UCL

Self-Organising Networks in Complex Infrastructure Projects

The Case of London Bank Station Capacity Upgrade Project

By:

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Declaration of Originality and Word Count

I, Huda M H Almadhoob, confirm that the work presented in this thesis is my own. Where ideas, expressions and information have been derived from other sources, I confirm that this has been duly acknowledged and the appropriate credit has been given.

I also declare that this thesis describes original work that has not previously been presented for the award of any other degree in any institution.

It is worth noting that some of the material presented in this thesis has influenced the production of several publications that link this research to project management, supply chain management and network analysis contexts. Some of the analysis and ideas, therefore, have already been communicated to a wider audience both in academia and practice. These are mentioned within the text and can be referred to in the bibliography and reference list, namely: Almadhoob and Pryke (2017), Pryke *et al.* (2018) and the recently published book Pryke (2020).

Signed,

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Acknowledgment

First and foremost, all thanks and praises are due to *Allah* (God) for helping me in fulfilling this task, which comes only from him. I am grateful for the opportunities provided to me to explore, learn, develop and "become" more both personally and intellectually.

The pressing need for a radical change in construction industry has become more and more apparent during my MSc. course at University College London (UCL). At that time, my supervisor, Professor Stephen Pryke has particularly inspired me with the idea of adopting network approach and using its associated Social Network Analysis (SNA) techniques and theory as a new avenue to initiate tangible change. Therefore, I would like to take this opportunity to express my sincere thanks to Professor Pryke for his inspiration, insightful comments and continued guidance throughout this dissertation. Unfortunately, he became sick during my third year and then died in March 2020. I am deeply saddened by the news of his passing. It was an honour to have worked with such a great person over the past eight years and had the opportunity to publish joint papers with him. He will always be in my prayers. God rest his soul in peace!

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To the apples of my eyes,
my boys: Ghayth
and Leo

Abstract

Managing large infrastructure projects remains a thorny issue in theory and practice. This is mainly due to their increasingly interconnected, interdependent, multilateral, nonlinear, unpredictable, uncontrollable, and rapidly changing nature. This study is an attempt to demystify the key issues to the management of large construction projects, arguing that these projects are delivered through networks that evolve in ways that we do not sufficiently understand as yet.

The theoretical framework of this study is grounded in Complexity Theory; a theory resulted in a paradigm shift when it was first introduced to project management post-2000 but is yet to be unpacked in its full potential. The original contribution of the study is predicated on perceiving large construction projects as evolving complex systems that involves a high degree of self-organisation. This is a process that transitions contractually static prescribed roles to dynamic network roles, comprising individuals exchanging information. Furthermore, by placing great emphasis upon informal communications, this study demonstrates how self-organising networks can be married with Complexity Theory. This approach has the potential to make bedfellows around the concept of managing networks within a context of managing projects; a concept that is not always recognised, especially in project management.

With the help of social network analysis, two snapshots from Bank Station Capacity Upgrade Project Network were analysed as a case study. Findings suggest that relationships and hence network structures in large construction projects exhibit small-world topology, underlined by a high degree of sparseness and clustering. These are distinct structural properties of self-organising networks. Evidence challenges the theorisation about self-organisation which largely assumes positive outcomes and suggests that self-organising could open up opportunities yet also create constraints. This helps to provide further insights into complexity and the treatment of uncertainty in large projects. The study concludes with detailed recommendations for research and practice.

Key Words: *Large Construction Projects, Complexity Theory, Self-organising Networks, Social Network Analysis (SNA), Network Roles.*

Impact Statement

The research was undertaken within the context of Centre for Organisational Network Analysis (CONA) at UCL. The core aim of CONA is to improve the effectiveness of organisations through the use of Social Network Analysis (SNA). The case study described here was part of Knowledge Transfer Partnership (KTP) between UCL and Transport for London (TfL) in the context of a consultancy, which had been running for two years from 2014 to 2016. The findings, therefore, will be shared with TfL to benefit from lessons learnt and provide recommendations to improve performance and successfully deliver future projects.

The network approach adopted in this research has provided a deeper and more empirically grounded understanding to the process of self-organisation within the context of complex infrastructure projects. The study is informed by Complexity Theory and analysed using the tools and techniques of SNA. Accordingly, this aims to enrich the study of self-organising networks within the construction industry and raise awareness to commence the setting of an agenda associated with the application of network theory in the field of project management.

