# CLIMATE CHANGE IMPACT SIMULATIONS ON ELECTRICITY SUPPLY INFRASTRUCTURE

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## ABSTRACT

There is increasing evidence that a combination of natural cycles and human behaviors is changing the global climate. Civil Engineers responsible for the design and operation of infrastructures and utilities need to be prepared to ameliorate the consequences for the sake of both their businesses and society in general. This paper proposes a generic process for, and demonstrates a performance-based approach to, the assessment of impacts, and the consequent adaptation and mitigation interventions on the UK Electricity Supply Industry as an example of a complex infrastructure. It shows how the combination of simulation software, through which various climate change scenarios can be run, interfaced with a performance management software tool, can produce powerful decision support tools for the industry.

The simulation models are implemented in the Simulink®, while the PeriMeta software is developed for performance assessment and decision aid. The effects on system performance of various interventions to enhance, for example, flood protection can be investigated using an embedded argumentation structure.

Four climate and socio-economic scenarios of capacity and demand are fed into the simulation. The model can then be run over various timescales to show the implications for long-term planning of capacity and short-term for the prediction of possible overloads and failures of the system components.

## KEY WORDS

Climate change, simulation, performance management, process, complex infrastructures.

## INTRODUCTION

This paper describes the development of a process for investigating how climate change might impact complex infrastructures and utilities. Climate change has to be recognized as one of the most serious environmental threats facing humankind today. There is compelling evidence that the climate will change over the coming decades due to a combination of natural and human causes, and that the greater part of the warming we have seen in the past 50 years can be attributed to human activities (IPCC 2001). Every business and industry

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should be aware of the impacts of climate change in order to be able to adapt to its potential consequences. Climate change can affect existing as well as future electricity supply facilities. The capability of existing facilities should be checked and reinforced, if necessary, for their whole lifecycle. Design standards need to be updated in order to incorporate the required provisions for a new climate-change-resisting plant and facility. Changes in weather conditions are an additional source of uncertainty for decision-makers, both in terms of uncertainties in predicting the future climate as well as imperfect knowledge of how societies, environment and businesses respond to those changes.

The Electricity Supply Industry (ESI) is an example of a complex infrastructure and utility that needs to adapt to the unavoidable impacts of climate change, while also reducing its greenhouse gas emissions. On the other hand, since the introduction of the private market in the UK, reserve capacity for electricity generation has fallen to its lowest recorded level. The energy regulator argues that the system was suffering from over-capacity and that market forces are restoring equilibrium, although there are concerns over whether current arrangements provide sufficient incentives to maintain supply security (POST 2003). The main components of the electricity industry are generation, transmission (high voltage), distribution (low voltage) and supply.

The main aim of this paper is to introduce a generally applicable methodology for assessing the impacts of climate change on the electricity supply industry, with the emphasis on the integration of physical system models within the overall picture of business performance measures. This would help the fragmented electricity industry to gain a broader view on how the performance each of their subsystems is affected by different demand and supply scenarios, and how interventions and various adaptation options can change the performance of the subsystems and the industry as a whole. We discuss these scenarios first and then describe how their impacts are modeled.

## CLIMATE CHANGE AND SOCIO-ECONOMIC SENARIOS IN THE UK

The UKCIP02 scenarios describe expected climate changes in the UK over the 21st century for four different greenhouse gas emission scenarios and three time slices centered around the 2020s, 2050s and 2080s (Hulme et al. 2002). The scenarios are based on four alternative views of the future in terms of both climate and socio-economical changes. The four emission scenarios have been paired with four UKCIP socio-economic scenarios (Dahlstrom and Salmons 2005), as below:

- Low Emissions – Global Sustainability
- Medium-Low emissions – Local Stewardship
- Medium-High Emissions – National Enterprise
- High Emissions – Global Market

In summary, the scenarios suggest that higher temperatures, combined with changing patterns of precipitation, will lead to hotter, possibly drier summers and milder, wetter winters. Annual warming of up to 3.0°C is expected by the 2050s, together with sea level rises and changes in storm patterns due to extreme weather. It is worth mentioning that a scenario is not a prediction or a forecast, but is a coherent, internally consistent, and plausible description of a possible future state of the world. This makes them useful tools for assessing future developments in complex systems that are characterized by high levels of uncertainty and insufficient understanding, so that strategies can be developed to be more robust under a variety of circumstances.

