INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

DIMENSIONS OF DECISION SITUATIONS IN COMPLEX PRODUCT DEVELOPMENT

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ABSTRACT

Decision-making is a multifaceted phenomenon. Yet in design, many models describing decision-making and approaches to decision support are based on simplistic process models and assumptions. This paper reviews the literature surrounding both decision processes and decision support systems, before presenting the authors' own insights from a series of construction and engineering case studies. Based on an analysis of the literature and case study findings, a set of dimensions for classifying factors influencing decision situations is presented. Using this taxonomy the authors then structure the decision process as a dynamic and iterative activity before discussing its implications for decision support systems in design.

Keywords: decision-making, decision support systems, complex product development

1 INTRODUCTION

Decision-making in design is an omnipresent activity. Project stakeholders such as clients, end users, designers, project managers, manufacturers, and contractors make decisions continuously throughout project implementation. While some design decisions may seem simple or trivial, others can have far-reaching consequences; some may be ad hoc and others may only be made after consideration of all available knowledge; and whilst some design decisions may be of the one-shot type, others will involve a sequence of actions constrained by previous decisions or their feedback [1]. This diversity of decision forms is reflected in the array of computational tools commonly used across all aspects of design practice. Design decision-making can be supported, in some form, by one or a mixture of decision support systems (DSSs). Yet a tool must meet the needs of the decision situation it is used in.

Research on decision-making and DSSs often focus exclusively on one type of design problem and ignore many of the factors that can affect continuous, dynamic and interconnected decision processes. Consequently, such reductionist approaches neglect the different dimensions that make up a decision situation. Factors affecting each stage of a decision process may arise from sources endogenous or exogenous to the project and compose the set of variables to be considered by the decision maker/s.

This paper explores the dimensions of decision situations in design. Section 2 outlines the problem and motivation of this research. Sections 3 and 4 respectively, present a brief review of the literature and insights from case studies on various design decision processes. Using the existing literature and the authors' own case study findings, Section 5 then derives dimensions for the classification of elements affecting decision processes. Using this taxonomy the paper provides a rich description of the structure and nature of decision-making and discusses process behaviours observed within the case studies. Finally, in Section 6, the implications (of these interconnected and dynamic elements) for the development of DSSs are discussed in relation to delineating decision process boundaries.

2 PERSPECTIVES ON DECISION MAKING

The term decision-making is used to refer to a range of intelligent activities. Definitions of design decision-making may therefore be conceived of as a continuum. At one end decision-making can include all conscious or unconscious choices and judgements inherent in designing. That is, decision-making encompasses all discrete events in the problem solving process or every design 'move' [2]. At the other end, decision-making is an explicit and conscious choice among design alternatives intended to influence the solution space. That is, as a specific choice distinguishable by the design problem or task type and its normative long-term character as a dynamic process [3].

Decision process models generally define six stages, beginning with problem identification and proceeding via analysis, development, evaluation and selection, then concluding with implementation [4]. Decision processes in design are often iterative and rely on information feedback loops as the decision maker/s cycle/s from first to final activity. In drawing a boundary around the decision process, the nature and range of influencing factors considered during decision-making can be identified. It follows that the particular decision problem must be identified before the boundary can be determined and the choice made about which factors need to be considered and which can safely be excluded. In utilising any DSS, boundaries are inherently delineated by the model and consequently the system implies that no 'outside' influences are necessary for solving the particular problem. This also means that the dynamics of the decision process are generated within these boundaries. However in practice, it does not mean that the boundary is inflexible or impermeable to new or latent influences.
At present there is no complete taxonomy of the dimensions and elements that influence design decision processes. In creating such a framework, a richer understanding of decision processes, their behaviour and a profile of their boundaries can be derived and planned for. While many models of decision process stages exist (many based around Simon's [5] three phases of decision-making, search, design and choice) there are only a few taxonomies of all the factors influencing them, and none which address each stage in relation to design. For example, many existing approaches focus on those factors that drive and constrain the analysis of alternatives and least on the successful implementation of the chosen alternative, resulting in a gap between problem identification and action.
Outside the design domain, in organisational psychology research, Beach [6] defines three dimensions (called 'images') that guide and limit decision-making, including: a set of values and beliefs; specific goals to which the decision maker or organisation is striving; and defined operational plans for reaching goals. From sociological research, a multiple perspective approach developed by Orasanu and Connelly [7] considers eight dimensions of decision-making, including: ill-structured problems; shifting, ill-defined and competing goals; multiple players; organisational goals and norms; uncertain and dynamic environments; time stress; high stakes; and feedback loops. In operations management research, Radford [8] explored three phases of the decision process – information gathering, strategic analysis and interaction – but focused only on the first phase when defining those factors critical to gathering information, namely: participants, social, technological and natural elements. Radford's categories provide a rich taxonomy yet fail in their neglect of detail in subsequent decision phases.
In contrast to these authors, this research considers explicitly design decision processes. Designing as an activity is aimed at changing existing situations into preferred ones, and this paper contests that design decision processes are therefore distinctive. This work investigates the design decision situations of complex product development. It seeks to understand how decision-making occurs in large, temporary, project-based organisations, which are not necessarily limited to- or predetermined by- the problem type and endogenous organisation-based conditions; but also by exogenous ones such as government policies and regulations, available technologies, state of the economy, etc.