Some of the initial research findings have been presented in Almadhoob and Pryke (2017), in the 1st North American Regional Social Networks Conference in Washington, D.C. This was part of a research strategy to use presentations and papers as a means to develop, shape and refine the ideas presented in this thesis. Additionally, the study influenced the production of several publications that link the research to project management, supply chain management with SNA. These are: Pryke *et al.* (2018) and the recently published book Pryke (2020). Hence, communicating the findings and ideas to a wider audience both in academia and practice as well as develop the research in the thesis.

Moreover, the findings in terms of providing quantifiable efficiency and cost measures to evaluate consequences of the dynamics in the evolving complex networks can be used as a tool by Project Managers to optimise project networks and infer problem areas to help identify where the project networks are falling short of achieving optimum/required outcomes. This can eventually lead to increased project efficiency and provide organisational cost savings. This is especially relevant in light of scarce resources and limited budgeting solutions for large infrastructure projects.

Finally, as an architectural design and project management academic and researcher, the interest in SNA, coupled with the understanding of project networks, has re-shaped my teaching strategies to focus on the collaborative student-centred approach. This permits dialogue and fosters a degree of student input to curricula and grading criteria. The implementation of self-organisation concept can also be brought about through adopting self-organised learning environments in design studios.

This can be developed as a way to encourage students to collaborate, solve problems and become more engaged in learning with minimal interventions from their teachers. Thus, this research might change actors' mind-sets and inspire cultural changes of how coordination and collaboration is conceived in projects both in academia and practice, leading to more interest and research in this field.

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List of Acronyms

Acronym	Full Form
BAA	British Aviation Authority
BIM	Building Information Modelling
BSCU	Bank Station Capacity Upgrade
CAD	Computer-Aided Design
CAS	Complex Adaptive Systems
CIOB	Chartered Institute of Builders
CONA	Centre for Organisational Network Analysis
CT	Complexity Theory
DNA	Dynamic Network Analysis
EC	Edge of Chaos
ICE	Innovative Contractor Engagement
IUK	Infrastructure UK
JCT	Joint Contracts Tribunal
KTP	Knowledge Transfer Partnership
LU	London Underground
LUL	London Underground Limited
M&E	Mechanical and Electrical
MDS	Multi-Dimensional Scaling
MEP	Mechanical, Electrical and Plumbing
MRQAP	Multiple Regression Quadratic Assignment Procedure
NOSQL	Not Only Structured Query Language
ONA	Organisational Network Analysis
PMP	Performance Measurement Programme
QAP	Quadratic Assignment Procedure
REC	Research Ethics Committee
RIBA	Royal Institution of British Architects
RICS	The Royal Institution of Chartered Surveyors
SC	Supply Chain
SCM	Supply Chain Management
SIENA	Simulation Investigation for Empirical Network Analysis
SNA	Social Network Analysis
SO	Self-Organisation
SW	Small-World
3-D	Three Dimensional
TfL	Transport for London
TMOs	Temporary Multi-Organisations
TWAO	Transport and Works Act Order
UCL	University College London
UK	United Kingdom
WBS	Whole Block Site

I

Introduction

1.1 Introduction

Large construction projects are usually characterised by poor performance, time and cost overruns, low public support, and high rates of uncertainties and failure (Flyvbjerg *et al.*, 2003). This study, in line with others (e.g. Walker, 2015; Pryke, 2012; Marsde and Campbell, 2012), suggests that the key underlying reason for such frequent failures is lack of a proper understanding of the nature of the construction systems to be managed. It aims, therefore, to challenge the foundation for managing large construction projects by focusing on the people involved in projects rather than focusing on contractual hierarchies, processes, and documents. By doing so, this study argues that the activities comprising construction projects might be conceptualised as social networks that are regarded as 'temporary systems'. These temporary systems form due to the continual evolution and decay of relationships supporting information exchange between project actors; they represent the vehicle for an insufficiently researched process referred to as 'self-organisation' (Pryke, 2017).

