A Systems Approach for Resolving Complex Issues in a Design Process

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Abstract: Engineers dealing with large-scale, highly interconnected systems such as infrastructure, environmental and structural systems have a growing appreciation that they deal with complex adaptive systems. We propose a systemic methodology based on discourse and negotiation among participants to help in the resolution of complex issues in engineering design. Issues arise which affect the success of each process. There are a number of potential solutions for these issues which are subject to discussion based on the available evidence assembled from a variety of sources with a range of pedigrees. An evidence-based argumentation is used to assemble and balance the evidence which results in a success measure showing how well each solution meets the system's objectives. The uncertain arguments used by the participants and other imperfect evidences are combined using an extension of the mathematical theory of evidence. This process-based framework helps not only in capturing the reasoning behind design decisions, but also enables the decision-makers to assess the support for each solution. The complexity in this situation arises from the many interacting and conflicting requirements of an increasing range of stakeholders. There is never a 'right' answer, only a satisfactory resolution which this system helps to facilitate.

Keywords: Systems Approach, Process Modelling, Uncertainty, Argumentation, Evidence theory.

Introduction

There is an ever-increasing need to design engineering artefacts and systems capable of meeting stakeholders' requirements in complex, uncertain and dynamic situations. A complex system or problem contains many components and layers of subsystems with multiple, non-linear interconnections that are difficult to recognise, manage and predict (Maxwell et al., 2002). In addition, a complex system involves people, organisations, cultural and political issues and software agents capable of affecting whole or a part of a system. Characterisation of these systems and their components is generally incomplete, often vague, and riddled with significant uncertainties (Hall et al., 2004). An organisation's success in solving complex problems through design will depend largely on its ability to manage the complexity associated with these problems. This requires a methodology and process to reduce and manage the complexity associated with the system. Complex systems can exhibit behaviours which are properties of the whole system. These properties seem more intricate than the behaviour of the individual parts. An effective and efficient design could not usually be achieved without a proper understanding of the relationship between the whole and its parts as well as the emergent properties of the system. A *wicked* and messy problem (Conklin & Weil, 1997) like engineering design has many interlocking issues and consequences which may be unintended. The vast range of stakeholders involved in an engineering design project, e.g. public, client, construction team, designers, financers, managers, governmental agencies and regulating bodies; and their changing requirements from the system, escalates the complexity of the situations. Furthermore, the objectives change in response to the actions taken and each attempt for a solution changes the problem situation. In other words, the problem definition evolves as new possible solutions are considered or implemented. This is in contrast with *tame* problems that are understood sufficiently to be analysed by established methods. The problem statement is well-defined and the solution can be objectively evaluated as right or wrong. In practice, there is no specific boundary between tame and wicked problems in design, but the tame problems are surrounded by the wider wicked problem. In fact, a design team need to be well-equipped with a mixture of capabilities in solving both. As we go down from initial social context to the detailed technical solutions, the problem's face gradually changes from wicked to tame. For a typical design activity of a construction project, this transient change may happens during design stages as shown in Figure 1. Design stages are presented according to BS7000-4, Design management systems (BSI, 1996).

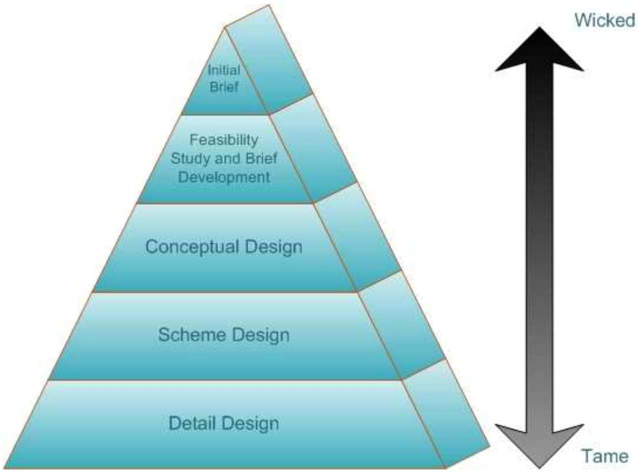


Figure 1 - Transient change of problem nature during design stages

The overall aim of the research described here is to address the need for improvement in managing engineering design and its decision-making process. A system-based approach is adopted to manage complexity, using a multi-level description of design activities. The proposed methodology also provides a framework for representing and capturing knowledge in order to offer a richer picture of design process by articulating process attributes, issues, alternatives and arguments leading to decisions. Communicating design intents between stakeholders and documenting the design process for review, verification, modification and reuse is another aim of this system.

