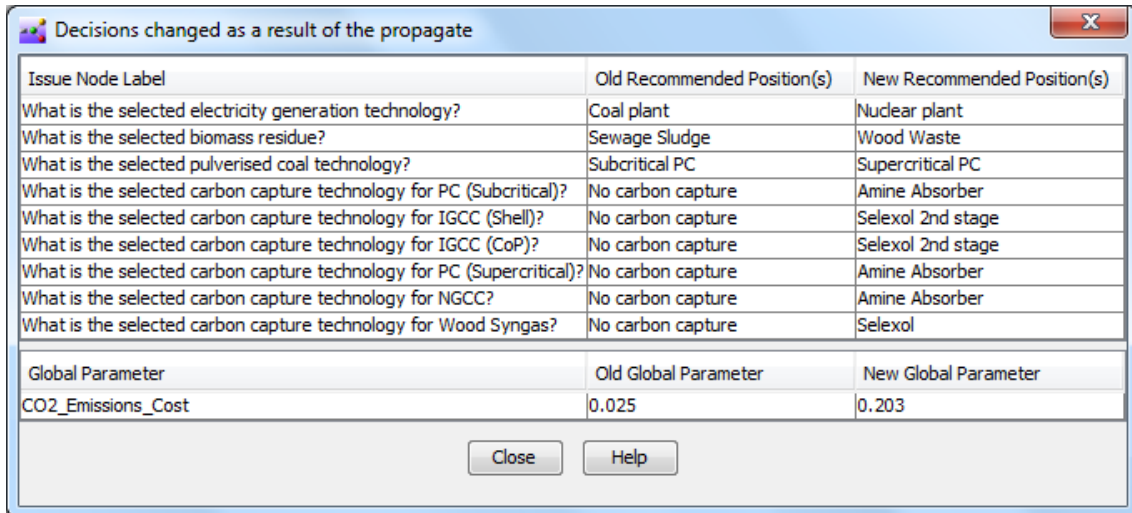
Equation 6.1 is divided into two parts. Equation 6.1(a) is used in the case where CCS is not included and the parameter *No_CCS_NGCC_Selected* is equal to 1. In this case, *Amine_Absorber_NGCC_Selected* equals 0 and section two is removed from the analysis. The value 277,814,869.6 is the plant capital cost in £ for a 700 MW NGCC [183]. The rest of the first line is used to levelise the capital costs, so it can be compared to the other costs in £/MWh. After the inclusion of the pipeline cost, the second line represents the *Gas plant* operation and management costs followed by fuel cost. Afterwards, the changes in both capital and operation costs with respect to the technology used for steam condensation are included. The Global Parameters represent the technology used and the numerical values represent the cost correction. *Wet_Cooling_Selected* implies that wet cooling (cooling tower) is used; *Once-Through_Cooling_Selected* implies that once-through cooling is used; *Dry_Cooling_Selected* implies that dry cooling is used; *CHP_Selected* implies that cogeneration is used and *Desalination_Selected* implies that desalination of sea water is used. Equation 6.1(b) is similar to Equation 6.1(a). The major difference between them, apart from the increase in costs due to the addition of CCS, is the inclusion of the CO₂ pipeline system to transport the CO₂ from the plant to the closest geological location for CO₂ storage. These locations are referenced in Appendix B.5.

6.4 Propagation and Sensitivity Analysis

There are numerous scenarios that can be analysed within the case study decision process. The decision process was structured in such a way that Global Parameters such as commodity prices, CO₂ emission costs, interest rate, water availability and location specific parameters (such as wind speed and solar irradiation,

etc.) can be changed, creating different future scenarios to evaluate which is the best energy technology for different circumstances and locations. Once a new scenario is set with the change in Global Parameters, the user can use the Propagate feature to update the decision matrices of all issue nodes with the new Global Parameters values.

To simplify the propagation analysis of the case study, only one Global Parameter, CO₂ emissions cost (*CO2_Emissions_Cost*), was changed from 0.025 £/kg to 0.203 £/kg in order to showcase this feature. The CO₂ emission costs of 0.203 £/kg were taken from the DECC high CO₂ emission costs estimate for 2040 [202]. The other Global Parameter values are the same as in Figure 6.1, which correspond to the same analysis performed in Figure 5.8. Figure 6.3 shows the changes in the recommendation resulting from this change and its propagation, and it can be seen that the recommendation of electricity generation technology changes from *Coal plant* to *Nuclear plant*. This is because a *Coal plant*, with CCS, emits more CO₂ than a *Nuclear plant*. For the same reason, the recommended design for the coal gasifier changes from *Subcritical PC* to *Supercritical PC* and biomass residue changes from *Sewage sludge* to *Wood waste*. With the increase in cost of CO₂ emissions, CCS with *Selexol* carbon capture technology becomes viable for *CoP* and *Shell*, IGCC design and for *Wood Syngas*, and for *PC* and *NGCC* with the inclusion of *Amine Absorber* carbon capture technology.

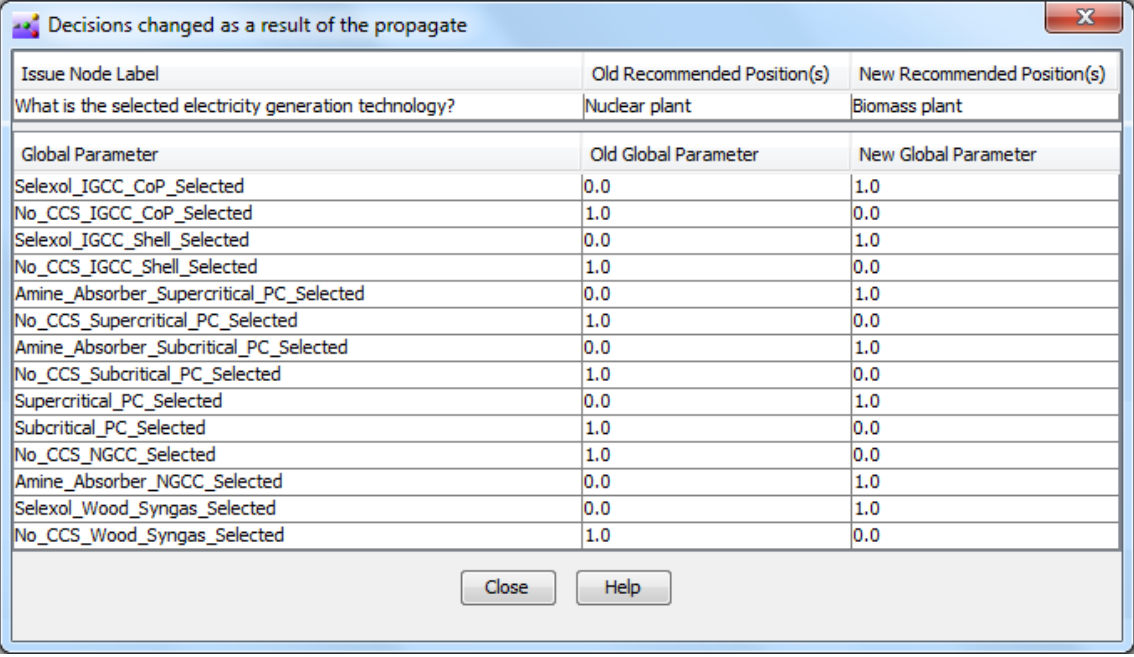


Issue Node Label	Old Recommended Position(s)	New Recommended Position(s)
What is the selected electricity generation technology?	Coal plant	Nuclear plant
What is the selected biomass residue?	Sewage Sludge	Wood Waste
What is the selected pulverised coal technology?	Subcritical PC	Supercritical PC
What is the selected carbon capture technology for PC (Subcritical)?	No carbon capture	Amine Absorber
What is the selected carbon capture technology for IGCC (Shell)?	No carbon capture	Selexol 2nd stage
What is the selected carbon capture technology for IGCC (CoP)?	No carbon capture	Selexol 2nd stage
What is the selected carbon capture technology for PC (Supercritical)?	No carbon capture	Amine Absorber
What is the selected carbon capture technology for NGCC?	No carbon capture	Amine Absorber
What is the selected carbon capture technology for Wood Syngas?	No carbon capture	Selexol

Global Parameter	Old Global Parameter	New Global Parameter
CO2_Emissions_Cost	0.025	0.203

Figure 6.3: First Global Parameter propagation of CO₂ emissions cost change from 0.025 to 0.203 £/kg.

After the first propagation, there are some changes in the recommendations (such as *Selexol* being recommended in the “*What is the selected carbon capture technology to use for Wood Syngas?*” issue node) that affect the resolution of other issues, so the propagation process should be repeated. This is automatically suggested to the user. Figure 6.4 shows that, after the second propagation, the recommendation changed from nuclear to biomass. This is because the *Selexol_Wood_Syngas_Selected* Global Parameter changes from 0 to 1. This Global Parameter has the type “Associated to the resolution of an issue” which is different than the type for *CO2_Emissions_Cost*, which is “Manually fixed by the user”. With CCS, the biomass cycle removes CO₂ from the atmosphere through photosynthesis and after the biomass is burnt, the captured CO₂ is eventually stored underground which results in an overall reduction of CO₂ in the atmosphere. As the CO₂ emissions cost per kilogram is high, the *Biomass plant* position is now recommended. The user should propagate the Global Parameters until there are no further changes in recommendations.



Issue Node Label	Old Recommended Position(s)	New Recommended Position(s)
What is the selected electricity generation technology?	Nuclear plant	Biomass plant

Global Parameter	Old Global Parameter	New Global Parameter
Selexol_IGCC_CoP_Selected	0.0	1.0
No_CCS_IGCC_CoP_Selected	1.0	0.0
Selexol_IGCC_Shell_Selected	0.0	1.0
No_CCS_IGCC_Shell_Selected	1.0	0.0
Amine_Absorber_Supercritical_PC_Selected	0.0	1.0
No_CCS_Supercritical_PC_Selected	1.0	0.0
Amine_Absorber_Subcritical_PC_Selected	0.0	1.0
No_CCS_Subcritical_PC_Selected	1.0	0.0
Supercritical_PC_Selected	0.0	1.0
Subcritical_PC_Selected	1.0	0.0
No_CCS_NGCC_Selected	1.0	0.0
Amine_Absorber_NGCC_Selected	0.0	1.0
Selexol_Wood_Syngas_Selected	0.0	1.0
No_CCS_Wood_Syngas_Selected	1.0	0.0

Figure 6.4: Second Global Parameters propagation.

Another resource used to verify MCDA methods is through the use of sensitivity analysis. In OUTDO, sensitivity analysis is performed with the variation of Global Parameters and the propagation of these changes in the decision process. The beauty of this is that the Sensitivity Analysis feature allows the study of more than one Global Parameter variation at a time, therefore the user can have a better idea of which Global Parameter value results in a change in recommendation. Thus, before making a definite decision, the user can study how different future scenarios can affect the decision process. For this reason, the Sensitivity Analysis feature can be used to analyse how a given percentage variation of the value of a single Global Parameter can affect the decision process. Figure 6.5 shows the Sensitivity Analysis window. The user is asked to input the Global Parameter to be analysed, the percentage range of variation of the Global Parameter value and the number of sub-divisions the user wants within this range. The sensitivity analysis window shown in Figure 6.6 shows the issue nodes that had their recommendations changed and their corresponding Global Parameter values.

Figure 6.5: Sensitivity Analysis data input window.

Percentage	Value	Node Label	Old Recommended Option(s)	New Recommended Option(s)
-80.0%	0.005	What is the selected carbon capture technology for IGCC (GEE)?	Selexol 2nd stage	No carbon capture
-80.0%	0.005	What is the selected coal plant type?	IGCC coal	Pulverised coal
-80.0%	0.005	What is the selected IGCC coal technology?	GEE radiant only coal	CoP E-Gas coal
80.0%	0.045	What is the selected carbon capture technology for IGCC (Shell)?	No carbon capture	Selexol 2nd stage
80.0%	0.045	What is the selected electricity generation technology?	Coal plant	Nuclear plant
80.0%	0.045	What is the selected carbon capture technology for IGCC (CoP)?	No carbon capture	Selexol 2nd stage

Figure 6.6: Sensitivity Analysis report window showing the changes in recommendations.

6.5 Future Analysis

The decision rationale can be significantly improved if, instead of only taking into account the present circumstances of the global variables affecting the decisions, the rationale also attempts to forecast their likely direction in the future. This enables decisions to be made based upon present Global Parameters as well as projections of their future behaviour, and the resulting decision process and outcomes can be stored as evidence of the previous decision rationale; combining the past, present and future seamlessly into the decision making process.

The inclusion of probabilistic forecasting in OUTDO consists of the *Future Analysis* block as shown in Figure 3.6. This block attempts to predict how Global

Parameters will behave in the future, either by using historic time series or by using the user's own future predictions. This forecast is then propagated into the decision matrix of an issue node to show how the forecast will affect the decision in the future in two different plots, the Forecast plot and the Confidence Interval plot. The Forecast plot shows the position that will be recommended at a certain time based on the propagation of the forecasted Global Parameter value to the decision matrix being analysed using the WSM method. As it is impossible to predict the exact value of a Global Parameter in the future, confidence intervals are used. Confidence intervals (exemplified in the next section) are probability distributions of future predictions of the Global Parameter. They are used to create the Confidence Interval plot, which shows the probability that the positions will be recommended as the Global Parameter probability distribution is propagated to the decision matrix at different times. These plots can then be used for risk analysis and to decide which are the best positions to be considered in the short, medium and long-terms. Examples of these two plots can be found below and in Section 6.5.2. Coupling MCDA methods and probabilistic forecasting enables the user to foresee how a decision will behave in the future and perform risk analysis.

A simple example used to explain how the forecast results in the Forecasting plot and confidence intervals result in the Confidence Intervals plot can be seen in Figure 6.7 and Figure 6.8. Figure 6.7 shows the variation of a Global Parameter value for the parameter called *Parameter1*. The forecast line, blue line, can be created with 1st, 2nd, 3rd and 4th order regression or exponential smoothing based on the time series data, in addition, the forecast can be a 6th order equation manually included by the user. Seasonality and trends can be included in the forecast. The length of these cycles has to be set by the user. First order regression was used to create the forecast in Figure 4.6.

The methodology used for the calculation of the confidence intervals was created by Hanbury [68] and is explained in Appendix A.1. The blue line represents the forecasted value in Figure 6.7. The confidence intervals indicate that there is a 50% chance that the *Parameter1* will be between the orange lines, 75% chance between the light green lines and 90% chance between the dark green lines. To simplify this example, the decision matrix (not shown) only has one criterion called *Criterion1* and three positions called, *Position1*, *Position2* and *Position3*. *Position1* has the value of 0.4 as its score, *Position2* has the expression “*Parameter1*” as its score and *Position3* has the expression “0.65-*Parameter1*” as its score. This is represented in Equation 6.2.

$$\begin{aligned}
 Position1_{WSM-score} &= 0.4 \\
 Position2_{WSM-score} &= Parameter1 \\
 Position3_{WSM-score} &= 0.65 - Parameter1
 \end{aligned}
 \tag{Eq. 6.2}$$

The Forecast plot in Figure 6.8 is found using the forecast, blue line in Figure 6.7, and propagating to Equation 6.2. For example, if the time is 2030, *Parameter1* is equal to 0.3. This results on *Position1*_{WSM-score} equal to 0.4; *Position2*_{WM-score} equal to 0.3; *Position3*_{WSM-score} equal to 0.35. Thus, *Position1* is recommended as shown in the Forecast plot in Figure 6.8 (2030 corresponds to the year 9 in the Forecast plot).

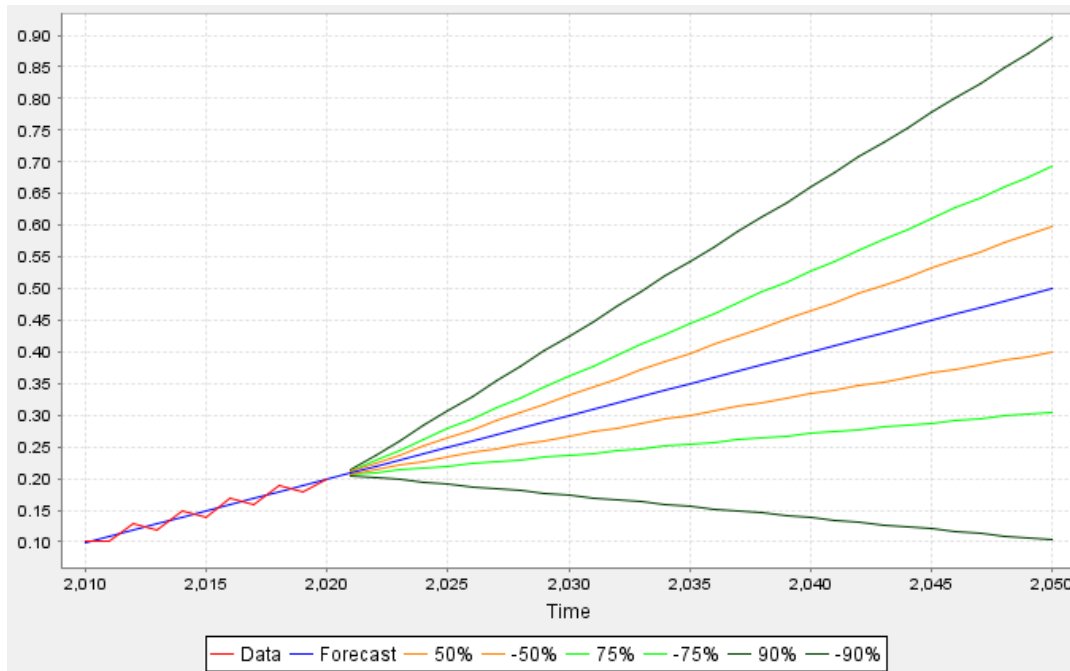


Figure 6.7: Forecast for *Parameter1* used to exemplify the Future Analysis feature.

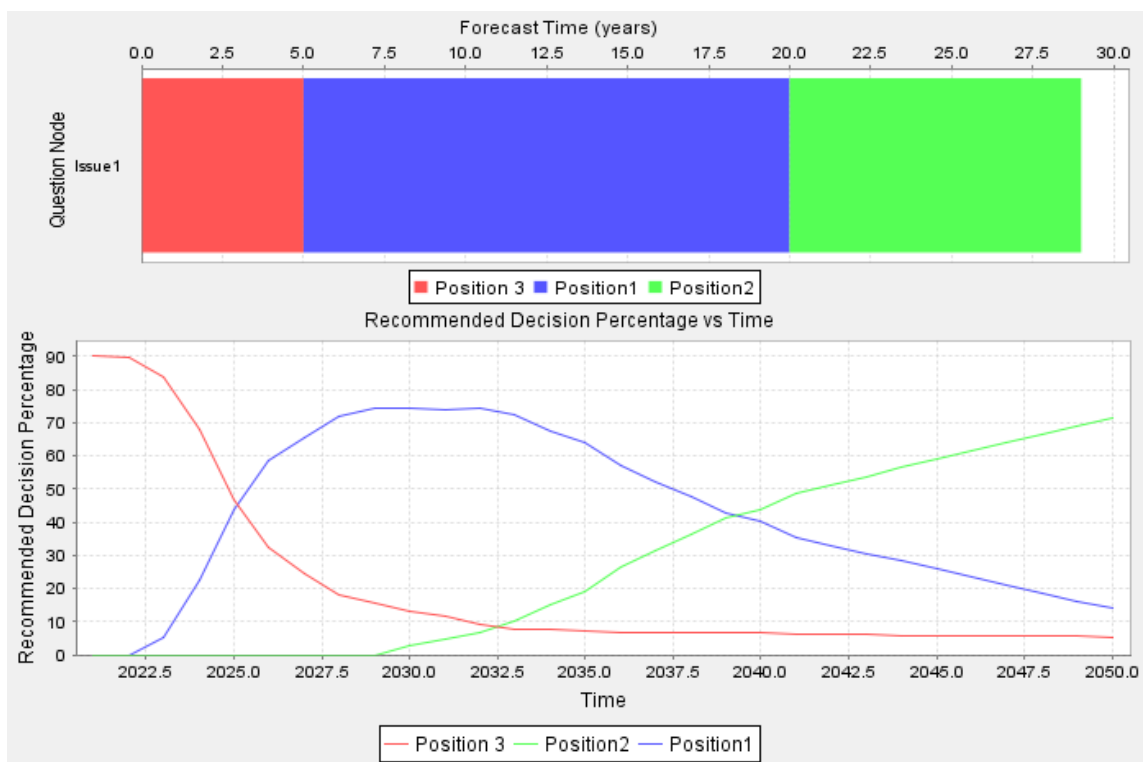


Figure 6.8: Forecast plot (above) and Confidence Intervals plot (below) used to exemplify the Future Analysis feature.

The Confidence Interval plot in Figure 6.8 shows the probability of recommendation of the positions. This is found with the propagation of the Global Parameter probability distribution in Figure 6.7 to the expressions in Equation 6.2 using the WSM method. The specific calculations involved in this methodology, created by the author, are shown in Appendix A.2.