3 RESEARCH ON DECISION MAKING IN DESIGN

Models of decision-making in design have been developed and studied in the context of business, economic, and engineering settings. Research efforts are mainly along three lines.

- *Descriptive*: Using models and theories to describe and explain a designer's decision-making behaviour by studying beliefs and preferences as they are.
- *Prescriptive*: Developing techniques and aids for supporting and improving human decision-making.
- *Normative*: Using axioms to make optimal decisions, study the logic of decision-making and nature of rationality, attempting to suggest how good decisions ought to be made.

Within each approach, many questions have been investigated by researchers, such as how to obtain knowledge about utilities; how to elicit and represent different types of knowledge; how to generate and present alternatives; and how to carry out the decision process? The approach and emphasis vary depending on which design research domain the problem is studied in, e.g., design computing, design/project management, business, or policy.

3.1 Decision Making in Engineering Design

In engineering design, how people make decisions and how they can be supported has been studied from a variety of different angles and intellectual perspectives since the 1960s [9]. The decision maker may be a human being, a computing machine, or an ideal agent. Topics of problem solving, mental imagery, memory, thinking, language, learning, and behaviour belong to the realm of design cognition. Cognitive studies of decision-making in design are founded in psychology research and are concerned with the nature of human judgment and reasoning processes, emphasising the types of choices designers make in design situations and suggesting ways of supporting them. Furthermore, research in design decision-making has drawn on philosophy and normative theories of human rationality, (see for example [10]) as well as on research from economics and the organisational and management sciences', particularly in the development of mathematical models of judgement and decision analysis. Sociological research has also impacted up our understanding of design decision-making. For example, Minneman [11], Bucciarelli [12] and Henderson [13], among others, have studied large-scale engineering design processes as participant observers. They report that complex designs are developed largely through social decision processes of argumentation and negotiation and view designs as arising through these processes.

More recently the design paradigm known as Decision Based Design (DBD) has been embraced by both academia and industry. DBD approaches the engineering discipline under the assumption that at the heart of design is decision-making [14]. In formalising the DBD approach, Hazelrigg divided engineering design into two parts: identification of options and selection of the best option [14]; stating that these tasks are complicated by the infinite number of options, the need for a metric to rank the options, and the infeasibility of searching all the options. Consequently, Hazelrigg asserts that information beyond the engineering discipline is necessary in modelling decision-making and decision processes.

In keeping with Hazelrigg's assertion, the US Board of Manufacturing and Engineering Design [15] identified a number of influencing factors and structured these based on input, output and through-put conditions. Input dimensions consist of constraints, requirements, knowledge base and options. Output dimensions consist of decision implementation and qualifiers. Through-put dimensions are divided between the 'controllable' business context and the 'uncontrollable' environmental context. Similarly, in an approach to information management, Courtney [16] introduced an approach to decision-making in the context of social, environmental and economic concerns, to address structured, semi-structured and ill-structured problems. Like Radford [8] Courtney first structures the phases of the decision process, defining a perspective development stage in addition to the three phases of traditional decision process models. Within perspective development, technical, organisational and personal dimensions are identified.

3.2 Decision Support in Engineering Design

Decision support systems (DSSs) have been developed to aid engineering design in a variety of ways and defined from different authors' points of view [17]. On the one hand, a DSS has been broadly described as "a computer-based system that aids the process of decision-making" [18]. On the other hand, in a more precise definition, DSSs are "an interactive, flexible, and adaptable computer-based information system" [19]. Other definitions fill the gap between these two extremes. For example, Sprague and Carlson [20], define DSSs as "interactive computer-based systems that help decision makers utilise data and models to solve unstructured problems."

