USING COMPLEX NETWORK ANALYSIS AND VISUALISATION TO ANALYSE PROBLEMATIC ENTERPRISE SCALE INFORMATION SYSTEMS?

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ABSTRACT

Society is demanding larger and more complex information systems to support increasingly complex and critical organisational work. During or after the deployment of these systems it is typical for problematic socio-technical issues to arise. Whilst troubleshooting socio-technical issues in small-to-medium scale situations may be achievable using approaches such as rapid ethnography combined with a theoretical framework such as distributed cognition or activity theory; troubleshooting enterprise scale situations is an open research question because of the overwhelming number of socio-technical elements and interactions involved.

Techniques and tools for complex network analysis enable the analysis of systems comprising large numbers of nodes. These tools are becoming increasingly accessible to non-computer scientists and mathematicians and so have been used to analyse a diverse variety of large-scale systems from social networks through to metabolic pathways in living organisms. We believe there is scope to use similar techniques to facilitate the analysis of problematic enterprise scale socio-technical systems.

This paper demonstrates, via means of a case study, proof-of-concept tools for large-scale network analysis and visualisation that may provide a promising avenue for identifying problematic elements and interactions amongst an overwhelming number of socio-technical elements. We demonstrate the potential of this approach by showing that: i) a problematic situation may be represented as a directed graph such that the elements in the situation are represented as nodes, and interactions between nodes as edges; ii) that *eigenvector centrality* may be used to rank the importance of elements in a situation and that highly ranked elements match those identified as important by a human analyst; iii) the 'complexity' of a situation, or a part of a situation, may be characterised using a *feedback degree* score which provides an indication of the extent elements are highly interconnected and involved in feedback loops. These findings indicate that computers may be used to aid the analysis of problematic large-scale complex socio-technical situations by highlighting elements, or groups of interacting elements, that are important to the overall outcome of a problematic situation.

Keywords: Sociotechnical Systems Engineering; Complex Network Analysis; Troubleshooting Information System Deployments

1. INTRODUCTION

Systems science has long since been applied to the study and troubleshooting of socio-technical systems. The conceptual reframing of work organizations in terms of socio-technical systems came with the publication of Eric Trist's (1950) "The Relations of Social and Technical Systems in Coal-Mining" (Trist 1981). This research arose due to 'human relations' problems arising from technocratic technology led work transformation approaches practiced during the era. Between 1950–1970 studies and action research evolved a set of socio-technical design principles to maximise productivity by optimising the organisation of workers and equipment rather than using Tayloristic principles to organise workers around equipment (Trist 1981; Clegg 2000). Whilst these insights and design principles were derived from studies and action research in industrial settings such as coalmines, textile factories, automotive manufacturing and power plants, similar problems were observed in office based work environments once information technology had been introduced (Ackoff 1967; Mumford, Mercer et al. 1972; Bostrom and Heinen 1977).

Problems associated with technocratic technology led work transformation have never been resolved. For example (Doherty and King 2001; Doherty, King et al. 2003; Doherty and King 2005) report that socio-technical issues are still common when information systems are implemented. In the 1990s we even witnessed the popularity and 'mixed results' associated business process reengineering – a form of technocratic technology led work transformation (O'Neill and Sohal 1999; Mumford 2006). These problems are arguably more acute today than ever before as society is demanding the development of larger and more complex information systems to support increasingly complex and *critical* organizational work (Bullock and Cliff 2004; RAE 2004; Baxter and Sommerville 2011). Whilst analysing socio-technical issues in small-to-medium scale situations may be achievable using approaches such as rapid ethnography (Millen 2000) combined with a theoretical framework such as distributed cognition (Hutchins 1995) or activity systems theory (Engestrom 2000); analysing enterprise scale situations is an open research question because of the *overwhelming* number of socio-technical elements and interactions involved (RAE 2004).

In recent years a new set of tools and techniques from complexity science has become available to socio-technical systems scientists and engineers. Advances in complex network analysis may provide a fertile territory for exploration as in the past these techniques were only accessible to mathematicians and computer scientists. Complex network analysis has enabled physicists, chemists, epidemiologists and social scientists to study systems comprising thousands and millions of nodes in applications as wide ranging as social network analysis to metabolic pathways. We believe that these techniques may be of practical use to the analysis of problematic socio-technical systems in organizational settings.

We demonstrate, via means of a case study comprising 30+ nodes and 50+ interactions, proof-of-concept tools for large-scale network analysis and visualisation that may provide a promising avenue for identifying problematic elements and interactions amongst an overwhelming number of socio-technical elements. We demonstrate the potential of this approach by showing that: i) a problematic situation may be represented as a directed graph such that the elements in the situation are represented as nodes, and interactions between nodes as edges; ii) that eigenvector centrality, a well established measure of node importance, may be used to rank the importance of elements in a situation and that highly ranked elements match those identified as important by a human analyst; iii) the 'complexity' of a situation, or a part of a situation, may be characterised using a feedback degree score which provides an indication of the extent elements are highly interconnected and are involved in feedback loops. The implications of these findings are that computers may be used to aid the analysis of problematic large-scale complex socio-technical situations by highlighting elements, or groups of interacting elements, that are important to the overall outcome of a problematic situation. This contribution is significant as it provides an avenue for developing scalable engineering techniques to troubleshoot large-scale situations.

This paper is structured such that section 2 provides an overview of social analysis approaches to inform information system development and aspects of complex network analysis that may be relevant to socio-technical systems analysis. In section 3 we describe our aim, hypotheses and research design. In section 4 we illustrate our approach to representing, visualising and analysing a problematic socio-technical situation as a directed graph. In section 5 we present our case study findings and analyse the relationship between: i) eigenvector centrality scores and node importance as ranked by an analyst; ii) feedback degree scores and node complexity as ranked by an analyst. Finally in section 6 we conclude and describe future research opportunities.