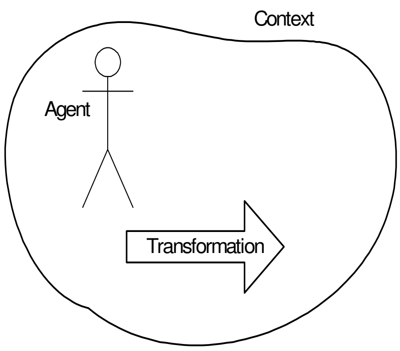
Process Modelling: A Systemic Way to Approach Complexity

The socio-technical and multi-disciplinary nature of design in engineering systems does not lend itself easily to a pure scientific and technical way of thinking. The *systems* movement which began during 1940s is a set of attempts to explore the consequences of holistic rather than reductionistic thinking. System Thinking (Checkland, 1999) is introduced as a holistic paradigm to understand the situation by seeing the big picture and the connectivity between elements in the situation. It is a method of learning the way towards effective action by looking at connected wholes rather than separate parts. The UML approach to enterprise modelling (Marshall, 1999) and the Soft Systems Methodology (Checkland & Scholes, 1990) are other examples of systems approaches, but recent developments in process modelling (Blockley, 2000), (Davis, 2002) may offer more clarity and accord with the engineering practice. For instance, the implementation of a process-based approach is a core requirement of International Standards for Quality Management Systems (ISO 9001, 2000) and Total Quality Management. As such, it is essential to achieve a unified, simple and intuitive understanding of a process in order to implement the process approach.

The processes can be defined at different levels of definition to give a continuous spectrum of hierarchically structured models. This is in line with the characteristics of a complex system as described by Simon (1999). In this view, complex systems are usually hierarchical, and these hierarchically organised complex systems may be decomposed into sub-systems. Because of their hierarchical nature, complex systems can frequently be described in terms of a relatively simple set of symbols. This allows for a description of system at a range of complexity levels. Such multi-level frameworks must provide a coherent calculus that allows for the transfer of information or knowledge between the levels. For instance, within a complex system such as the rail network, evidence on performance must propagate upwards from the lowest levels to network management levels. On the other hand, government targets must be filtered down to the level of train operators and then to local network managers.

Blockley (1999, 2000) has identified a number of attributes for a process and an algorithm for building a process model based on its attributes. Although Checkland does not use the ‘process’ term, the notion of ‘building purposeful activity models’ in Soft Systems Methodology using CATWOE notation (Customers, Actors, Transformation, World-view, Owner and Environment) resembles a similar view.

We describe the process here as a set of activities which realises a transformation. The process elements can be described in terms of the simplest sentence structure, i.e. 'Subject + Verb + Adverbials', which is meaningful in the context of a language. The core element of every process is a transformation, which is a verbal definition of the action in a process. The transformation is carried out by or affects a number of human or software agents in a specific context. In this definition, the important elements of a process can be categorized in terms of Agent, Transformation and Context (Marashi & Davis, 2004b). This is what we call the 'ACT' model (Figure 2).



Agent: Those who are involved, affected or concerned about transformation
Transformation: The conversion of a state or entity to another state or entity
Context: The situation in which the transformation is meaningful