Whilst it may not be possible to give a precise definition which includes all the facets of a DSS, their classification is helpful, see authors [21, 22, 23]. Of these classifications, Power's [23] taxonomy is useful in differentiating at the conceptual level between *communication-driven DSS*, *data-driven DSS*, *document-driven DSS*, *knowledge-driven DSS*, and *model-driven DSS*. A *communication-driven DSS* supports more than one person working on a shared task. A *data-driven DSS* or data-oriented DSS emphasises access to and manipulation of a time series of internal company data and, sometimes, external data. A *document-driven DSS* manages, retrieves and manipulates unstructured information in a variety of electronic formats. A *knowledge-driven DSS* provides specialised problem solving expertise stored as facts, rules, procedures, or similar structures. Finally a *model-driven DSS* emphasises access to- and manipulation of- a statistical, financial, optimisation, or simulation model. Model-driven DSS use data and parameters provided by DSS users to aid decision makers in analysing a situation, but are not necessarily data intensive. Yet, despite the lack of over-arching definitions and taxonomies for DSS, what can be identified at a systems-level are two general approaches. DSSs provide for social negotiation or alternatively provide for the production, mathematical analysis, and/or optimisation of design solutions.

Based on our review of the literature surrounding both DSSs and approaches to decision-making, there appears to be considerable divergence between the theoretically optimal strategies and the behaviour observed in practice. It is, therefore, generally accepted that rational decision-making in designing complex products is problematic and difficult even with sophisticated decision support tools. This is often because DSS are typically developed for specific scenarios, and when a wider range of use is considered, the broader dimensions influencing decision-making reveal potential downsides.

4 OUR RESEARCH ON DECISION MAKING PROCESSES

The authors have carried out a series of case studies investigating design decision processes in UK construction and engineering sector companies, which have examined decision-making in the context of multiple stakeholders collaborating on complex product development. Case studies were conducted using semi-structured interviews [24], where relevant topics were predefined whilst allowing interviewees to elaborate. Our interviews covered an account of various design stages, focusing on how decision-making occurred at different levels of the design organisation and between different project stakeholders. Refer to [25, 26] for further details of our case study methodology.

In two separate construction projects a total of 23 stakeholders belonging to six different groups were interviewed, including architects and design team managers, clients, end user groups, construction contractors, project managers, and consultants. The first study investigated the decision processes in the design and development of a large performing arts centre and the second of a large hospital.

The construction case studies on decision-making were complimented by existing research on (aerospace and automotive) engineering design, which examined complex product development in relation to design change [27], conceptual design processes [28], and comparisons of design practice between domains [29, 30]. Engineering design case studies consisted of experienced designers and design managers. In these existing studies, interviewees had been asked to describe specific decision-making situations but were studied under a different heading. Decision processes were therefore not the primary target of these engineering design interviews, but were dependent on aspects of decision situations such as communication, design rationale, and collaborative team processes.

4.1 Findings: Decision Making across Organisational Boundaries

The design of complex products is inherently a shared process, which requires joint problem solving and decision-making across project organisations. Construction projects typically pull architects, construction firms and multiple consultants together, who all work closely and interact with their users or clients. In the two construction projects studied, joint decision-making more typically manifested itself as distributed collaboration rather than face-to-face decision-making. For example, the architectural designers jointly worked with structural, fire, and mechanical engineers to resolve shared design problems. Initially, interaction between the architectural design firm and a particular consultant occurred via preliminary meetings to establish shared understandings, transfer data, establish exchange protocols and discuss design representations; then decision-making occurred as an iterative process to reach a solution. These interactions occurred via CAD, shared workspace tools, email and phone conversations. Group decision-making did sometimes occur as a face-to-face collaboration, but were mostly between managing designers, select consultants, and the client/user group. These group decision-making processes occurred primarily when: (i) contentious decision processes (e.g., value engineering exercises) required group negotiation and necessitated multiple stakeholder expertise; (ii) decisions were taken ahead of time (in principle) and required the approval/expertise of stakeholders due to cost, quality or time implications; or when (iii) stakeholder value propositions were affected by the decision outcome. The construction project case studies also revealed that user and/or client involvement played a significant role in decision-making. Their involvement also introduced volatility into decision situation – most often as the result of changes to preferences and requirements.