The assumption that complex construction projects can be viewed as numerous social networks, whose structures evolve over time, has brought with it a growing interest in the study and visualisation of actors and their relationships (Pryke, 2012). Unlike Barnes' (1988) idea of the 'iron triangle' that defines effective project management as a function of achieving specified cost, time and quality, the conceptualisation of the project as networks provides *'an opportunity to look at a wide range of relationships between individuals and firms in a manner that is free from artificial boundaries'* (Pryke, 2012, p.9). Project networks are complex because they involve multitude of relationships among a large number of actors with multiple and sometimes conflicting interests and objectives (Flyvbjerg, 2009). Despite playing a crucial role to the delivery of the project, these networks are usually not managed in projects because they are largely invisible, i.e. have no contractual status (Pryke, 2017). They exist in an environment that is to a great extent not contractually envisaged, but rather uncertain and frequently loosely structured (Flyvbjerg, 2009). More importantly, these networks are instigated and managed by the project actors themselves, i.e. self-organising (Stacey, 2010); they form in order to secure and disseminate the information necessary for decision-making and problem-solving. Self-organising networks, therefore, can be viewed as the vehicle by which project uncertainty is reduced. It allows project actors to discharge their contractual responsibilities through continually re-defining their roles that are acquired as a function of their network positions (Pryke, 2017).

1.2 Research Objectives

The study applies Complexity Theory to explain communication and information exchange networks as multi-agent interacting and interdependent systems. This theory is chosen to establish the theoretical framework because it has the potential to enrich the project management area of inquiry by expanding the application of the systems perspective to the nonlinear operation of sufficiently complex, fragmented, diverse, and coordinated activity, such as in the case of large infrastructure projects (Pryke *et al.*, 2018). Complexity Theory places great emphasis on the forces of discontinuity, continuous change, disorder, instability, nonlinearity, and unpredictability; yet it postulates that complex systems exhibit a greater degree of adaptability and resilience (Mitleton-Kelly, 2003). Such behaviour is explained by having a high degree of self-organisation. This is an inevitable process that allows complex systems to have the characteristics of flexibility, effectiveness, and adaptivity to continually adapt around the changing needs of the project actors and the project itself over time (Pryke, 2017).

The broader objective of this study is to investigate 'self-organisation' phenomena in large construction projects. The detailed objectives are multi-fold; these are summarised as follows:

- **First:** to provide a new perspective of large construction projects grounded in Complexity Theory with the aim to introduce some principles that can be used as a foundation for a new kind of project management. This will be achieved by understanding the mechanisms governing the self-organising process, such as distribution of power, decision-making process, and actors' interactions;
- **Second:** in response to the recent calls to enrich social network analysis (e.g. Mazzocchi, 2016; Borgatti *et al.*, 2014; Pryke, 2012), this study aims to move away from the "static" model of networks and reorient it towards "dynamic stability" perspective. The latter conceptualises networks as "*Complex adaptive systems that exhibit both persistence and change*" (Kilduff *et al.*, 2006, p. 1032). It suggests that the behaviour of systems is not determined solely by its ingredients (i.e. the agents) but also by the interactions between them (Gell-Mann, 1994; Stacey, 1996);
- **Third:** to enhance our knowledge of the dynamics and evolution of project networks as they transform from a simpler state into a higher degree of complexity and order. This entails investigating how this transformation takes place and how it will reflect on the project network in terms of topography, individual roles, efficiency and cost. Embracing such understanding would ultimately provide some explanations to enable large complex projects to be managed more effectively and to provide organisational cost savings (Pryke, 2017; Pryke *et al.*, 2018).

1.3 Research Question

Research in the discipline of project management is concerned with a wide range of different managerial and organisational problems, such as contractual arrangements, opportunistic behaviour, incentive systems, interdependence, trust and communication (Söderlund, 2011). While many of these problems are investigated by drawing on different assumptions, organisational studies have long spoken to *'two fundamental and opposing requirements: the division of labour into various tasks to be performed and the coordination of these tasks to accomplish the activity'* (Mintzberg, 1979, p. 2). Building on the work of Grant (1996) and Roberts (2004), Söderlund (2011) classifies these problems broadly into two separate origins, which are referred to as problems of *'cooperation'* and *'coordination'*. Although in real life these two problems are frequently intertwined, each problem deals analytically with a different set of challenges and thus requires specific solutions, with the caveat that *'what might solve one problem could easily accentuate the other'* (Söderlund, 2011, p. 55). *'The problem of cooperation originates from the fact that individuals and actors have conflicting goals and behave opportunistically, whereas the problem of coordination stems from the complexity of the task and the necessity to communicate and synchronise activities to achieve action efficiencies'* (Söderlund, 2011, p. 46). Cooperation studies are typically concerned with governance, analysis of incentives, authority, contracts, trust and control, whereas coordination studies are typically concerned with communication, analysis of interdependence, learning, knowledge integration and planning (Söderlund, 2011).