2. SOCIAL ANALYSIS TO INFORM SYSTEMS DEVELOPMENT

An information system is a system that collects, processes and distributes information. The classes of information system that this paper is concerned with are those that exist to "serve, help or support people taking action in the real world" (Checkland and Holwell 1998). These information systems are socio-technical systems, meaning that they are composed of interrelationships amongst technical components (such as computers) and humans, whom are members of multiple social systems e.g. teams, divisions, organisations, wider society (Trist 1981).

2.1 Social Analysis and Information Systems Development

Information system development is the process of conceiving, analysing, designing and implementing an information system (Avison and Fitzgerald 2006). The process of developing information systems is challenging because problematic socio-technical issues arise due to them being maladjusted to their environment resulting in failures to meet stakeholder expectations.

To address this issue the socio-technical systems engineering community has developed methods of social analysis to inform development. These approaches such as ETHICS (Mumford 1995), MULTIVIEW (Avison, Wood-Harper et al. 1998) and I* (Yu 1997) primarily inform the *design* of technical artefacts, or human activity surrounding the artefact, with the intention of minimising problematic socio-technical issues arising during deployment or post-deployment. Approaches to inform the *troubleshooting* of problematic socio-technical issues during and after deployment have largely come from related fields outside of socio-technical systems engineering such as HCI (Human Computer Interaction), CSCW (Computer Supported Collaborative Work), Ergonomics and Soft OR (Operations Research). Some of the most notable approaches include situated action (Suchman 1987), distributed cognition (Hutchins 1995), activity systems theory (Engestrom 2000) and SSM (Soft Systems Methodology) (Checkland 1999).

Situated action, distributed cognition and activity theory are approaches originally designed to analyse small-medium scale situations comprising a single individual interacting with a machine, scaling up-to a number of groups of people interacting with a system to achieve a set of relatively well defined tasks e.g. control room systems, groupware systems. SSM, a problem structuring method, was designed to facilitate troubleshooting *problematic situations* in larger organisational settings. Problematic situations are situations where their existence, nature, or otherwise is largely observer dependent (Checkland 1999). However, unlike the prior mentioned domain specific approaches, SSM was not designed to provide detailed and specific guidance as to how to conduct socio-technical analyses of information systems thus limiting its usefulness in identifying typical sources of socio-technical issues. For instance SSM's social analysis suggests exploring roles, values and norms whilst a more domain specific approach like the activity systems framework proposes the systematic identification of tensions between finer grained elements such as stakeholders' rules, tools, skills, beliefs, divisions of labour, responsibilities and objectives (Engestrom 2000). Approaches from CSCW may highlight the importance of awareness, distributed coordination, plans and procedures, local knowledge, spatial temporal knowledge and organisational memory (Viller and Sommerville 2000).

Troubleshooting enterprise scale situations remains an open research question within the socio-technical systems engineering community. This is because current approaches to analysis are based on ethnography and a theoretical framework (such as distributed cognition or activity systems theory) and thus do not scale-up to enterprise scale situations with large numbers of socio-technical elements and interactions. This is because existing methods have typically relied upon detailed observation of work activity, which is a time intensive data collection process as well as time consuming analysis process. In order to develop a more scalable approach, elsewhere we have argued that the exploration of structural and intentional factors using interviews may enable a more scalable way of analyzing a situation as it has a different set of trade offs (Greenwood and Sommerville 2011). This approach is similar in spirit to SSM but incorporates a variant of the 'activity space' framework (Halloran 2000; Halloran 2001) - a framework that analyses a broader range of socio-technical elements than SSM.

In this paper we provide evidence that problematic enterprise scale situations are amenable to computer-aided analysis using advances from complex network theory. This is significant to the problem of scalability as it enables the partial automation of the process of identifying important elements and complex behaviour thus reducing the burden of work and perhaps enabling the analysis of large situations where a human cannot be expected to analyse every element in the problem due to their vast number.

2.2 Complex Network Theory

Network theory is a rapidly evolving branch of computer science and mathematics that studies mathematical structures that model relations between discrete objects. Complex networks are "networks whose structure is irregular, complex and dynamically evolving overtime" (Boccaletti, Latora et al. 2006). In recent years network analysis and visualisation tools have become accessible to non-mathematicians or computer scientists due to the increasingly widespread availability of off-the-shelf tools. These tools have enabled the analysis of systems of thousands - millions of nodes such as electric power grids, the Internet and social networks. This ability to analyse vast numbers of nodes and interactions makes network analysis attractive for the purpose of developing scalable techniques for analysing problematic enterprise scale situations.

There are two significant barriers to using network analysis for analysing a problematic socio-technical situation. Firstly the socio-technical situation must be representable as a set of nodes and a set of links. Secondly, appropriate graph analysis techniques or metrics must be identified or invented to enable the identification of nodes or links that are important to overall outcome of a problematic situation.

There exist a number of candidate metrics that may lend themselves to this purpose. Firstly, the 'influence' or 'importance' of an element (node) in a messy socio-technical situation (graph) may be identifiable using network centrality metrics. Network centrality metrics have been used for this purpose in other domains such a social network analysis (Boccaletti, Latora et al. 2006). Secondly the 'complexity' (interconnectedness and extent of feedback) of an element may be estimable by combining existing techniques to count the number of loops a node is involved in and its number of links to other nodes. The counting of loops, referred to as *k*-cycles, is a well-established practice (Vázquez, Oliveira et al. 2005) as is counting the links of node (Opsahl, Agneessens et al. 2010).