Like the construction projects studied, the engineering design projects also typically pulled design engineers, manufacturers and consultants together, and all worked closely within a single organisation. These participants may or may not have interacted with the customer during design decision processes and typically had little interaction with end user groups. As such by contrast to the construction case studies, the engineering design studies demonstrated that much of the day-to-day design decision-making occurred within each functional team or across the organisational hierarchy. Relatively little face-to-face decision-making involved outside stakeholders from the supply chain or the customer, and when it did, these interactions were typically handled by dedicated staff.

In addition, in the construction case studies, during the early design stages contractors and suppliers had lower levels of power and influence in relation to the design team, even despite their being closely integrated with decision processes or their tasks being dependent on decisions outcomes. In the engineering design companies the separability of decision-making between supplier and designers is often embedded in the system architecture. The influence of a supplier therefore was found to be dependent on the role or criticality the suppliers' component part played in overall design innovation.

In both case studies, decision processes which crossed organisational boundaries were often seen by interviewees as being problematic and when "champions" of strategic design goals were absent change and subsequent decision conflicts often arose. In the construction case studies, if people knew each other, conflicts were sometimes resolved through informal negotiation. However decision processes that crossed organisational boundaries (particularly where life cycle expertise was required), also contained higher levels of ambiguity between participants [25]. This was seen to relate to an absence of information and increased levels of uncertainty. In such instances, the short-term value propositions of some stakeholder groups often influenced decisions that carried long-term implications.

4.2 Findings: Decision Making within Organisations

In the two construction case studies it was found that groups of architectural designers working on a project jointly made design decisions within individual work packages, e.g., footings and foundations package, building structure package, etc. The detailed design of these construction packages therefore evolved in groups that were either developing on the job or already had different technical expertise. Decision-making therefore relied heavily on informal face-to-face meetings, shared workspace tools, and CAD. Design decisions and outcomes were negotiated or shared in regular weekly meetings. As is common in construction, during the early design stages the principle architect made major design decisions independently. In both studies, the conceptual design decisions were formulated as 'back-of-the-envelop' ideas by the Principal Architects before being handed over to their Directing Architects and design teams in the form of inaccurate and incomplete design representations. From this point the Directing Architects then developed and in some cases negotiated over the broader design decisions with the client and end user groups. In the design's evolution, when subsequent detailed design decision outcomes resulted in changes to the Principal Architect's earlier conceptual level design decisions important trade-offs were negotiated in joint decision processes involving all key stakeholders. During negotiations the stakeholder's ability to influence the course of action was predominantly based on their level of interest and power within the project.

While similar joint decision-making was found to occur across functional teams in the engineering design firms studied, established structures within the organisation created formal hierarchical decision and reporting pathways, which were sensitive to the quality of communication across a complex chain of people. For example, an individual engineer would alert the group leader, who passed information on to their manager, who in turn passed it on the team leader, etc. See for example Eckert et al. [31] who found similar patterns in relation to managing information flow.

4.3 Findings: Other Insights on Design Decision Making Processes

Many decisions and decision processes were interdependent as each decision needed to be understood in the context of other decisions in a series, either because they were constrained by earlier decisions, or because they may constrain later decisions. Furthermore the state of the decision problem often changed over time, either through the development of the system or as a consequence of decision-makers' actions. Design decisions that impacted upon or were influenced by through-life considerations were seen by interviewees to be even more difficult since reasoning relied on the generation of a *most likely* "forecast" for future use of- or demand for- the product.

What and how decisions were successfully negotiated or analysed depended not only on the particular problem, but also on project structures and the culture of the organisation. Eckert and Stacey [32] have studied design cultures in which passing on specifications and other asynchronous communication was found to be important but highly problematic. Typically the engineering design organisations studied had complex teams with high levels of specialised expertise and hierarchies in each field of expertise, as well as complex managerial structures with specific process management as well as business and financial management systems. In contrast, whilst the construction sector firms studied reflected similar degrees of organisational complexity, they had more opportunity to open informal lines of operation, communication and transpose hierarchy within the project platform.

To summarise, these studies found that decision processes were extremely dynamic and influenced by a raft of different dimensions, which often contributed to their being highly iterative. Some of the most important factors influencing the decision situation were the sharing of information between multiple decision-makers and the lack of recognition of stakeholder value propositions and their interdependent timescales [26]. These case study findings illustrate that decision-making is a rich and complex phenomenon due to: the nature of design problems, (including such factors as their interconnectedness, multiple objectives and constraints, imprecise goals, risk and uncertainties), and the nature of the environment, (including factors like multiple decision makers, incomplete sharing of information, technology and government regulations).