## A GENERIC IMPACT ASSESSMENT PROCESS

In order to describe the flow of activities that are required for carrying out an impact assessment exercise, a generic process has been developed as part of this study and is shown in Figure 2. The four main stages of this process are described below:

### IDENTIFYING THE PROBLEM, OBJECTIVES AND CRITERIA

At the beginning of an impact assessment, the scope of the problem and the system boundaries need to be specified. An important part of the problem is to recognize the stakeholders and their requirements. Combined with legislation and standards of practice, a set of criteria and Key Performance Indicators can be obtained.

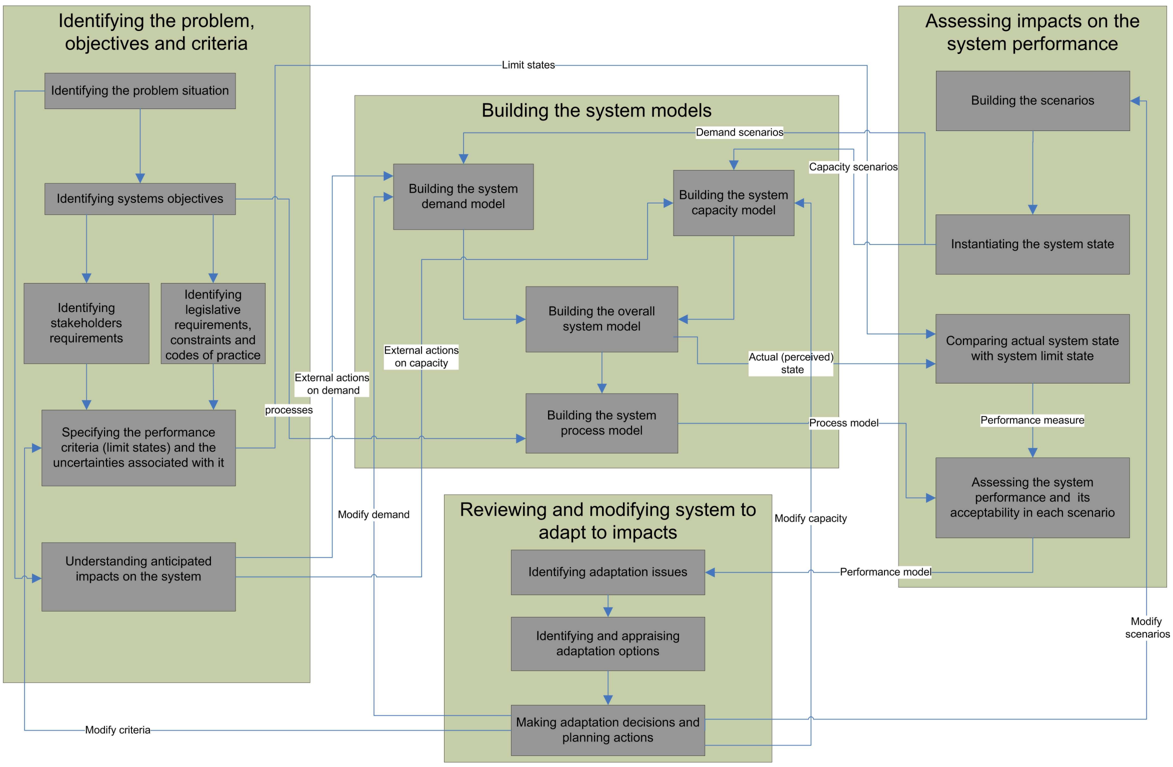



Figure 2: Generic process for assessing climate change impacts on electricity supply