A particularly well-suited centrality metric for our purposes is *eigenvector centrality*. The metric captures the intuition that a node that influences many other nodes is influential, whilst also taking into account the notion that a node that influences many highly influential nodes is more influential than a node that influences many weakly influential nodes. A node's eigenvector centrality (Bonacich 1972) is defined as its summed connections to others weighted by their centralities. The centrality of node i is given by $\lambda\upsilon_i=\Sigma A_{ij}\upsilon_j$ - the defining equation in matrix notation is $\lambda\upsilon=\mathbf{A}\upsilon$ where $\mathbf{A}$ is the adjacency matrix, λ is a constant and υ is the eigenvector. The metric is particularly well-suited for our purpose as it has the following properties: it assumes that all nodes influence their neighbours (rather than influence being restricted to a single shortest path) (Borgatti 2005); influence is subject to feedback loops such that nodes are revisited multiple times (rather than assuming no node is visited more than once) (Borgatti 2005).

We propose that the 'complexity' (extent of interconnectedness and of being involved in feedback loops) of a node may be captured using a metric that we call feedback degree. It captures the intuition that the complexity of a node is primarily determined by the complicatedness of its interactions (number of feedback loops it partakes) and secondarily by its total number of interactions. Mathematically it comprises the linear combination of a nodes *degree* and the number of *k-cycles* (feedback loops) it partakes.

The degree of a node in a directed graph is the sum of the number of outgoing links (termed outdegree) and incoming links (termed indegree). The defining equation for the outdegree is $k_i^{out} = \Sigma_j a_{ij}$, the indegree is $k_i^{in} = \Sigma_j a_{ji}$, and the total degree is $k_i = k_i^{out} + k_i^{in}$, where k_i is the degree for the node i and a_{ij} represents an element in the adjacency matrix of the network. We define feedback degree as $f_i = k_i/2n + c_i$ where f_i is the feedback degree for a node i, k_i is the degree of the node i, n is the total number of nodes in the network, and c_i is the number of cycles the node partakes.

3. RESEARCH DESIGN

This research adopted a case study approach because our aim was to provide proof of concept that techniques for network analysis help to analyse real world problematic socio-technical situations. We formulated the following hypotheses from our aim:

1. Eigenvector centrality may be used to rank the importance of elements in a situation i.e. high eigenvector centrality scoring nodes correspond to those identified as 'most important' by a human analyst. Our null hypothesis was that there would be no difference between the distributions of eigenvector centrality scores for the population of important elements and unimportant elements.
2. Feedback degree may be used to rank the 'complexity' of elements in a situation, or a part of a situation i.e. feedback degree scores correlate with node complexity as ranked by a human analyst. Our null hypothesis was that any correlation between node complexity as ranked by a human analyst and feedback degree is due to random chance.

3.1 Data Collection and Analysis

We collected our case study data using 16 one-hour semi-structured interviews of the document management system's stakeholders. Interview participants were selected on the basis of availability by a facilitator within the organisation. The interviews comprised a set of open-ended questions and a set of closed questions comprising 7-point semantic differential scales and 7-point Likert scales. A copy of our survey can be found here (http://www.cs.st-andrews.ac.uk/~dsg22/P/EDM_Survey.pdf).

Interviews were digitally recorded and transcribed when permitted. The open-ended interview questions were designed to elicit the relationship between the participant's view of the their work (role, responsibilities, their day-to-day activities, most serious work challenges) and the deployed system (their history with the system, which responsibilities/activities the system helps them accomplish, how it does so, what problems it introduces to their work, how the system impedes their responsibilities and activities). The closed interview questions elicited the relationship between the participant and the system by exploring aspects of IT systems that are associated with intention to use (performance expectancy, effort expectancy, information quality, system quality, support quality, system usage policy) and aspects of organizational change that can lead to conflict (interfering with roles, goals, values, resources, capabilities/skills, job satisfaction, status, procedural justice, distributive justice, importance, ownership).

Dialogue mapping (Buckingham-Shum, Selvin et al. 2006) was then used to organise interview data into more abstract units of information. Dialogue maps were compared to the participant's responses to closed questions to corroborate findings. Dialogue maps were compared across participants to identify themes. An adapted version of the 'activity space' framework (Halloran 2000; Halloran 2001) was then used to structure the findings into elements and identify tensions/interrelationships between different elements within the situation.

The 'activity space' framework is a framework derived from cultural historical activity theory (CHAT) and may be used for structuring data and identifying problematic intentional and structural aspects of a system. The framework comprises three intentional constructs comprising: mediators (tools, beliefs, skills); subjects (roles, responsibilities) and object(ive)s. And three structural constructs comprising: rules (formal / informal norms); community (actors involved in a situation); and the division of labour (how work is divided). According to 'activity space' theory the outcome of a situation (e.g. the problematic nature of an IS) is brought about by interactions between actors behaviour. Each actor's behaviour is mediated by intentional and structural elements. So problematic situations arise when tensions exist within and between actors' intentional and structural elements. By understanding these tensions a situation can be modified to change the outcome. We chose this framework as it gives primacy to the interrelationships between 'soft' (intentional and structural) and technical aspects of a situation and also because variants of this framework have been used to assess relatively large organisational situations (Engestrom 2001; Isssroff and Scanlon 2002; Barnard 2010; Hartmann and Bresnen).

To test the hypotheses outlined above we firstly analysed the elements and interactions (without the aid of network analysis software) to identify important elements and interactions that mediate the problematic outcome. Secondly we repeated the analysis with the aid of network analysis and visualisation software (Gephi.org) by parsing the elements and interactions into a machine-readable file format (DOT language).