Figure 2 - Elements of a process using the ACT model

Based on this general categorisation of process elements, a unified understanding of process attributes which enables a complete definition of a process is presented in Table 1. The transformation is an answer to the question 'what' to do as well as 'how' and 'why' to do it. "Selecting the site for windfarm power generation" and "Evaluating the noise level of windfarm" are two examples of process. The root process can be decomposed to a number of sub-processes. The contractual agreement or the scope of work of a project could be used as a guideline for start. In the absence of such information, a careful investigation of the activities and their nature should be done in order to identify the required sub-processes. Although the identification of sub-processes is somewhat subjective, it is constructive to think about each process in terms of three stages of Appreciating, Operating and Controlling (Table 1), as it is discussed in (Checkland, 1999). This leads naturally to the concept of a hierarchically structured set of sub-processes which realises the achievement of the defined objectives of that decision (see also Davis & Hall, 2003). In fact, process modelling can augment the notion of Checkland's purposeful activity systems by introducing a multi-level, connected set of processes which is more manageable and industry-oriented. The ACT model also generalises the CATWOE notation in Soft Systems Methodology to a form that is closer to the structure of natural language.

It is important to recognize that there is no 'right answer' to this identification and the process model is not a unique, one-off outcome for the whole life-cycle of the project. Several different hierarchies should be built by the design team in an iterative way until one emerges which is perceived to be robust enough and practical for the task in hand. It should be borne in mind that the engineering process creates systems for a purpose; that purpose is to satisfy the requirements of the systems' stakeholders. Thus, the characterisation of stakeholder requirements is a crucial sub-process.

At the heart of the methodology must be the recognition that creation and management of real engineered systems requires many disciplines and capabilities to work in harmony. This is one of the weaknesses of the existing engineering approach, which is based on disciplinary demarcations that inhibit interdisciplinary working.

At the lowest level of hierarchy, the achievement of each process may be viewed as addressing one or a number of issues. This could raise a debate which will be structured in an argumentation framework as we will see in the next section.

Evidential Discourse for Engineering

The need for argumentation and discourse is apparent in most complex decision-making situations. In general, a group of people reach a decision through debate and negotiations. Each stakeholder may have his own sets of preferences and view points, with arguments for or against a potential solution. Argumentation is primarily useful for tackling wicked and messy problems (Conklin & Weil, 1997).

Table 1- Attributes of a process based on the ACT model

Agent	Transformation	Context
Who?	Why? /What? /How?	Where? /When?
Roles (people): Customer Client Stakeholder Sponsor Owner Manager Worker	Appreciating: Objectives Purpose Scope Issues Criteria Success Failure	World-view Time Place Description of Situation: Hierarchy Uncertainty
Roles (other agents): Function	Operating: Activity Input Realization Output Sub-activities	Environment: Resources Constraints Hazards Risks
Roles: Responsibility Authority Accountability Communication	Controlling: Performance Measurement Monitoring	Social/Cultural dimensions Roles Norms Values Political situations
Subject , Object	Verb	Adverbials

In contrast to tame problems, the definition, requirements and criteria for whether a solution has been reached are not well-defined. Ill-structured problems, like those encountered in design and management, lack the predetermined linear route through problem solution stages applicable for structured problems. This is the reason why solving messy problems is an argumentative process requiring logical as well as informal reasoning. The study of argumentation is deeply rooted in various disciplines such as philosophy, logic and linguistics, but it is important to note that argumentation study tries to deal with the verbal, contextual, situational and other pragmatic factors of communication process in areas where logic can not adequately address the situation..

Argumentation is defined as "*The action or operation of inferring a conclusion from propositions premised* "(OED, 2005). The study of argumentation dates back to Greek antiquity, around 2400 years ago. The development of informal logic and argumentation theory within philosophy has represented a backlash against formal logic. Despite immense power and wide application of formal logic, it is not a suitable choice for representing and characterising complex, natural and real world language and arguments. Toulmin developed an intermediate approach between formal proofs of logic and persuasive strength of rhetoric (Toulmin, 1958). He developed a "layout of argument" which has been used largely for the analysis, evaluation and construction of arguments, especially in jurisprudence context.

According to Toulmin (1958), the argumentation process starts with formulation of a problem in the form of a question. A list of possible solutions is taken into consideration in the next stage, setting aside the solutions that appear inadequate straight away. The possible solutions are then weighed up against each other. A choice has to be made between possible solutions in order to select "the best" one, though it might be difficult to arrive at a solution in some fields of argumentation which deal with soft aspects of human affairs. An open-ended, dialectical process of collaboratively defining and debating issues, having its roots in dialectic of Aristotle, is a powerful way for reaching a consensus and conclusion. This perspective motivated the development of Issue-Based Information Systems (Kunz & Rittel, 1970) as a framework for modelling argumentation. Having its background in planning and policy problems, IBIS addresses design problems by using argumentation structures to facilitate a discussion amongst the stakeholders about issues, which allows the problem to be explored and framed. IBIS tries to identify, structure and settle issues raised by problem-solving groups. Issues are brought up and disputed because different positions are possible.

