A Network Theoretic Perspective of Decision Processes in Complex Construction Projects*

Julie Jupp

Abstract: This paper proposes an approach to modelling and visualising decision processes in large complex construction projects by incorporating a network perspective. Computer modelling and visualisation of decision processes as social and task-entity networks makes possible the identification of key participants, critical tasks, latent networks, vulnerabilities and dynamics that impact upon complex decision situations. New advances in network theory can help reveal the ways in which social, organisational, political and technological relationships shape decision outcomes. By conceiving decision processes as a complex system and modelling this system using network-theoretic principles, it is possible to include a tremendous amount of information that has remained untapped by conventional qualitative, game-theoretic, and statistical approaches. This research contributes to the understanding of the strategic implications of decision processes as complex systems of interacting actors and problem tasks, and provides the technological means for supporting them. The approach has been verified through the development of an experimental network-theoretic system.

Keywords: decision processes, complex projects, network theory.

1. INTRODUCTION

Computational modelling and visualisation of decision processes holds the promise of uncovering the key participants, critical tasks, latent networks, vulnerabilities and dynamics that impact upon complex decision situations, such as those found across the design and delivery stages of large building and infrastructure projects. What is intriguing about decision processes in such circumstances is their multi-network character, defined by both the objects of decision making i.e., the problem task itself that undergoes transformation, and the subjects of decision making i.e., the actor/s exerting influence. The multi-network nature of decision-making in complex projects accounts for the latent networks that are created or implied through uncertainties and complex interactions inherent in design and construction management situations; as e.g., wherein decision makers simply do not know who or what is affected and when by a decision outcome, those decisions that are taken 'in principle' so as to avoid disruption to work-flow, and those that are influenced to a large degree by varying stakeholder power and participation levels.

New advances in network theory promise to uncover the ways in which social, organisational, political and technological relationships shape decision outcomes. By conceiving decision processes as a complex system and modelling this system using network-theoretic principles, it is possible to include a tremendous amount of information that has remained untapped by conventional qualitative, game-theoretic, and statistical approaches. Therefore, the overall aim of this research is to model complex decision processes using a "multi-network" perspective in order to understand the dynamics of decision situations and develop methods for their performance measurement and evaluation. Under this aim sit four research questions:

(1) How can multi-network formalisms be used to examine the mechanisms that influence decision processes in construction?

(2) How do connections between- and aggregations of- different project stakeholders and problem tasks influence each other?

(3) How do implied "multi-networks" operate on top of explicit (social or task-entity) networks and what are their effects, e.g., influences on network structure, behaviour, patterns, etc?

Via the investigation of these questions, this research seeks to contribute to the understanding of the strategic implications of decision processes as complex systems of interacting actors and problem tasks, and provide the technological means for supporting them. Thus our objective is to allow participants of decision processes to exploit shared awareness and collaborative planning to communicate and understand decision intent and interdependencies so as to enable enhanced decision management. The logic of the approach is highlighted in Figure 1.

Achieving this support presents a large modelling challenge and progress to date is presented here. The outcomes of the experimental study of a multi-network system that adequately characterises complex decision processes via participating actors and tasks demonstrates how existing information technologies can be mobilised so as to facilitate the dynamic extraction, visualisation and analysis of key participants, hidden networks, vulnerabilities and changes in decision processes at varying levels of fidelity. The work presented in the remaining sections therefore illustrates and discusses the enhancing and enabling indicated in Figure 1 by exploring the first of our four research questions.

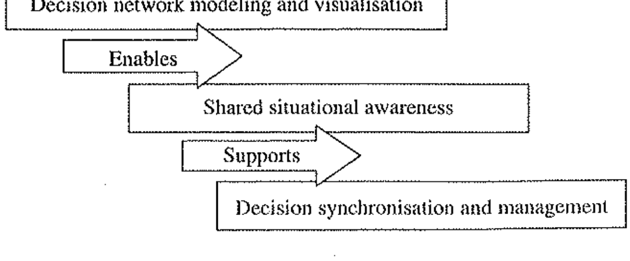

Figure 1: Multi-network approach to decision modeling

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2. NATURE OF DECISION MAKING IN COMPLEX CONSTRUCTION PROJECTS

Decision making across the design and delivery stages of any construction project is an omnipresent activity. Project stakeholders such as architects, engineers, project managers, manufacturers, contractors, clients, and end users make decisions continuously throughout each stage of the project. While some decisions seem simple or trivial, others can have far-reaching consequences. Some decisions are of the one-shot type, while others involve a sequence of actions constrained by previous decisions or influenced by feedback of results (Sarma 1994).