The genesis of the problem being investigated in this thesis is related to c*oordination*, focusing on the study of self-organising project communication networks within the construction industry. It is based upon the premise that studying network topography could provide a better understanding of how projects are *really* delivered. For this purpose, an exploratory single case-study research approach is adopted (Eisenhardt and Graebner, 2007). This approach can offer an in-depth understanding of the complex and non-hierarchical communication process in construction projects (Howell *et al.*, 1996). The Bank Station Capacity Upgrade (BSCU) Project has been chosen as the focus for this research. The BSCU project is a complex infrastructure project and was fourth in line of a programme of major station capacity projects for Transport for London (TfL), the statutory body accountable for all public transport within the City of London in the United Kingdom. Analysis is based on two sets of secondary long-term data, collected as part of a two-year Knowledge Transfer Partnership (KTP) between University College London (UCL) and TfL. Further details on the case study and data will be provided in the Methodology Chapter.

Against this background, the main question of this study is defined as follows:

How do self-organising networks either support or constrain coordination in large construction projects?

Methodologically, coordination will be evaluated by examining the constitutive elements of the self-organising networks in the BSCU project (as processes), and thereafter determine the impact of their structural changes through calculating the efficiency and cost measures of communication (as evaluative outcomes/consequences). The synthesis of self-organising networks in the BSCU project will be investigated by employing various network analysis methods applied at different levels of analysis, as follows:

1. **Micro-Level:** the investigation of the role of individuals in project self-organising networks;
2. **Meso-Level:** the study of the structure of clusters, underlying interactions, and decision-making strategies;
3. **Macro-Level:** the analysis of the whole self-organising networks at two different project stages. A comparative analysis will be conducted to understand the change in the structure of the two networks, and how this is translated in terms of efficiency and cost (as evaluative outcomes/consequences).

The analytical framework of the thesis will be organised by following the levels above. They constitute the research sub-questions that are to be investigated.

The knowledge gap of this study will be established by conducting an extensive literature review in the areas of Complexity Theory and self-organising networks. The aim is to provide an account of the published literature and previous research which in turn will help to identify where this study fits into and how it adds to the existing body of knowledge. For the purpose of this chapter, some introductory summary on knowledge gap is provided next.

1.4 Knowledge Gap

Although there is a growing body of research that is concerned with Complexity Theory and self-organising behaviour, very little has been done to focus on construction project networks. As a result, there is a lack of awareness and understanding on how these systems are established and coordinated, how they evolve and decay, and the changing nature of roles that are acquired to support or constrain the design and delivery of large projects. The dearth of research means self-organising project networks are usually not facilitated or managed in practice.

This study aims to bridge the knowledge gap by demonstrating how the concept of managing self-organising networks can be located within a context of managing complex projects. The key contributions are as follows:

- Enriching the research of self-organising networks within the construction industry, specifically in the infrastructure sector. This will be achieved by empirically analysing a case study of a large complex project using Social Network Analysis (SNA) tools and techniques;

- Proposing a theoretical framework to the study of large construction projects that is based on the world of complex systems. This framework will introduce the concept of self-organising networks to Complexity Theory as an internal complementary critique in the sense that:
    - Self-organisation expands application of Complexity Theory by taking into the account the informal interpersonal relationships. Such complementarity helps explain how things work in a broader system (covering both formal and informal relationships) that is not always recognised, especially in project management;
    - The important feature of self-organisation is its capacity to transform to accommodate higher levels of complexity (McMillan, 2006; Capra, 1996). For example, projects, at procurement stage, are usually aligned with the contractual conditions, whereas, at delivery stage, they transition to be largely reliant on non-contractual networks of individuals working together to realise project-related common goals (Pryke, 2012). Self-organisation, therefore, is conceptualised as the vehicle by which uncertainty and complexity are reduced in projects;
    - The study of self-organisation highlights the importance of social aspects as a factor affecting the establishment of effective project delivery networks and their evolution and maintenance over time. Therefore, the concept of complex systems is complemented by recognising that socialisation is important in forming relationships in the complex and uncertain environments that most large construction projects constitute;
    - The concept of self-organisation provides the opportunity to link Complexity Theory with the study of project networks. This allows exploiting social network analysis (SNA) as an analytical method, which consequently offers the possibility to transform Complexity Theory (which has a high level of abstraction especially for the practitioners) into an applied science.