To assess hypothesis 1 we divided the nodes into two populations, those thought 'most important' by the analyst and the rest that we labelled 'least important'. Secondly we generated eigenvector centrality scores for each node using Gephi. Thirdly, we used Independent-Samples Man-Whitney U-test to compare the distribution of eigenvector centrality score between each population using the PASW statistical package. Our null hypothesis for hypothesis 1 was that there would be no difference between the distributions of the 'most important' and 'least important' populations thus confirming that eigenvector centrality is not an indicator of importance. To confirm hypothesis 1 we expected each population to have a different distribution and that the 'most important' population would have a larger median and mean eigenvector centrality score than the 'least important' population. This would enable us to conclude that elements with a large eigenvector centrality are more likely to be members' of the 'most important' population than the 'least important' population; thus confirming that ranking elements by eigenvector centrality is a reasonable method of ranking the importance of an element.

To assess hypothesis 2 we firstly generated three sub graphs of the problematic situation. We used sub graphs comprising fewer than 10 nodes, rather than the whole graph comprising 30+ nodes, to make the ranking scenario a manageable size for a human analyst. Secondly we (without the aid of network analysis software) ranked each element on the basis of its complexity as judged by a human analyst. Thirdly we generated feedback degree scores for each node. Fourthly we used Spearman's correlation to analyse the relationship between feedback degree and a node's complexity as judged by an analyst. Spearman's correlation is a non-parametric measure of statistical dependence between two variables and is also implemented in PASW. Our null hypothesis was that a correlation between feedback degree and complexity would be due to random chance. To confirm hypothesis 2 we firstly expected a statistically significant correlation between feedback degree and complexity. Secondly we desired the $r>0.83$ such that feedback degree accounts for a meaningful proportion of the variance (>70%) of the complexity as judged by an analyst. This would enable us to conclude that feedback degree is a reasonable indicator of the complexity of an element in a problematic situation.

3.2 The Case Study Organisation and the Socio-Technical System

The fieldwork was performed at three different sites of a large multinational system-engineering corporation that we will call 'Company A'. Their main work activity comprises the design, manufacture and maintenance of specialist electro-optical components and systems. The organisation is divided into a number of functional groups that come together under a project structure to produce customer deliverables e.g. components, systems and documents. The design of components and systems is a collaborative activity and the sharing of documents is considered to be an important aspect of this activity by those involved.

'Company A' deployed an electronic document management (EDM) system in the early 2000s as it was perceived by the IT director that an EDM system would be more advantageous than using shared folders on a file server to exchange documents. There was a perception that the introduction of the system would bring about greater visibility and awareness of work rather than having different teams and functions working in information silos. Within projects it was envisioned that EDM would be an up-to-date repository of all project documentation. Teams would store their documents in personal working areas and upload them to locations in standardised EDM project file structures.

When we visited the organisation in 2010 the EDM was perceived by engineering management to be problematic due to "socio-technical factors". The use of the system was mandatory so all projects had an EDM project area but the extent that documents were being uploaded from working areas to the EDM project areas varied between teams. In addition to this the use of the EDM file structure varied between teams, as did the location of files within the file structure. As our investigation unfolded it became clear that engineering management perceived the system to be problematic because teams did not use it in a "common way".

4. REPRESENTING A PROBLEMATIC SITUATION AS A DIRECTED GRAPH

We represented the elements and interactions composing our problematic situation using a plain text graph description language called DOT (Gansner and North 2000). The language enables the description of a problematic situation in a machine-readable format so that a network analysis and visualisation package, such as Gephi (Bastian, Heymann et al. 2009), can process the data. The DOT language has a simple syntax that enables the expression of nodes, links and presentational information such as shapes, colours and labels. A directed graph (See Figure 1) representing the interactions between the responsibilities in the problematic situation described in section 5.1 is represented in DOT language below:

```
digraph g {
"20"[color=yellow, label = "20. EM_Responsibility : Improving delivery time, quality, safety, efficiency,
repeatability"];
"21"[color=yellow, label = "21. EM_Responsibility : Implementing change / process improvements"];
"22"[color=pink, label = "22. PM_Responsibility : Delivering product on time, on budget in accordance to contractual
obligations"];
"23"[color=pink, label = "23. PM_Responsibility : Meeting customer expectations"];
"26"[color=purple, label = "26. Eng_Responsibility : Meeting time, budget, and quality pressures"];
"20" -> "21"[color=green, label = "" ];
"22" -> "23"[color=green, label = "" ];
"22" -> "21"[color=orange, label = "" ];
"26" -> "21"[color=orange, label = "" ];
"21" -> "22"[color=orange, label = "" ];
"21" -> "26"[color=orange, label = "" ];
"20" -> "26"[color=green, label = "" ];
"20" -> "22"[color=green, label = "" ];
}
```

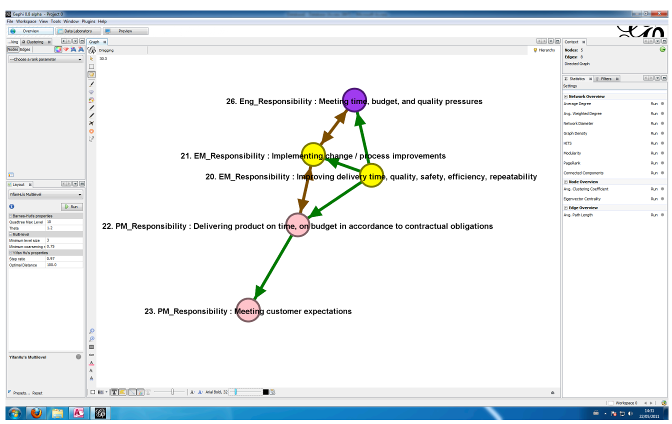

Figure 1 – Sub graph of a problematic situation being visualised using Gephi

A useful aspect of the language for the purpose of representing problematic situations is its ability to express the colour of nodes and relationships. We have found this feature useful for highlighting node and relationship types when visualising situations with many nodes. In Figure 1 the yellow nodes belong to engineering managers, the purple to engineers and the pink to programme managers. The colour of the links between the nodes represents the type of relationship. A green link represents one node supporting another. An orange/brown link represents a tension (potential incompatibility).