This framework has also been developed through the Compendium methodology (Selvin et al., 2001) and HERMES system for multiple criteria decision-making (Karacapilidis & Pappdias, 2001). Fletcher & Davis (2003) also proposed a framework for simulation and capture of dialectical argumentation in a complex situation. Argumentation structures based on IBIS and QOC (Question, Option, Criteria) have also attracted a lot of attention in developing design rationale systems (Shum & Hammond, 1994).
The argumentation structure in IBIS model consists of *Issues*, *Positions* and *Arguments*. The issues are brought up by the participants and are subject to debate. Issues normally have the form of a questions or a controversial statement, which is raised, argued, settled, dodged or substituted. Each issue consists of a set of positions or options which represent the possible answers, ideas or choices of action that could be taken in response to that issue. Arguments are asserted by participants to support or rebut a position. The argumentation structure attached to each process is presented in Figure 3.

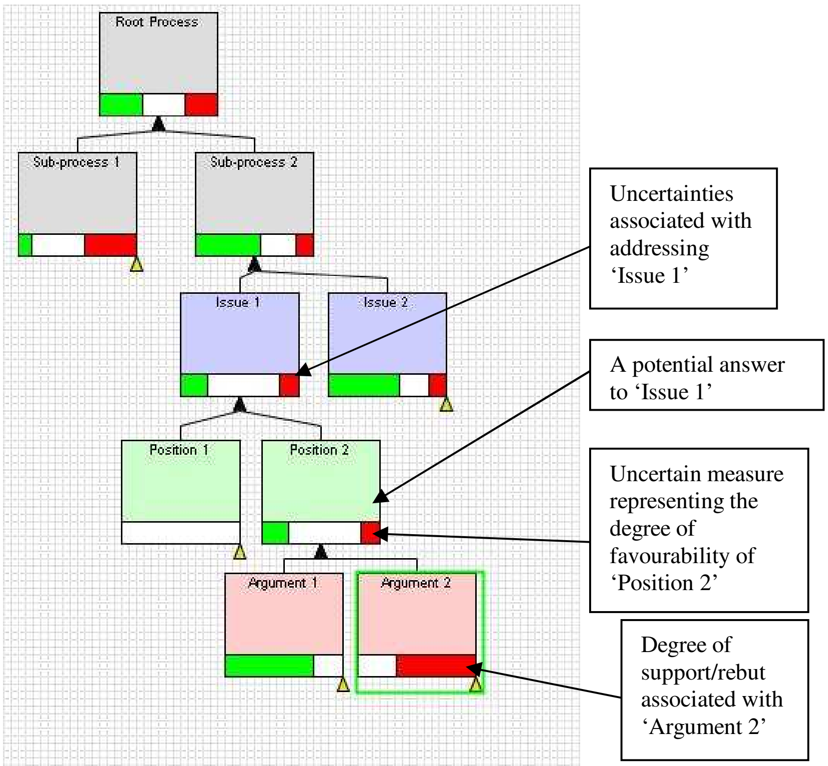


Figure 3 – Evidential Discourse for ENgineering (EDEN) framework (Marashi & Davis, 2004b)