- The study of self-organisation gives precedence to ongoing change over stability. This necessitates challenging the predetermined and prescribed forms of organisation and rational-based project management approaches. It entails understanding how people collaborate to deliver projects rather than being constrained by hierarchical-based terminologies or an array of discrete systems, such as those dedicated to the management of value or cost or design;

- Drawing upon the principles of Complexity Theory, self-organising networks are defined as emergent structures; they form as a result of the agents' local interactions. In turn, this establishes a good understanding of the interdependencies between the local levels (e.g. daily interactions occur between a number of individuals) and global patterns (e.g. network performance[4]).

1.5 Research Core Premises

Accepting Complexity Theory as the main theoretical framework for this research entails recognising the key Core Premises (CP) that guides this investigation. These are drawn from the theoretical framework that will be explained in detail in later chapters:

CP1: Large construction projects to be perceived as complex systems;

CP2: In projects, self-organisation can be observed by key events, dramatic change in the network structure, changing actor roles, and output performance;

CP3: The new self-organised structure has a higher adaptability than the original formal structure;

CP4: The performance[1] of the new self-organised structure is higher than those of the original formal structure;

CP5: The resilience level of a system varies from one situation to another even if the parameters remain the same because of the nonlinearity and discontinuity of relationships, where changes are not proportional; small changes in one of the elements can result in dramatic overall changes.

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[1] In this thesis, performance will be evaluated by measuring network efficiency and cost.

1.6 Research Philosophy and Methodology

In order to set the scene, it is important to provide a summary of what informs this project in terms of research philosophy, i.e. ontological or epistemological perspectives (Hatch and Cunliffe, 2013). This is because research methodology will be shaped by these two views (Hatch and Cunliffe, 2013; Smyth and Morris, 2007).

In an attempt to extend our knowledge at theory-practice interface of project management, the broader ontological debate of this study is that projects are delivered through social networks, comprising of multiple actors responding to the pressures of finding and dissemination information in a highly uncertain environment (Pryke *et al.*, 2018). These networks evolve and naturally decay over time, influenced by actors' interactions and their network position. Hence, this ontology highlights the pervasiveness of change and transformational nature in organisations/networks (Tsoukas and Chia, 2002). The epistemology of the study is how project delivery systems in complex projects can be understood as self-organising networks. From a project management perspective, this approach "*views managing social relationships as a means to manage and add value to, and through, projects*" (Smyth and Morris, 2007, p. 425). Philosophically, this focuses on a 'becoming' ontology (i.e. subjectivism) that 'constructs' project reality based on interpretivist epistemology (Pasian, 2015; Magoon, 1977; Tsoukas and Chia, 2002). This means that projects, and the coordination process, as social phenomena are continually being created from consequent actions of those actors involved (Bryman, 2016; Grove *et al.*, 2018). This view emphasises on issues that reflect the ever-changing and evolving nature of project environment (Pasian, 2015) and the intrinsic flux of human action (Tsoukas and Chia, 2002).

Adopting this research philosophy, this study places huge emphasis on the context of the project being investigated and how it influences and shapes the relationships between the project team, leading to self-organisation as an emergent property. This follows Tsoukas and Chia's (2002, p. 570) 'organisational becoming' perspective in which they place importance on social interactions as the primary locus of social order. Tsoukas and Chia (2002, p. 570) advocate that '*change is ontologically prior to organization*', while '*organization is an outcome, a pattern, emerging from the reflective application of the very same rules in local contexts over time*'. The latter in particular emphasises the local (or situated) character of human agency that constitutes both actions and inactions (Tsoukas and Chia, 2002).