In this paper, we focus on the capacity margin as a key indicator for reliability and security of supply. This is the percentage of installed generation capacity in excess of electricity demand in a given period. The reserve requirement depends greatly on the characteristics of the electricity system, particularly on the transmission and distribution capacities, the physical size of the system, and the portfolio of the generating plants. In the liberalized UK market, generation capacity availability is driven by the commercial decisions of the market participants. National Grid Transco, however, is responsible for holding a short-term reserve to deal with events within a day, such as higher than expected levels of demand or plant loss, and also to correct any potential short-term imbalances that the market does not fully resolve. NGT requires at least 10% capacity margin to cope with the demand peaks, otherwise they may require some control on electricity demand, like short-term voltage reduction or even black-out. This requirement can be translated to a performance function as it is shown in Figure 3. In this figure the actual capacity margin available at a given time is mapped from the horizontal axis through a performance function (of a given uncertainty) onto a figure of merit expressed by the green white and red flags. Green indicates that the evidence suggests an adequate margin (the objective has been met). Red indicates that there is evidence that the margin is too small (the objective has not been met); white indicates the evidence is uncertain (we don't know). In the example given the evidence suggests that the margin will be good enough for most situations with a slight chance of failure.

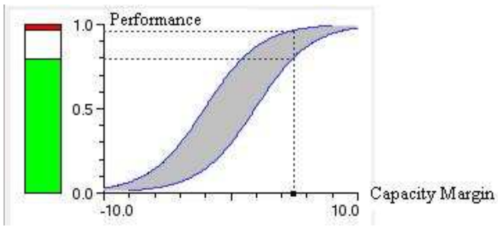



Figure 3: An example of a performance function and figure of merit for capacity margin

**BUILDING THE SYSTEM MODELS**

Based on the understanding obtained from the previous stage, different models of the system need to be built. This includes models relating the climate and socio-economic parameters to the electricity demand (demand model) as well as the effects of climate on external actions on the infrastructure. Hor et al. (2005) have developed a multi regression model to project daily electricity demand based on weather variables, growth domestic product and population growth. UKCIP02 scenarios are further refined by the Climate Research Unit (CRU 2005) to produce daily time-series for a number of sites across the UK. The impact of the external actions on the capacity of the system (capacity model), together with the overall relationship between the system capacity and demand, also need to be investigated in the modeling stage. The impacts of ambient climate on capacity are approximated through a capacity-temperature curve, while more studies are under way to investigate the impacts of climate on generation, transmission and distribution capacities. A hierarchically structured model of the system processes is built to present an overview on how the results of different models can contribute to achieving various aspects of the systems objectives. A snapshot of the overall system process model is shown in Figure 5, and Figure 8 demonstrates a section of the model in more detail.

**Simulations**

A micro model of the system is built using Simulink® software (Figure 4).

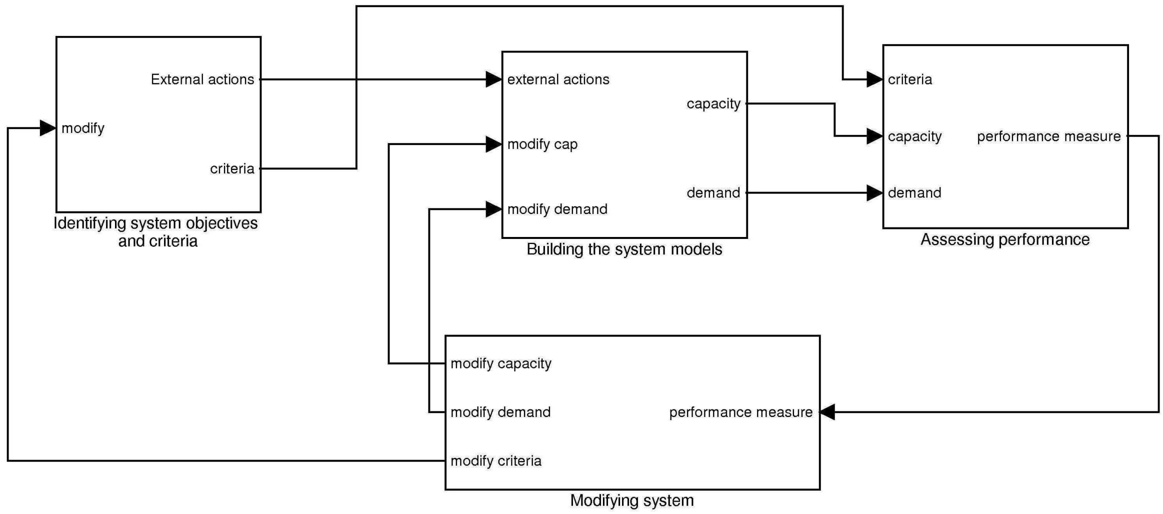



Figure 4: A Simulink® model of capacity vs demand for calculating capacity margin