Further, many decisions in construction projects are influenced by the coalition of stakeholder groups in unanticipated ways. Selection amongst alternatives may be made under high levels of uncertainty, amid competing decision makers, or involve a complex of interconnected components where decision outcomes may result in unforeseen knock-on effects. The variety of project stakeholders required to collaborate in complex construction projects (as for example nuclear power stations, and high-tech medical facilities) can be seen to stem from product complexity. Stakeholder groups will therefore come in different sizes and forms involving e.g. a variety of design and delivery teams, consultant groups, end user committees, and a host of strategic partnerships throughout the supply chain. Groups of project stakeholders are connected through membership of the same, associated, or aggregated decision problems and sub-problems. These connections span not only between individuals within the same organisation, or functional business unit, but also across organisational boundaries. Furthermore, coalitions of stakeholders in most large construction projects are temporary. Thus relationships in construction are seldom stable and often only last for the project's duration.

2.1 Knowledge Gap

Whilst the problematic social characteristics of the construction sector are well documented (see for an overview Green *et al.* 2004), the effect of differing levels of stakeholder participation, power, and value proposition, combined with their impact on dynamic and interconnected problem tasks is still relatively unknown. Hierarchical levels of decision problems and the interdependencies between problem tasks means that a design change that has a knock-on effect may be obscured by the complexity of the product, by the lengthy design and development stages, or by the complex of social actors working in isolation. Further, the hierarchical levels and interdependencies of decision tasks related to the overall design problem, or even sub-problems, may be ignored or overlooked due to complex technical relationships which were not obvious to decision makers. Crucially, the solution of one problem may be inter-related with another task but at a different level of abstraction. That is, e.g, the outcome of a decision at the *strategic level* (e.g, broader planning based decisions) may have knock-on effects at the *systems level* or at the *component level* – and vice versa. Thus, any one specific decision outcome may have knock-on effects on tasks at either of the other levels and may be furthermore bi-directional.

Seen from this perspective, decisions can depend upon information generated from previous decisions, e.g., made when solving a different problem tasks and/or by different actors. Such 'interconnectedness' can be further complicated when decisions are made "in principle", which is often the case when time constraints dictate the need to maintain work-flow. In such cases, work is continued whilst approval is sought from e.g., a client, regulatory or advisory group.

Current decision-theoretic characterisations of decision processes are therefore incomplete (Shaffer 2008) as they fail to adequately account for knowledge concerning the causal connections between acts, states, and outcomes so as to account more fully for both the objects and subjects of decision situations. Consequently, the support of collaborative decision processes via computational tools is inadequate since a tool must meet the needs of the *situation* it is used in. Development of decision support systems is often focused exclusively on one type of problem and ignores many factors that can affect continuous, dynamic decision processes, their behaviour, the different actors that influence their resolution, and crucially their implementation. Consequently, such reductionist approaches neglect many of the interconnections between objects and subjects that make up a decision situation.

It is therefore desirable to examine simultaneously both the interconnections of actors and problem tasks quantitatively (which may change throughout project stages as relationships are defined, developed and redefined), to determine whether any additional structures might relate to and influence collaborative decision-making efforts. However, there is no consensus explanation of how different actors, groups of actors and problem task structures influence decision-making, how they are initially determined, how the decision process itself is affected and how decision alternatives are modified from one decision situation to another.

2.2 Related Work

In addressing these issues, this research draws on network theory, which provides powerful tools for representing and analysing complex systems of connected actors and tasks. The quantitative study of real-world networks has a long history in the social sciences (Newman 2003, Watts 2004) and among the topics studied are evolving social groups (Kossinets and Watts 2006), collaborations (Guimera et al. 2005), community detection (Danon et al. 2005), hierarchical organisation (Ravasz et al. 2002, Sales-Pardo et al. 2007) and communication (Monge and Contractor 2003). These studies have generated important insights into the effects of network topology on individual behaviour, including community formation, and hierarchical and modular organisation. However, such investigations in the application domain of construction are nascent and modelling the modular, hierarchical and community structures of both actor (social) and problem (task-entity) networks can further understanding of decision processes in this important domain.