This graphical representation of argumentation enables externalization and communication of discourse among participants and stakeholders. This integrated framework is called EDEN (Evidential Discourse for ENgineering) and its software implementation is under way in the Civil Engineering Systems Group at the University of Bristol, through extending its predecessor software tools Juniper and PeriMeta (Davis & Hall, 2003). From a linguistic point of view, this model allows for the representation of participle phrases (processes), interrogative statements (issues) and declarative statements (positions and arguments) which adds to the expressiveness of the process modelling system.
The arguments taken for or against a position are the basis for developing an uncertain success measure for the performance of that position or option. It shows the level of acceptance of that option in comparison with other options under the same issue. These measures provide a clearer understanding of which alternative solution is more prominent at the moment. In the same way, the uncertain measures attached to issues represent the successfulness of the debate in addressing that issue. These measures are combined and propagated up through the hierarchy using mathematical theories of uncertainty which is the subject of discussion in the next section. The advantage of this argumentation framework compared to previous works based on IBIS is that it provides the computational support for assessing the strength of arguments as well as a graphical representation of the connectivity of the argumentation elements. The use of visual language

has been shown to be a powerful tool in the facilitation of dialogue and debate (Horn, 1998). Like any other form of knowledge representation and elicitation, the added expressive dimension of argumentation would however bring in its own overhead to the designers. This could be balanced by longer term benefits that the system can provide during design review and reuse. Argumentation is also a way of recognising, communicating and protecting stakeholder's social and technical interests and requirements (Goguen, 1994).Another difficulty arises with cultural and political dimensions of knowledge sharing, especially during the elicitation of tacit knowledge in an organisation (Turban & Aronson, 2001). An example of the application of this framework has been presented later in this paper.

Combining Uncertain Evidence

In many cases, there is insufficient knowledge to allow for the perfect transfer of information between levels and hence the incorporation of uncertainty management and propagation is vital for any multi-level system. Theories of evidence allow us to combine uncertain pieces of information issued from various sources dealing with the same subject. Unlike the Bayesian approach, these models do not require the additivity of beliefs, so ignorance and inconsistency in sources of evidence is also permitted.

The uncertain positions are combined using the generalized natural combination rule which has been derived from a generic method of aggregation of uncertain evidence, called Triangular-norm-based Combination Rule (Marashi & Davis, 2004a). This new combination method has emerged from an amalgamation of generalized fuzzy set operations with belief functions computations. This rule allows the aggregation of uncertain information with various levels of dependency between bodies of evidence.

Let Ω be a finite set of elements called the *frame of discernment*. It can be seen as a set of possibilities or hypotheses under consideration. By definition, a mass assignment could be built over the power set of Ω, such that $m: 2^{\Omega} \to [0,1]$ and

$$\forall X \subseteq \Omega \qquad \sum_{X \subseteq \Omega} m(X) = 1$$

$m(X)$ represents that part of belief that supports X as being the true hypothesis.

Now lets consider two pieces of evidence represented by mass assignments m_1 and m_2, supporting proposition $A \subseteq \Omega$. The aim of the TCR combination rule in Eq. (2) is to sum up the masses assigned to a subset A during the meet of two or more evidence, and to redistribute the conflicting mass $m(\varnothing)$ on a specified subset $P \subseteq \Omega$ according to weighting factors w in normalization step. The combined mass can be expressed as:

$$m(A) = \sum_{X \cap Y = A} m_{XY} + w(A, \mathbf{m}).m(\varnothing) \quad \forall A \subseteq \Omega \setminus \varnothing$$

$$m_{XY} = T^{XY}(m_1(X), m_2(Y)) \quad \forall (X,Y) \in S \subseteq F_1 \times F_2 \tag{1}$$

$$m(\varnothing) = \sum_{X \cap Y = \varnothing} m_{XY} \qquad w(A, \mathbf{m}) = 0 \;\; A \not\subset P \qquad \sum_{A \subseteq P} w(A, \mathbf{m}) = 1, \forall A \subseteq P$$

where F_1 and F_2 are sets of focal elements for mass assignments m_1 and m_2, respectively. S is a subset of $F_1 \times F_2$ for which the masses are allocated using a t-norm. P is a subset of Ω on which the conflicting mass should be distributed and w are weighting factors associated to each subset of P. Function T^{XY} is a triangular norm. The selection of elements of S and values for m_{XY} should be in such a way that satisfies a set of constraints imposed by support pairs, i.e.