The capacity and demand models are two subsystems of the 'Building the system models' block shown above. Daily electricity demand projections are run through the simulation model for four different scenarios, while the capacity degradation is taken into account using the variations in the average daily temperature predictions. The daily capacity margin for the UK is calculated as the difference between available capacity and demand divided by demand for each day. The results are shown in Figure 6.

**Performance model**

The result of playing the climate scenarios through the micro model is a series of statistics related to predefined performance indicators. For instance, the simulation would tell us the variation of capacity margin with time. It may also tell us the number of times that overhead power lines failed and the consequent power outages. Each of these data relate to some aspect of the overall performance of the system. An overview of the system including all these data would give the planners insight into what areas of the system are predicted to become stressed over time.

The system performance model is built in the PeriMeta software which is an example of a Problem Structuring Method (PSM) tool. The tool facilitates the building of a hierarchical process model. The use of process as the building block of the model provides a means to bring together all sorts of different types of data with a rich description which includes a figure of merit to show how well that process is performing at a given time. The use of hierarchy enables a manageable overview of a very complex system as each part of the model can easily be built down to an appropriate level of detail. Figure 5 shows an overall model of the ESI relevant to the climate change impacts. Detailed branches of the model are shown in Figures 8 and 9.

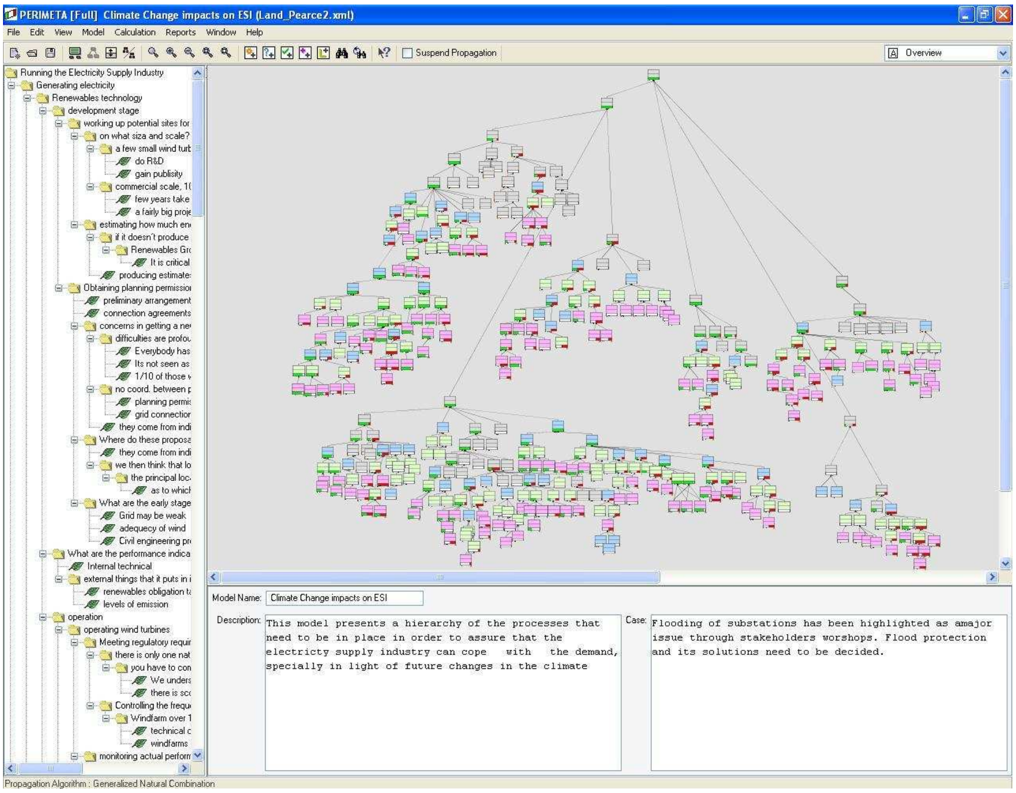



Figure 5: Systems performance model using PeriMeat tool

The model is built from understanding of the system obtained through the first stage of the generic process and interviews with a cross-section of stakeholders from different sectors of the industry.