Over the past few years, a number of researchers investigating complex construction projects have led a nascent effort to develop the understanding of the interconnections of decision processes of complex engineering design projects (Jupp et al. 2009). This work primarily builds on the author's previous interdisciplinary research with UK companies conducted from 2006-2009 under the EPSRC-funded Knowledge and Information Management (KIM) Grand Challenge project and more recent research with Australian companies conducted in 2010. Completed case studies on complex projects have captured detailed information on decision-making across collaborating stakeholder organisations, and found that individual actor preference and value assignments, as well as associated value timescales, yield multiple families of social and task-entity networks (multi-networks). Further, related macro analyses based on a variety of factors that are endogenous and exogenous to the project and which influence each stage of the decision process has also been undertaken (Jupp et al. 2007).

This previous research has therefore considered decision structures composed of ties based on stakeholder value assignments and value timescales (Jupp et al. 2009). What this work shows is that network methods would be particularly effective at uncovering structures among stakeholder group memberships and inter-related problems tasks. Utilisation of such case study data in a network theoretic approach would enable a more in-depth analysis to be undertaken.

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3. RESEARCH FRAMEWORK

The difficulty in understanding decision processes of complex construction projects surrounds the interconnectedness of the key actors, hidden groups and technological component interdependencies. To enhance current understanding of these aspects this research has developed a three stage approach. The first stage commences with in depth analyses of case study observations. The second stage consists of the reconstruction of observations using formal modelling techniques derived from network theory, which includes network visualisation and formulation of hypotheses. The final stage relies on building a visualisation framework where the key characteristics identified in the previous stages will become variables and parameters of behaviour for the computational visualisation of dynamic social and task-entity networks.

Stage 1: In-depth analyses of architectural, engineering and construction (AEC) design decision processes have utilised in-situ case study methods, as well as semi-structured interviews and focus group workshops (Yin 2009). The main objective being to utilise case study data derived from large complex building and infrastructure projects so as to reconstruct and describe social group memberships (committees, teams, interest groups, etc.) and task entities (hierarchical breakdowns as decision chains generated as a result of problem decomposition).

Stage 2: Based on the data analysed in Stage 1, this research utilises a 'complete network analysis' approach (Wasserman and Faust 1994, Hanneman 2001). Complete network analysis attempts to capture all the relationships among a set of agents. Through complete network analyses, this research explores both the social structures, i.e. "patterns of connectivity and cleavage within social systems" (Wellman 1988) as well as problem task structures derived from the architecture of the object, i.e., patterns of connectivity and cleavage within technological systems, which may be defined by e.g, physical, mechanical, or electrical connections between components. Most of the terms used in network analysis are based on complete networks and well-known network techniques like cluster analysis and measures like density. Key terms used in later sections of the paper are provided in Table 1 and concepts central to our discussion of network analysis in Section 4 are presented in Table 2 and Figure 2 and Figure 3 (Wasserman and Faust 1994, Nugroho and Ozcan 2009).

In social network analysis, researchers have explored emergent structures by comparing them with other structural maps of the same actors to determine the degree of overlap between

Table 1: Key Terms in Network Analysis

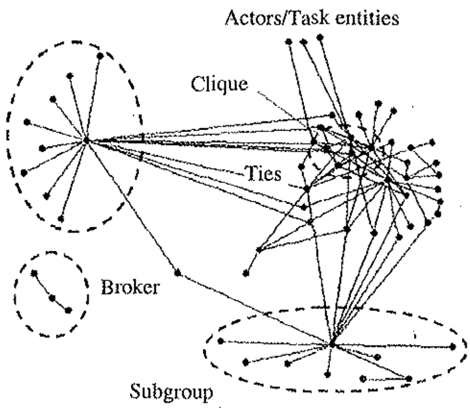
Term	Definition
Betweenness	The extent to which a node lies between other nodes in the network. Nodes bridging clusters have higher value
Centrality	Indication of social power / criticality of a node based on how well it "connects" the network through the measure of betweenness and closeness
Centralisation	A centralised network is like a star, having many of links dispersed around one or a few nodes
Closeness	The degree a node is near all other nodes in a network (directly or indirectly)
Cohesion	The degree to which nodes are connected directly to each other by cohesive bonds
Structural cohesion	The minimum number of nodes, which if removed from a group, disconnect the group
Network density	Number of ties among nodes in the network expressed as a % of all possible ties. If every node is tied directly with every other node the density is 100 percent (sparse versus dense networks)