5 DIMENSIONS OF DECISION SITUATIONS

Given a design decision one should be able to define the boundary that encloses all relevant elements of the decision process. The boundaries of a decision can be thought of as the environment in which the design problem is resolved. In an attempt to develop a more complete taxonomy of the different elements affecting decision situations three core constituents are identified, including the:

- Nature of the design problem
- Elements that may be classified conveniently into two groups, namely elements arising from *endogenous* or *exogenous* project sources.
    1. Elements arising from endogenous project sources include -
        - Participant elements, being those stakeholders involved in/ affected by the design problem and decision outcomes,
        - Social elements, those factors that result from relationships between participants,
        - Technical elements, where technical factors may guide or constrain a course of action open to participants.
    2. Elements arising from exogenous project sources include economic and regulatory factors as well as natural and quasi-natural conditions.

5.1 Nature of Design Problem

One of the main challenges to understanding (and supporting) decision-making lies in the nature of design problems and problem solving. Design deals with a sequence of interconnected problems which span the different stages of designing. The characteristics of a design problem are important to the decision process in terms of the influence of the problems structure and class, associated requirements, constraints, level of uncertainty and ambiguity, risk, criticality, qualifiers and feedback.

Problem Elements

- **Structure and Class**. The structure of the design problem may range from being well-structured to ill-structured [33]. The design problem will also be defined by the class of problem and its features which range from under-constrained to over-constrained, conceptual to detailed, operational to strategic, routine to non-routine, subjective to objective, social to technical and abstract to concrete.
- **Requirements**. Information describing the desired product's objectives, its capability and performance. Specifications may also define any rules for creating the product. Requirements may not always be aligned resulting in conflict or may sometimes not be in conflict per se but rather where a plethora of requirements exist they may be difficult to manage without making the product unwieldy. The challenge here lies in determining which requirements to focus on.
- **Constraints**. There are two types of constraints. The first are those that derive directly from requirements and specifications and are therefore intrinsic. The second are constraints that are created or emerge as the result of surrounding extrinsic conditions, e.g. physical, legislative or disturbances to the design process. Instances of design process disturbances include freezing or changing products, parts, or parameters (see [34]), and therefore the design problem may be constrained as a result of previous decisions.
- **Uncertainty**. Very few decisions are made with absolute certainty because complete knowledge about all the alternatives is seldom possible. Uncertainty involves information which is unknown, and there are many different forms, [35], e.g., known unknown, unknown unknowns.
- **Risk**. Every decision involves a certain amount of risk. Risk can be assessed quantitatively or qualitatively throughout each stage of the design process. It is often analysed formally at the

outset of early design decision processes when the overall design need has been recognised, e.g., business case, feasibility study, safety analyses, etc, as well as when technical design decisions are being made, such as during structural design specification. Risk in decision-making therefore constitutes a condition where not all information is available, but where a probabilistic description is.

- **Criticality**. Different conditions define decision criticality, such as cost, quality and time. The criticality of a decision will also be dependent on the viewpoint. For example, cost-based criticality can be defined from an overall production cost perspective, when decision-making in early product development can impact largely on production cost [36]; or from a change cost perspective, when the later a change is made the more costly it becomes to carry out that change.
- **Qualifiers and Feedback**. Design decision problems and their successful/unsuccessful resolution carry with them qualifiers. Decision qualifiers are consequences, dependent conditions and criteria related to the implementation of a decision. Qualifiers vary according to the design problem and may be related to issues such as competitive advantage, cost reduction, quality improvement and schedule performance. If key decision qualifiers get dropped, the design alternative selected may be misrepresented and unrelated issues dragged in. Qualifiers also serve to provide feedback to recursive decision processes. Feedback from a decision process is crucial in understanding updated knowledge and information about the design problem and its relevance to the ongoing decision process.

5.2 Participants

Participants of a decision process are those stakeholders that can exert some influence over the outcome, either by choosing and implementing an alternative or a course of action or by otherwise interacting with other participants. The extent to which any stakeholder is a participant in a decision situation depends on their potential to exert influence on the outcome, rather than on apparent involvement in the situation at any time [37].