## ASSESSING IMPACTS ON THE SYSTEM PERFORMANCE

The climate scenarios have been processed by colleagues at the University of Loughborough to produce the variation of demand with time. These demands need to be compared with available capacities to produce a measure of performance. Capacity scenarios from the Royal Commission on Environmental Pollution (2000), expanded by Nedic et al. (2005), have been used to give the variation of capacity with time. Four scenarios proposed by RCEP are paired with the four climate and socio-economic scenarios. Capacity scenarios differ in their assumptions on demand for energy, use of renewable sources, and whether base load capacity is provided by nuclear power or by fossil fuel. This data only has predictions at the date 2050, so linear interpolation has been used to give the variation between now and 2050. Work on refining the capacity predictions is ongoing.

The demand and capacity scenarios are then fed into the simulation to generate the statistics for the parameters under consideration. A typical output for the capacity margin is shown in Figure 6. These raw data give an impression of the predicted problem but not how serious it is for the whole system. If this is processed through the performance function of Figure 3, then the figures of merit of Figure 7 are generated. This performance measure is related to the 'Ensuring capacity meets demand' process at the bottom right of Figure 8.

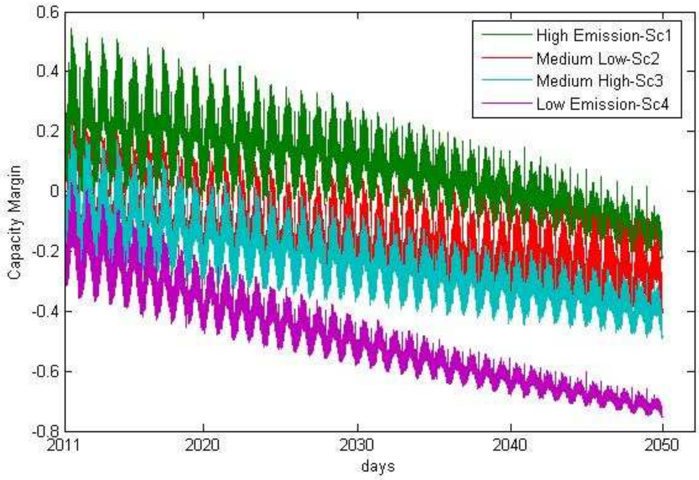
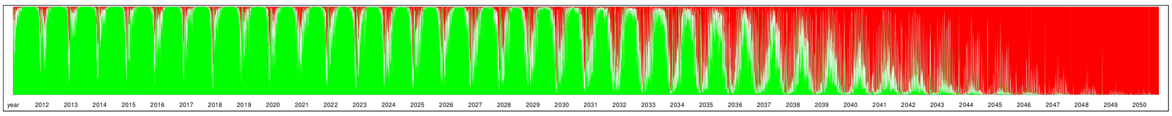
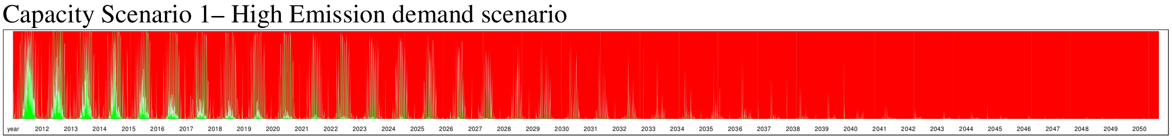



Figure 6: The system capacity margin for the period 2011 to 2050

The figures below show the variation of the figures of merit for the first two scenarios (plotted vertically instead of horizontally to show the change through time). We can now see when serious problems begin to occur. This is only one part of the picture, however. If we were to include all the other indicators as well, we would obtain a better picture of which parts of the system would need intervention and when. This can be seen as a forward looking asset management system.