$$S_{n_1}(A) = \sum_{Y \in F_2} m_{AY} \qquad \forall A \in F_1$$

$$S_{n_2}(A) = \sum_{X \in F_1} m_{XA} \qquad \forall A \in F_2$$

$$\sum_{X \in F_1} \sum_{Y \in F_2} m_{XY} = 1$$

Now consider the following special case for a bipolar frame of discernment:

$$\Omega = \{A, \overline{A}\},\ 2^{\Omega} = \{\varnothing, \{A\}, \{\overline{A}\}, \{A, \overline{A}\}\}$$

The following mass assignment for this representation introduces a support pair (Baldwin, 1986) as $A:[S_n, S_p]$ where S_n is the necessary support and S_p is the possible support for proposition A:

$$m(A) = S_n(A) \qquad m(\overline{A}) = 1 - S_p(A) \qquad m(\Omega) = S_p(A) - S_n(A)$$

This concept with its graphical illustration called the *Italian Flag* is used to represent the support pairs (see Figure 7). The green area on the left hand side represents evidence in favour of A, the red area in right is the evidence against A, and the white area is the amount of ignorance about A.
The generalized natural combination rule is derived using the following assumptions in Eq. (1) (Marashi & Davis, 2004a):

$$\begin{aligned} m_{AA} &= T_{\lambda}^{F}(m_1(A), m_2(A)) \\ m_{\overline{A}\overline{A}} &= T_{\lambda}^{F}(m_1(\overline{A}), m_2(\overline{A})) \\ m_{A\overline{A}} &= T_{\frac{1}{\lambda}}^{F}(m_1(A), m_2(\overline{A})) \\ m_{\overline{A}A} &= T_{\frac{1}{\lambda}}^{F}(m_1(\overline{A}), m_2(A)) \end{aligned} \qquad T_{\lambda}^{F}(x,y) = \begin{cases} \min(x,y) & \lambda = 0 \\ x.y & \lambda = 1 \\ \log_{\lambda}\left(1 + \dfrac{(\lambda^x - 1)(\lambda^y - 1)}{\lambda - 1}\right) & \lambda \in \left]0,1\right[\cup \left]1,\infty\right[\\ \max(0, x + y - 1) & \lambda = \infty \end{cases}$$

where $T_{\lambda}^{F}(x,y)$ is the Frank's triangular-nom function (Frank, 1979).
The parameter λ can be used to model various dependency assumptions between bodies of evidence.

Climate Change Impacts on Electricity Supply Indusry: a Case of Application
There is growing evidence that the UK climate is changing over the coming decades due to a combination of natural and human causes. The Electricity Supply Industry (ESI) is an example of a complex utility which needs to tackle the climate change by:

- complying with the policies for reducing greenhouse gas emissions
- planning to adapt the industry to the unavoidable impacts of the climate change

The ESI is involved with a diverse range of stakeholders. Since privatisation, the gas and electricity industries have become fragmented and the central long-term planning of the pre-privatisation period has largely disappeared. The main players involved here are the generators, transmitters, distributors, suppliers which provide electricity to the customers under Ofgem (Office of Gas and Electricity Market) regulations in Britain. These relatively large groups of stakeholders place their own particular performance demand on the system. Effective management of the ESI must recognize this, and treat specific demands, such as those arising from climate change, in a holistic manner alongside other system requirements.
Energy supply, and particularly electricity generation, was responsible for a quarter of the UK's greenhouse gas emission in 2000. Consequently, ESI is under growing pressure to reduce the consumption of fossil fuels by increasing the use of renewable sources. The Energy White Paper (DTI, 2003) has set a 10% target for the fraction of the UK's electricity that should be supplied from renewable energy by 2010. A large part of this renewable energy will be provided by windfarms both on and offshore, as wind power will be the most competitive form of renewable energy in the medium term. Through the following brief example, we demonstrate how the EDEN methodology and tool can be used during the course of the feasibility studies and design of a new windfarm.
Figure 7 shows a snapshot of a process model for designing a windfarm. The root process "Designing the windfarm power generation" has been broken down into a number of sub-processes, namely "Developing