Note that the methods presented in the thesis for forecasting Global Parameters and for estimating probability of recommending one decision are still preliminary and mainly for the purpose of demonstrating the potential benefits of introducing these features into decision support, as shown in the OUTDO framework.

6.5.1 Probabilistic Forecasting Creation

After running sensitivity analyses on several Global Parameters, it was found that the most influential Global Parameter in this study is the CO₂ emissions cost, for this reason its forecast, which is based on data from the DECC [202], is shown in Figure 6.9. The forecast, the blue line at the centre of the plot, represents the medium price scenario for CO₂ emissions and the light green lines (75% and -75% lines) represent the high and low price scenarios suggested in [202]. The dark green and orange lines were set by the user following the blue and light green lines. The values entered in the Confidence Intervals table in Figure 6.9 were set to reproduce the results presented in the graph in Figure 6.9.

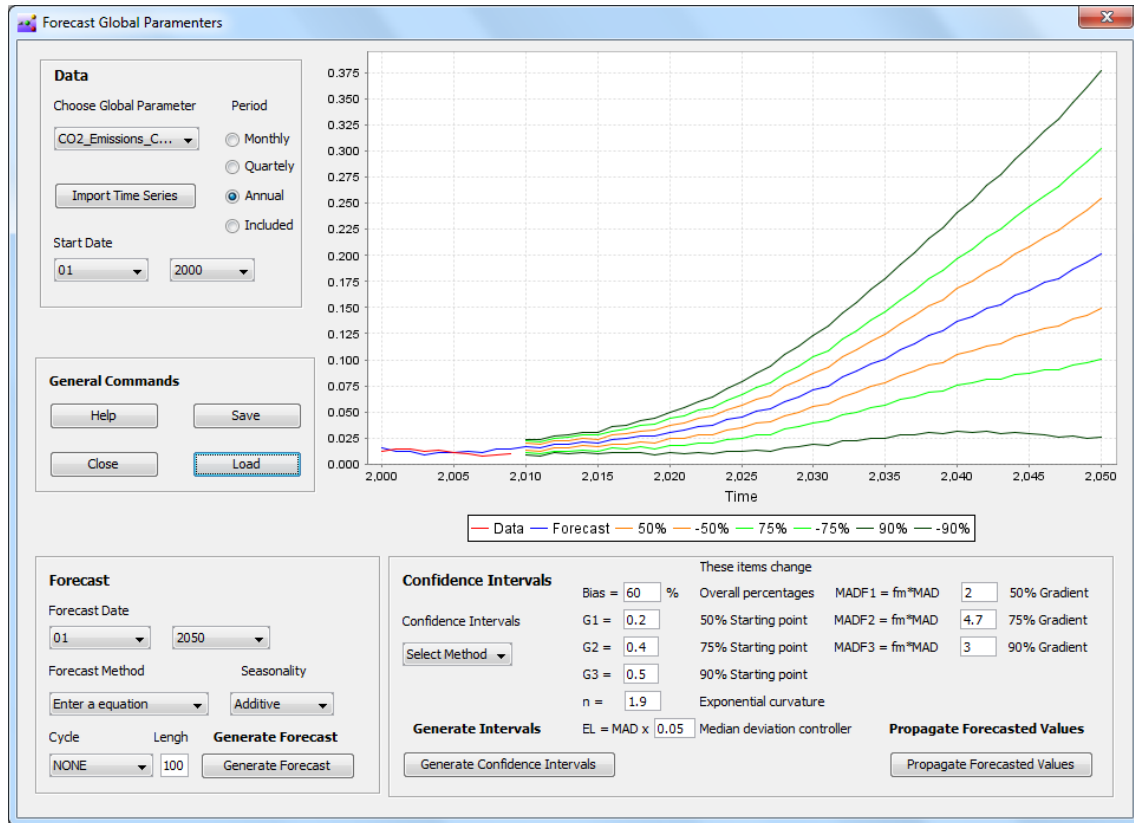


Figure 6.9: Forecast and Confidence Intervals for CO₂ emissions costs up to 2050.

6.5.2 Future Analysis Results for the Yorkshire and the Humber Region

The principle decision for introducing a power plant in a specific year should consider not only the predicted value of each important Global Parameter for the year when the decision is made, but also (and perhaps more importantly) what may happen during the whole life of the plant. Assuming the Global Parameters from the Yorkshire and the Humber region (Figure 6.1) and that CCS is not recommended for all positions, the Forecast plot (horizontal bar chart) in Figure 6.10 shows how the recommended position for a variety of issue nodes of the decision process changes in time with respect to the forecasted value for CO₂ emissions cost (the blue line in Figure 6.9). These recommendations are calculated through the propagation of the forecasted CO₂

emissions cost values into the decision matrix. Note that a change in time affects the Global Parameters of the type *Varying with respect to time*, such as gas fuel cost and wind power capital cost. Unfortunately, the Future Analysis feature does not propagate the changes in the Global Parameters to all issue nodes during its calculations. It only analyses one decision matrix at a time. Thus, it does not include in the analysis the fact that CCS will eventually be recommended as the cost of CO₂ emissions rises. Therefore the analysis has to be divided into two, one assuming that CCS is included (Figure 6.10) and one assuming that CCS is not included (Figure 6.11). This problem is addressed in detail in Section 9.2.3.

The Confidence Interval plot (graph) at the bottom of Figure 6.10 shows the probability that a position will be recommended in the future (the sum of the percentages adds to 90% because the user cannot be 100% sure of the prediction). The probability calculations are explained in detail in Appendix A.2. This graph shows that, for the Yorkshire and the Humber region, *Gas plant* is the recommended electricity generation technology for new plants built before 2027 with a subsequent change to *Nuclear plant*. The main reasons for this change are firstly, that gas thermoelectric generation plants emit CO₂ and the cost of CO₂ emissions increases considerably in the forecast, and secondly, because gas fuel costs increase according to the expression for the *Gas_Fuel_Cost* Global Parameter taken from [183].

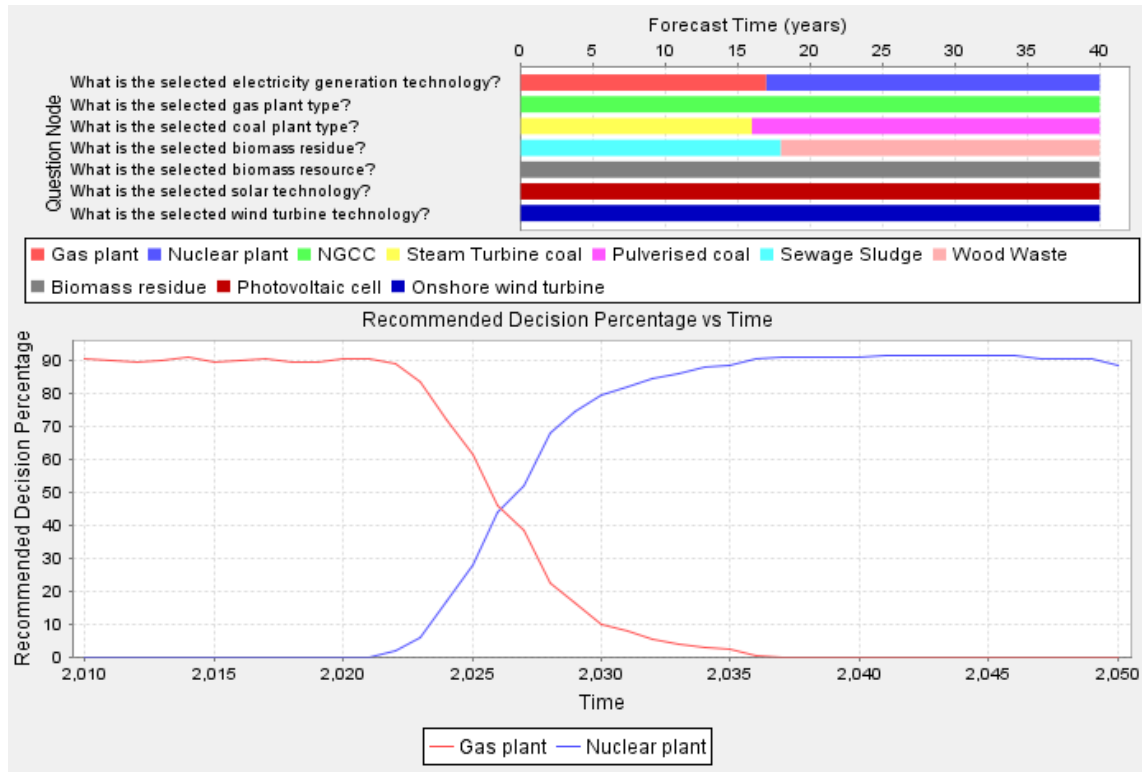


Figure 6.10: Future Analysis for the Yorkshire and the Humber region without CCS.

Assuming the Global Parameter values from the Yorkshire and the Humber region, the Forecast plot (horizontal bar chart) in Figure 6.11 focuses on the impact of increasing CO₂ emissions cost with time on the issues nodes involving CCS. It shows that Coal IGCC is the first technology viable to implement CCS with the inclusion of Selexol (2nd stage), followed by PC with Amine Absorber, Biomass IGCC with Selexol and finally NGCC with Amine Absorber.

The Confidence Interval plot (graph) at the bottom of Figure 6.11 assumes that CCS is recommended for all positions that burn carbon and shows that, in the Yorkshire and the Humber region, *Gas plant* with CCS will be the recommended solution up to 2022, after which *Coal plant* becomes the preferred candidate, followed by *Nuclear plant* in 2032 and then *Biomass plant* in 2036. This occurs for similar reasons to those relevant to Figure 6.10, but the Biomass upward trend around 2036 is driven by the fact

that CO₂ is absorbed from the atmosphere and stored underground after the biomass is burnt resulting in an overall negative CO₂ emission of 598.9 kg/MWh. Biomass with CCS assumes the IGCC design and values from [182] and [183]. This assumption takes into account the fact that biomass combustion emits more CO₂/MWh than coal given its lower heat of combustion. The solution for the Yorkshire and the Humber region is presented in the conclusion section of this chapter.

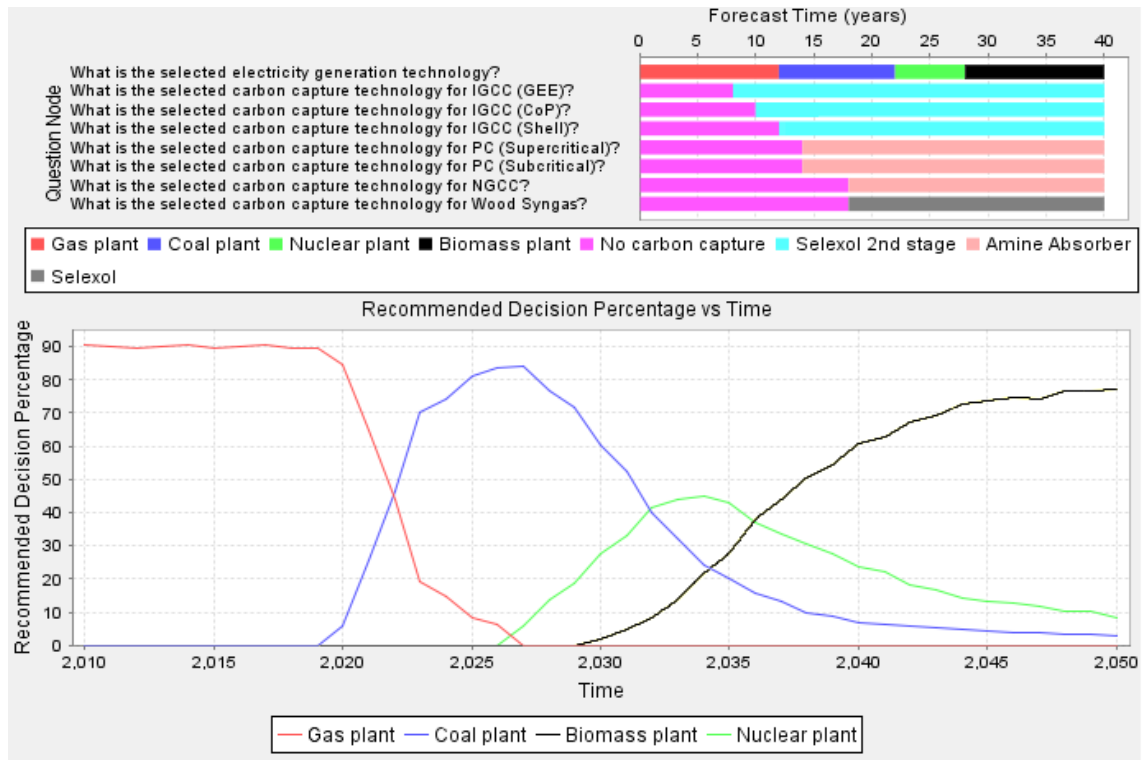


Figure 6.11: Future Analysis for the Yorkshire and the Humber region with CCS.

6.5.3 Results for the different locations

Ten different regions in the UK were studied in this work. However, the weights of criteria considered to compare the alternative generation technologies were kept the same, apart from the water availability weight of criterion in the steam condensation issue node in Figure 5.6 (b). In other words, a very similar decision process was used

for all regions. The decision matrices in Figures 5.8 and 5.6 (b), and the forecast in Figure 6.9 were unaltered, and only key Global Parameters were changed during the decision process. The Global Parameters used for the different regions such as: wind speed, biomass yield, underground temperature, solar radiation, pipeline length, rail track length, etc. are shown in Table 6.1. These were either found in the literature or estimated, and are further explained in Appendix B.

Table 6.1: Global Parameters for the 10 different locations.

Global Parameter	OX ²¹	LD	SE	ES	YK	ST	SL	NL	NT	SC
Wind_Speed (m/s)	5.8	5	6	6.1	6.5	7	7.9	8.9	10.1	10.4
Biomass_Yield (odt/(ha*y))	10	9	10	9	9	8	12	11	12	9
Net_Land_Use (%)	40	10	30	50	50	50	50	50	50	50
Solar_Irradiation (kWh/m ²)	861	869	922	894	847	936	883	847	824	740
Geothermal_Temp (°C)	60	70	90	70	80	90	60	60	80	60
Gas_Pipe_Length (km)	153	52	72	18	32	251	41	11	73	18
Coal_Rail_Length (km)	150	15	120	240	25	180	140	140	200	20
Coal_Ship_Length (km)	3400	2300	3400	2100	1050	3400	3400	3600	3000	3000
CO2_Pipeline_Length_S (km)	0	0	57	18	0	132	55	0	18	18
CO2_Pipeline_Length_M (km)	93	0	93	0	0	91	119	0	55	18
CO2_Pipeline_Length_L (km)	59	96	56	0	32	87	87	23	18	0
CO2_Offshore_Pipeline_Length (km)	62	62	62	62	73	31	31	31	31	163
Water_Availability (Weight of Criteria)	-6	-4	-6	-2	-6	-1	-1	-1	-1	-1
Located_By_The_Coast	0	1	1	1	1	1	1	1	1	1
Local_Heat_Demand	0	0	0	0	1	0	0	0	0	0

²¹ Where OX is Oxfordshire, SE is South East England, ES is East England, YK is the Yorkshire and the Humber region, ST is South West England, SL is South Wales, NL is North Wales, NT is North West England and SC is Scotland. Northern Ireland was not included in this study.

After the Global Parameters of a region are input into OUTDO, the values are propagated until there are no more changes in recommended positions. In the case of the steam condensation technology recommended for the different regions, it was found that *Dry cooling* is recommended for Oxfordshire, *Once-through cooling* is recommended for East Anglia, South West, South Wales, North Wales, North West England and Scotland, and *Desalination of sea water* is recommended for London, the South East England, and the Yorkshire and the Humber region. As the recommendation of CCS technologies changes during future analysis with the increase in CO₂ emissions cost, two graphs were created, one assuming CCS is not included (shown in Figure 6.12) and another assuming CCS is included (shown in Figure 6.13).

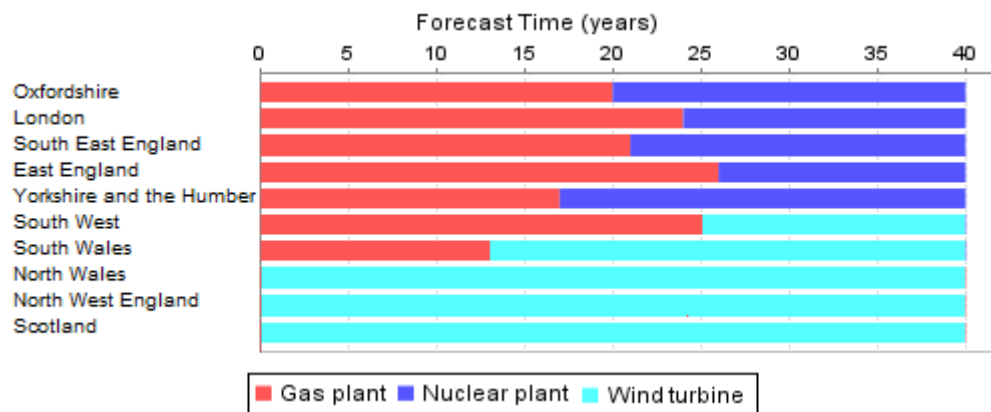


Figure 6.12: Electricity generation technologies, without CCS, recommended for different regions of the UK from 2010 until 2050.

Figure 6.12 presents a prevalence of *Gas plant* for the next 15 to 20 years, changing to a focus on *Nuclear plant* for the Oxfordshire, London, South East England, East England and the Yorkshire and the Humber regions. In South West England and South Wales, *Gas plant* changes to *Wind turbine*. In North Wales, North West England and Scotland *Wind turbine* is always recommended. In Figure 6.13, the

recommendations are more random, but the main trend for the regions in England below North West England is *Gas plant* with CCS, *Nuclear plant*, and then *Biomass plant*. In the case of London, and the Yorkshire and the Humber region, *Coal plant* with CCS is the recommended position for some time. In South Wales *Wind turbine* is recommended followed by *Biomass plant*. In North Wales, North West England and Scotland, *Wind turbine* is the only recommendation, as wind speeds are relatively high. These results could have changed considerably if the weights of criteria, *Direct employment*, *Diversity of supply*, had been varied for the different locations.

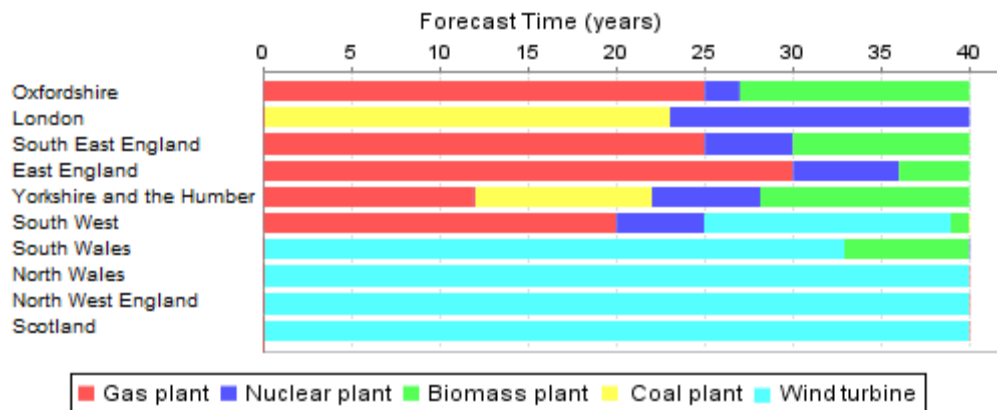


Figure 6.13: Electricity generation technologies, with CCS, recommended for different regions of the UK from 2010 until 2050.

One important problem with this approach is that the WSM requires a normalisation factor. The normalisation factors may vary considerably when the Global Parameters change and thereby change the relative importance of the criteria weights in the decision process. For example, if the same decision process is used to compare electricity technologies and the wind speed parameter changes from an average of 5 m/s (as in London) to 10.4 m/s (as in Scotland), the price of electricity as well as all the criteria related to MWh will result in a more than tenfold reduction. This is because the wind velocity increases the electricity generated from wind turbines to the power of

three, and also because an increase in the average wind speed considerably increases the distribution of higher wind speeds. If wind power is the score that influences the normalisation factor (the highest score for a criterion), then a slight change in its score will affect the comparison of all positions for the given criterion. This might result in an unwanted change in recommendation. This is the reason why *Coal plant* is the first recommended position in Figure 6.13 for London instead of *Gas plant*. Other cases that affect the normalisation factor are the inclusion of CCS in *Coal plant* and then *Gas plant*, and the inclusion of *Desalination of sea water* in the thermoelectric positions. This problem is further explained in Section 9.2.1 and a solution is suggested with the inclusion of MAUT into OUTDO.