Capacity Scenario 1– High Emission demand scenario



Capacity Scenario 2 – Medium Low Emission demand scenario

Figure 7: The Capacity margin viewed as a performance indicaor (ver. axis) in the system model for two scenarios from 2011 to 2050 (hor. axis). Green indicates acceptable, red indicates unacceptable and white represents uncertain performance measure

Capacity Scenario 1 of RCEP assumes no increase on 1998 demand and a combination of renewables and either nuclear or large fossil fuel power stations to produce electricity (RCEP, 2000). However, the Hor et al. model predicts a rising demand in the future. Figure 7 shows that the capacity might cope fairly well with demand in this scenario up to 2020, with a few peaks shown in red for winter load surges, but the situation does not look very promising after that. Capacity Scenario 2 assumes a 25 to 50 percent reduction on 1998 demands by 2050, while the corresponding demand model does not consider any demand reductions in its projections. It could be explained as if the capacities were planned based on demand reductions while there were no changes in the society to actually cut the demand, the situation would be gloomy even in the near future.

The PeriMeta software cascades the figures of merit up the hierarchy, inferring how the individual child processes will impact the parent process. This again allows the picture to be viewed at a higher level for reporting to different levels of an organization or showing the branches of the hierarchy which are likely to be in most trouble.

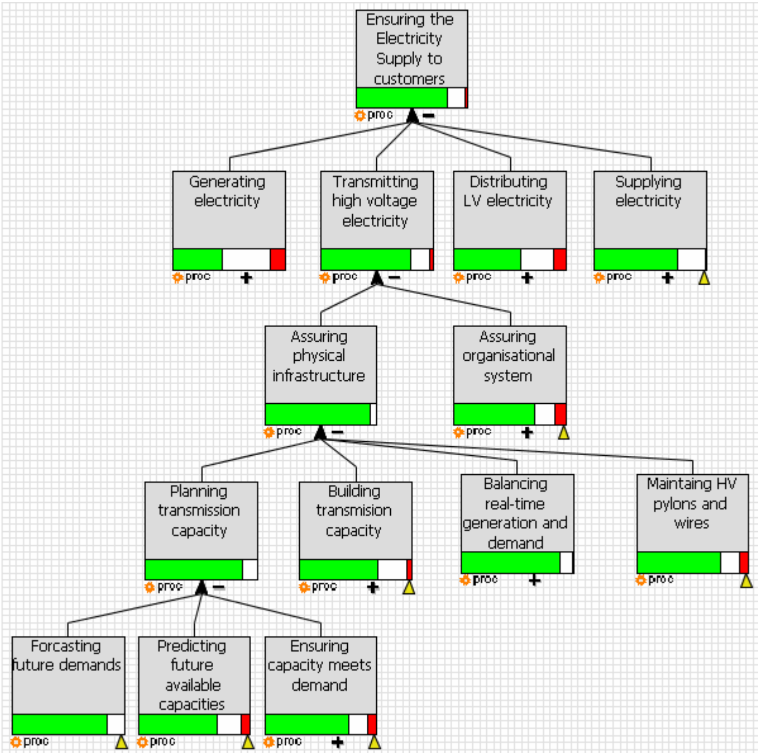



Figure 8: A section of the PeriMeta systems performance model

It should be emphasized that the purpose of this work is not to determine or predict an indicative measure for the security of electricity supply or the overall performance of the industry, but to demonstrate the process of impact assessment and scenario analysis. This could help the decision-makers to structure their debate on future planning and to visualize the consequences of their decisions in different scenarios.

The output from the Simulink simulation is passed by output file to the PeriMeta system model – the programs are run separately, although a particular scenario can be requested from the system performance model. The application of 'use case' analysis showed this to be preferable to an intimate linking of the two software tools. The system model can be stepped through to show the overall picture for a given year, or to show graphs of the individual performance indicator variation over the timescale of the run.