Participant Elements

- **Objectives**. Stakeholders in decision problems have objectives that determine in part their preference between design alternatives, courses of action and the future outcomes that can be expected from their implementation. Most organisations within complex design projects have a set of objectives. Items in the set of objectives may be to some extent in conflict with one another.
- **Value Propositions and Beliefs**. Stakeholders bring to a design problem both their organisations value proposition and their own personal beliefs. The value proposition of a stakeholder is a declaration of the way its organisation proposes to use its resources and competencies to deliver a particular combination of values to other project stakeholders [38]. Beliefs can be defined by a host of personal preferences and approaches. Stakeholders must communicate the design they want to achieve, or think should be achieved. While value propositions and patterns of belief are not always apparent or openly expressed, they nonetheless influence the views and actions of those involved in the decision situation.
- **Skills, Knowledge Base and Information Sets**. Each participant has available a set of skills, knowledge and information related to the decision situation at hand. These are made up partly of data and experience that has been accumulated over long periods of time; and in part as a direct response to other decision outcomes occurring at the time.

5.3 Social

The social elements of a decision situation consist of those factors that result from relations between stakeholders and their organisations. These factors may introduce constraints that affect the feasibility of a proposed design option or course of action or they may act to reduce the effect of other such constraints.

Social Elements

- **Standards of Behaviour**. Stakeholders are expected to act in accordance with what is widely accepted as correct industry behaviour. Standards of organisational behaviour exist explicitly and implicitly. Factors therefore surround organisational norms, standards and ethics [2, 6]. Critical aspects of decision-making from this perspective derive from the interaction of standards, organisational protocols and decision makers.

- **Relationships and Governance**. Stakeholders in design decision situations often have some form of relationship the other participants. Relationships between participants provide opportunities for communication and information exchange. Relationships may be formally expressed such as in a hierarchical pattern of authority. Alternatively, it may be of a less formal nature and based on shared values. Organisations may have formal or informal relations between them based on contractual or relational forms of governance.
- **Organisational Commitments**. If the decision process under consideration is one of a sequence or one of a number of concurrent design problems, commitments to other stakeholder organisations, or organisational participants may exist, e.g., as a result of support obtained from them on other issues.
- **Shared Value Systems**. A stakeholder's value proposition or personal beliefs may also reflect what communities, societies, cultures and governments want to achieve. Organisations and groups have value systems that in some way reflect those of their members. This is similar in many ways to Buccarelli's object world concept [12] in which he describes conceptual and procedural knowledge and the habits of professional engineering groups as being concomitant with problem solving.
- **Power**. The process of resolution of a design problem depends on the relative power of the participants to influence the choice of an outcome. If all participants have roughly the same degree of power, the outcome is often determined by prolonged processes of negotiation.

5.4 Technical

In design there are problems that require objective mathematical solutions and innovation can therefore be treated in a purely technical manner. In addition, technical elements of decision situations surround the use of systems and tools in design.

Technical Elements

- **Technical Innovation**. The opportunity for technical innovation will be determined by the problem type and perceived risks (see Section 5.1). Technical innovation is often among the most critical influences, because technical failure is a "show-stopper." It is impossible to sell a new product, or to implement a new manufacturing process, if innovations in key technical components fail. Furthermore, when social or human-centric issues are associated with technical design problems the complexity of the decision situation will increase unless there are adequate processes capable of translating these problems into technical ones.
- **Computational Tools**. How a decision situation proceeds will be to some extent dependent on the systems and tools available to the organisation. The use of mathematical models, such as optimisation models in attempts to identify one "best" answer [16] as well as those that aide distributed organisations via shared workspaces, (e.g., CAD, online communication systems, etc.), provide the means and opportunities by which stakeholders can make more informed decisions.

5.5 Exogenous Project Sources

External dimensions can include attributes ranging from industry structure and competition, to government policy, legal considerations, technology, and state of the economy.

Exogenous Project Elements

- **Business environment**. Difficulties can arise in business environments that contain long and complex supply chains, which are driven by increased outsourcing to low cost sub-tier suppliers [39]. The supply chain is as a result both broad and deep and complexities surrounding decision situations in practise can arise from these networks and the inability to resolve the 'disconnects' created by the lack of planning and alignment of operation.
- **Industry Structure and Competition** are often characterised as being either consolidated, where a relatively few number of organisations dominate a global business market; or as fragmented, where a large number of organisations operate in local markets.
- **Technology** can also be considered as an exogenous factor in a decision situation. This is because a project team or organisation may not always have the ability to 'control' technology. A variety of external conditions can constrain the use or development of software or hardware technologies. Examples of this include government regulations prohibiting the development of an existing or future hardware technology due to environmental laws, or the use of software technologies being constrained by suppliers due to a lack of skills integration.