Source: Wasserman and Faust (1994); Moody and White (2003)

Table 2: Key Concepts in Multi-Network Analysis for Complex Decision Processes.

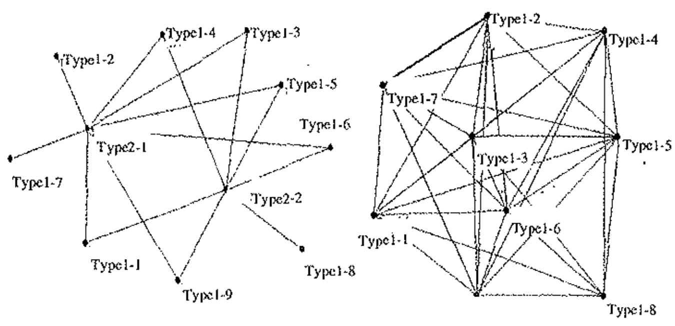
Concept	Description
Actor	Social entities are referred to as actors, i.e., discrete project, organisation or collective social units. Actor is depicted as a 'node' or 'vertex' in network
Task entities	Problem tasks defined by product architecture. Entities may be components or task activities.
Relational tie	In the case of a social network, what establishes a linkage between a pair of actors; and in the case of a task-entity network, what establishes a linkage between a pair of task entities and may specify the criticality of the interconnections
Group	The collection of all actors or task entities on which ties are to be measured. A group consists of a finite set of actors or task entities. Groups are defined as:'cliques' if every node is directly tied to every other node'social circles' or 'task circles' if there is less stringency of direct contact, which is imprecise or as structurally cohesive block if precision is wanted
Subgroup	A subgroup (of actors or task entities)
Relation	The collection of ties of a specific kind among members of an actor or task entity group
Broker	Individual actors or task entities that connect two otherwise disconnected cliques or by bridging from one group to which it belongs to another that may join them
Social network	Social network consists of a finite set of actors and the relation or relations defined among them
Task-entity network	Task network consists of a finite set of task entities and relation or relations defined among them

Source: Wasserman and Faust (1994); Nugroho and Ozcan (2009)



(a) ne-mode network (b) wo-mode network

Figure 2: Multi-Network Map (links between actor and task nodes)



(a) One-mode (b) Two-mode

Figure 3: Network modes, showing task-entity networks

"observed" structure and "theoretical" structure (Kilduff and Tsai 2003). Research related to task entity networks and product architectures is however by comparison a nascent area of research in construction. Researchers in engineering design have developed these networks in relation to Change Prediction Methods (CPM) - developing tools for identifying relationships among entities, which may be based on physical components or tasks, so as to determine criticality of interconnections (Eckert et al. 2006). Such methods can be used to create task- and component based networks and record information about component connectivity, change impact types, likelihoods, and display change prediction result.

By uniting these approaches in a multi-network approach, we are able to define network nodes by actors and problem tasks and network ties as attributes defining the relationship between them. Studying social and task entity structures simultaneously helps to reveal two important features of decision processes: (1) how actors cluster or group in social space, and (2) how tasks are grouped in the problem space. Consequently, attention of analysis during this stage of the framework includes examination of "community", hierarchical structures of networks and hidden or latent networks.

Stage 3: Modelling and visualisation enables the conversion of the descriptive models generated in the previous stages into formal models to describe the dynamic nature of decision processes. The strength of network analysis is that it can analyse both the whole system of relations and parts of the system at the same time. Researchers are therefore able to "trace lateral and vertical flows of information, identity sources and targets and detect structural constraints operating on flows of resources" (Wellman 1988). The ability to capture the structure of the whole, or parts, of interacting systems makes the two-mode approach to network analysis particularly interesting for research on complex decision making processes. It is this particular ability that we feel is important in making the combination of decision processes and a network-theoretic perspective so attractive.