6.6 Decision Hub

A tool for decision rationale capture can be useful by itself. However, the value of decision rationale capture considerably increases when it is integrated with other decision support systems [117]. The inclusion of numerical simulation packages in the framework gives added benefit to the OUTDO framework and can extend the applicability of numerical simulation packages. The numerical simulation packages will improve the analysis for each position, providing appropriate data for the decision matrix in order to find the recommended solution. On the other hand, the OUTDO framework will provide a clever way of structuring a decision process, allow the incorporation of criteria that would not be considered in a numerical simulation package because of its limitations, and will also preserve the context of the decision process and the decisions made. As an example, suppose a chemical plant is being designed. Apart from the evaluation of process alternatives that can be modelled in Aspen Plus [1], there

will be other important decisions such as the location of the plant and market share allocation that are not supported by Aspen Plus but which can be incorporated, using other packages, into OUTDO. Therefore, OUTDO can be used as a template where the comparison of the possible courses of action is strengthened with detailed analyses using different numerical simulation packages and optimisation models. OUTDO will thus be a means by which scattered information from different sources can be brought together in a meaningful way, at the same time organising, managing and effectively recording the decision rationale.

6.7 Conclusion

This chapter has presented the different types of Global Parameters and shown how they can be used to improve the decision analysis in OUTDO. Global Parameters are important because they allow the decision maker to dynamically change the analysis, considering the time when the decision is to be made, location where to implement the decision, and other external parameters affecting the decision (such as gas prices, CO₂ emissions cost, etc.). Some work has to be performed to create the equations that vary with the Global Parameters, but the result is that a decision process can then be applied to several other situations. Thus, once the equations are included in the analyses, a single variation of Global Parameters can be performed by the Propagation feature to study how this change would affect the whole decision process. The Sensitivity Analysis feature in OUTDO also does this, but it allows multiple variations to happen at the same time. Finally, as a decision made today will be operational for a considerable time in the future, it is important to include the time scale into the analysis. This results in the Forecast and Confidence Interval plots which can be

used for risk analysis and to decide which are the best positions to be considered in the short, medium and long-terms.

An analysis of the electricity generation technologies for the different areas in the UK has also been presented in this chapter. Assuming the predictions for CO₂ emissions cost from the DECC [202], the recommendations below can be made. These recommendations are in accordance with the predictions in the White Paper on electricity generation planning from the DECC [5].

- 1) The areas of North Wales, North West England and Scotland always have *Wind turbine* as their recommended electricity generation technology.
- 2) For the other areas the recommendation changes from *Gas plant* (with and without CCS) to *Nuclear plant* and then *Biomass plant* (with CCS) according with Figures 6.12 and 6.13.
- 3) For the Yorkshire and the Humber region, from 2010 up to 2018, the selected technology should be *Gas plant* (NGCC), without CCS but with sea water desalination. As CO₂ emission costs increase and CCS becomes relevant, the recommended technology changes to *Coal plant* (IGCC) with CCS between 2019 and 2035. *Nuclear plant* should not be considered for the Yorkshire and the Humber region, because nuclear power becomes advantageous only for a four-year span, and a nuclear power plant has a much longer lifetime. As CO₂ emissions cost predictions from DECC [202] might be too high, Biomass based generation with CCS is recommended after 2036 as a coal and biomass co-fired plant.

Combining MCDA and probabilistic forecasting, as has been done in this thesis, has not been attempted before. As the above analysis shows, it has proved to be a powerful tool for the inclusion of uncertain parameters into multi-criteria issues and,

thus, perform risk analysis. Further improvements to this combination are discussed in Section 9.2.3. The next two chapters will present the approach used for the inclusion of semantic-based decision support capabilities.

Chapter 7

Decision and Energy Ontology

7.1 Introduction

This chapter and the next chapter present the inclusion of semantics into OUTDO. This is the first chapter dedicated to describing the *Semantic Capabilities* block shown in Figure 3.6. The inclusion of semantics is one of the most innovative contributions to this thesis. OUTDO without semantics is already a robust tool for decision making. However, any information in a text format can be entered in OUTDO without semantics as the meaning of the words is ignored. This allows the decision maker to make mistakes that could be avoided if the computer had a level of understanding of the decision in hand. Semantics adds a new dimension to decision support in OUTDO.

With the intent to support decision making processes with the use of semantics, the Decision and Energy Ontologies are presented. The Decision Ontology consists of the translation of the decision process into an ontological format. This translation facilitates the communication with the Energy Ontology. The Energy Ontology is a knowledge representation of the electricity generation domain. It attempts to describe, with the use of description logic, the technologies involved in the generation of electricity and the aspects needed for a country to generate electricity in a cheap, clean and safe manner. These ontologies are intended to be as simple and clear as possible to facilitate their applicability within OUTDO.

Section 7.2 describes the approach in which semantics is used to support decisions and introduces the ontological representation language used for the inclusion

of semantic capabilities in OUTDO. Section 7.3 gives details on the Decision Ontology. It presents its classes and relations and shows how the decision process in OUTDO is translated to an ontological format. It then presents the OUTDO language, needed for the semantic capabilities to function, and the possible applications with the Decision Ontology. Section 7.4 presents the Energy Ontology, its classes, relations and axioms. Section 7.5 concludes the chapter.

7.2 Inclusion of Semantics in OUTDO

In the version of OUTDO without the semantic-based capabilities the user has the freedom to add any information in the form of the OUTDO components (Goals, Issues, Positions, Recommendations, Decisions, Criteria and Parameters). The user may therefore input information that might not be relevant to the decision process, or that may inappropriately link the different OUTDO components. With the inclusion of semantics (in the form of a Decision Ontology and an Energy Ontology), OUTDO gains a level of understanding of the overall process of decision making in the energy area, and so is able to provide feedback on the decision process and run consistency checks to evaluate whether the decision rationale components are appropriately linked to each other. It also looks at the lessons learnt from previous decisions and uses them to help form new decisions, runs multiple qualitative analyses, suggests possible improvements to the decision process and gives valuable information about a specific field to the decision maker.

Once the decision maker constructs his or her personalised decision process in OUTDO, the Ontology Dialogue (see Figure 7.1) can be used to further analyse the decision process with semantic-based decision support capabilities. The Ontology

Dialogue is the interface used to create the Decision Ontology, access the Decision and Energy Ontology instances and run the different semantic features in OUTDO which are explained in Chapter 8.

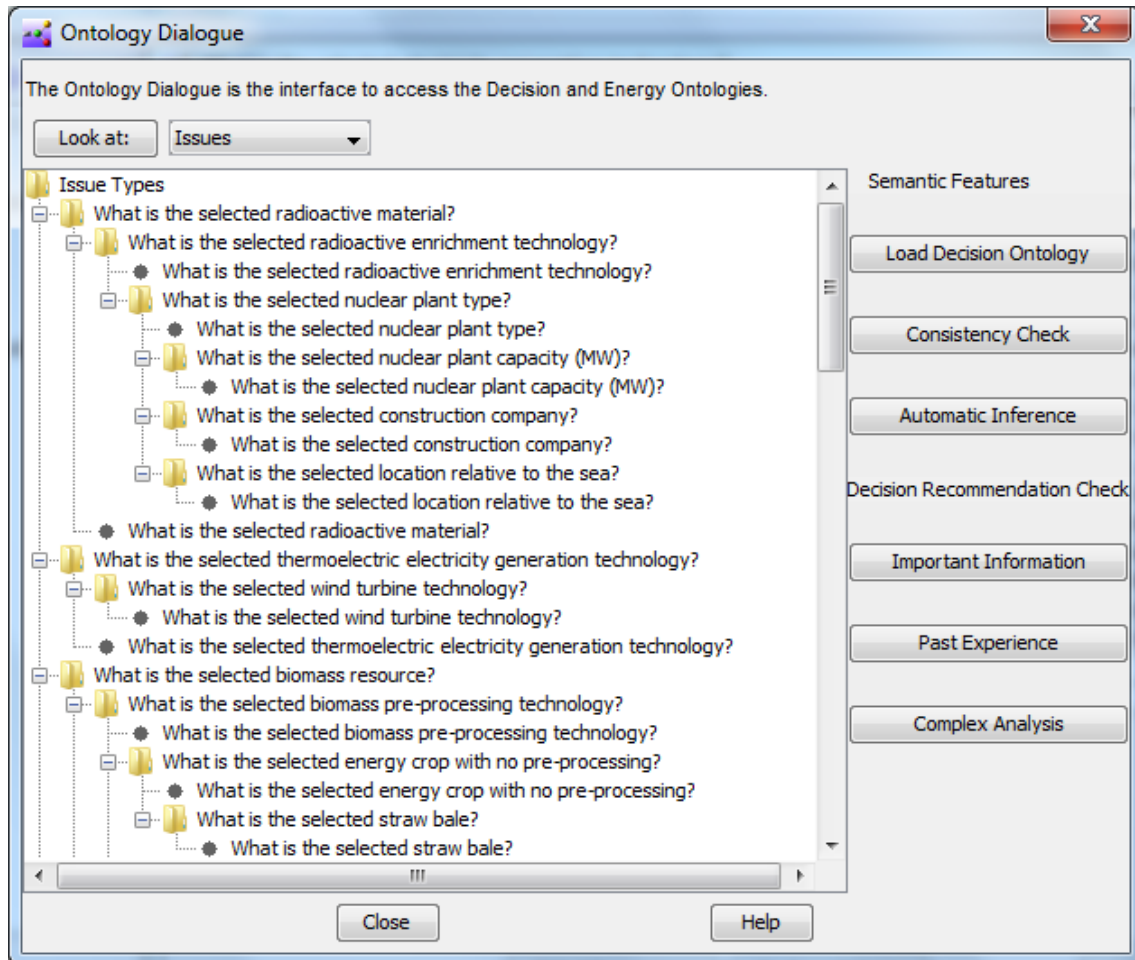


Figure 7.1: Ontology Dialogue window.

Figure 7.2 shows how the ontologies are integrated into OUTDO. Firstly, the decision maker extracts all the OUTDO components and their relations into an ontological format (Decision Ontology), as explained in more detail in Section 7.3. The Energy Ontology describes some of the most important aspects of the UK's energy sector and is detailed in Section 7.4. Once the decision process is in an ontological format, OUTDO compares the information in the Decision Ontology with the

information in the Energy Ontology with three different approaches, which are explained in Chapter 8. If OUTDO finds problems in the decision process, warning messages and suggestions for improvements are displayed.

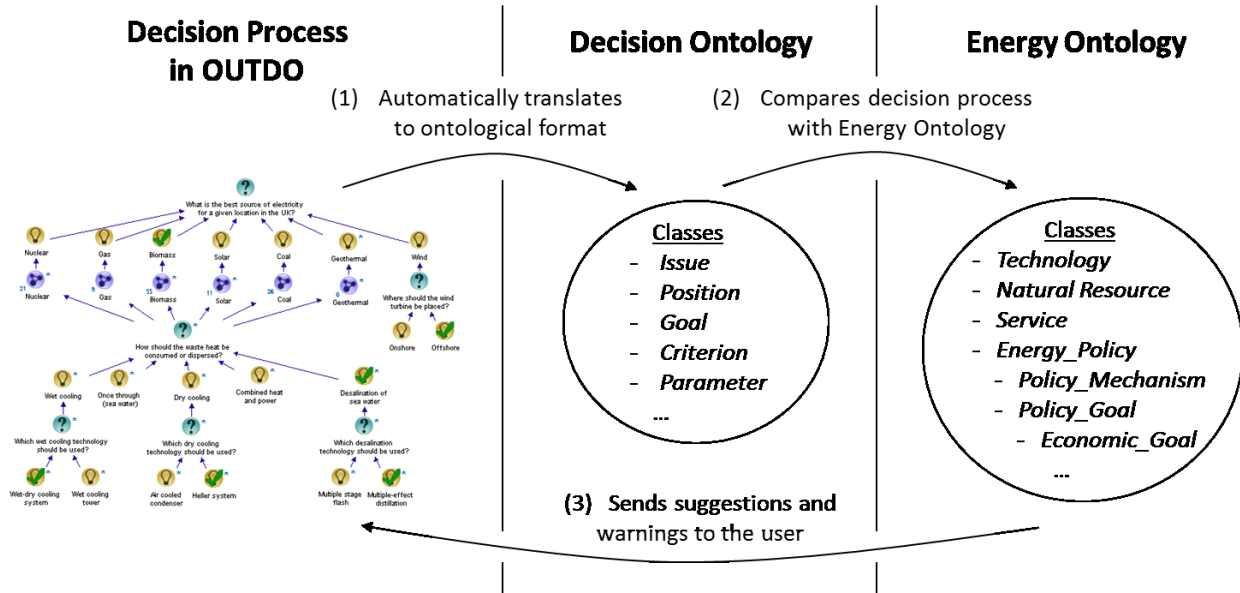


Figure 7.2: Connection of OUTDO with the semantic-based capabilities.

7.2.1 Ontology Structure

The backbone of the ontology is the taxonomical structure which consists of a formal description of a knowledge domain using classes, instances and properties [204]. Classes represent the types of concepts that share a set of properties and relations [205]. For example, in an ontology, the class *Electricity_Generation_Technology* can be a set of technologies that **consume** (relation) certain *Resource* (class) and **produce** (relation) *Electricity* (class). The more generic classes are followed by sub-classes if the relation 'is a(n)' applies, for example, a *Nuclear_Plant* is an *Electricity_Generation_Technology* [206]. Classes and subclasses are collections of instances that have the same properties

and constraints. Instances are the concepts with the highest granularity²² in an ontology. It is a specific instantiation of a class and is used to represent a single concept. For example, *Sizewell_B* can be an instance of *Nuclear_Plant*. Instances are the basic components of an ontology. In fact, it can be said that the general purpose of an ontology is to provide a mean of classifying instances.

There are two types of properties: object properties and data properties. An object property represents the relation between classes. For example, ***produces*** is a relation that combines *Coal_Plant* with *CO₂*. A data property is a pointer from a class (or instance) to its numerical or Boolean value, or text. In some cases, both data properties or object properties can be used to express the same information; for example, the water requirement for an electricity generation technology could be represented with the data property ***Water_Usage_(kg/MWh)*** with a value of 3,000 or it could be represented by an object property i.e. *Coal_Plant consumes 3,000_kg/MWh_Fresh_Water*. The property choice should reflect the intentions for using the ontology. Annotations are text inputs that can be used to add further information to classes, instances, properties and axioms. Axioms are used to define the specific relationship between concepts using the properties. An axiom is based on a proposition or sentence that is always true. Axioms are the most powerful means of representing knowledge in ontologies, and are often used to represent knowledge that cannot be represented with the other primitives of the language [207].

The ontologies described in this thesis use the OWL 2 DL [208] language, the Protégé v.4.2 [209, 210] ontology editor and the OWL/XML [211] file format. The description logic (DL) language used in both ontologies is *SR_QIQ^(D)*, which is one of

²² The most specific concepts from a taxonomy. For example, the concepts with the highest granularity in the animal kingdom taxonomy are the species.

the most expressive DLs commonly used today [212], and the reasoner²³ is FaCT++ v.1.5.3 [213]. In order to use the knowledge in the ontologies to provide problem solving capabilities, the OWL API v.3.2.4 [214] was used to connect to OUTDO and process the information contained in the ontologies to provide decision support.

An important advantage of the inclusion of semantics in OUTDO is that the Issue-Based Information Systems representation organises the decision process in a hierarchical manner with the intention of giving as much detail as possible about the decision process. The IBIS approach for decision making fits very well with the taxonomical representation of knowledge in ontologies. For example, consider the case where a decision maker wants to use OUTDO to select a thermoelectric technology for a city's supply of heat and electricity. From the given positions and input parameters, he or she could end up choosing to build a nuclear plant. After the choice of nuclear plant, the type of nuclear power plant has to be selected. In other words, the OUTDO user would input *Nuclear plant* as a position for the issue “*What is the selected electricity generation technology?*” and *PWR* (Pressurised Water Reactor) as a position for the issue “*What is the selected nuclear plant type?*”. This IBIS representation is easily represented in the ontological structure as *Nuclear_Plant* is a subclass of *Electricity_Generation* and nuclear plant types (i.e. *PWR*) are instances of *Nuclear_Plant*. Other advantages of the combination of IBIS and ontological representations are presented in Chapter 8.

²³ Reasoners enable implicitly represented knowledge to be inferred from the knowledge that is explicitly contained in the knowledge base [246].

7.3 The Decision Ontology

The issues, positions, criteria, goals, parameters (Global Parameters), recommendations and decisions from OUTDO are automatically translated into an ontological format and added to the Decision Ontology. The issues are organised in the Decision Ontology following the modified IBIS structure used in OUTDO. The criteria, goals and parameters are organised in different types and sub-types and are automatically updated in the Decision Ontology as the user adds and removes criteria, goals and parameters instance and types (subclasses). Positions, recommendations and decisions are included in the Decision Ontology as a list, with no further organisation. The Decision Ontology is created so that the meaning behind the decision process components in OUTDO can be manipulated by the computer thereby providing decision support.

In the construction of an ontology there is no unique way to model a domain, there are always viable alternatives [215]. In the case of this thesis, characteristics explored by the author were practicality, simplicity and efficiency. The Decision Ontology uses relations (object properties) to connect the following classes: *Issue* and *Position*, *Position* and *Criteria*, *Position* and *Parameter*, and *Criterion* and *Goal*, as shown in Figure 7.3 (a). Figure 7.3 (b) shows examples of instances from the classes represented in Figure 7.3 (a). An example of relations between *Position* and *Issue* is: *IGCC (GEE) has_Issue* “What is the selected coal unit cycle?”. The *Recommendation* and *Decision* classes use the same object properties as the *Position* class for their relations with the *Issue*, *Criterion* and *Parameter* classes. The difference is that the instances of the *Recommendation* class are positions with the highest score in the WSM decision matrix analysis and the instances of the *Decision* class are the positions

selected by the decision maker. It should be noted that an instance from the class *Position* can be an individual from the class *Recommendation* and/or *Decision* simultaneously.

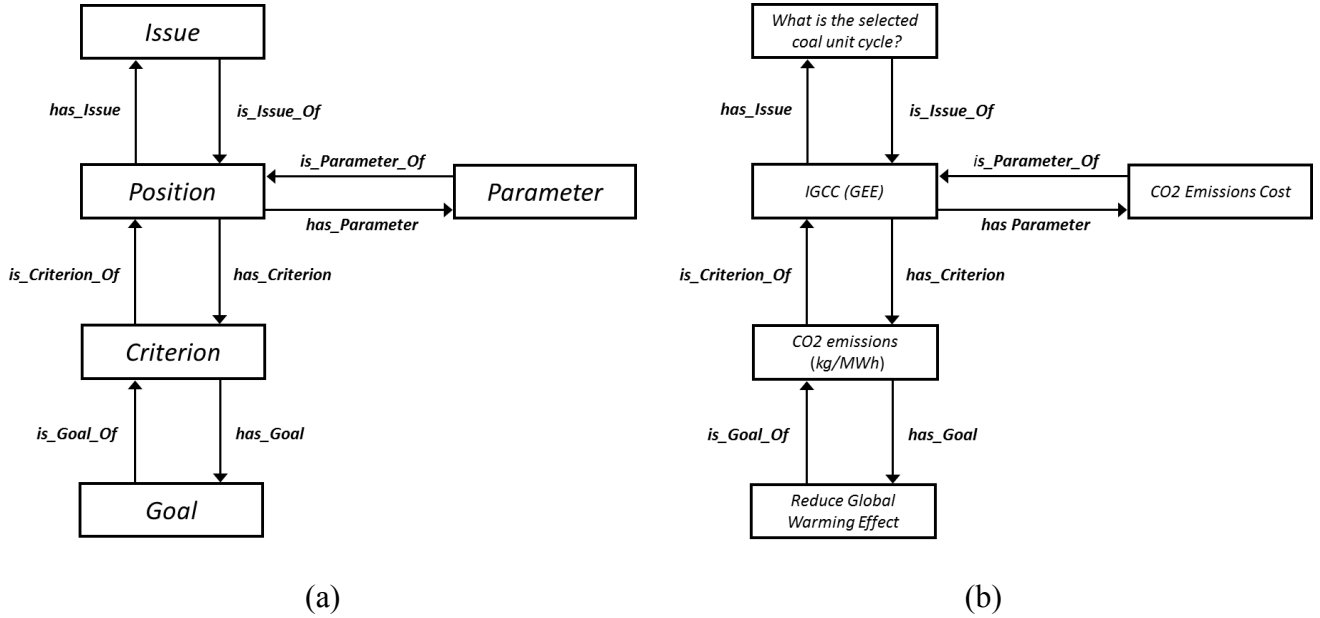


Figure 7.3: (a) Decision Ontology, (b) Example of instances of the Decision Ontology.

7.3.1 OUTDO Language

One of the problems with the implementation of semantics in OUTDO is that, in order for the semantic-based capabilities to function, the user has to input text into the OUTDO components following certain guidelines. In other words, the implementation of semantics in OUTDO does not attempt to automatically parse the text input. These guidelines are referred to as the OUTDO language. The OUTDO language is user-friendly and allows the user to express all his or her needs in a comprehensive fashion. The two main guidelines in OUTDO are:

- The user should define an issue node as “*What is the selected <Super Class>?*”.