the initial brief", "Performing the feasibility study" and "Performing the basic and detail design". Feasibility study of a power generation plant requires a wide range of technical, social, economical and environmental studies. "Selecting the site location" is an example of a process that not only needs to satisfy technical specifications of different design disciplines, but at the same time is involved with getting permission from local authorities, inquiring about public viewpoints and dealing with environmental campaigners. For this example, we only focus on two issues that have been raised which are the subject of discussion as shown. The first question here is to identify objectives/criteria, which has been answered subsequently through quantitative and descriptive explanations. The objectives/criteria can be translated to performance indicators using an appropriate value function. The value function can be numeric or linguistic depending on the nature of evidence. The importance of each criterion can be adjusted by setting the weighting factors attached to that performance indicator. Figure 5 shows an example of an S-shape value function for assessing a site based on its distance from the dwellings. Two alternatives are under consideration for the location of this new windfarm. We assume that the local authority requires a minimum distance of 2 km from dwellings in order to minimise visual domination, noise and reflected light. The argument for Alt-1 which is located at 3 km from the city has been mapped to an Italian Flag using the value function in Figure 5. The evidential value of an argument is being assessed by measuring the value of its attributes against a set of criteria assigned to that argument. This is what we call the justified evidence for or against an option as it is based on the explicit criteria. The importance of the argument can also be adjusted through the importance factor assigned to its link. The combined interval value represents the uncertain support measure of the corresponding alternative. In a similar way, other objectives/criteria, e.g. wind speed, are translated into a value function. One of the important qualitative aspects of a windfarm is its visibility. This is one of those subjective issues that can not be easily assessed without incorporating public and experts viewpoints. A fuzzy mapping has been used to handle qualitative and linguistic assessment of the visual aspects. Opinions can be expressed in terms of a linguistic scale like very poor, poor, medium, good and very good, together with the confidence of the evaluator on her assessment. Figure 6 shows the value function corresponding to a 'good' assessment of visual aspect with medium confidence. Note that "Connection to the network is easy" has been added as an argument without referring to an explicit criteria. These types of arguments enable the participants to express their opinions and implicit judgments in an informal way. The participants are allowed to express their subjective opinions without a reference to a performance indicator. This feature of the methodology enables the inclusion of expert subjective opinions into the decision-making process.

The graphical representation of the arguments and its effect on supporting or rebutting a potential option helps the design team to easily communicate the reasons behind their decisions. The arguments should not be necessarily independent of each other, as the uncertainty calculi is able to deal with various levels of dependency between bodies of evidence. Each option should be assessed against the same set of performance indicators related to that issue, based on the value of the corresponding attribute of that option which could also be uncertain.

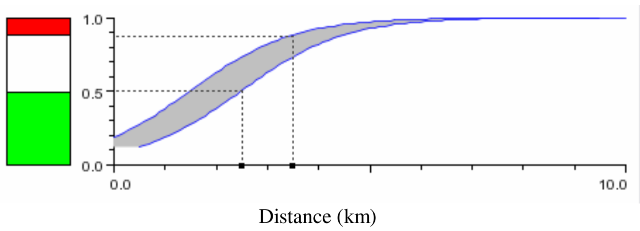


Figure 5 - Value function for site distance from the dwellings; support pair for x=3±0.5 km