The philosophical perspective that informs this research entails adopting Network Approach to managing and understanding projects. This will be facilitated by Social Network Analysis (SNA) as a research analytical method. Such adoption supports the application of 'bottom-up' interpretivist approach to better understand and manage project networks. By doing so, it provides insights into the invisible self-organising aspects of the projects, focusing on the actors, their activities and interactions, rather than using fixed hierarchical models (Blomquist *et al.*, 2010).

1.7 Outline of the Thesis Structure

The thesis is organised in ten chapters as summarised below:

- **Chapter One: Introduction**

This chapter provides an overview of the thesis. It commences by defining key objectives and research question. The study focuses on understanding the self-organising networks (as a coordination-based research problem) and their role in supporting delivery of large infrastructure projects. The empirical examination is conducted through a large complex project and social network analysis (SNA) provides the means to analyse self-organisation. The chapter, then, gives a summary about research knowledge gap, its significance and contribution, research core premises, and philosophical and methodological approach. It highlights that very few researches used the concept of self-organising networks to study construction industry. These networks are largely not managed in practice. This provides an opportunity to extend our knowledge at theory-practice interface of project management. The chapter concludes with the thesis outline and a resume of the chapters' contents.

- **Chapter Two: Theoretical Context**

This chapter along with Chapter Three form the central trunk of the study from which the other chapters branch off. It presents the first part of the theoretical framework. It starts by reviewing the relevant literature in the field of project management, in particular systems theory as the predecessor of Complexity Theory (CT). It then discusses the knowledge gap in the study of large construction projects by arguing that project management has not kept pace with rapidly increasing complexity in projects. Key underlying concepts of CT are explained highlighting their potential to provide a better understanding of the relationships in project organisations. The discussion turns to the self-organisation, putting great emphasis on the conceptualisation of projects as evolving self-organising systems. It stresses on the need to focus upon relational and social aspects of projects as a means of understanding the non-linear, complex, iterative and interactive processes that projects constitute. In this way, it sets the scene to propose a network approach to understanding projects.

- **Chapter Three: A Network Approach to Understanding Projects**

This chapter presents the second part of the theoretical framework. By reviewing the key reports about the UK construction industry since 1930s, the chapter argues that there is a significant number of recurring issues that are yet to be addressed. It further argues that the currently used analytical and presentation approaches in the study of large construction projects have a number of shortfalls. It, therefore, explores the contextual drivers for a network approach to analysing construction project systems. It discusses why social network analysis (SNA) is useful highlighting its benefits and introducing some of the key structural properties of self-organising networks. The chapter also provides a little history about the research carried out on the application of network approach and SNA to construction projects and other industries/disciplines. It highlights that little is known about how the project networks function and form and that very little has been done by industry thus far to identify and manage these invisible networks. The chapter ends with a call for more research using SNA in projects; thereby forming the knowledge gap of the study.

- **Chapter Four: Methodology**

This chapter outlines the philosophical and methodological stance of the study. The research methods are classified broadly as quantitative and qualitative. Social network analysis (SNA) is proposed as the key analytical tool and thus a number of its key concepts and measures are discussed. The chapter also develops a framework to investigate the decision-making processes as a function of uncertainty and amount of resources associated with making a decision. It further presents small-world models to establish a basis for project network costing. This is built on the premise that studying network topography as multi-layered systems would enable achieving higher efficiencies and provide organisational cost savings. Additionally, the chapter provides some details about key project informants, project-related documents, programs used for SNA data analysis and visualisation, and the identification of network boundaries.

The study is sponsored by the UCL Centre for Organisational Network Analysis (CONA) and benefits from an existing Knowledge Transfer Partnership (KTP) dataset. The Bank Station Capacity Upgrade (BSCU) Project is chosen as the focus for this study. A case study approach is, therefore, adopted; reasoning for which is highlighted. The chapter discusses the sources of data, the key challenges and ethical considerations. The Methodology Chapter concludes by proposing a road map for the analysis chapters to follow.

- **Chapter Five: Introduction to BSCU Case Study**

This chapter provides a description of the case study, the Bank Station Capacity Upgrade (BSCU) project. It is the introduction of the following detailed empirical analysis, aiming to familiarise the reader with the key features and context in which BSCU project operates. It is a two-year research project in collaboration with Transport for London (TfL), comprises a rail infrastructure interchange upgrade costing approximately £563m, and uses a novel procurement approach. The chapter provides a high-level analysis, describing the formal organisational structure in comparison to project informal communication networks.