The *Super Class* should correspond to a class in the Energy Ontology. For example:

“*What is the selected cooling system?*”. This allows the computer to understand that the issue node is trying to compare different cooling systems.

- The user should define a criterion as “<*Criterion name*> (<*Criterion units*>)”. For example, *Cost (£/MWh)* or *Water usage (kg/MWh)*. In this way, OUTDO is able to distinguish the criterion name and the criterion unit. If the user does not include the brackets, OUTDO assumes the units refer to a qualitative criterion.

However, the decision maker might employ a different vocabulary to the one used in the Energy Ontology. For example, if the user enters the position node called *Cogeneration*, OUTDO will not recognise that this position has the same meaning as *Combined_Heat_and_Power* in the Energy Ontology. For this purpose, the user can tag different instances in the Decision Ontology with instances in the Energy Ontology. But it should be noted that the Energy Ontology is always the same. OUTDO creates a synonymous instance in the Decision Ontology, with the name of the similar instance in the Energy Ontology.

7.3.2 Decision Ontology Applications

It is essential to know, before building an ontology, what are the reasons for building the ontology and what are its intended uses [101]. The Decision Ontology can be used for different purposes. These include: supporting the decision process, monitoring the decision implementation, re-using the decision process, re-evaluating the decision process with automatic sensitivity analysis or case-based reasoning, among others. In this thesis the Decision Ontology is only used to support the decision process and this usage is exemplified in Chapter 8.

7.4 The Energy Ontology

The Energy Ontology is designed to contain relevant information about the energy generation and management domain in a coherent and well-structured way. The Energy Ontology mainly focuses on electricity generation technologies, with particular attention to the consumption or disposal of the waste heat from the condensation of thermoelectric power plants. Its main objective is to contain as much information as possible about the energy domain. However, trying to include as much information in an ontological format is not that simple. One problem taken into account when structuring the Energy Ontology is that one ontological structure cannot fit all purposes, as each structure follows rigid description logic concepts. An example of this is that *Electricity_Generation* should not be divided into *Thermoelectric* and *Non-Thermoelectric* technologies as a *Solar_Plant* can be categorised as both and its inclusion would result in inconsistencies in the ontology. This problem was solved by dividing the *Electricity_Generation* class into *Renewable* and *Non-Renewable* classes instead of *Thermoelectric* and *Non-Thermoelectric* classes. OUTDO uses the knowledge in the Energy Ontology to aid the decision processes involving energy generation systems with different semantic capabilities. The methodologies behind these semantic capabilities are explained and exemplified in the next chapter.

The principal concepts of the Energy Ontology are shown in Figure 7.4 and can be divided into eight classes: *Energy_Policy*, *Technology*, *Natural_Resource*, *Product*, *Actor*, *Location*, *Finance* and *Time*. The subclasses are shown in Figures 7.5 and 7.6. Several cases in which the Energy Ontology supports decision making are exemplified in Chapter 8. The instances of the concepts in the Energy Ontology are static and are generated by a specialist before the user apply OUTDO for making energy decisions. In

principle the Decision and Energy ontologies could be merged as they share common concepts such as goal and criterion.

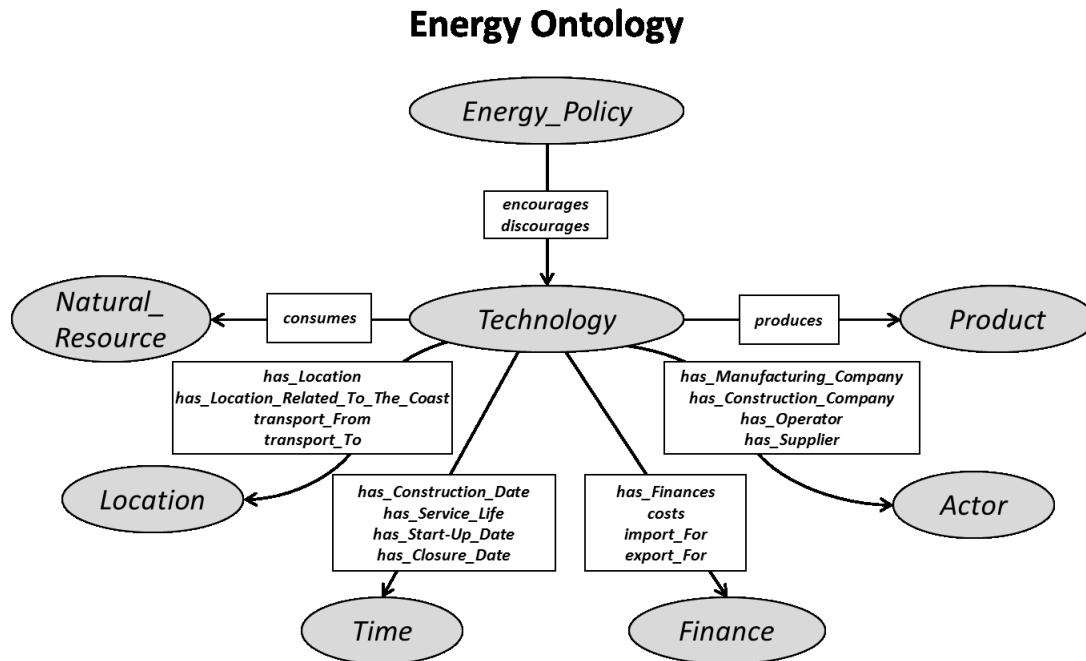


Figure 7.4: Overall structure of the Energy Ontology

7.4.1 Energy Policy Class

The *Energy_Policy* class represents the general intent (goals) and mechanisms behind the construction of energy infrastructure, the evaluation of policies, and the monitoring of their implementation. The subclasses of this class are shown in the first column of Figure 7.5. The *Policy_Evaluation* and *Policy_Monitoring* classes are not represented in detail in the Energy Ontology and thus are not discussed here.

- The *Policy_Goal* class describes the goals intended to be reached through the construction of new energy infrastructure. It is organised in different subclasses, for example, *Economic_Goal*, *Energy_Supply_Stability* and *Social_Goal*. Examples of Policy Goals instances are: *Reduce_Investment_Cost*,

Improve_Peak_Load_Response, *Increase_Employment*, etc. These instances have *Associated_Criterion* data properties, which is the list of criteria that relates to each goal.

- The *Policy_By_Country* class looks at the Energy Ontology and infers policy mechanisms instances that would achieve intended changes in a country's energy system. Examples of *Policy_By_Country* instances are: *UK_High_Electricity_Cost_Policy*, *UK_Low_Water_Usage_Policy*, etc. An example of the axiom that would result in *Policy_Mechanism* inferences from these instances is: *UK_Low_CO2_Emission_Policy* **encourage some** (*Electricity_Generation* **and** *'CO2_Emissions_(kg/MWh)'* **some double** [**<= 150**])²⁴.
- The *Policy_Mechanism* class describes the different mechanisms for the implementation of energy policies. Examples of instances of this class are: *Coal_Energy_Subsidy*, *Wind_Feed-in_Tariff*, *CCS_Regulation*, *Renewable_Energy_Certificate*. These instances are automatically inferred to the *Policy_By_Country* sub-classes given their axioms, as shown above and because the *Policy_Mechanism* class **encourage some** *Technology*.

²⁴ This axiom attempts to reproduce the following meaning: UK low CO₂ emission policies encourage electricity generation technologies that have CO₂ emissions lower than 150 kg/MWh.



Figure 7.5: The *Energy_Policy*, *Technology*, *Natural_Resource* and *Location* subclasses in the Energy Ontology.

7.4.2 Technology Class

The *Technology* class is the main Energy Ontology class both in terms of classes and axioms. This class describes the main technologies involved in the generation of

electricity, heating, cooling, seawater desalination and so on. The subclasses of this class are shown in the second column of Figure 7.5. The two classes below infer electricity generation technologies.

- The *Thermoelectric_Electricity_Generation* class infers *Electricity_Generation* technologies that produce heat. This class is equivalent to *Electricity_Generation* **and** (*produces some Heat*). Examples of inferred instances are: *Biomass_Gasification*, *Concentrating_Solar_Power_Plant*, *IGCC_Coal*.
- The *Non-Thermoelectric_Electricity_Generation* class infers *Electricity_Generation* technologies that do not produce heat. This class is equivalent to *Electricity_Generation* **and** (*produces only Electricity*). Examples of inferred instances are: *Wind_Turbine*, *Photovoltaic_Cell*.

Other classes that could have been included that would infer electricity generation technologies are *Fossil_Fuel_Based_Electricity_Generation*, *Non-Fossil_Fuel_Based_Electricity_Generation*, *Intermittent_Electricity_Generation*, *Continuous_Electricity_Generation*, *Dispersed_Electricity_Generation*, *Concentrated_Electricity_Generation*, etc.

7.4.3 Natural Resource Class

The *Natural_Resource* class describes the natural resources that are consumed by the technological processes in the *Technology* class. This class is divided into two subclasses: *Renewable* and *Non-Renewable*. To represent the amount of natural resources consumed, the Energy Ontology refers to instances representing the quantity of natural resource consumed. An example for the water consumption of an Integrated Gasification Combined Cycle plant is *GEE_IGCC consumes 1400_kg_Water/MWh*

[182]. This extends the applicability of the ontology and thus the possibilities to support decision making. The subclasses of this class are shown in the third column of Figure 7.5.

- The *Non-Renewable* class describes the natural resources that are exhaustible. An important aspect is that resources from different locations have different characteristics. For example, the coal from *South_Africa* has a high concentration of sulphur, the coal from *Australia* has to travel far to be burned in the *UK*, the cost of *UK* coal is high, etc. Therefore the non-renewable natural resource should specify its origins. For example: *Bituminous_UK*, *Bituminous_Russia*, *Bituminous_South_Africa*, *Bituminous_Colombia*, etc.
- The *Renewable* class describes the natural resources that are not exhaustible. The same problem with change in location should be taken into account for renewable natural resources. For example, the wind speed in Scotland is considerably higher than the wind speed in South West England. Thus the wind instances should be divided in *Wind_Scotland*, *Wind_South_West_England*, etc.

7.4.4 Location Class

The *Location* class describes the location for each instance in the Energy Ontology. This class is divided into three different subclasses: *Site*, which describes how the location has been previously used, *Continent*, which describes the exact location of the instance and *Location_Relative_To_The_Sea*, which describes the location relative to the sea. The subclasses of this class are shown in the fourth column of Figure 7.5.

7.4.5 Product Class

The *Product* class describes the products that result from the technological processes in the *Technology* class. This class is divided into several subclasses: *Electricity*, *Heat*, *Cooling*, *Desalinated_Water* and *By-Product*. Every time a *Product* is mentioned in the Energy Ontology it is referred to an instance of the *Product* class. The subclasses of this class are shown in the first column of Figure 7.6.

The *By-Product* class describes unintended products that cause inconvenience to society and the environment. This is divided into four major subclasses: *Solid_Waste*, *Radioactive_Waste*, *Flue_Gas* and *Water_Pollution*. These classes have instances for each value, for example, the instance ‘400_kg_CO2/MWh’ is created to represent a CO₂ emission of 400 kg/MWh. The same is carried out for all the other instances of this class.

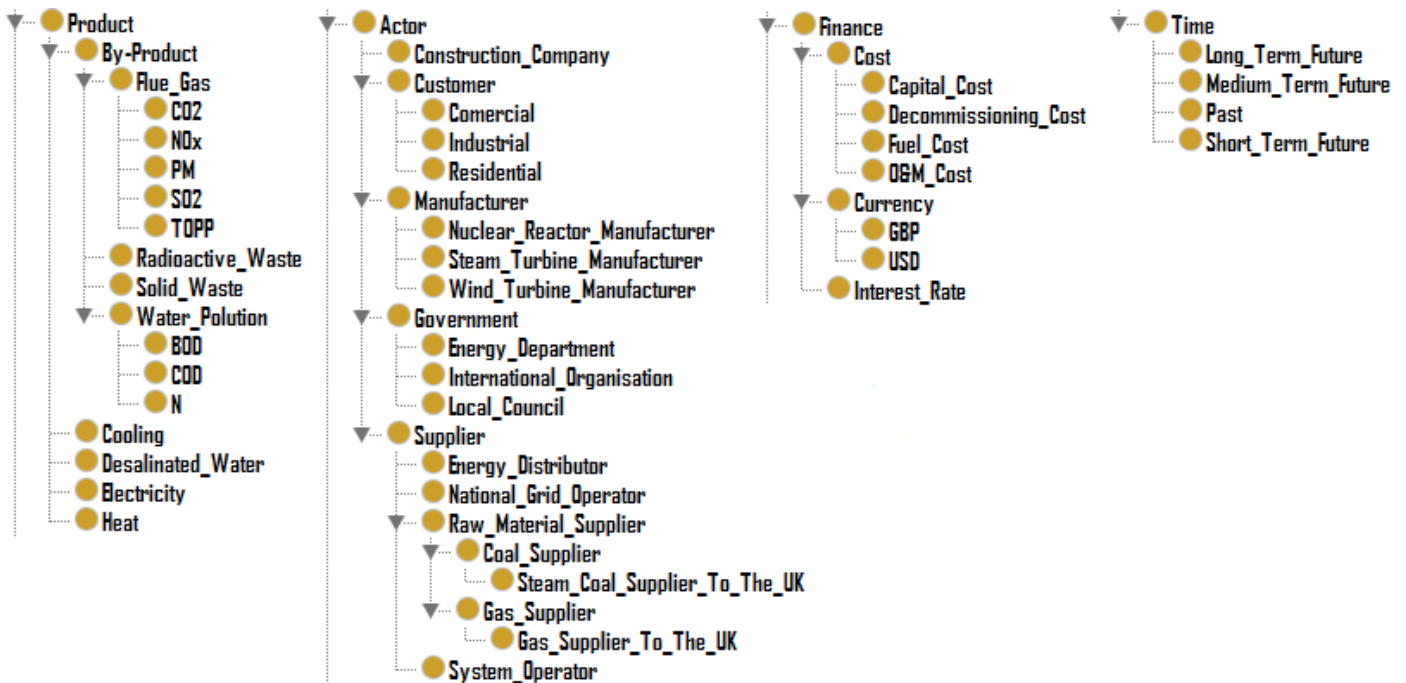


Figure 7.6: The *Product*, *Actor*, *Finance* and *Time* subclasses in the Energy Ontology.

7.4.6 Actor Class

The *Actor* class describes the people and organisations involved in the Energy Sector. This class is divided into five subclasses: *Customer*, *Government*, *Supplier*, *Construction_Company*, *Manufacturer*. The subclasses of this class are shown in the second column of Figure 7.6.

- The *Customer* class describes the people or organisations that buy the energy products (*Electricity*, *Heat* and *Desalinated_Water*) from the supplier. There are three types of customers: *Commercial*, *Industrial* and *Residential*.
- The *Supplier* class describes the people or organisations responsible for producing services and raw materials. There are four types of suppliers: *System_Operator*, *National_Grid_Operator*, *Energy_Distributor*, *Raw_Material_Supplier*.
- The *Government* class describes the organisations responsible for allowing the suppliers to produce and sell energy. Governments have the power to control how energy should be produced and consumed.
- The *Construction_Company* class describes the companies responsible for the construction of power generation plants.
- The *Manufacturer* class describes the companies responsible for the manufacturing of the equipment used in the construction of power generation plants.

7.4.7 Finance Class

The *Finance* class describes the financial aspects of the Energy Ontology. It was created due to the need to include the financial aspects of energy systems and thus allow for the creation of relations between technologies and their costs. This class is divided

into three subclasses: *Cost*, *Currency* and *Interest Rate*. The subclasses of this class are shown in the third column of Figure 7.6. An example of a relation using this class is: *GEE_IGCC has_Capital_Cost 39£/MWh* [182].

7.4.8 Time Class

The *Time* class describes time in years. This class is divided into four subclasses: *Past*, *Short_Term_Future* (2010-2020), *Medium_Term_Future* (2020-2040) and *Long_Term_Future* (2040 onwards) [216]. The subclasses of this class are shown in the fourth column of Figure 7.6. An example of a relation using this class is: *GEE_IGCC has_Service_Life 25_Years*.

7.4.9 Axioms

The main axioms used in the Energy Ontology are described below.

- The ***Combustion*** axiom describes the combustion phenomenon. An example of this axiom for the class *Coal_Plant* is: ***consumes some (Coal and consumes some (Air or Oxygen) and produces some (Heat and CO2 and SO2 and NOx and PM and TOPP))***. For this axiom to function properly, the instances of the *Coal_Plant* class (e.g. *GEE_IGCC_Coal*) require the object properties: *GEE_IGCC_Coal consumes Bitumious_Russia*, *GEE_IGCC_Coal produces 796_kg_CO2/MWh* [182], etc.
- The ***Steam_Turbine*** axiom describes the process in a steam turbine cycle. The axiom is: ***consumes some (Heat and produces some (Electricity))***. This process

has particular characteristics such as: overall efficiency, capital cost, etc. These characteristics can be included as annotations.

- The ***Steam_Condensation*** axiom describes the condensation of the steam from the steam cycle. The axiom is: *has_Cooling some (Cooling_System and consumes some (Air or Water)) or has_Cooling some (Combined_Heat_And_Power) or has_Cooling some (Desalination and consumes some (Air or Sea_Water)) and produces some (Cooling)*. For this axiom to function properly, the instances of the *Coal_Plant* class (e.g. *GEE_IGCC_Coal*) require the object properties: *GEE_IGCC_Coal has_Cooling Wet_Cooling*, *GEE_IGCC_Coal consumes 1420_kg_Water/MWh* [182], etc.
- The ***Solid_Waste_Disposal*** axiom describes the disposal of solids resulting from processes from the *Technology* class. This axiom is: *has_Disposal_Cost some (Cost) and transport_From some (Location and transport_By some (Resource_Transport and transport_To some (Location)))*. Similarly a *Radioactive_Waste_Disposal* axioms were created.
- The ***Electricity_Transmission*** axiom describes the transmission of electricity. This axiom is: *transmit_From some (Location and transmit_By some (Electricity_Transmission and transmit_To some (Location)))*.
- The ***Resources_Transport*** axiom describes the transportation of natural resources. The axiom is: *transport_From some (Location and transport_By some (Resource_Transport and transport_To some (Location)))*.

These axioms have great potential to improve the semantic-based decision support capabilities. However, unfortunately, there are no proposed mechanisms to use them in Chapter 8. The Future Work Section in Chapter 9 will suggest some approaches

as to how these axioms could be used to support decision processes.

7.5 Conclusion

In conclusion, developing ontologies is a time-consuming task which requires expertise to tackle structural and logical difficulties in the definition of concepts as well as their relationships. However, ontologies provide the means to effectively build robust knowledge databases and to support the construction of these databases using description logic to check for internal inconsistencies and also expand the initial knowledge input to the ontology with the inference of classes, instances and objects, thus reducing its construction time.

The Decision Ontology was designed to store the information available in OUTDO in a simple and organised fashion so that this information can be easily handled by the computer. The knowledge contained in the Energy Ontology intends to simply and clearly contain as much information about the energy field as possible so that it can be used to support the decision process in OUTDO.

The main reason why it makes sense to include semantic-based capabilities into OUTDO is the similarity between the IBIS representation and the ontological representation of knowledge. The fact that the technologies in the Energy Ontology's taxonomy can be directly linked to issues and position nodes in OUTDO without much difficulty has considerably facilitated the construction of decision support mechanisms which are presented in the next chapter. The next chapter uses the Decision and the Energy ontologies introduced in this chapter to present three different semantic-based approaches for decision support.

Chapter 8

Reactive Decision Support

8.1 Introduction

Having translated the decision process in OUTDO into an ontological format, added to the Decision Ontology, and described the energy domain with the Energy Ontology, it is time to find how to most effectively use this information to support decision processes. This chapter presents the reactive decision support features which interface the decision rationale stored in OUTDO to the Energy Ontology via the Decision Ontology. The Reactive Decision Support feature analyses the decision rationale and displays warning messages when it finds inconsistencies or potential mistakes. There are three different ways of using semantics to support decision processes: Consistency Check, Automatic Inference and Decision Check. These semantic-based decision support methods are innovative concepts that benefit from the similarities between the IBIS and ontological representations. This is the second chapter to describe the *Semantic Capabilities* block shown in Figure 3.6 and it is the last chapter that describes OUTDO's decision framework in detail.

This chapter was named Reactive Decision Support (RDS) because it does not attempt to guide the user through his or her decision process. RDS only checks if the decision process is consistent, suggests issues and positions that the user might not be aware of and gives feedback on the decision made. The reason for this is that, if the program tries to guide the user, the user might be distracted by the semantic capabilities which would in turn reduce the user's creativity when making his or her own decisions. A good balance between the creation of innovative concepts by the user and decision

support based on existing knowledge with RDS is intended in the inclusion of semantics into OUTDO.

The three main methods of using semantic capabilities to support decision making are described each in its own section. Section 8.2 describes the Consistency Check feature. Section 8.3 introduces the two different types of the Automatic Inference feature. Section 8.4 presents the three different types of the Decision Check feature. Section 8.5 concludes the chapter.