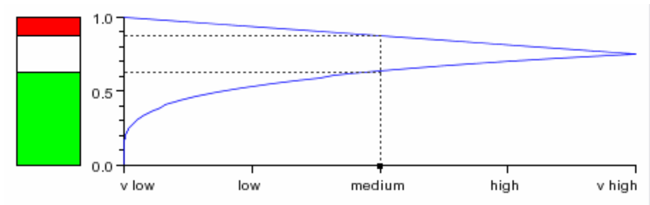


Figure 6 - Value function for 'good' visual aspect with 'medium' confidence

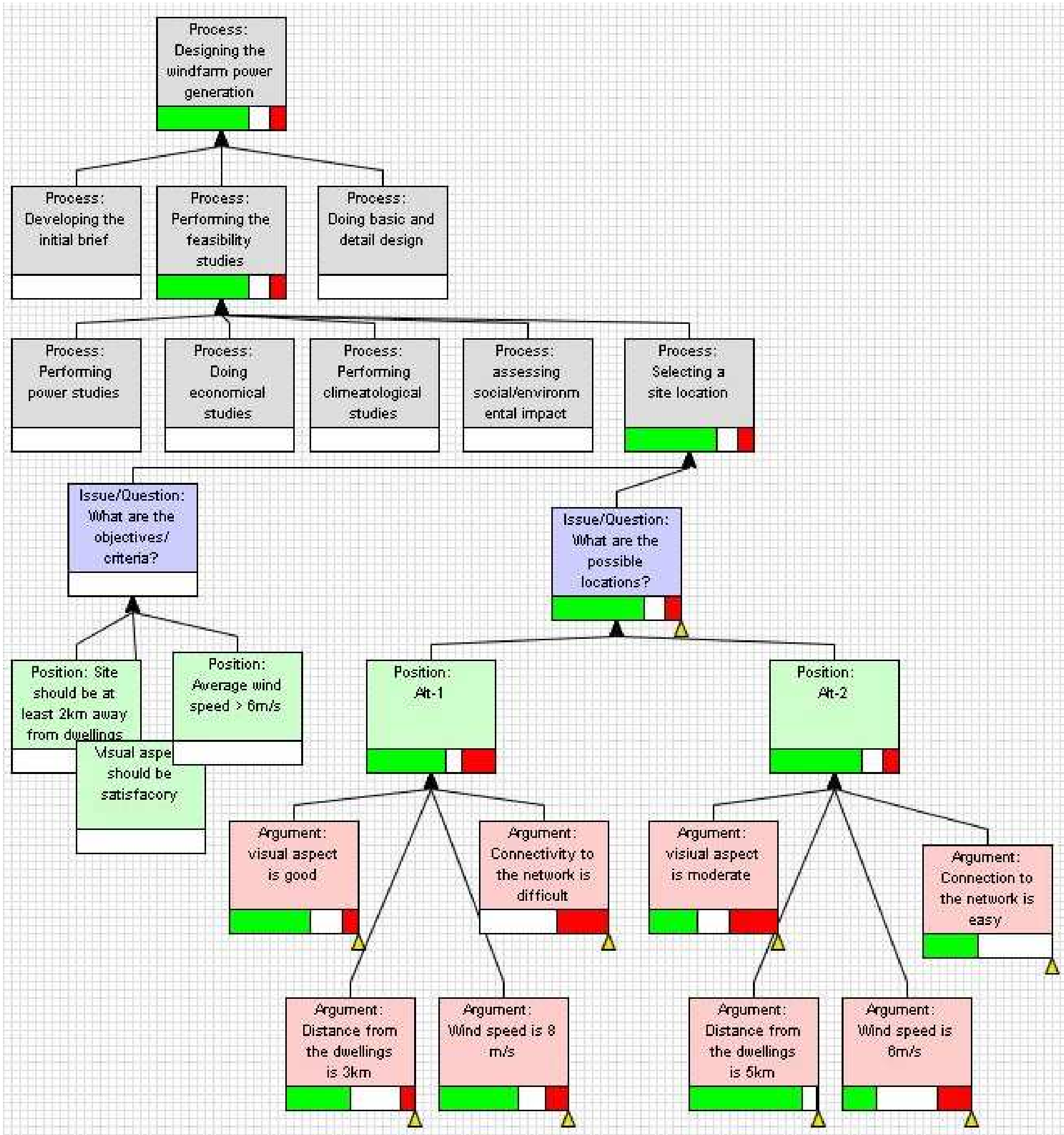


Figure 7 - A Snapshot of argumentation during a design decision-making process

Conclusion

An integrated framework is presented based on process decomposition and argumentation to help designers tackle complex, messy and ill-structured problems. The methodological steps are as follows:

- Understand the problem situation
- Decompose the complex system to its sub-systems and sub-processes
- Identify process objectives and criteria
- Resolve issues based on evidence through discourse and negotiation
- Decide on appropriate action and solution
- Continually review and update the above steps

A systemic view of the activities in the design process recognises the need for handling uncertainty, which is being addressed through a novel use of evidential and argumentation theories. Design rationale can be represented among of stakeholders in a more intuitive way. Visualizing the trend of arguments, with appropriate calculi for assessing the strength of claims, results in a clearer picture of the design decisions.

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