## Handling Uncertainty

Combination and propagation of uncertain evidence through the system hierarchy requires a mathematical formalism. Evidence theory (Shafer 1976) provides an alternative calculus to the classical probability theories by allowing incompleteness to be dealt with in more general terms. The non-additivity of beliefs is represented by white area in the figures of merit. A generalization of the combination rule of evidence theory (Marashi and Davis 2006) is used in the PeriMeta software tool to aggregate uncertain measures of performance.

## REVIEWING AND MODIFYING THE SYSTEM TO ADAPT TO IMPACTS

When problems are encountered in the system performance, the users will want to brainstorm the issues involved, the possible solutions and the arguments related to these possible solutions. The PeriMeta software allows the user to record this information as further nodes on the screen. The linkage of this 'argumentation system' (Marashi and Davis 2004) into the main process model shows how different solutions may alleviate the performance problems. Figure 9 shows how arguments can develop around an *issue* on 'protecting the substation from flooding'. Different potential *options* proposed are point defense, area defense, etc. *Arguments* for or against various options are built. The figure of merit of an option shows the degree of its favorability compared to others. The argumentation system facilitates exploring the decision space and assessing the strength of arguments (Marashi and Davis 2004; 2006).

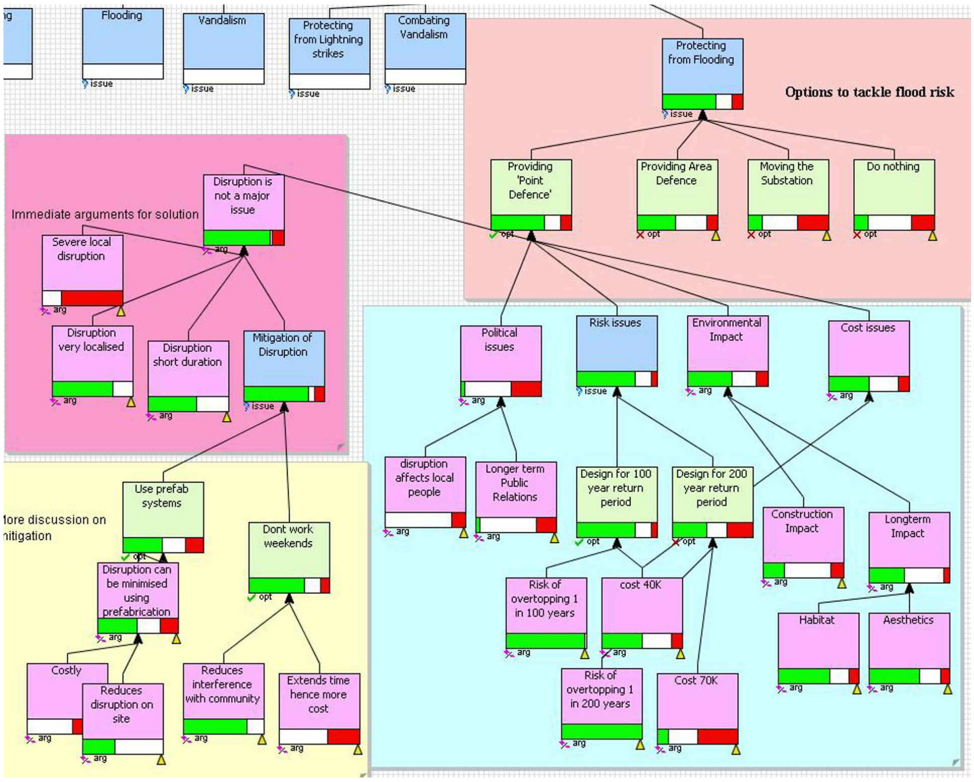



Figure 9: Argumentation structure for deciding on adaptation options for substation flooding

## CONCLUSIONS

A systemic methodology and tool is developed with the aim to support the decision-making process in complex infrastructure and utility systems. The application of this performance-based methodology is demonstrated through an example on climate change impact assessment for the UK electricity supply industry. The hierarchical structure of the process model provides a mean for managing complexity, while visualizing the performance measures and arguments behind decisions facilities communication of the results among a group of stakeholders. The results of modeling and computer simulations can be integrated into the overall picture of the process and performance model to produce a forward looking asset management tool.

## ACKNOWLEDGMENTS

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