8.2 Consistency Check

It is an essential step for the construction and verification of ontologies to certify that the ontologies are consistent. This is particularly important when agents-based autonomous software make use of ontologies [217]. Reasoners (FaCT++, Hermit, etc.) are sometime referred to as consistency check tools as they look at inconsistencies in axioms and relations between classes and instances [217], i.e. they focus on the ontology structure. However, the consistency check in this thesis focuses on ensuring that the Decision Ontology is free of inconsistencies related to the decision making process in the energy domain. With this intention the Decision Ontology is compared with the Energy Ontology to ensure that the decision process in the energy generation domain is coherent and relevant. For example, if a criterion is connected to a goal in OUTDO and its corresponding *Policy_Goal* does not have the same *Associated_Criterion* in the Energy Ontology, OUTDO will warn the user. Five specific applications of the Consistency Check feature have been implemented in OUTDO, these are: Goals vs. Criteria, Issues vs. Positions, Positions vs. Criteria, Positions vs. Parameters, and the Issues Ordering Consistency Check.

8.2.1 Goals vs. Criteria Consistency Check

In a decision process, criteria are used to compare different positions. The selection of these criteria should be dictated by the decision maker intent to achieve pre-established goals. It would be inconsistent to select criteria that do not correspond to the decision process goals. If this is the case, OUTDO has the ability to warn the user when a criterion is not relevant to the goals declared in the decision process. In particular, if a criterion is connected to a goal in OUTDO (via the Goals vs. Criteria matrix, see Figure 4.3) and the corresponding *Policy_Goal* does not have the same associated criterion in the Energy Ontology, OUTDO will warn the user. The diagram in Figure 8.1 shows in detail how this consistency check is performed. The steps below are represented by the numbered arrows in Figure 8.1.

- 1) The decision rationale is extracted from OUTDO into the Decision Ontology.
- 2) The *Criterion* class (in the Decision Ontology) is screened, and each criterion is checked.
- 3) The goals related to the criterion are retrieved from the values of the *has_Goal* object property, and the goals are searched in the *Policy_Goal* class of the Energy Ontology.
- 4) If the corresponding goal is found as an instance of the *Policy_Goal* class in the Energy Ontology, it is looked at in detail. If it is not found, OUTDO asks the user if he or she wants to relate this goal to another existing goal in the Energy Ontology.
- 5) Looking at the goal in the Energy Ontology, the values of the *Associated_Criterion* data property are compared with the name of the criterion in the Decision Ontology.

- 6) If one of the values of the *Associated_Criterion* property matches the criterion label, the goal-criterion pair is consistent and OUTDO does not intervene in the decision process.
- 7) If however, none of the values of the *Associated_Criterion* properties matches the criterion label, OUTDO will warn the user, see Figure 8.2.

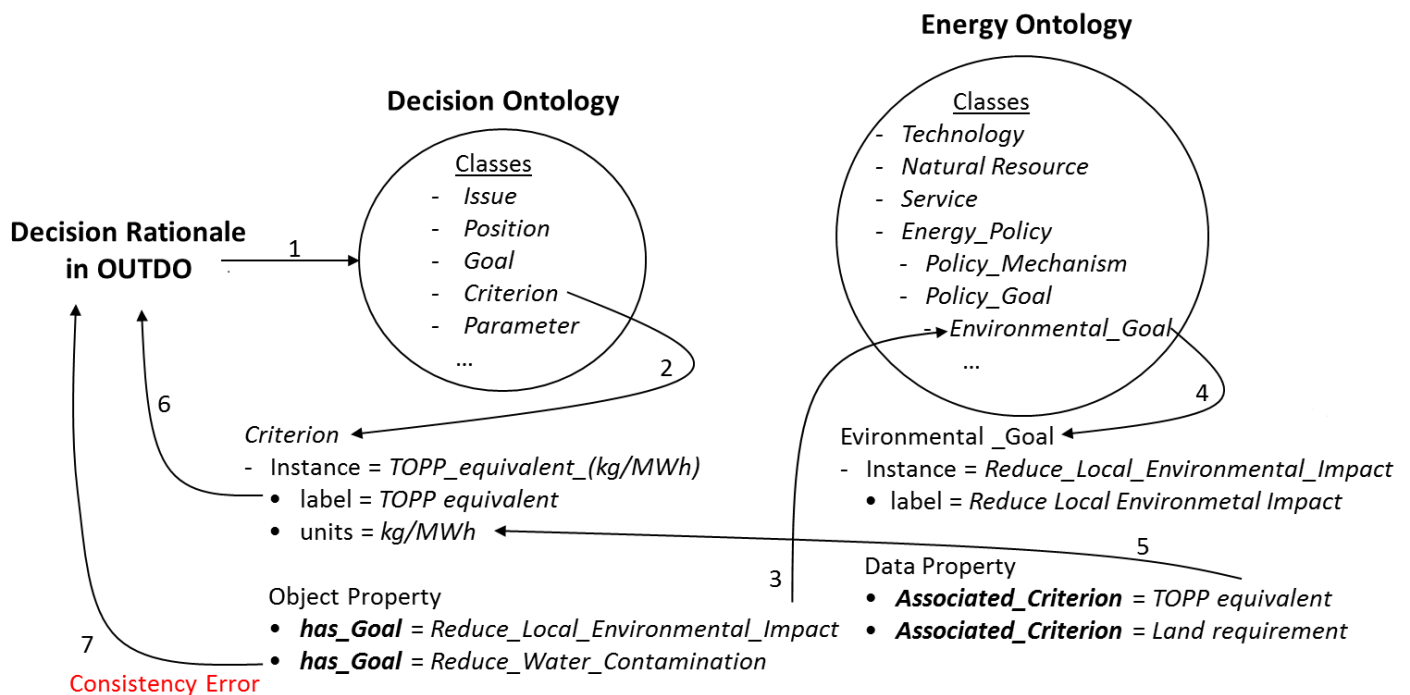


Figure 8.1: Diagram for Goals vs. Criteria Consistency Check.

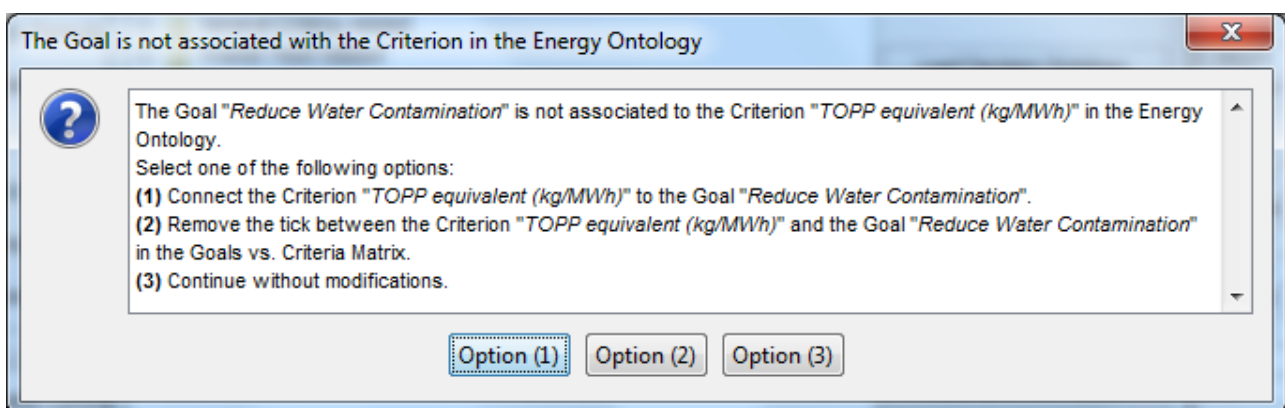


Figure 8.2: OUTDO message if a goal is not associated with a criterion in the Energy Ontology.

The Positions vs. Criteria and the Positions vs. Parameters Consistency Checks work in a similar manner to the Goals vs. Criteria Consistency Check.

8.2.2 Issues vs. Positions Consistency Check

The decision framework applied in OUTDO uses an extension of the IBIS representation. This IBIS-like representation fits in well with the ontological representation of knowledge. For instance, if a decision maker is interested in determining “*What is the selected electricity generation technology?*”, “*What is the selected cooling system?*”, “*What is the selected wind turbine?*”, the possible positions to address these issues are subclasses or instances of the respective classes *Electricity_Generation*, *Cooling_System* and *Wind_Turbine* respectively. This makes the connection of issues with positions in the Energy Ontology simple and efficient.

If a position is connected to an issue in OUTDO and this issue does not have a subclass or instance corresponding to this position in the Energy Ontology, OUTDO will warn the user. Figure 8.3 presents the mechanisms behind the Issues vs. Positions Consistency Check feature.

- 1) The decision rationale is extracted from OUTDO into the Decision Ontology.
- 2) The *Issue* class in the Decision Ontology is screened, and each issue is checked.
- 3) In accordance with OUTDO conventions, only the words after “*What is the selected*” will be searched in the Energy Ontology. For example, if the issue is “*What is the selected cooling system?*”, OUTDO will firstly search for a *Cooling* class (text1 in Figure 8.3) in the Energy Ontology, and then search for a *Cooling_System* class (text2 in Figure 8.3). If OUTDO finds text1 and text2, text2 will be analysed as it contains a more detailed meaning than text1.

- 4) If the text1 and text2 are not found, OUTDO asks the user if he or she wants to manually tag the issue in OUTDO to its corresponding class in the Energy Ontology.
- 5) The subclasses of the *Cooling_System* class are compared with the instances connected to the object property **has_Position** in the Decision Ontology.
- 6) If some positions do not correspond to the subclasses or instances of the class being analysed, OUTDO will warn the user, see Figure 8.4 (a).

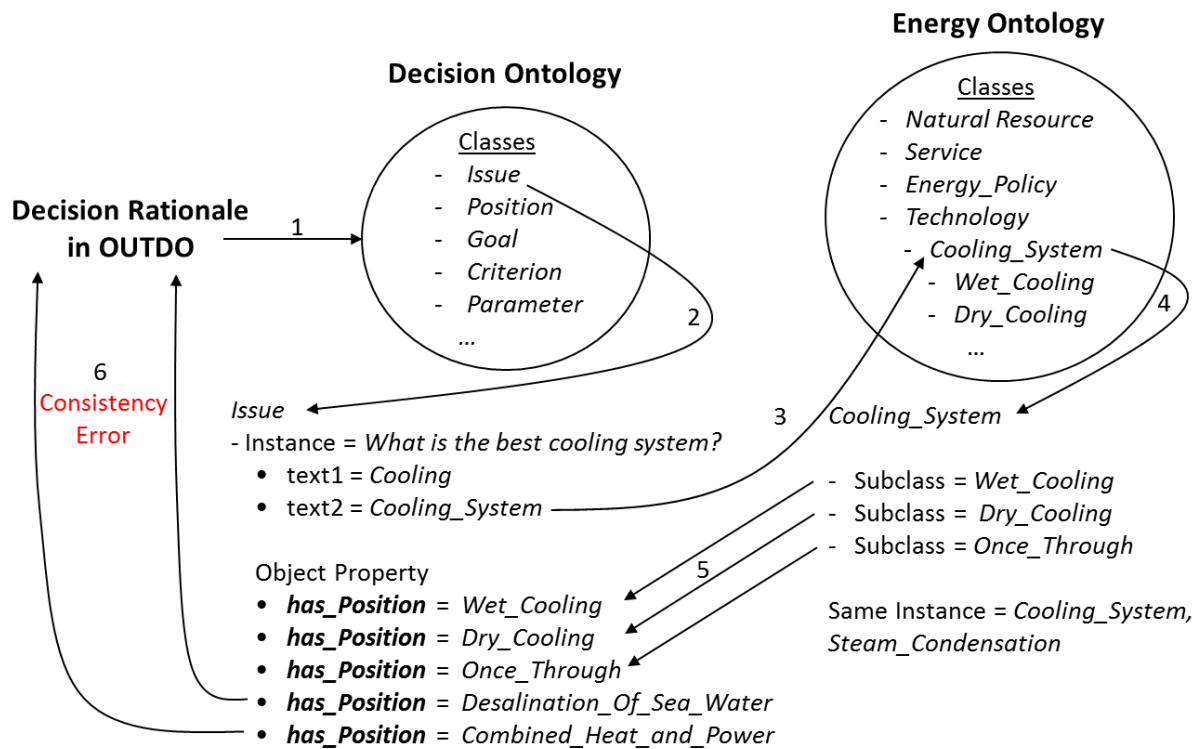


Figure 8.3: Diagram for Issues vs. Positions Consistency Check.

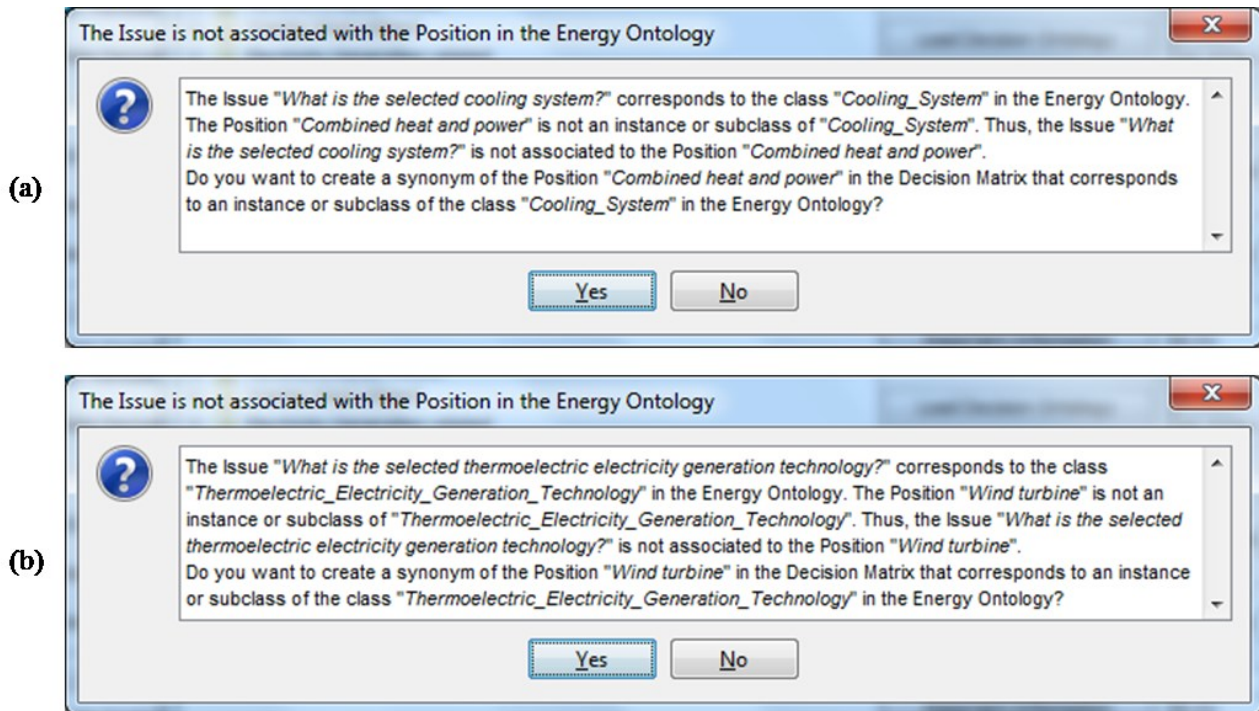


Figure 8.4: Warning message for an issue which is not associated with a position.

Another interesting message is shown in Figure 8.4 (b). In this case, the instances from the class *Thermoelectric_Electricity_Generation* are inferred from instances that are *Electricity_Generation* technologies and that *produce Heat*. As *Wind turbine* is not a thermoelectric electricity generation technology, OUTDO warns the user. In this case, future development of OUTDO semantics capabilities could improve the decision support as the logical reasoning would be able to “explain” to the user the reasons why *Wind turbine* is not a *Thermoelectric_Electricity_Generation*. A possible suggestion for this mechanism is to input the *Wind turbine* class into the *Thermoelectric_Electricity_Generation* class and run the reasoner. This input will result in an inconsistency in the Energy Ontology. The mechanism could then translate this inconsistency from description logic language to readable text, so that the reasons are clearly stated to the user.

8.2.3 Issues Ordering Consistency Check

This feature looks at the decision rationale structure and checks for inconsistencies in the ordering of the issues. Each issue node corresponds to a class in the Energy Ontology. The issue (e.g. *Issue2*) that is subordinated to another issue (e.g. *Issue1*) in the OUTDO decision process must correspond to a subclass of the class that corresponds to *Issue1* in the Energy Ontology. Alternatively, *Issue2* must correspond to a class in a different branch to the class that corresponds to *Issue1* in the Energy Ontology. If this is not the case, OUTDO will warn the user. For example, if the decision maker selects the position node *NGCC plant* as the solution to the issue node “*What is the selected type of gas plant?*”, and then he/she connects a new issue node “*What is the selected electricity generation technology?*” to the position node *NGCC plant*, OUTDO generates the message shown in Figure 8.5.

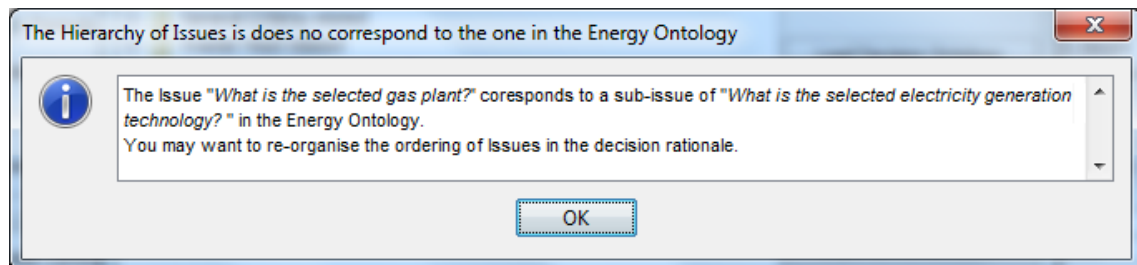


Figure 8.5: Message corresponding to an ordering of issues that does not correspond to the taxonomy in the Energy Ontology.

8.3 Automatic Inference

The Automatic Inference section looks at the decisions made in OUTDO, suggests issue nodes relevant to the decision process and possible positions that address those issues. In this way, the Automatic Inference section automatically creates a

preliminary decision template. There are two ways in which Automatic Inferences are preformed, the Issue Nodes Inference and Position Nodes Inferences.

8.3.1 Position Node Inference

The Position Nodes Inference looks at the class in the Energy Ontology corresponding to the issue node in OUTDO and, if its instances or subclasses are not position nodes connected to the issue node, OUTDO infers them as possible positions for the issue, as shown in Figure 8.6.

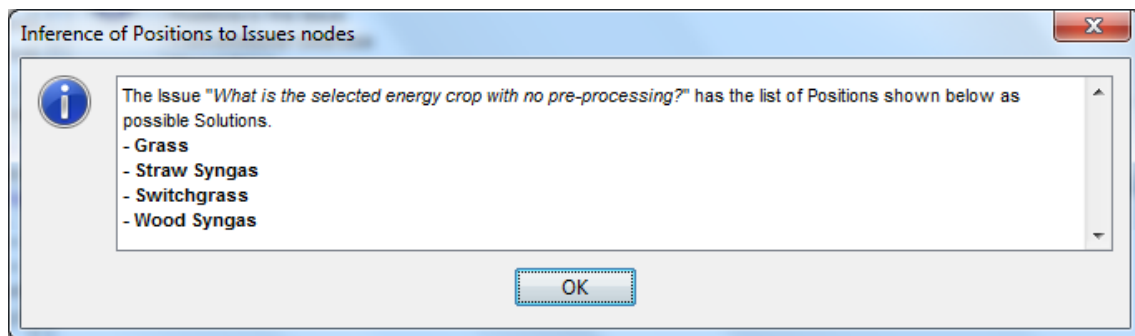


Figure 8.6: Inference of suggested position nodes.

8.3.2 Issue Node Inference

The Issue Node Inference looks at the decisions that have been made in OUTDO to suggest relevant issue nodes and positions that address those issues. Figure 8.7 shows a representation of this concept.