Visualisation is a particularly powerful technique as seeing the relationships laid out spatially with colours identifying each node type enables the complexity of a problematic situation to be articulated extremely rapidly.

Since writing and rewriting DOT files by hand can be tedious and time consuming we developed a prototype GUI using Microsoft Access 2010. This enables the analyst to rapidly enter each socio-technical element and subsequently indicate which elements interact together using a spreadsheet like interface rather than via code. This enables graphs to be generated, viewed, reviewed or modified rapidly using features typically available in any database or spreadsheet e.g. filters, queries and so on. We found this to be very fruitful when combined with Gephi as it enabled us to rapidly visualise a graph or perform statistical analyses.

5. RESEARCH FINDINGS

In this section we describe the results of unaided analysis and the results of our network aided analysis. The findings of unaided analysis reveal the nature and extend of interactions in the problematic situation and the importance of elements in the situation according to a human analyst. The findings of network aided analysis reveal the rankings of nodes according to eigenvector centrality and feedback degree. By comparing the findings using statistical techniques we determine: i) the relationship between important nodes identified by an analyst and a node's eigenvector centrality ranking; ii) the relationship between the complexity of nodes as ranked by an analyst and a node's feedback degree ranking.

5.1 Findings from Unaided Analysis

Overall we found that the extent and nature of EDM use varies on a project-by-project basis and that the nature of use is dependent upon individual programme managers and engineering teams. Engineering management perceive this to be problematic and at the time were pursuing an improvement strategy that encourages standardisation of EDM use. We analysed this problematic situation as the outcome of the following interacting elements: roles; objectives; mediators; division of labour; communities; and rules.

Roles

- There is a potential for conflict between the roles of engineering management and programme management. Whilst it is the responsibility of engineering management to take a strategic (long-term) view and run improvement projects. This is at tension with the tactical (shorter-term) responsibilities of programme management. Introducing change, even when successful, can cause short-term productivity degradation as changes are being 'bedded in'. This can be at odds with programme managers' contractual obligations such as milestones.

Objectives

- The objectives of engineering management, programme management and engineers are aligned such that their overall objectives are positively dependent. This means it is in all parties' interests to coordinate their activities as one party's success contributes to the success of the other parties.

- Whilst objectives are positively dependent there is scope for process conflict and our study suggests that it may be occurring. For example engineer managements' objective of improving deliver time is compatible with programme managements' objective of meeting contractual obligations however the way in which the objective is pursued, such as modifying the EDM may interfere with meeting a contractual obligations if not carefully coordinated.

Mediators

- EDM is acknowledged by all communities to suffer from usability issues at both the software and system level that ultimately results in frustration. These usability issues provided a motive in some communities to use a shared drive rather than EDM.

Division of labour

- A matrix structure is a conduit of tensions. Engineers are within the focal point of matrix and so they resist change when incompatible demands are placed.
- The division of labour can result in disconnects of responsibility or ownership. This has occurred with respect to the domestication of EDM.

Communities

- Communities have emerged around the division of labour and thus roles/responsibilities e.g. program management, engineers. There is a divergence between the viewpoints of each of these communities with respect to the value of EDM and the salience of its capabilities and purpose.

Rules

- There is a strong practice culture rather than a process culture within programme management and engineering. This means that work is performed on the basis of norms (e.g. individual and shared experience of what has happened in the past) rather than following explicit 'rules' (e.g. referring to process documentation).

Having identified tensions between these elements, we used a cognitive map to integrate the parts into a representation of the problematic situation. We found that these tensions interacted to create four vicious circles that are contributing to sustaining the problematic situation.

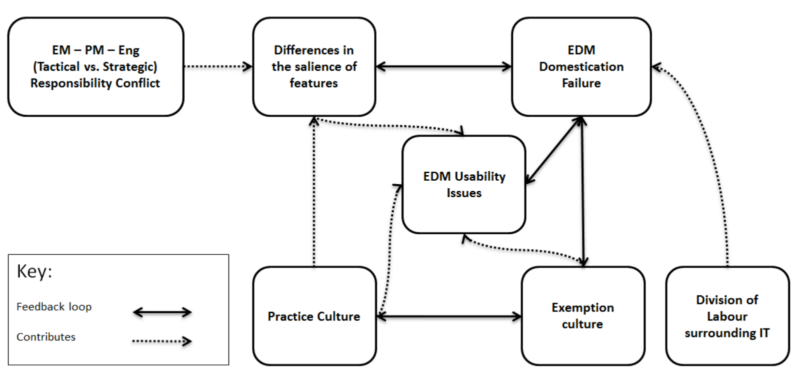

Figure 2 - Interactions of the socio-technical issues identified

The first vicious circle occurs between the differences in saliencies of usability issues and the domestication of EDM. The programme managers and engineers do not value the visibility and control features of EDM as much as engineering management. This has resulted in the continued use of shared drives, rather than the use of EDM as intended, resulting in an absence of domestication (familiarity, adaptation) of EDM. Conversely as domestication has not occurred, programme managers and engineers did not have the opportunity to become familiar with the benefits and drawbacks of the visibility and control features.