- **Government**. Decision problems can be considered against a background of government laws, policies, guidelines, rules and precedents that act as constraints on the choice of course of action. One of the main influences of government on decision situations in complex product development is via legislation, especially through taxation and emissions laws which impact directly upon the development of new technologies.
- **Physical Factors** relate to characteristics of the physical environment, in which the decision situation exists. These factors are concerned with geography, physical resources, climate and man-made objects.
- **Economic Factors** include the limits of available economic and financial support for the decision process itself and for implementation of any selected course of action.
- **Natural and Quasi-Natural** events are an important element in a decision situation insomuch as they affect the future state of the world in which the recommended courses of action are implemented [37].

5.6 Mapping Dimensions to Decision Process Phases

In mapping the dimensions of influence identified in the previous sections to each phase of decision-making it is possible develop a unified framework that enables a boundary to be drawn around those factors influencing the decision situation as the process evolves and thereby identify those elements handled or ignored by a DSS. As illustrated in Figure 1, the decision process itself is composed of three stages: (1) identification (problem recognition and diagnosis), (2) perspective development and synthesis (search, judgement and analysis), (3) implementation (actions, authorisation and results). The three dimensions classifying the various elements of decision situations are assigned to each phase, where the nature of the design problem is divided between *input* and *output* dimensions of phases (1) and (3) and endogenous and exogenous dimensions are themselves assigned to phase (2).

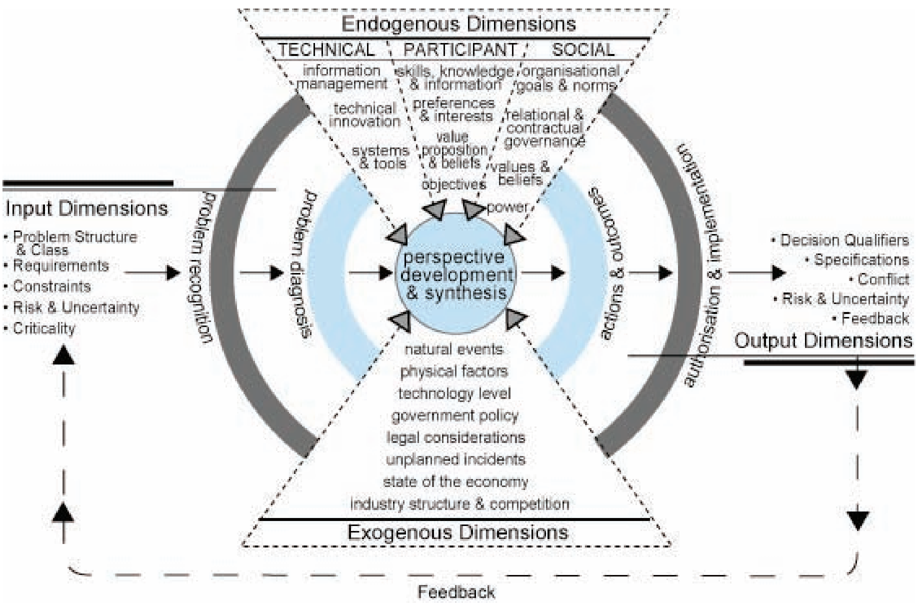

Figure 1. Structuring dimensions of influence throughout recursive DM processes

The boundaries of a recursive decision process may continuously change rather than remaining static. The dynamic and turbulent nature of the boundary has the effect of increasing the uncertainty experienced by the participants with regard to the exact nature of the dimensions and factors surrounding their situation; and also with respect to the possible actions of other stakeholders participating in that decision process.

The key to understanding the different elements and their impact on decision processes to a large extent will depend on the degree of influence that an element has on mitigating risks or exploiting opportunities arising from the design problem. Uncertainty may decrease when progressing from the first to final stage of the decision process (see Figure 1), however the ability to control dimensions outside the project or organisational context will always remain relatively low. For example, stakeholders in a particular design decision situation may have more or less full control in choosing the firm's technical architecture, selecting its suppliers and adapting its operational strategy, but it may only ever have limited impact on future regulations (e.g. through lobbying efforts) and no influence on the occurrence of natural disasters. This does not mean that nothing can be done about the consequences of exogenous elements (e.g. the procurement of flood insurance, redundancies in a global supply chain [40]) but their occurrence in the first place cannot generally be controlled or managed.