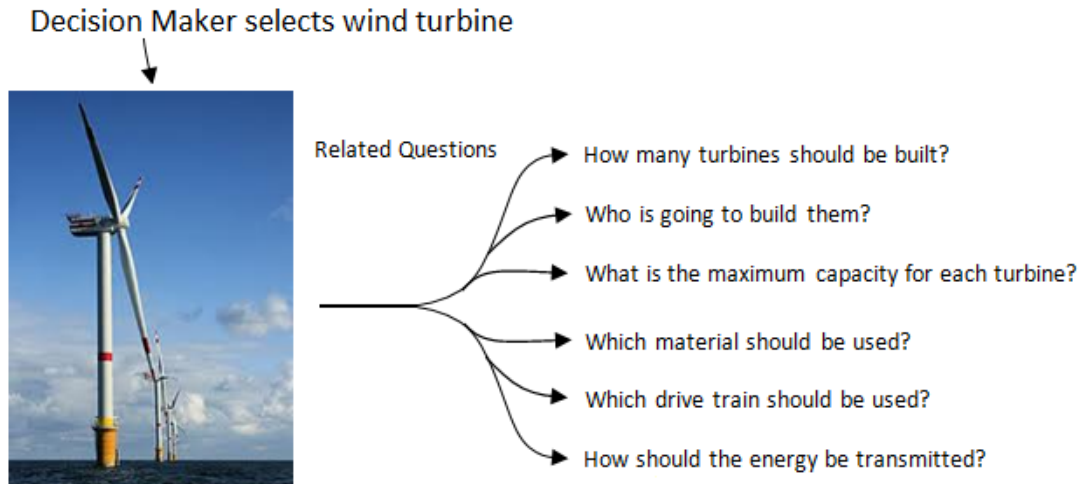


Figure 8.7: Issue Nodes Inference for wind turbines.

There are two ways in which the Issue Nodes Inference is performed. One approach is similar to the Position Nodes Inference, but instead of instances, it only looks at subclasses in the Energy Ontology. If OUTDO finds a subclass that extends the decision rationale in OUTDO and this subclass has not yet been included in the decision rationale recorded in OUTDO, then this subclass is suggested as a potential issue to the user. For example, if the user includes a position node *Coal plant* in OUTDO, OUTDO suggests the issue node “*What is the selected coal plant type?*” and its associated positions *IGCC coal* and *Pulverised coal*.

In the other approach, classes in the Energy Ontology have a specific object property that is acknowledged by OUTDO to contain an issue node related to it. This object property connects the classes or instances representing a position in OUTDO (e.g. *Wind turbine*) to other related classes or instances in the Energy Ontology. An example of this is *Wind_Turbine has_Wind_Turbine_Drive_Train Drive_Train*. The object properties are organised in such a way that OUTDO understands that each object property suggests issue nodes for a given position node. The way the Energy Ontology accommodates this is through the use of a hierarchy of object properties. Similarly to

classes, object properties can be organised in hierarchies. For example, the object properties *discourage* and *encourage* are a child of the object property *policy*. This hierarchy is used to organise the specific functionalities of a group of object properties. In the case of Automatic Inferences, any child property of the *has_Component* object property implies that there are details to be explored for that particular class or instance. In other words, there are issue nodes that could be inferred for the decision process. Examples of child properties of the *has_Component* object property are: *has_Drive_Train*, *has_Material_Of_Construction*, *has_Wind_Manufacturer*, and so on. So, if OUTDO recommends *Wind turbine*, the Automatic Inference will look at the *has_Drive_Train* object property and will suggest the issue node “*What is the selected wind turbine drive train?*”. In addition, it will suggest the associated position nodes *Conventional Gearbox* and *Direct-Drive*. These are instances of the *Drive_Train* class. This is exemplified in Figure 8.8.

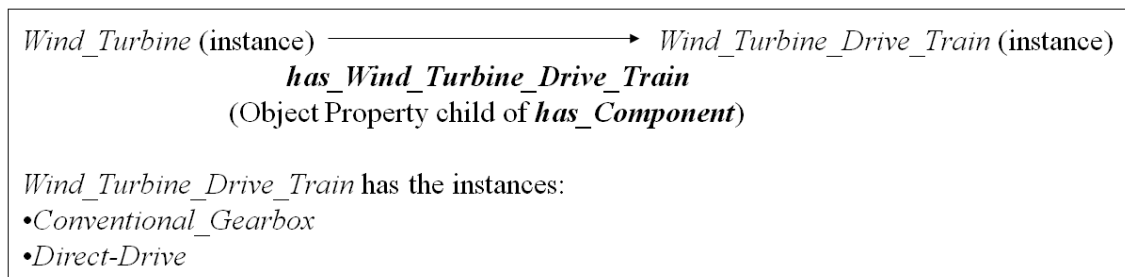


Figure 8.8: Representation of Issue Nodes Inference with object properties.

OUTDO sends a message with the inferred issue and its corresponding positions as in Figure 8.9.

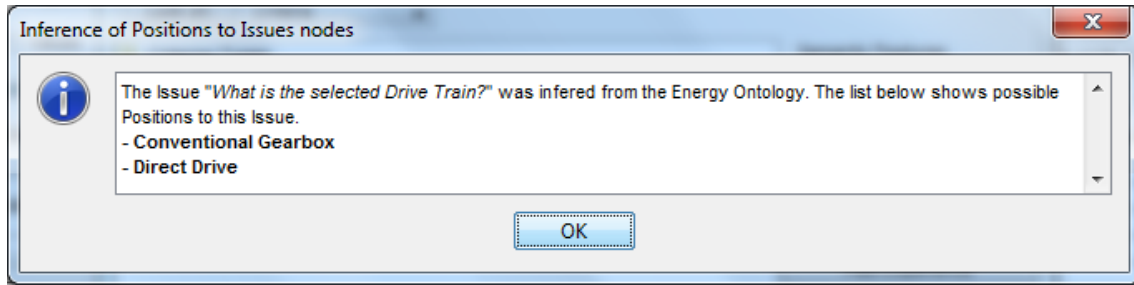


Figure 8.9: Inference of issues and positions.

8.4 Decision Check

Once a decision is made, there might be some aspects that have not been considered during the decision process. Some of these aspects might not have been included because quantitative analyses were difficult to apply. Alternatively, it could be that the decision maker was not aware of them. The latter might include qualitative aspects (such as public acceptance, geopolitical issues) and previous experiences which can be as important as quantitative aspects (such as cost, emissions) when making decisions.

There are three ways to run the Decision Check: Retrieval of Important Information, Past Experience and Multiple Qualitative Analyses. These capabilities are exemplified through the selection of nuclear plant technologies for the UK as shown in Figure 8.10 and through the selection of a coal supplier for the UK. Figure 8.10 shows a specific example of the decision process results in OUTDO, focusing on the design and construction of a nuclear power plant. In this case, the decision maker decided to select the positions that were recommended by the decision matrix (WSM method). After the decision maker has selected the positions he or she prefers, the semantic-based decision support can be used to check for problems in the decision process. This check provides

a good preliminary overview as the user can use the semantic capabilities to check for any potential problems with the decision process that he or she might not be aware of.

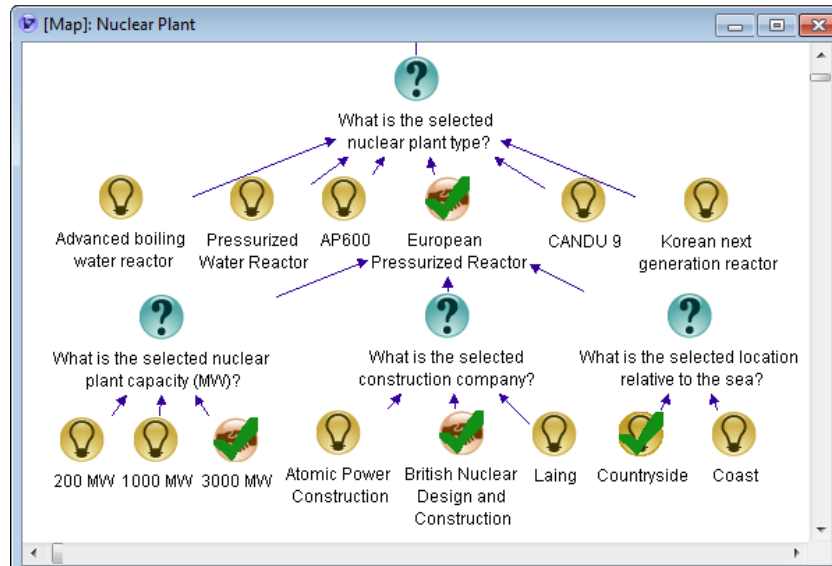


Figure 8.10: Decision rationale for the design and construction of nuclear plants in the UK.

8.4.1 Retrieval of Important Information

The Retrieval of Important Information functionality generates warnings for problems related to a single decision. This can involve the decision itself or other aspects that are inherently related to the decision. Once a decision is made, OUTDO searches for aspects that might not have been considered in the decision (for example, due to the difficulty in quantifying them), and mentions them to the user.

The main issues that the Energy Ontology tries to resolve involve technological processes. These follow the conceptual framework depicted in the diagram in Figure 8.11, which shows the general scheme representing engineering processes. This scheme

was translated into an ontological format and makes the concepts involved in engineering processes explicit.

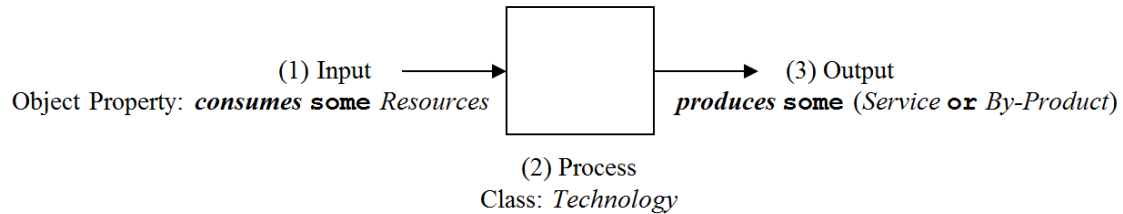


Figure 8.11: Engineering process diagram and its Energy Ontology representation.

As in all engineering processes, electricity generation has three main components:

- 1) The input resource (*Coal, Gas, Water, Wind, Solar_Radiation*, etc.).
- 2) A *Technology* to produce electricity.
- 3) The desired output (*Electricity, Heat, Cooling*); but it comes with the generation of other by-products such as *CO₂_Emissions, Polluted_Water, Particulates, Solid_Waste, Radiactive_Waste*, etc.

This feature looks at a decision in OUTDO, which corresponds to an instance here called *A* in the Energy Ontology. It then checks if instance *A* inherits a relation called *X* that connects to another instance here called *B*. If instance *B* or any of its super classes have an annotation called *warning*, OUTDO sends a message mentioning the problems involved with instance *B*. The text of the message is contained in the *warning* annotation. For example, the *Nuclear_Plant* class has the relations **consumes** connecting to the *Radiactive_Material* class. As the *Radioactive_Material* has an annotation called *warning*, OUTDO sends the warning in Figure 8.12. The same happens with the relation **produces** *Radiactive_Waste* and the warning in this case is shown in Figure 8.13.

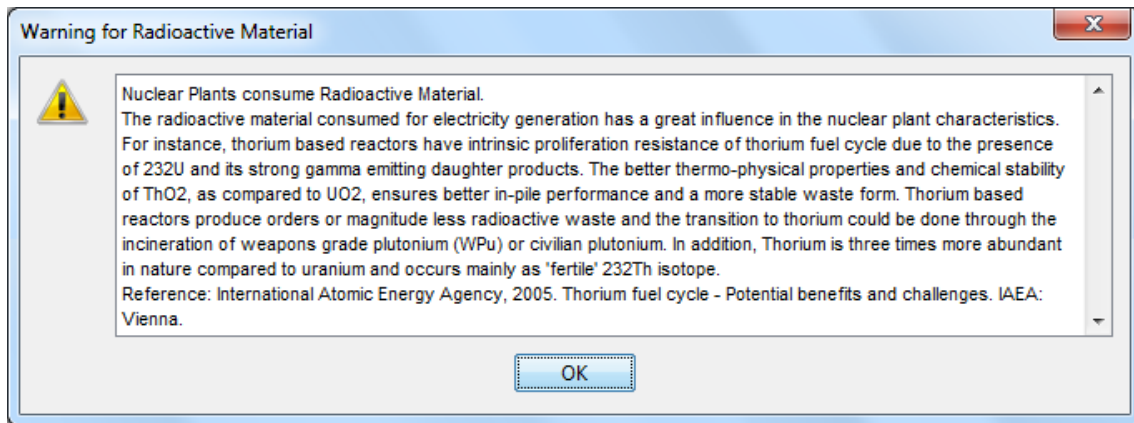


Figure 8.12: Warning message regarding the input to the system (i.e. radioactive material).

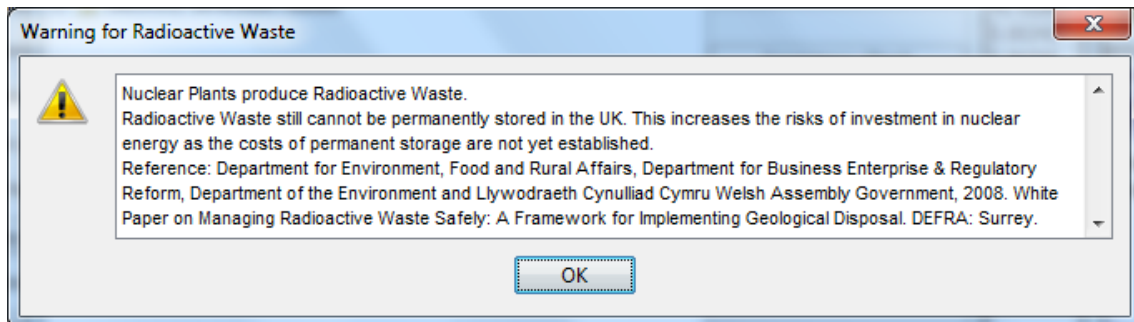


Figure 8.13: Warning message regarding the output from the system (i.e. radioactive waste).

Lastly, the instance itself might have an annotation called *warning* or inherit it from super classes. This would automatically trigger a warning. Two examples of warnings associated to the instance *Nuclear_Plant* are shown in Figure 8.14 (a) and (b).

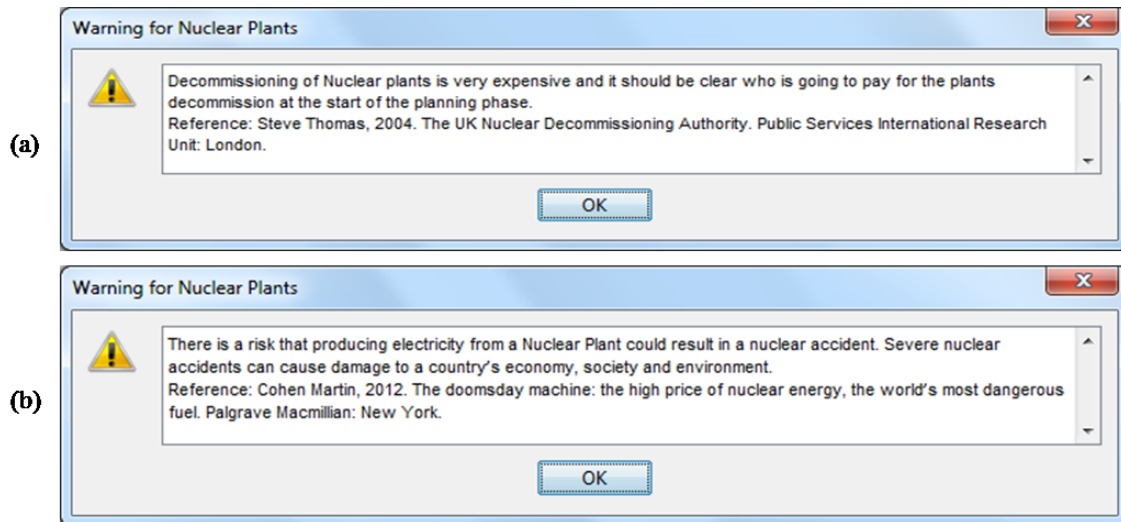


Figure 8.14: Warnings regarding the system itself (i.e. nuclear plant).

8.4.2 Past Experience

The Past Experience feature looks at decisions made in the past and uses this information to support new decisions, e.g. to suggest improvements or warn the user regarding some aspects of the position that has been selected. Once a position is selected, OUTDO looks for a past experience database related to this position in the Energy Ontology. This database is a subclass of the class under consideration and has the name of the class and the location under consideration. For example, for the position *Nuclear plant* the name of the database is *Nuclear_Plant_UK*. The past construction of nuclear power plants is used to exemplify this feature. For this, all the nuclear power plants built in the UK (19 nuclear plants, including those in operation and those that have been shut down) have been recorded and characteristics such as ***Location***, ***Plant_Capacity***, ***Type_Of_Reactor***, ***Construction_Company***, ***Operator***, ***Construction_Date***, ***Operation_Date***, ***Shutdown_Date***, ***Decommission_Date***,

Accidents, *Comments*, etc. have been included as data properties in the Energy Ontology. This data was taken from the various references in [218].

The Past Experience feature focuses on certain decision characteristics, for example: The *location*, *plant capacity*, *technology used*, *construction company*, *system operator*, etc. It compares the number of times that a given characteristic appeared in previous decisions. If the recommended position appeared less than other positions in the past, OUTDO warns the user and gives reasons why the other positions might have been selected more often in the past. This feature looks at a decision in OUTDO, which corresponds to an instance here called *A* in the Energy Ontology. If instance *A* (e.g. *Nuclear_Plant*) has a class *A_Location* (e.g. *Nuclear_Plant_UK*), OUTDO checks whether instance *A* inherits a relation called *X* (e.g. *has_Location_Relative_To_The_Sea*, *has_Type*, *has_Construction_Company*) that connects to another instance called *B* (e.g. *Coast*, *Magnox*, *Lang*) in the *A_Location* class. If *B* corresponds to a position selected in OUTDO, all the instances connected to *A* via *X* in the *A_Location* class are counted. If one of these instances (e.g. instance *C*) is connected to *A* more often than *B*, OUTDO then suggests the user to reconsider the decision.

As an example, OUTDO finds that *Nuclear plant* in the UK and *Countryside* are selected positions in OUTDO. Then it looks in the Energy Ontology for the number of times that the *Nuclear_Plant* instance is related to *Coast* and *Countryside* instances, through the *has_Location_Relative_To_The_Sea* relation, in the *Nuclear_Plant_UK* class. If the number of relations connected to *Coast* is larger than the number connected to *Countryside*, OUTDO generates the advice shown in Figure 8.15. As 18 nuclear plants in the UK were built by the coast and one was built inland, OUTDO suggests a

change of decision from the *Countryside* to the *Coast* and mentions the advantages, disadvantages and accidents involving nuclear plants by the coast in the UK. Note that the accidents mentioned in Figure 8.15 did not happen because the nuclear plants were built by the coast, but they happened with nuclear plants by the coast. The inclusion of the accidents in the message makes more sense when comparing different types of reactors.

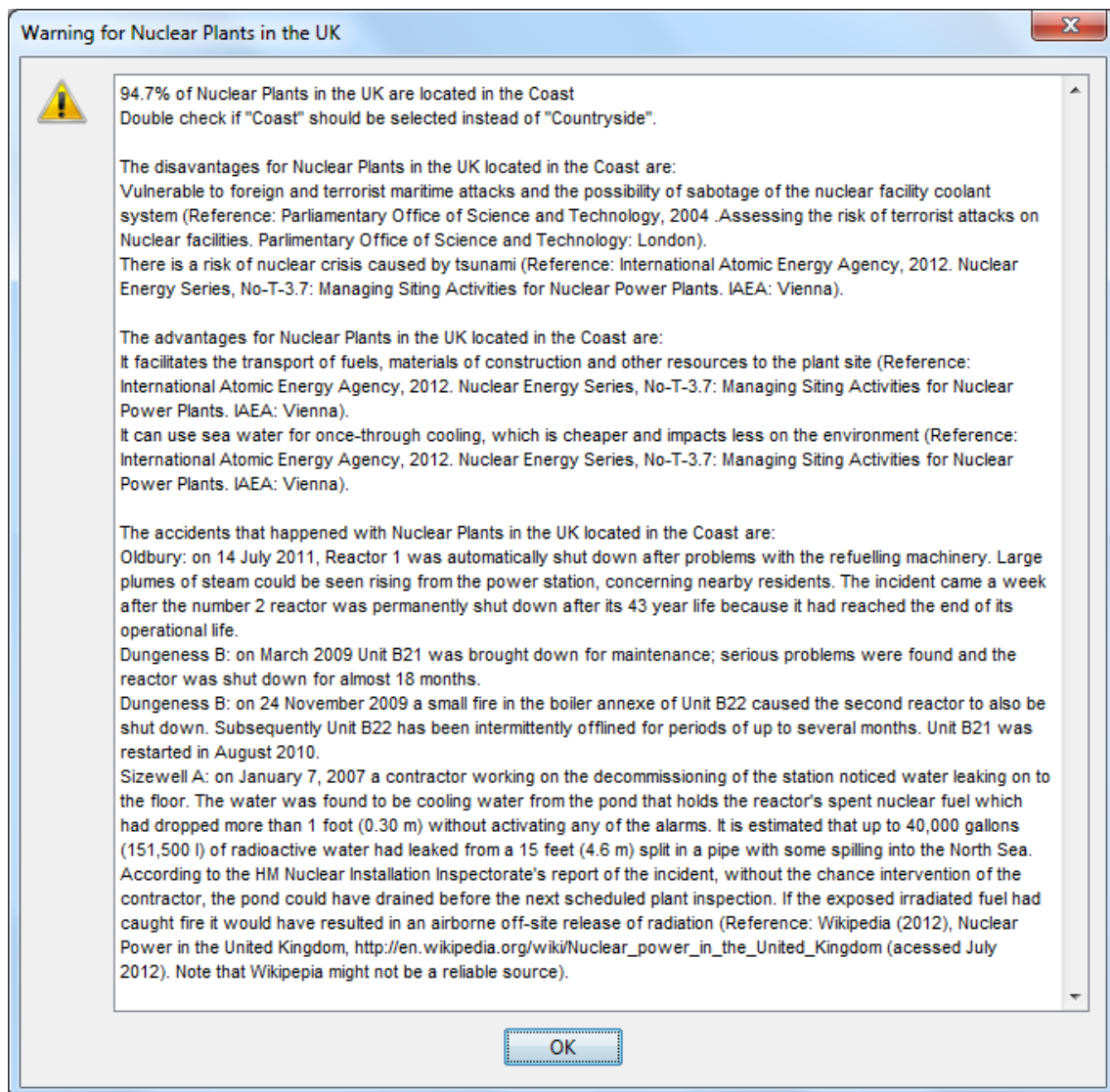


Figure 8.15: Advice associated with Past Experience specifications.