By utilising and customising advanced visualisation techniques for decision networks the intention is to enhance understanding of these structures and behaviours and how they change over time so as to study their dynamics and extract general principles. Dynamic visualisation is considered appropriate because the target system is complex and there are important nonlinearities between variables that can be identified via visualisation methods that enable the dynamic patterns of networks to be mapped. This will enable the extraction of principles and patterns of decision processes by simultaneously observing and manipulating variables in both social and task entity networks.

4. PRELIMINARY RESEARCH FINDINGS

Whilst our incorporation of a network perspective into the study of decision processes is still in its early stages, the remainder of the paper presents some preliminary findings which have revealed some valuable insights so far.

4.1 Case studies and initial discoveries

The first stage of this research has conducted analyses of the case study data that describes hundreds of decision situations and processes which occurred during the design and delivery stages of complex construction projects. Data was captured with the primary focus on describing decision processes as they occur in practice; it includes the type of design decision problems, identified tasks, decision protocols, decision support tools and detailed variables surrounding those actors involved in collaborative decision-making situations (e.g., their goals, preferences and unique value propositions) that are routinely seen in complex construction projects.

Although project stakeholders do not broadcast lists of their values and attributes by which they individually or their organisations measure the project's success, their decision preferences and choices provide a paper trail so as to identify relationships. This first stage has therefore examined these connections by analysing hundreds of collaborative and independent design decisions made during project implementation. Based on preliminary analyses of four detailed cases for completeness of available data and unique decision-making contexts, two case study projects were identified as containing sufficient and detailed data to support in-depth analysis; they included two UK projects:

- **Case 1**: The Curve, Performing Arts Theatre. This study tracked the decision making processes across the main design and construction stages of this state-of-the-art centre.
- **Case 2**: The Royal London and St. Bartholomew's Hospital. The case study documents the late detailed design, construction documentation and construction stages of Britain's largest hospital.

Data captured across both case studies provided the adequate level of detail in their descriptions of the actors and task entities surrounding numerous decision situations across four of the main stages of the RIBA Plan of Work (RIBA 2007), including schematic design, detailed design, construction documentation and construction. Each data set was 'cleaned', 'coded' and mapped into matrices to present information relating to stakeholders and their organisations (with detailed data on the 10-12 most active firms), contractual and governance based relationships, project mission, identified problem tasks, their interdependencies, suggested solutions, decision opponents and proponents and the unique value propositions of decision participants. The case studies were also mapped in terms of how tasks related to strategic, system, and component levels of decision making. Interconnections between actors and actor organisations were then mapped in further detail in relation to their participation in identified decision processes. This data was derived from their involvement in both face-to-face decision situations, as well as captured through a variety of electronic forms of communication (e.g., emails, faxes, etc).

Social and task based relations were then reviewed based on documentation covering specifications of roles and responsibilities, contractual arrangements, and the information exchange protocols. For example The Royal London and St. Bartholomew's provided a rich data source in relation to the documentation covering this complex Private Finance Initiative contractual form and the information exchange protocols established to support Building Information Modelling. Detailed information relating to politically oriented or audit committees surrounding these projects also provided a rich source of information to review our initial social and task network maps.

Mapping of the object and subject characteristics across multiple decision processes has therefore resulted in re-constructed decision process matrices for each of the stages studied. Changes in social group memberships that occurred both within and across each project stage have been tracked and mapped. However smaller changes in stakeholder group memberships that occurred within a project stage have been ignored as they have been captured as they alter across stages. Taking 'The Curve', Performing Arts Theatre case study as an example of our findings thus far, the descriptive mappings of actor and task-entity connections into the matrix includes approximately 84 individual actors (including stakeholder replacements), 21 stakeholder organisations, comprising of three different coordinating and audit committees, more than 40 different functional business units, with an average of seven actor memberships per decision situation. For the descriptions of task-entity interrelations, on average approximately 960 problem tasks (including sub-problems and sub-sub-problems) across strategic, systems and component level interconnections have been mapped.