The second vicious cycle occurs between domestication and usability issues. Domestication (adaptation and familiarisation) did not occur because of usability issues making users avoid using the system. Conversely because users were unfamiliar with and avoided the system the extent and nature of usability issues were not identified, reported and the system adapted.

The third vicious circle occurs between the exemption culture and domestication. The exemption culture allowing projects to decide on the extent and nature of EDM use has resulted in a lack of familiarity with the full capabilities of EDM. Consequently EDM is not perceived as an acceptable substitute to shared drives nor has it been adapted to be made acceptable. Conversely because EDM has not been domesticated this has reinforced the culture of exemptions by permitting users not to use the tool.

The fourth vicious circle occurs between the practice culture and the exemption culture. As work is performed on the basis of norms (e.g. individual and shared experience of what has happened in the past) rather than explicit rule adherence it has made it acceptable for projects to exempt themselves from standard ways of working such as EDM. Conversely, since projects are permitted to exempt themselves from standard practices this reinforces the ‘practice culture’ as enacting an exemption is in itself an exercise of the primacy of experience over standards.

5.2 Findings from Network Aided Analysis

To test whether eigenvector centrality is a good indicator of element importance we firstly categorised the nodes into two groups – those that we believed to be ‘most important’ (See Table 1) and the rest we labelled ‘least important’. The ‘most important nodes’ were those that we believe contributed most to creating and sustaining the problematic situation according to our unaided analysis. This may be observed in our node selection for Table 1. Node ‘3 Domestication Responsibility’ supports the domestication failure element in Figure 2 and thus is present in Table 1. Node ‘6 Practice Culture’ supports the practice culture element in Figure 2 and therefore is present in Table 1. The same may be said of nodes ‘7 EM_Outcome’ and ‘8 EM_Outcome’ which are supporters of the EM-PM responsibility conflict represented in Figure 2. Node ‘9 PM_Outcome’ supports both the practice culture and exemption culture elements represented in Figure 2. Node ‘10 Eng-Outcome’ is a supporter of EDM usability issues and EDM domestication failure represented in Figure 2. Nodes 21-26 are supporters of the EM-PM responsibility conflict. Node 28 is a supporter of EDM domestication failure and practice culture. And finally Node 29 is a supporter of the EDM domestication failure and of the exemption culture.

Table 1 - 'Most Important' nodes identified during unaided analysis

Node ID and Description of Most Important Nodes
3. Domestication Responsibility : Domestication responsibility has fallen between the cracks
6. Practice Culture : Tendency to follow norms rather than procedures
7. EM_Outcome : Encouraging the use of EDM in a standardised manner
8. EM_Outcome : Pursuing an improvements strategy based on process standardisation
9. PM_Outcome : Each PM encourages the use of EDM according to their own practices
10. Eng_Outcome : EDM is perceived to be a source of frustration
21. EM_Responsibility : Implementing change / process improvements
22. PM_Responsibility : Delivering product on time, on budget in accordance to contractual obligations
23. PM_Responsibility : Meeting customer expectations
25. Eng_Responsibility : Design Systems / components
26. Eng_Responsibility : Meeting time, budget, and quality pressures
28. Eng_Outcome : Extent and use of EDM varies on project by project basis
29. PM_Outcome : Each PM implements and follows data management plans according to their own practices

Secondly, having identified the 'most important' nodes we generated eigenvector centrality scores and visually inspected the results to explore the relationships. We observed that all the nodes ranked from 1-8 (in Table 2) are members of the 'most important' group (Table 1). In other words there appeared to be a good correspondence between the 'most important' nodes as identified during unaided analysis (See Table 1) and those highly ranked according to eigenvector centrality (See Table 2).

Table 2 - Ranking of Node Importance using Eigenvector Centrality

Ranking by EV	Node ID and Description	EV Centrality
1	6. Practice Culture: Tendency to follow norms rather than procedures	1.00E+00
2	9. PM_Outcome: Each PM encourages the use of EDM according to their own practices	9.08E-01
3	7. EM_Outcome: Encouraging the use of EDM in a standarised manner	8.94E-01
4	28. Eng_Outcome: Extent and use of EDM varies on project by project basis	7.60E-01
5	3. Domestication Responsibility: Domestication responsibility fallen between the cracks	6.30E-01
6	29. PM_Outcome: Each PM implements plans according to their own practices	4.95E-01
7	10. Eng_Outcome: EDM is perceived to be a source of frustration	4.55E-01
8	8. EM_Outcome: Pursuing an improvements strategy based on process standardisation	3.05E-01
9	30. EM_Objective: Pursue an improvements strategy based on Lean thinking	1.55E-02
10	16. PM_Objective: Meet customer expectations	1.50E-02
11	15. PM_Objective: Meet contractual obligations	9.91E-03
12	19. Eng_Objective: Meet programme managers schedule, cost and quality expectations	6.60E-03
13	31. Eng_Objective: Meet engineering managers process expectations	5.83E-03
14	21. EM_Responsibility: Implementing change / process improvements	2.69E-03
15	22. PM_Responsibility: Deliver on time, on budget in accordance to contractual obligations	1.90E-03
15	26. Eng_Responsibility: Meeting time, budget, and quality pressures	1.90E-03
17	18. Eng_Objective: Design high quality component or system	1.56E-03
18	23. PM_Responsibility: Meeting customer expectations	1.33E-03
19	11. EM_Objective: Improve delivery time	2.96E-05
19	12. EM_Objective: Improve quality	2.96E-05
19	13. EM_Objective: Improve safety	2.96E-05
19	14. EM_Objective: Improve efficency	2.96E-05
19	17. PM_Objective: Timely Internal reporting	2.96E-05
24	1. EDM: Document Management System	0.00E+00
24	2. Matrix Structure: Engineers managed by programme management & engineering	0.00E+00
24	20. EM_Responsibility: Improving delivery time, quality, safety, efficiency, repeatability	0.00E+00