8.4.3 Multiple Qualitative Analyses

The Multiple Qualitative Analyses is a preliminary piece of work intending to use the data in the Energy Ontology to perform mathematical and statistical analyses that might reveal problems if two or more positions, corresponding to different issues, are selected at the same time. These analyses are very case specific and each example might only be applied to one position or one criterion inside a specific issue node. Multiple Qualitative Analyses plays an important role in the inclusion of qualitative analyses which are essential to the decision process but which are not easy to quantify and include in the decision process. An example of this feature is shown in the Supplier Risk Analysis Section below.

8.4.3.1 Supplier Risk Analysis

Supplier Risk Analysis is an example of the Multiple Qualitative Analyses feature and is triggered when the selected position for the issue “*What is the selected thermoelectric electricity generation technology?*” is *Coal plant* and the selected position for the issue “*What is the selected coal supplier to the UK?*” is answered. In this case OUTDO will run calculations and warn the user if the risk of coal supply to the UK will increase with the selected coal supplier and will suggest other positions. The analysis used in this section was taken from Frondel and Schmidt [219]. This paper conceives a statistical indicator that aims at characterising the energy supply of nations that are heavily dependent on imported energy. The data in Table 8.1 are used to calculate whether the risk of coal supply reduces or increases with *Russia* as the recommended *Coal_Supplier_To_The_UK*.

Table 8.1: Data in the Energy Ontology used in the Multiple Qualitative Analyses

feature.

Positions	Steam Coal (thousand tonnes per year)	Fraction of UK supply	National Risk Indicator
Russia	9,356	0.2561	3
Colombia	6,360	0.1741	4
USA	2,390	0.0654	0
European Union	881	0.0241	0
South Africa	781	0.0214	3
Indonesia	275	0.0075	3
Other countries	87	0.0024	1

This feature only applies to very specific cases. OUTDO looks at a decision, which corresponds to instance *A* (e.g. *Coal_Plant*). Instance *A* has a relation *X* (e.g. *has_Supplier*), with an annotation called *supplier_risk_analysis*, connected to instance *B* (e.g. *Steam_Coal_Supplier_To_The_UK*). This means that instance *B* in the Energy Ontology has all the data required to run a detailed supplier risk analysis for instance *A*. This data includes the text if the warning message is triggered and the relations *has_Location* connecting to instances *C*, *D*, *E*, etc. (e.g. *Russia*, *Colombia*, *USA*, etc.). The *Fraction_Of_Supply* data property, shown in Table 8.1, is contained as an annotation to the relation *has_Location* and the *National_Risk_Indicator* is a data property of the *Location* instances *C*, *D*, *E*, etc. With all the data required, the *SupplierRiskAnalysis* Java class in OUTDO's code calculates whether the risk of supply of a given commodity to a certain country will increase if *C*, *D* or *E* is the

selected position in OUTDO using Equation 8.1. If the risk of supply increases, OUTDO warns the user.

$$Risk_{UK} = \sum_{s=0}^v x_s^2 r_s \quad \text{Eq. 8.1}$$

where $Risk_{UK}$ is the indicator of risk supply of steam coal to the UK, x_s is the fraction of the of steam coal supply from a country s to the UK taken from the Department of Energy and Climate Change [184] and r_s is the Normalised OECD²⁵ National Risk Indicator taken from an OECD technical report [220]. The square of x_s intends to increase the risk of supply if the UK depends heavily in one country, for example, if the UK relies only on Russia, $Risk_{UK}$ would be equal to 3, if the UK relies on half of its coal from Russia and the other half from South Africa (which has the same National Risk Indicator), $Risk_{UK}$ would be equal to 1.5.

For example, if the user selects *Coal plant* as the electricity generation technology and *Russia* as the steam coal supplier, OUTDO calculates the current risk of steam coal supply using Equation 8.1 and compares to the risk of supply assuming 1% of the steam coal imports is added to the previous Russian share (25.61%) and 1% is removed from *Colombia*, *USA*, *European_Union*, etc. As a result the risk of supply of steam coal to the UK (calculated using Equation 8.1) increases from 0.3195 to 0.3351. As the risk increases, OUTDO displays the warning message shown in Figure 8.16.

²⁵ Organisation for Economic Co-operation and Development.

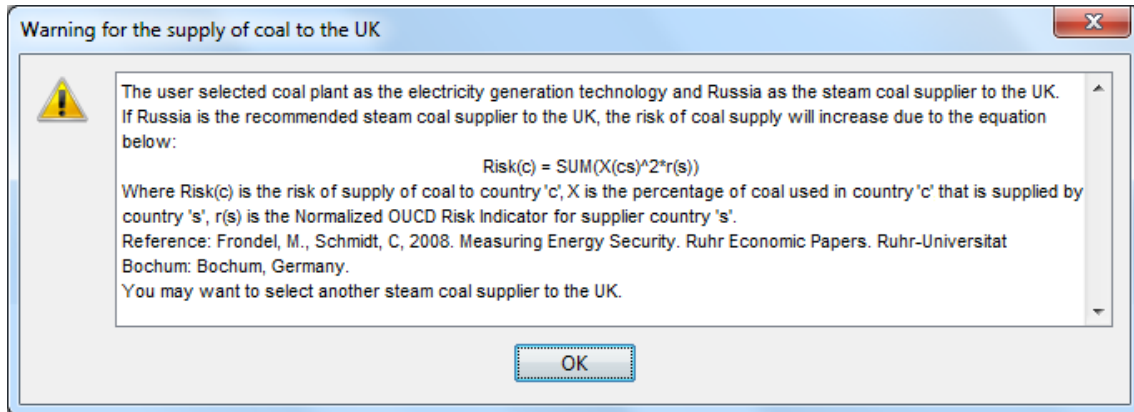


Figure 8.16: Multiple Qualitative Analyses for the calculation of risk of coal supply.

The Decision Check feature attempts to find problems in the decision process that the decision maker is not aware of. It looks at possible faults in single decisions to an issue and two or more simultaneous decisions, corresponding to different issues. The Decision Check feature can be used after a detailed analysis has been performed with MCDA methods. However, if the decision maker already has a preferred position, he or she can select his or her decisions and run the Decision Check feature to see whether there are potential problems in the decision process before a detailed analysis is performed. These problems could then be manually included by the decision maker as new criteria for the MCDA analysis.

8.5 Conclusion

This chapter concludes that, given the similarities between the IBIS representation in OUTDO and the ontological representation of knowledge, the effort dedicated to the development of ontologies used to support decision making within the OUTDO framework is justified. The semantic capabilities in OUTDO do not distract the decision maker in forming the solution, but can be used after the decision process is

constructed to make sure that his or her solution is coherent, relevant and appropriate for each specific case.

Three new applications of ontologies for decision support were created. The first, Consistency Check, checks the consistency of the relations between different decision process components (i.e. positions, issues, criteria, etc.). The second, Automatic Inference, infers issues and positions for the decision process. The third, Decision Check, uses previous decision experiences to support or question the new decision and uses already existing knowledge to run automatic analyses when qualitative aspects of the decision are difficult to quantify and are not included by the decision maker. These semantic-based decision support mechanisms could be implemented by reasoning directly based on the axioms defined in the ontology.

The reactive decision support capabilities have proven to be very easy to apply and shown to have the potential to effectively support the decision processes involving engineering designs in the OUTDO framework. It would be very interesting to further expand the Energy Ontology so that OUTDO, with semantics, becomes a forefront DSS when it comes to the selection of electricity generation technologies.

The methodology presented for the inclusion of decision support with semantic capabilities has been adapted for decisions regarding the selection of electricity generation technologies. However, the semantic capabilities presented in this chapter are not limited to electricity generation technologies. As the concepts behind the design of other engineering artefacts are similar to those relating to electricity generation technologies, the semantic capabilities presented in this thesis are able to support engineering designs in general. In this thesis, semantic-based decision support has been limited to electricity generation technologies because, apart from the Decision

Ontology, only one ontology was created, the Energy Ontology, and this ontology only addresses electricity generation technologies. If the user wants to apply the semantic-based capabilities to other types of problems, he or she will have to create a new ontology for each different domain related to those types of problems. Note that these new ontologies will have to be created following the same structure of the Energy Ontology. This issue is further discussed in Section 9.2.4.

Chapter 9

Discussion, Conclusions and Future Work

9.1 Introduction

The final chapter of the thesis aims to perform an analysis of the construction of OUTDO, the case study and the creation of semantic-based decision support capabilities. In addition, this chapter concludes the thesis and propose the continuation of the development of OUTDO.

Section 9.2 presents the main discussions relating to the construction and application of the OUTDO framework. Section 9.3 draws out some conclusions from this thesis and Section 9.4 proposes future work to improve the OUTDO decision support framework and its applications.

9.2 Discussion

This section highlights some possible improvements that may be implemented into the OUTDO framework as brought to light by the case study.

9.2.1 Inclusion of MAUT in OUTDO

There is a lack of consensus among decision making professionals as to the selection of a particular decision method for a given problem or in the implementation of decision-based design [221]. Ideally, decision support tools should accommodate various decision methods [95]. As mentioned in Chapter 2, there are many benefits such as simplicity and transparency of using the WSM to compare the positions of each issue

node. The WSM shows the exact values under comparison; for example, the cost criterion might be scored with 90 £/MWh for a position such as nuclear plant. The decision maker, therefore, has a clearer idea of the possible effect that each criterion would have for each position. However, OUTDO also inherits the drawbacks of WSM, such as the need to choose a normalisation factor and the lack of functions that control the way the positions are scored.

Normalisation factors are used to make sure that each criterion only contributes to the decision process the amount specified by its weights. There are a number of ways to calculate these normalisation factors. In OUTDO, the normalisation factor used is the inverse of the highest score for a criterion. In the OUTDO framework, a problem arises as the highest score for a criterion, and therefore the normalisation factor, might change with a change in the Global Parameters. A change in the normalisation factor affects the decision matrix as a whole and thus might change the decision arrived at previously. For example, using the case study described in Section 6.5.3, the cost criterion for wind turbine technology in London is the highest and equal to 550 £/MWh, considering an average wind speed of 5 m/s. If the user then wants to use the same decision process in the Yorkshire and the Humber region, the cost criterion for a wind turbine will reduce to 132 £/MWh as the average wind speed increases to 6.5 m/s. In this case, the highest score for the cost criterion will be 334 £/MWh for photovoltaic cells. Thus, the normalisation factor for the cost criterion will change from 0.0018 for London to 0.0030 for the Yorkshire and the Humber region. The importance of the cost criterion will be reduced by 40% for the other positions being compared, such as gas plant and coal plant, assuming all the criteria weight are kept constant. Therefore, the change in Global Parameter might affect the normalisation factor, which will then affect the relative

importance of the criteria weights in the decision matrix. This is not what the OUTDO framework intends because the change in Global Parameter should only affect the analysis of the positions that the Global Parameter influences and not the whole decision matrix, and because using only the criteria weights to quantify their importance simplifies the re-use of the decision rationale.

To solve this problem the correct choice of MCDA method has to be made. Looking back at the selection of the MCDA method incorporated into OUTDO, it turns out that MAUT would be an improvement over ELECTRE III and WSM. ELECTRE III is a good choice as it does not require a normalisation factor, as shown in Section 2.3.7. However, the implementation of ELECTRE III is complex, user unfriendly, opaque and time consuming, as a large amount of effort is required to create the thresholds. This is undesirable, as speed and transparency are major aspects of decision making in the OUTDO framework.

OUTDO would benefit from the inclusion of MAUT as it would allow the creation of an overall comparison between all sets of decisions, i.e. the different locations, date for implementing the decision and circumstances (CO₂ emissions cost, interest rate, etc.) for each issue node. MAUT is an improvement because the maximum and minimum scores for each criterion for all the possible set of decisions will be automatically normalised with a utility function to a value of 1 and 0 respectively [52]. For example, in the case study, the minimum score for the cost criterion is for *Wind turbine* in London in 2010²⁶, which is equal to 664 £/MWh and thus would be given a value of 0. The maximum score is for *Wind turbine* in Scotland in 2050, which equals 28 £/MWh and thus would be given a value of 1. The values between 28 and 664

²⁶ This assumes an interest rate of 0.08 per year and CO₂ emissions costs of 0.025 £/kg.

£/MWh would follow the linear equation shown in Equation 9.1. In this way, a single and simple decision process could be used for a variety of different decisions.

$$MAUT_{score} = 0.001572 \text{ Criterion}_{value} - 0.044025 \quad \text{Eq. 9.1}$$

where $MAUT_{score}$ is the value from 0 to 1 to be multiplied by the weight of criteria using the MAUT method and Criterion_{value} is the value of the score used in the WSM method (e.g. 664 £/MWh).

9.2.2 Case Study Discussion

There are some important aspects of the electricity generation processes that would have been beneficial to include in the assessment. These include geopolitical conflicts, public opinion, political pressure, the environmental impact of coal mining, the disposal of solid waste from coal power plants and radioactive waste from nuclear power plants, among others. For example:

- The steam coal for power plants comes from Russia, a country that has cut off energy supplies to countries in the past. In 2010, 45.5% of the steam coal consumed in the UK was imported, mainly from Russia [222].
- The disposal of solid and radioactive waste is included in the cost assessment, but the potential environmental impacts were not included in the decision process. The residue of the coal-burning process, for example, is fairly toxic and may contain significant amounts of uranium. Indeed, some coal contains so much uranium that some of its residual ash has been further processed in China to remove the uranium for the nuclear fuel cycle [223].

The verification of the results from the case study in OUTDO could have been extended through studies using the Sensitivity Analysis feature and with different

scenarios created by the Future Analysis feature. It should be noted, however, that the main intention of this thesis is to present the new OUTDO decision support framework so a detailed evaluation using the Sensitivity Analysis feature would have gone beyond this main intention.

9.2.3 The Future Analysis Feature

The Future Analysis feature in OUTDO allows the creation of confidence intervals for only one variable at a time. Many Global Parameters such as interest rate, gas prices, coal prices, capital costs, CCS costs, social risk aversion and availability of water have uncertain future tendencies and should be fully analysed with probabilistic forecasts in order to properly analyse the risks associated with the final decision. The possibility of creating probabilistic forecasts where more than one Global Parameter is simultaneously varied and propagated to the decision matrices will greatly improve the analysis.

Another limitation of the Future Analysis feature is that it only focuses on one issue node. However, the modification of a Global Parameter can change the recommendation of other issue nodes in the decision process. The change in recommendation could, in turn, affect the issue being analysed. This can clearly be seen in the horizontal bar chart in Figure 6.11. After eight years (in 2018), when the CO₂ emission cost is foreseen to be 0.025 £/kg, the use of CCS will be recommended for Coal IGCC with a GEE technology. This should change the recommendation of coal without CCS position to coal with CCS in the main issue node during Future Analysis, but this is not the case as the Global Parameters are not propagated to all decision matrices.

The solution is to propagate the values from the probabilistic forecast to all the decision matrices for each change in Global Parameter value. However, if this were to be included in the current version of OUTDO, each graph would take around half a day to converge to a solution. The convergence is not scalable with the number of decisions in the project. If this function were to be implemented, the resulting Future Analysis graph would look similar to Figure 6.10 for the first eight years, as CCS is not recommended, but will gradually become like Figure 6.11 as CO₂ emission costs increase and CCS is recommended. In other words, for the Yorkshire and the Humber region, Gas without CCS is recommended from 2010 until 2018, Coal with CCS is recommended from 2019 until 2032, Nuclear is recommended from 2033 until 2036 and Biomass with CCS is recommended from 2036 onwards. These recommendations seem sensible, but it should be stressed that they depend strongly on the data used for the case study, the particular selection of criteria and their corresponding weights as selected by the decision maker.

9.2.4 The Inclusion of Semantics in OUTDO

The addition of semantic capabilities in OUTDO has considerably broadened its application to decision support through a novel and efficient approach that looks at the meaning behind the decision components. However, the reactive decision support capabilities are still limited. At present there are only a few ways in which the Energy Ontology supports the decision process and these are focused on electricity generation technologies. The Energy Ontology can be expanded into more classes, instances, relations, axioms, lessons learned from past experiences, examples of Multiple Qualitative Analyses and possibly new semantic-based mechanisms similar to the ones

presented in this thesis. This would improve OUTDO's decision support capabilities, and make OUTDO a more robust DSS to be applied in the energy field.

Furthermore, new ontologies describing other engineering processes can be created. Here, the decision maker would have to create new ontologies containing knowledge about the other domains. These ontologies would have to follow the same structure as the Energy Ontology to accommodate the semantic-based decision support mechanisms described in Chapter 8. If OUTDO were to be used to support decisions concerning social sciences or other types of decisions that do not involve the design of engineering artefacts, a detailed study of the semantic-based decision support mechanisms would need to be performed to verify whether semantics can be efficiently applied.

Another important limitation is related to the recognition of text input in OUTDO. At the moment, the user has to know that the names of the issue nodes should be written in a specific format and that, for a given criterion, the information in brackets represent the units of measurements for that criterion. Furthermore, the criteria, issues and positions written in OUTDO have to have exactly the same name in the Energy Ontology. This limitation can be overcome by the inclusion of Semantic Web annotations. Semantic Web annotation goes beyond textual annotations related to the format of the documents to formally identify concepts and relations between concepts in documents [224]. A similar approach to Semantic Web annotations can be used in OUTDO to extract the meaning from the OUTDO components and connect to the corresponding instances in the Energy Ontology. Thus, the OUTDO component texts would not have to be the same as the text in the Energy Ontology for the semantic capabilities to function.

To make the inclusion of semantics in OUTDO more appealing, it would also be beneficial to create automatic mechanisms to dynamically extend and update the ontologies with information and data from the internet.

9.3 Thesis Conclusions

Documenting the decision process and applying MCDA instead of simpler assessments can be very resource intensive. It is also important that capturing and recording the decision process does not disrupt the process itself [22]. The act of recording should have immediate value and help decision makers to better analyse the problem and reach a compromise. With this in mind, this thesis foresees the importance of a flexible decision framework that, in the context of uncertain technology deployment, records the essence of decision processes and aids decision making through the integration of rationale management, MCDA, probabilistic forecasting and semantics. The result is a powerful decision framework that combines past, present and future factors that may affect a decision as well as the inherent meaning behind each decision component. This decision framework resulted in the DSS called OUTDO.

OUTDO, without the semantic capabilities, is already a flexible tool, which can be used to resolve complex and long-term issues, capturing the decision rationale and facilitating the re-use of the decision rationale in regard to other similar decisions in a dynamic way. MCDA methods are provided for the decision maker to perform in-depth analysis of multi-criteria issues. The decision rationale can then be re-used to analyse how a change in the decision process parameters can affect the decision results. This brings about robust and transparent solutions for complex decision processes, which can be effortlessly adjusted to varying parameters. These parameters can be taken from

optimisation and simulation packages external to OUTDO. Thus, OUTDO can work as a hub where different optimisation and simulation packages can be brought together. Moreover, the integration of probabilistic forecasting and MCDA can be used to predict how the parameters will behave in the future and how these predictions can affect the decision rationale, providing insights for long-term decision planning.

Another major benefit of using MCDA in the decision process is that the reasoning behind a decision becomes clear to all participants. Thus, it can be used as a framework for a democratic decision making process where the different stakeholders can express their interests by specifying criteria weights during the decision process. Analysing the results from OUTDO for each location, companies and the government could then spend more time in evaluating which locations would benefit the most from which types of technology. Environmental issues are addressed, social and economic incentives are considered, and technologies that are not welcome by the local community are rejected.

Apart from making the decision more democratic, once the proposed changes in the discussion section (Section 9.2) are made, OUTDO can become a tool through which decision processes can be standardised. In other words, a decision process in OUTDO can be easily compared to past decisions and thus create a standard decision process. Gaining familiarity with an established decision process, the user attains a better understanding of which weight to give to each criterion. For example, if the selection of electricity generation technology is too inclined in favour of reducing CO₂ emissions, which would in turn affect the country's economy, this situation can easily be perceived by comparing the weights of criteria for previous decisions.