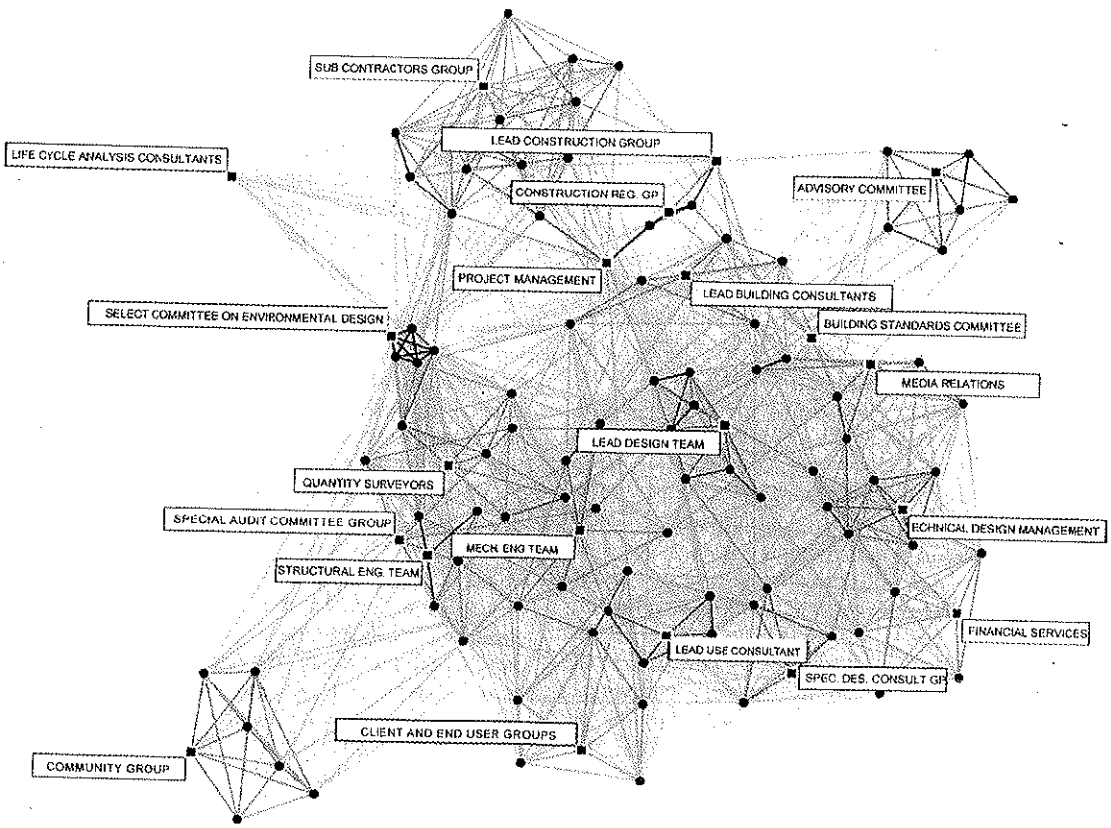
These preliminary findings have produced a matrix based mapping of actors, actor groups, task entities and chains of task entities. From this map it is predicted that the top five to seven groups or clusters of actors will reflect the dominant levels of stakeholder power and participation (a traditional project management measure of decision influence). These social groups may be consistently successful in influencing decision situations and will be among one of the many hypotheses tested in future stages of this research.

4.2 Experimental network visualisation

Some basic modelling and visualisation of the social and task-entity matrices described in the previous section have been undertaken. This stage has utilised and customised tools from network analysis to visualise group memberships, problem decomposition, and the alignments and realignments of preferences and values, which affect decision process behaviour. As an experimental study, the complex interactions that underlie the myriad of decisions processes that can be defined across project stages, this research has so far drawn on single and multi-network approaches to better understand the role of actor groups, task interdependencies, and their structures throughout dynamic decision situations. However, what this experimental modelling stage has revealed via the exploitation of the fact that nodes are typically embedded in the two types of networks (with multiple ties of differing strengths, either between individual actors, clusters of actors, problem tasks or chains of tasks), is that within the unique structures of networks, the relational attributes of actors and tasks are interdependent and subject to change across project stages.