24	24. PM_Responsibility: Internal reporting	0.00E+00
24	25. Eng_Responsibility: Design Systems / components	0.00E+00
24	27. Eng_Responsibility: Following process	0.00E+00
24	4. Shared Folders: Document Management System	0.00E+00
24	5. PDM/Sherpa : Product Data Management Tool	0.00E+00

Statistical Test of Hypothesis 1

In order to test hypothesis 1 we performed an Independent-Samples Mann-Whitney U test using PASW. The results of the Mann-Whitney U test indicated to reject the null hypothesis with a $p = 0.05$. The distribution of eigenvector centrality scores were not the same across the population of 'most important' and 'least important' elements. Via inspection of each population's descriptive statistics (See Table 3) we observed that the median and mean of the 'most important' population was larger than the 'least important' population. This enabled us to conclude that elements with a large eigenvector centrality are more *likely* to be a member of the 'most important' population than the least important population[1]. This confirms that ranking elements by eigenvector centrality is a reasonable indicator of the importance of an element in a problematic situation. These findings thus indicate that computers may be used to aid the analysis of large problematic socio-technical situations by identifying elements that are most important to sustaining the current problematic situation.

Table 3 - Descriptive Statistics of 'Most Important' and 'Least Important'

Statistics

		Least_Important	Most_Important
N	Valid	18	13
Mean		**.0030**	**.4196**
Std. Error of Mean		.00125	.10901
Median		**.0000**	**.4555**
Std. Deviation		.00530	.39305
Minimum		.00	.00
Maximum		.02	1.00

Statistical Test of Hypothesis 2

In order to test whether feedback degree is a good indicator of 'complexity' (hypothesis 2) we ranked (without the aid of network analysis) the 'complexity' of nodes in three subsections of the overall problematic situation. The reason we used subsections is because the ranking of every node in the whole problematic situation (with over 30 nodes and over 60 interactions) may have been unreliable due to human error. Therefore we opted for three chunks of the problematic situation comprising 10 or fewer nodes. The subsections we selected were responsibilities and their interactions (see Figure 3 and

[1] One must of course be sensible when interpreting eigenvector centrality rankings as a higher score indicates an element is more *likely* to be a member of the 'most important' population but it does not mean it is *necessarily* a member of the 'most important' population.

Table 4), outcomes and their interactions (see Figure 4) and objectives and their interactions (see Figure 5). We selected these sub graphs as a convenience sample since they each had 10 or fewer nodes.

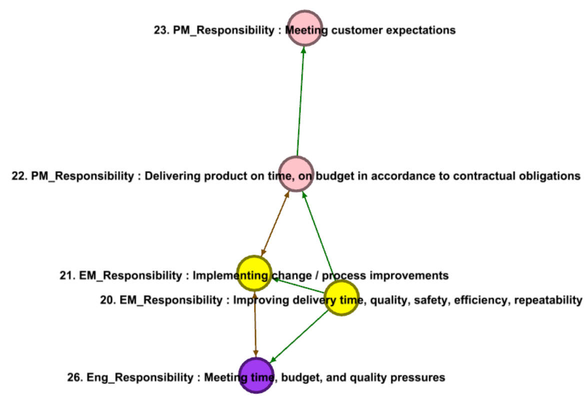

Figure 3 - Directed Graph of Responsibilities

Table 4 - Ranking of Complexity of Responsibility Nodes

Rank by Perceived Complexity	ID	FD
1	21. EM_Responsibility: Implementing change / process improvements	2.5
2	22. PM_Responsibility: Delivering product on time, on budget in accordance to contractual obligations	1.4
3	26. Eng_Responsibility : Meeting time, budget, and quality pressures	1.3
4	23. PM_Responsibility: Meeting customer expectations	0.1
5	20. EM_Responsibility: Improving delivery time, quality, safety, efficiency, repeatability	0.3

Our rationale for ranking the complexity of responsibility elements (Figure 3) is as follows. One may observe that node 21 is involved in the most complex interactions in comparison to its peers. This may be observed by the fact that it is involved in two feedback loops - one with node 22 and one with node 26. The loop with node 22 represents the situation where engineering managers' responsibility for implementing process improvements is at tension (interferes) with programme managers' responsibility for delivering products on time and on budget due to the short-term productivity degradation associated with introducing change. Similarly the responsibility for delivering products 'on time on budget' is at tension (interferes) with the responsibility for implementing process improvements, as new ways of working cannot be tried when aiming for tight deadlines or budgets. The loop with node 26 represents similar tensions with engineers' responsibility to meet time, budget and quality pressures. Similarly to the loop with node 22, engineering managers' responsibility for implementing process improvements is at tension with engineers' responsibility for meeting time, budget and quality pressures. Similarly engineers' responsibility for meeting time, budget and quality pressures interfere with trying out process improvements.

The second most highly ranked node is node 22 as it is involved in the feedback loop with node 21 and also influences another node, node 23, which is programme managers responsibility to meet customer expectations. The responsibility for meeting customer expectations is supported by node 22 (the responsibility for delivering products on time on budget) as it is a part of meeting customer expectations. Node 26 is the third most complex node as it is involved in similar interactions to node 22 but does not influence any other nodes. Node 23 is the fourth most highly ranked as it is being supported by node 22, which is involved in relatively complex interactions. Lastly node 20 is the least complex node as it is neither involved in feedback loops nor supported by nodes involved in feedback loops. A similar rationale was used for ranking the complexity of nodes in outcome (Figure 4) and objectives (Figure 5) sub graphs however due to space restrictions we are unable to present them here.