OUTDO's features were tested using a case study to find the most appropriate electricity generation technologies for ten different regions in the UK, paying particular attention to the availability of water. The UK's energy sector will have to go through considerable changes due to the need to reduce CO₂ emissions, to reduce the dependence on fossil fuel imports from other countries, and to reduce the consumption of water due to its lower availability in the future. Turning OUTDO's recommendations, as shown in Section 9.2.3, into a final decision must take the decision's time horizon into account. Every prediction has an associated risk, and the further into the future the recommendation extends, the higher the risk. Indeed, there may be so many variables influencing a forecast that it can be argued that it is impossible to determine the magnitude of the risks involved. In OUTDO, the decision maker has the freedom to add further arguments to the OUTDO analysis and make a decision that differs from OUTDO's final recommendation. For instance, the decision maker could choose a more conventional decision such as nuclear with the risk of it becoming obsolete in the future due to political pressure or choose a position more uncertain at present that may become more robust in the future such as coal with CCS.

This thesis concludes that, assuming the predictions of CO₂ emissions costs from DECC [202], if a new 700 MW power plant is to start-up operation in the Yorkshire and the Humber region in a year from 2010 until 2050, the following technologies should be considered for plant start-up. From 2010 up to 2018 the selected technology should be NGCC, without CCS but with sea water desalination. As CO₂ emission costs increase and CCS becomes relevant after 2018, the recommended technology changes to Coal (Integrated Gasification Combined Cycle design) with CCS between 2019 and 2035. Nuclear power plants are the recommended option between

2033 and 2036. However, nuclear should perhaps not be considered for the Yorkshire and the Humber region because nuclear power becomes advantageous only for a four-year span, and a nuclear power plant has a lifetime of at least 30 years. However, as the CO₂ emissions cost predictions from DECC [202] might be overestimated, biomass-based generation with CCS should only be considered after 2036.

The recommendations of electricity technologies for the ten different locations from 2010 until 2050 as shown in Figure 6.12 and 6.13 are mainly linked to the increase in wind speed as the location moves from the southern to the northern regions of the UK. However, as discussed in Section 9.2.4, the results are influenced by the change in normalisation factor and thus do not precisely reproduce the decision analysis set for the Yorkshire and the Humber region in Chapter 5. This is the reason why, in Figure 6.13, a coal plant is wrongly recommended for London between 2010 and 2033. This issue would have been resolved if the MAUT method was implemented in OUTDO. However, it needs to be stated that the combination of MCDA with probabilistic forecasting creates a powerful tool for the inclusion of uncertain parameters in the decision analysis, which thus allows the user to perform valuable risk analyses.

The semantic-based decision support capabilities based on an ontological language representation included in OUTDO have proven to successfully support the design of engineering artefacts. An ontological representation of the knowledge domain for electricity generation technologies and energy policies is present in the Energy Ontology. Through the use of the Decision Ontology, this knowledge domain was used to check the consistency of the OUTDO components and their relations, and to suggest new issues and positions for the decision process in order to make the decision maker aware of aspects of the decision process that he or she might not have considered. The

ontology was also used to check whether there are potential problems with the selected decisions through the provision of general information on the energy field that the user might not be aware of. The successful integration of semantics into OUTDO is due to the similarities of the IBIS representation and the ontological representation of knowledge. This makes semantics a very effective tool for decision support in the OUTDO framework.

On the understanding that more work is done on the development of the extension of the Energy Ontology, OUTDO can be a useful tool for decision makers in the selection of electricity generation technologies for different regions in the world. In addition, OUTDO can be used to support other engineering-related problems as soon as ontologies become available.

9.4 Future Work

OUTDO is a useful tool for use in consulting companies or for government policy making. As OUTDO captures the decision rationale, previous decision processes can be used as a standard format for future decisions, thereby making the decision making process more efficient. OUTDO will not replace the need for people in the decision making process, but it will allow decision makers to focus on all the important aspects of the decision, some of which may not have received attention due to the lack of time and resources.

The main focus of the proposed future work is to continually improve OUTDO and the OUTDO framework. There are several ways that OUTDO can be improved, some of which are listed below:

- The inclusion of MAUT in the framework would improve the way the decision rationale is re-used, keeping the same decision analysis for every decision process.
- The creation of confidence intervals for more than one Global Parameter in the Future Analysis feature should be supported.
- The inclusion of the propagation of the Global Parameters when performing the Future Analysis feature as discussed in Section 9.2.3.
- The Energy Ontology should include new classes, instances and examples where the semantic-based decision support mechanisms can be used so that OUTDO can be used as a robust tool to support the selection of electricity generation technologies for different locations.
- New mechanisms for semantic-based decision support should be created, which can be done using the axioms in the Energy Ontology. Axioms can support consistency check approaches that differs from the ones presented in this thesis. For example, in the Energy Ontology, the *Combustion* axiom describes how coal can be used. If the Energy Ontology were expanded to include other uses for coal such as steam reforming, coal liquefaction, etc., then this information could be used to answer questions such as “*What is the selected use for coal?*”.
- The creation of other ontologies to extend the semantic-based decision support to different areas of knowledge.
- There is an initiative by the Compendium development community to further develop Compendium [35]. Any improvements to Compendium will potentially improve OUTDO. It is recommended to update OUTDO when new versions of Compendium become available, to allow, for example, multiple users to work simultaneously.

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Appendix A

Forecasting Equations

A.1 Confidence Intervals Equations

The method for the creation of confidence intervals proposed by Hanbury [68] has the advantage of being applicable to any forecasting technique, and to derive projected confidence intervals using the mean error when the forecast is compared with the actual data. The method is outlined below and the associated equations are shown in Figure A.1:

- 1) Load the time series data and create a forecast.
- 2) Assume that the error is likely to grow according to some defined function with a forecast horizon, for example a power law: $e = a f^n + b$, where e is the error, f is the discrete number of forecast points at that moment in time and a , b and n are all constants (the value of the rate of growth n and b could be determined from empirical results). The expected forecast Mean Absolute Deviation (MAD is the average difference between the data and the forecast) times the total forecast horizon (F , shown in the plot of Figure A.1) should be equal to the area underneath the curve, or the integral of the relevant equation, from which the value of the constant a can be determined:

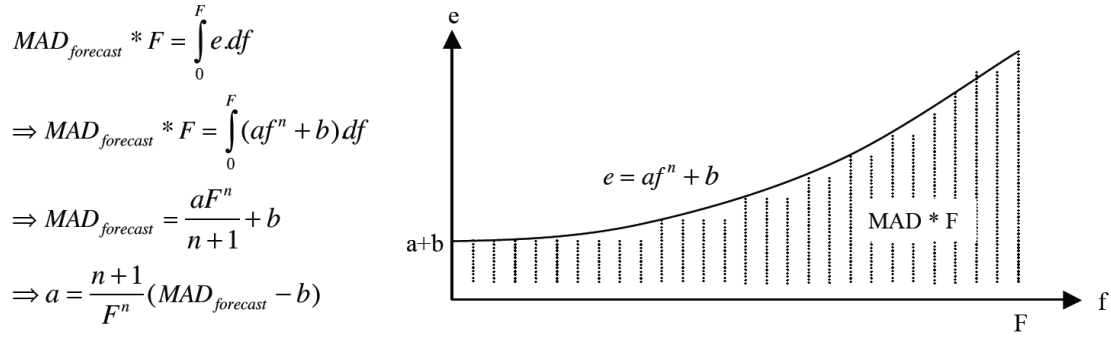


Figure A.1: Method for the creation confidence intervals.

3) The confidence intervals are produced by adding and subtracting the estimated error on either side of the forecast.

A.2 Future Analysis Equations

For each point in time in Figure 6.8 the system propagates the value of the Global Parameter (GP) to the decision matrix of the selected issue starting from its lowest value (at the -90% line). The Confidence Interval range (from 90 to -90%) is divided into 80 intervals of equal size. This number of intervals can be higher than 80, but this would require more computation time. Each interval is assigned a GP value corresponding to the middle value of each interval. This value is then propagated to the decision matrix and a recommended position is found. All recommendations are gathered and a final recommendation position probability is calculated.

The calculation of the probability for each recommended position is shown in Equation A.1.

$$ROP_i = \left(\frac{x \times 15}{(GP_{90\%} - GP_{75\%}) \times 2} + \frac{y \times 25}{(GP_{75\%} - GP_{50\%}) \times 2} + \frac{z \times 50}{(GP_{50\%} - GP_{-50\%})} \right) \times \left(\frac{GP_{90\%} - GP_{-90\%}}{80} \right) \quad \text{Eq. A.1}$$

$$\sum_{i=0}^n x_i + y_i + z_i = 80$$

Eq. A.2

where, ROP_i is the set of recommended positions probabilities, n is the number of positions and $GP_{x\%}$ is the Global Parameter value in the 90%, 75%, 50%, -50%, -75% and -90% Confidence Interval curves. The number 15 is the number of percentage points in the section between the 90% and 75% lines and between the -75% and -90% lines. $(GP_{90\%} - GP_{75\%}) \times 2$ is the size of the section between the 90% and 75% lines plus the section between the -75% and -90% lines. The second and third terms in the first parenthesis have a similar purpose. The expression inside the second parenthesis is the size of one interval. x is the number of intervals that result in the recommendation of position i in the sections between the 90% and 75% lines or between the -75% and -90% lines, y is the number of intervals that result in the recommendation of position i in the sections between the 75% and 50% lines or between the -50% and -75% lines and z is the number of intervals that result in the recommendation of position i in the sections between the 50% and -50% lines.

Equation A.3 shows an example calculation of the probability of recommendation in the year 2050 in Figure 6.8.

$$\begin{aligned}
 \text{Position 1} &= \left(\frac{5 \times 15}{(0.305 - 0.103) \times 2} + \frac{9 \times 25}{(0.399 - 0.305) \times 2} + \frac{1 \times 50}{(0.599 - 0.399)} \right) \times \left(\frac{0.895 - 0.103}{80} \right) = 71.17\% \\
 \text{Position 2} &= \left(\frac{20 \times 15}{(0.305 - 0.103) \times 2} + \frac{9 \times 25}{(0.399 - 0.305) \times 2} + \frac{21 \times 50}{(0.599 - 0.399)} \right) \times \left(\frac{0.895 - 0.103}{80} \right) = 16.16\% \quad \text{Eq. A.3} \\
 \text{Position 3} &= \left(\frac{15 \times 15}{(0.305 - 0.103) \times 2} + \frac{0 \times 25}{(0.399 - 0.305) \times 2} + \frac{0 \times 50}{(0.599 - 0.399)} \right) \times \left(\frac{0.895 - 0.103}{80} \right) = 5.51\%
 \end{aligned}$$

In Equation A.3, the sum of the probabilities of the recommended positions is 92.84%. If the number of intervals were infinite, instead of 80, the sum of the probabilities would be exactly 90%.

Appendix B

Expressions

The expressions presented in this Appendix were created by the author to compare the positions of the issue node “*What is the selected electricity generation technology?*” in Section 5.4.2. Not all equations were described here and not at full depth due to space limitations. These equations are perhaps too large and complicated. They intend to make the changes in Global Parameters as detailed as possible. If this is not required, the equations could have been implemented in Excel or other programs and imported into OUTDO with a simpler Global Parameter. Other studies for the creation of expressions, such as the ones presented in this Appendix can be found in [225].

B.1 Wind Turbine Expression

The data taken for the wind speed in different location was taken at 45 meters from the ground from [226]. The correlation between wind speed at 45 meters to 60 meters (the height of the turbine’s rotor) is calculated using Equation B.1 assuming agricultural land with some 8 meters houses approximately 500 meters away from the turbine taken from [227].

$$\frac{V_2}{V_1} = \left(\frac{h_2}{h_1}\right)^\gamma \quad \text{Eq. B.1}$$

where V_2 and V_1 are wind speeds at heights h_1 and h_2 and γ is the wind shear.

The Rayleigh wind probability distribution, in Equation B.2, is assumed [228]. This is the simplest velocity probability distribution to represent the wind resource since it only requires knowledge of the mean wind speed $\bar{U}$ at a height of 60 meters. The equation used to calculate the electricity generation is shown in Equation B.3 and assumes electricity generation starting from a wind speed of 4 m/s and stopping at 14 m/s. This is an approximation as turbines usually produce the maximum generation at 12 m/s but can still produce energy until it has to be shut at around a wind speed of 20 m/s to conserve the turbine. The GEMIS database assumes a turbine with 1.8 MW capacity.

$$p(U) = \frac{\pi}{2} \left(\frac{U}{\bar{U}} \right)^{\frac{\pi}{4} \left(\frac{\bar{U}}{U} \right)^2} \quad \text{Eq. B.2}$$

where $p(U)$ is the probability distribution at the speed U

$$P_W = \frac{1}{2} \rho \pi R^2 \delta U_c^3 C_{p,Betz} \int_4^{14} (x)^3 \{2x \exp[-x^2]\} dx \quad \text{Eq. B.3}$$

where P_w is the average power generated by the turbine, ρ is the density of the air, R is the radius of the wind rotor (40 meters), δ is the drive train efficiency (assumed to be 1), $C_{p,Betz}$ is the rotor power coefficient (16/27), U_c is equal to $2\bar{U}/\sqrt{\pi}$ and x is equal to U/U_c .

The equation for *Wind turbine* cost is shown below. A similar explanation for this and following equations is shown in Section 6.3.

$$\begin{aligned} & ((\text{Wind_Capital_Cost} * (\text{Interest_Rate} * ((1 + \text{Interest_Rate})^{20}) / (((1 + \text{Interest_Rate})^{20}) - \\ & 1)) / (2000 * 700) + \text{Wind_O\&M_Cost} + \text{CO2_Emissions_Cost} * 22.8477 + \text{Water_Price} * 58.1 \\ & 31) * 3600 / (487.09 + 140.06 * (\text{Wind_Speed}^2) - 712.75 * \text{Wind_Speed})) \end{aligned}$$

B.2 Photovoltaic Cell Expression

The estimation of electricity generation cost from photovoltaic cells is more straightforward than wind as the average solar irradiation of an area gives a good estimate of the cost of electricity generation for different locations. The GEMIS database assumes a solar irradiation of 1000 kWh/m² per year. The average solar irradiation of the different areas in the UK was taken from [229].

The equation for *Photovoltaic cell* cost is shown below.

$$\begin{aligned} & ((1767591049 * (\text{Interest_Rate} * ((1 + \text{Interest_Rate})^{30}) / (((1 + \text{Interest_Rate})^{30}) - \\ & 1)) / (1000 * 700) + 55.667 + \text{CO2_Emissions_Cost} * 106.724 + \text{Water_Price} * 649.71) * 1000 / \text{Solar_Irradiation}) \end{aligned}$$

B.3 Biomass Expression

The main parameter used in the analysis of fuel costs for biomass plants are related to the biomass yield (odt²⁷/ha²⁸ year) for each area. This data is taken from [230]. From this data the amount of area required to produce 1 MWh can be estimated. Assuming the biomass yield from the GEMIS database is 10 odt/ha year, the equation for estimating fuel cost is equal to $\text{Fuel Cost}_1 = 1088.6 \times \text{Biomass_Yield}^{-1.0176}$.

Another important aspect that influence fuel costs is the area available for biomass plantation around the biomass plant. This aspect only affects the transport costs. The fraction of the biomass fuel cost directed to the transport of the biomass is 0.084 and was taken from [231]. The final equation for fuel cost is shown below where

²⁷ Oven dry tonne is a unit to express the dried weight of an agricultural commodity such as biomass that contained significant water weight when harvested.

²⁸ Hectares with is equivalent to 10,000 square meter.

105.357 is the fuel cost assuming 10 odt/ha year. The *Net_Land_Use* Global Parameters is estimated with the results from [232].

$$Fuel\ Cost_{final} = Fuel\ Cost_1 + 105.357 \times 0.084 \times \frac{126.19 \times Net_Land_Use^{-0.5} - 17.846}{17.846}$$

The expression for *Biomass plant* cost without CCS is shown below.

$$\begin{aligned} & (No_CCS_Wood_Syngas_Selected * ((492396323.8 * (Interest_Rate * ((1 + Interest_Rate)^{20} - 1)) / (6000 * 700)) + 7.549 + CO2_Emissions_Cost * 126.10 + \\ & 1825.76 * Water_Price + (1088.6 * Biomass_Yield^{(-1.0176)} + 105.357 * (0.084 * (126.19 * \\ & Net_Land_Use^{(-1/2)} - 17.846) / 17.846) * (Gasoline_Price - 1.24)) + (Wet_Cooling_ \\ & Selected * (0)) + (Once_Through_Cooling_Selected * (-0.636)) + (Dry_Cooling_Selected \\ & * (1.346)) + (CHP_Selected * (2.948)) + (Desalination_Selected * (4.167))) \end{aligned}$$

B.4 Gas Transport Expression

A simplified model in Excel of the UK Gas Transmission Network was used to estimate the length of the gas pipeline needed to transport the gas to the different areas of the UK [233] in accordance with the gas transmission costs proposed in [234].

The expression for *Gas plant* cost without CCS is shown below.

$$\begin{aligned} & (No_CCS_NGCC_Selected * ((277814869.6 * (Interest_Rate * ((1 + Interest_Rate)^{15} - 1)) / (6000 * 700)) + (0.0137 * Gas_Pipeline_Length - 0.0442) + 3.290 + \\ & Gas_Fuel_Cost + CO2_Emissions_Cost * 413.14 + Water_Price * 775.89 + (Wet_Cooling_Se \\ & lected * (0)) + (Once_Through_Cooling_Selected * (-0.276)) + (Dry_Cooling_Selected * \\ & (0.584)) + (CHP_Selected * (1.279)) + (Desalination_Selected * (1.806))) \end{aligned}$$

B.5 CO₂ Transport Expression

Apart from the increase in costs, the inclusion of CCS includes an estimate for the cost of the CO₂ pipeline system to transport the CO₂ from the plant to the closest geological location for CO₂ storage. The locations considered for CO₂ storage are shown in [235] and in the sites that meets best practice requirements in [236]. The cost estimation was divided into three different stages as the cost of piping 1 kg of CO₂/hour varies with the length of the pipe and the flow of CO₂ being piped at one time and this was taken from [237]. For estimating the cost of offshore pipeline was taken from [238]

The expression for CO₂ transport cost is shown below.

$$(((0.003944*(CO2_Pipeline_Length1+CO2_Pipeline_Length2)+0.02151)*14.3*0.8229 + (0.002761*CO2_Pipeline_Length3+0.02151)*28.4*0.4114 + (0.002115*CO2_Offshore_Pipeline_Length+0.02151)*56.8*1.558*0.2076 + 4.837*11.787)*1000000/12000000)))$$

B.6 Geothermal Expression

In order to adapt the geothermal costs to the different locations, some arrangements were made. The temperature gradient from [239] is used to predict the depth required to reach 150°C temperatures. This is because the assumed values in GEMIS correspond to a temperature of 150°C at a depth of 2,700 meters [240]. The ground temperature at a depth of 2,000 meters for the different locations is found in [241]. The difference in capital cost resulted from the bigger borehole required to reach a temperature of 150°C was taken from [241].

The expression for *Geothermal plant* cost is shown below.

$$\begin{aligned}
& (((-360731.04082948 * \text{Geothermal_Temperature}^2 - (119522218.194825 * \text{Geothermal_} \\
& \text{Temperature} - 27107735281.5309)) * (\text{Interest_Rate} * ((1 + \text{Interest_Rate})^{30}) / (((1 + \text{Interest} \\
& _Rate)^{30}) - 1)) / (7500 * 700)) + 37.111 + \text{CO2_Emissions_Cost} * 94.863 + \text{Water_Price} * \\
& 457.97 + (\text{Wet_Cooling_Selected} * (0)) + (\text{Once_Through_Cooling_Selected} * (-0.167)) + (\\
& \text{Dry_Cooling_Selected} * (-0.357)) + (\text{CHP_Selected} * (0.781)) + (\text{Desalination_Selected} * \\
& (1.104)))
\end{aligned}$$

Appendix C

Publications and Other

Publications:

- J. Hunt, R. Bañares-Alcántara and D. Hanbury, “A new integrated tool for complex decision making - application to the UK energy sector,” *Decision Support Systems*, 2012. [Accepted]. [242]
- A. Sanchez, R. Bañares-Alcántara, J. Hunt, J. d. J. Rodriguez and G. Magana, “Conceptual Design of Biorefineries Using Agrowaste, Its Decision Support and Design Rationale,” in *American Institute of Chemical Engineers Annual Meeting*, Pittsburgh, October 31, 2012. [154]

Future Publication:

- J. Hunt, R. Bañares-Alcántara, “Broadening the Applicability of Decision Support Systems with Semantics: Application to the UK Energy Sector”, *Decision Support System*, 2013. [To be submitted].

Posters:

- “Oxford Energy Futures” Conference organised by the Continuing Professional Development Centre, 20th of March 2009, Oxford.
- Engineering Department Poster Presentation for Second Year D.Phil Students, 1st of October 2010, Oxford.