However it should also be noted that while rich in their data content, two-mode networks are difficult to visualise and interpret. This experimental visualization method has therefore utilised a common strategy to manage such cases of visualisation in a one-mode "projection" of the network onto either the individual actor and actor groups, or the tasks and sets of task entities. Taking the collective of stakeholder organizations within 'The Curve' case study as an example, the projection of the groups were modelled, in which nodes show groups of actors, i.e., organisations, and ties represent common membership or "interlocks" (Mizruchi 1996) - both between organisational groups and between task entities. Figure 4 shows this experimental visualisation using an adaptation of the Visone network modelling software (Baur 2008).

The experimental network visualisation in Figure 4 illustrates that the more common members of two types of actor groups have, the stronger their connection is in the network. The strength of the connection can be quantified by the 'normalised interlock' (Porter et al. 2007, Robins and Alexander 2004). Using this experimental network and developing the analysis method makes possible the utilisation of this weighting in the visualisation of a network by darkening the links between nodes accordingly. Via the application of this mode of analysis to our networks as they are developed, it is anticipated that whilst some of the connections that can be identified may be unsurprising, other connections between stakeholder groups will be much less obvious. Further, thus far the multi-network approach has enabled these early stages of research to simultaneously consider multiple ties between different actors and task entities, and in future research will enable us to take advantage of the enormous amount of information that has consequently become available.



SQUARES indicate the network of social groups, while individual actors (stakeholders) are shown as CIRCLES. Each link between two groups or individuals is assigned a strength (indicated by the link's darkness) equal to the normalised interlock (where the "interlock" between two groups is equal to the number of their common members)

Figure 4: Network visualisation: one-mode projection of a two-mode network.

5. DISCUSSION

By way of the research framework and preliminary application and findings of the multi-network approach to modelling decision processes, this paper has shown that the challenge of supporting complex decision situations is a significant problem for the construction industry. With the tremendous impact that complex development projects have on the economy, it is crucial that we better understand how social and task entity networks influence project success. Decision-making across lengthy design and delivery efforts involves multiple organisations and occurs in what are essentially temporary project-form organisations, where no single corporate structure or strategy dominates throughout all stages of the development process. An understanding of decision processes, much as network theory has already yielded a better understanding of other corporate practices, will result in their effective ICT-based support, facilitated by increased understanding of their dynamics, hidden networks, hierarchical structures, key actors, vulnerabilities and changes.

This research takes the important step of explicitly considering the interconnection, dynamics and potentially the co-evolution of social and task entity networks simultaneously. Despite advances made in the study of real-world networks in other domains, there are few results on the dynamics of networks in the context of actors collaborating on inter-related tasks and their bi-directional influences, which are exemplified in complex construction projects. With the longitudinal data obtained from previous case studies of complex construction projects, this research is well placed to provide important insights on the dynamical evolution of the microscopic (individual actor and tasks), and macroscopic (collective behaviours of actors and tasks), structures in these networks. The approach presented here therefore addresses a gap in research which has important strategic implications for the development of knowledge in academia and effectiveness of design and management practices in construction.

The multi-networks approach is a conceptual innovation that adds a level of sophistication to the modelling of actor and task structures and behaviours. It is well known that personal relationships greatly affect group decisions and outcomes, but these relationships are difficult to observe and quantify in large groups such as those which occur in complex engineering design projects whose development phase may span several years. Further, due to the complexity of the product, intricate groups of inter-related decision problems and sub-problems are generated. It is common practice in network studies to look at one type of connection at a time and then to make simple comparisons between the separate networks. The modelling approach will allow a direct comparison between different social and task networks that arise from complex architectural and engineering design problems.

It is also anticipated that visualisation will shed light on the effects of "in principle" decision-making – a particular decision process phenomenon, common within complex design projects, wherein decisions are taken ahead of time prior to approval by all relevant decision-makers. Where this occurs, resulting information interdependencies increase levels of uncertainty and risk in subsequent and inter-related decision processes. It is predicted that these deviations and events may also indicate that individual stakeholders and their organisations are not the most significant communities influencing decisions across the project platform, but rather the co-evolution of different decision processes can set a "train" of actions, states and outcomes in motion.