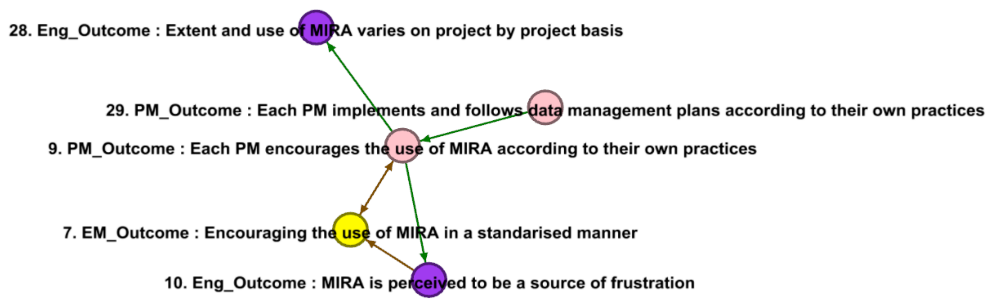

Figure 4 - Directed Graph of Outcomes

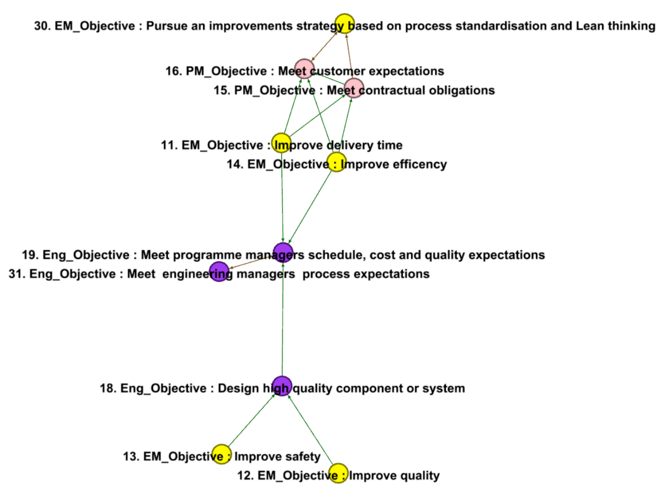

Figure 5 - Directed Graph of Objectives

In order to test hypothesis 2, we performed Spearman's correlation test on the data from these three sub graphs using PASW. For all sub graphs tested we were able to detect statistically significant correlations between feedback degree (FD) and complexity as judged by an analyst. For the responsibility sub graph it may be observed that FD has a correlation of -0.9, which is statistically significant at the 0.05 level (Table 5). For the outcome sub graph it may be observed that FD has a correlation of -0.973, which is statistically significant at the 0.01 level (See Table 6). For the objectives sub graph it may be observed that FD has a correlation of -0.981 which is statistically significant at the 0.01 level (See Table 7). This enables us to reject the null hypothesis. These findings confirm hypothesis 2 as the correlations are statistically significant account for a significant proportion of the variance e.g. r>0.83. These findings thus indicate that computers may be used to aid the analysis of large problematic socio-technical situations by identifying elements that display the most complex behaviour.

Table 5 Spearman's Rho for Responsibility Sub Graph

Correlations

			Rank	Degree	Feedback	FD
Spearman's rho	FD	Correlation Coefficient	**-.900***	.975**	.949*	1.000
		Sig. (2-tailed)	.037	.005	.014	.
		N	5	5	5	5

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 6 - Spearman's Rho for Outcome Sub Graph

Correlations

			Rank	Degree	Feedback	FD
Spearman's rho	FD	Correlation Coefficient	**-.973****	1.000**	.889*	1.000
		Sig. (2-tailed)	.005	.	.044	.
		N	5	5	5	5

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 7 - Spearman's Rho for Objectives Sub Graph

Correlations

			Rank	Degree	Feedback	FD
Spearman's rho	FD	Correlation Coefficient	**-.981****	.846**	.930**	1.000
		Sig. (2-tailed)	.000	.002	.000	.
		N	10	10	10	10

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

6. CONCLUSION

In this paper we provided proof-of-concept that that tools for large-scale network analysis and visualisation may provide a promising avenue for developing *scalable* techniques for identifying problematic elements and interactions amongst an overwhelming number of socio-technical elements. We do not recommend network analysis as a replacement for human judgment but as an aid to human judgment. We demonstrated the potential of this approach by showing that: i) a problematic situation may be represented as a directed graph such that the elements in the situation are represented as nodes, and interactions between nodes as edges; ii) that *eigenvector centrality* may be used to rank the importance of elements in a situation and that highly ranked elements correspond to those identified as important by a human analyst; iii) the 'complexity' of a situation, or a part of a situation, may be characterised using a *feedback degree* score which provides an indication of the extent of feedback loops and the interconnectedness of elements.

These findings thus indicate that computers may be used to aid the analysis of problematic large-scale complex socio-technical situations by highlighting elements, or groups of interacting elements, that are important to the overall outcome of a situation. This contribution is significant as it demonstrates the partial automation of a laborious process and opens an avenue for developing engineering techniques suited to troubleshooting situations where analysts cannot be expected to inspect each individual node due to their overwhelming number.

We hope this paper may be the starting point of a discussion within the socio-technical systems community as to how network analysis may aid the analysis and engineering of large complex socio-technical systems. There is a need for further work in this area. Of up most importance is the pursuit of further case studies to verify these early findings in other situations, contexts and domains. Whilst the analysis of problematic situations has been traditionally a qualitative process we believe as the scale of problematic situations increases the use of metrics to guide analysis becomes increasingly compelling.

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