6 IMPLICATIONS FOR DSS

No single approach to supporting decision-making is sufficient to handle the richness and variety of possible decision situations and process behaviours. Hence we should be suspicious of any assumptions that tools for technical analysis and optimisation or for information management, communication, or real-time interaction are going to meet all the different dimensions of recursive and dynamic decision processes. However we can draw some lessons from our studies of design decision-making in light of two systems-level approaches to DSS, i.e., *enterprise-wide* DSS and *desktop* DSS [23]. Enterprise-wide DSS are linked to large data warehouses and may serve many decision participants in a project. Desktop, single-user DSS are systems that reside on an individual's PC. Each level is helpful in giving support to designers and other project stakeholders, yet the danger is that when utilised independently they may not adequately address situations where there are common dimensions influencing and impacting upon the decision situation.

As many design decisions refer to a variety of different visual media, shared workspace systems are vital for distributed decision-making. Such systems should support different forms of visual media as well as the use of formal documents and CAD models. Many decision processes also rely on contextual information, especially about previous decisions, involving, e.g., prior design options, past design products, competitor products, etc., and therefore depend on stakeholders, as decision participants, being familiar with this context. Support for rapid retrieval and display of archive information could make enterprise-wide DSS much more effective. Here support for decision-making overlaps with long-term information management [31].

However the range of decision situations that participants interact in indicates that there is scope in DSS for joint decision-making that goes beyond efficient document retrieval or video conferencing technologies available in current enterprise-wide DSSs, e.g., for supporting formal meetings, or record management and transmission. Important issues include translation between alternative notations and graphic representations, enabling less-informed stakeholders to establish the context of the discussion, supporting awareness of other participants in remote interactions, and maintaining security [31]. Speedy, low-effort interactions are as important as formal organised meetings and information management. DSSs generally neglect this area. Hence it is essential for cooperative and enterprise-wide forms of DSS to facilitate easy and efficient initiation of unscheduled and informal interactions; especially if interconnect decision processes and their rationale are to be integrated with formal information management tools, (see e.g., Design Rationale editor (DRed) [41]). Taking the example of rationale capture further, rationales held on desktop single-user DSS can affect wider decision processes, and when an ongoing decision process relies on rationale generated by an individual or team it may not be possible to utilise it at the project or enterprise-level if the DSS does not have access to it.

Approaches to *intelligent decision support system* (IDSS) are aimed at managing multiple dimensions of influence factors by integrating separate decision support tools (primarily handling technical and social elements). IDSS are interactive computer-based support systems that use data, expert knowledge, and models for aiding decision makers in semi-structured problems incorporating problem-solving techniques of artificial intelligence (AI). IDSS can be characterised as decision process management and planning systems [42], which:

- Support problem formulation – allowing the decision participants to formulate the originally ill-defined problem on an incremental and evolutionary basis,
- Accept diverse types of knowledge which decision participants can readily provide and attempt to use it to the maximum extent possible,
- Are human centric focused – where the decision participants dominate the decision-making process, unlike an autonomous expert system or an independent optimising tool.

Consequently IDSS depend on training stakeholders in decision processes so as to identify the boundary of the decision situation. It is the provision of training that must also be stressed as being one of the main implications of the multiple dimensions of decision processes for DSS in design.

CONCLUSIONS

This paper has described decision-making as complex and rich process. A critical factor that researchers and theorists in decision-making sometimes neglect to emphasise is that in spite of the utility of a specific DSS, decision-making is a nonlinear, recursive process, influenced by a complex range of factors. That is, most decisions are made by moving back and forth between the choice of criteria (characteristics the decision participants want selection to meet), the identification of alternatives (possibilities to choose from among), whilst managing the various factors of influence. Those factors that are considered affect the criteria the decision maker applies to the problem and the alternatives developed and selected. In short, there's more to decision-making than is behind many DSSs in design. Given a design decision problem and the available systems to support its resolution, one should be able to define the boundary that encloses the fewest permissible number of influencing factors and manage them in relation to the scope of the DSS. From this point of view, the taxonomy and unified framework presented in this paper can support decision process management and planning in two ways. That is, the approach allows stakeholders to not only determine whether the element may be present in the decision situation, but also provokes its consideration in relation to the phases of decision-making – revealing whether the boundaries of the decision will be improperly represented and potentially result in a sub-optimal solution if the element is overlooked or omitted.

ACKNOWLEDGEMENTS

This work is sponsored by the EPSRC and ESRC as part of the Immortal Information and Through Life Knowledge Management (KIM) Project.

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