The paper has introduced a methodological innovation in modelling decision processes by exploiting a network perspective and the fact that nodes are typically embedded in multiple types of networks. The insight presented is that not only are the problems, sub-problems and solutions inter-related but that the structure of social networks and the behaviour of the actors embedded within them are often interdependent. By investigating these different networks simultaneously, this approach is able to analyse the inter-relations of organisational and political "communities" to obtain an understanding of decision processes dynamics via identification of microscopic and macroscopic structures. Connections between actors and between tasks in each network can thus be represented by many different quantities that each yield estimates for the strength of the tie between them.

6. FUTURE WORK: VISUALISATION TECHNIQUES

Future stages of research target more advanced network analyses and visualisation to provide a deeper understanding of decision networks. Further analysis involves incorporating measures associated with two-mode connections, such as Horton-Strahler numbers (Horter 1945, Strahler 1952) and modularity (Newman 2004a) (Newman 2006). The modularity of each network map can be measured so as to identify its compartmentalisation. Calculating modularity within the networks is needed to investigate e.g., hierarchies in actor relations via the allocation of weights to network ties. Modularity measures the difference between the total fraction of ties that fall within - rather than between - groups and the fraction one would expect if ties were placed at random. The projected one-mode networks to be constructed will be weighted and calculations will employ the weighted generalisation of modularity described in Newman (2006), in which e.g., instead of counting numbers of ties falling between particular groups, the sums of the weights of those ties are counted, so that heavily weighted ties contribute more than lightly weighted ones. A longitudinal analysis of the modularity of actor and task entity networks constructed across projects stages can then be conducted. By comparing design and delivery stages analysis may reveal patterns within networks that deviate (in some cases drastically) from the same prior actor groups and/or task sets. Such techniques will enable identification of close relationships, nonlinearities and latent networks.

More advance network visualisation techniques will also be targeted, including visualisation of dynamic network structures and behaviours. This is considered appropriate because the target system is complex, there are important nonlinearities between variables, and this research is interested is in understanding the dynamics of the system. Visualisation is also of particular relevance as a tool to discern patterns of behaviour. The main concepts targeted in network visualisations relate to the effects of one and two-mode expansion and contraction within the network. Advanced network visualisations will aim to derive insights from dynamic network models and explore network dynamics by testing behaviour. Since the properties of actors and tasks change over time, network nodes adapt and change propagates from one node to the next. The objective of dynamic network analysis is to study elements of both the social and task-entity networks' evolution, altering variables under which change is likely to occur. A visualisation framework will be developed by specific calculations of characteristics described on network nodes and ties including clustering coefficient, average path length, shortest longest path, preferential attachment, etc. Exploring these aspects is important because they will provide greater understanding of critical variables such as time, and time-varying changes, group and network size, connectedness, density and degree, as well as provide information regarding actor and task embeddedness.

7. CONCLUSIONS

As participants of infrastructure projects worldwide, AEC companies face an unusual challenge in managing decision processes owing to the geographic and temporal dispersion of project stakeholders. This research addresses 'smart information use' through decision network modelling and visualisation. For participants of many and varied decision situations, making use of the visual analyses of a network of project stakeholders and understanding decisions and their outcomes in relation to the project at large so as to 'work smarter', continues to pose a daunting challenge. An increasing trend towards distributed virtual teams linked through computer-mediated communication tools means that project stakeholders face an even greater challenge in managing decision processes effectively.

Conceiving of decision processes as a complex system, and modelling this system using network-theoretic principles, so as to construct network maps 'on-the-fly', has powerful implications for supporting decision situations and managing large construction projects. Network modelling and visualisation aims to uncover a tremendous amount of information surrounding decision situations that has remained untapped by conventional qualitative, game-theoretic, and statistical approaches. Through computational modelling and visualisation of actors and tasks, this research enables analyses of the inter-relations of decision-making communities to obtain a better understanding of the dynamics of decision processes. It is intended that this research can be applied to important decision support problems facing AEC companies in and beyond complex construction. By establishing analysis and evaluation methods to assess the dynamics and nonlinearities of decision processes, progress can be made towards enabling and sustaining competitive projects which form the cornerstone of our knowledge industries.

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