- **Chapter Six: Micro-Level Analysis – *"The Roles of Individual Actors"***

This is the first chapter of the detailed analysis. It investigates the roles of individual actors, being the most basic element in forming project-based self-organising networks. Methodologically, network roles are investigated using SNA centrality measures, namely: degree centrality, eigenvector and betweenness. The chapter illustrates that roles of individual actors are defined based on their positions within networks. These roles are quite different than those defined by formal contracts. A multi-level classification of the measures is developed, providing further insights into the different types of network roles. The chapter argues that an understanding of these roles is important in pursuit of successful project outcomes. In this context, it suggests individuals may perform very effectively or may be quite dysfunctional (i.e. disrupt the functioning of project networks).

- **Chapter Seven: Meso-Level Analysis – *"Self-Organising Clusters"***

Stemming from the theoretical framework that suggests that projects are delivered by a range of activities that are essentially hidden from view, this chapter deals with the study of clusters in projects. Empirical analysis reveals that there are seven self-organised clusters embedded within BSCU network. These represent groups of actors who are densely connected and are centred on problem-solving. They are formed in response to the need to gather and exchange information. These clusters are inter-organisational/cross-functional, i.e. not related to the organisational/hierarchal formal chart. Furthermore, they evolve and decay over time. Interestingly, the investigation of decision-making demonstrates an interplay between different types of strategies. This explains the extent to which social processes are used, which ranges from autonomous actions to social integration, in response to uncertainty. The chapter concludes by exploring the inter-cluster relationships and how these can form multi-functional communities/themes. A number of potential benefits associated with these themes are highlighted.

- **Chapter Eight: Macro-Level Analysis - "Whole Network Advantages"**

The analysis of this chapter is built on the small-world (SW) network topology. It investigates the cost and efficiency measures of a network from a multi-level perspective. It takes into account the understanding of project networks as Complex Adaptive Systems (CAS), which in turn comprise interrelated levels of interactions. Investigation of BSCU network dynamics highlights the importance of its local properties in determining the emergent global outcomes. For example, re-orientation of actor positions can enhance network resilience and improve the flow of information. It, therefore, suggests that some aspects of project-based communication networks can be optimised by exploiting their self-organising features. The chapter concludes by suggesting that project managers should consider network interventions to speed-up the process of forming relationships and reduce any disproportionately high costs.

- **Chapter Nine: Discussion**

This chapter reflects on the preceding analysis chapters. It discusses the findings of the study and proposes a response to the research question. It argues that hierarchical approach to the analysis of large and complex projects is actually quite limiting and restricts our understanding of relationship structures. Alternatively, the study shows how a number of SNA-based results signify the importance of self-organising networks as a way to manage large construction projects and understand how they are actually delivered.

- **Chapter Ten: Conclusions, Limitations and Future Work**

This is the final chapter of the study. It synthesises the key conclusions, sets out the limitations of the study, highlights opportunities for future research and proposes key contributions. The chapter is then followed by a complete bibliography and reference list and supported appendices.

Next, theoretical context of this study is presented, highlighting the key concepts informing the analytical research to follow.

2

Theoretical Context

2.1 Introduction

Complexity can be managed. Failure to manage complexity sufficiently can lead to chaos. The words "complexity" and "chaos" or "noise"[2] are used daily to describe a lot of situations around us. Yet, very few people have ceased to ask what these words truly mean and what the science of complex systems might contribute to our understanding of and responses to unexpected events, dynamic situations and emerging issues in projects. This chapter provides the foundation for the theoretical framework and the context for the detailed discussions that will follow in later chapters. It commences by giving a historical background and prelude, including a discussion on social systems theory, and then it goes to identify Complexity Theory as the theoretical underpinning of this study. The chapter aims to demonstrate how a better understanding of the construction environment settings can be established through the lens of Complexity Theory and its key underlying concepts. Self-organisation is married with Complexity Theory to form the research niche area.

2.2 Origins and History

Monsanto *et al.* (2013) highlights the need to have a better-developed theory relating to the study of projects. Winter *et al.* (2006) suggest that this entails moving away from relatively abstract conceptualisation of project activities towards a more practice and practitioner position. As a starting point, Pryke (2017) suggests looking into project organisations. These can be viewed as phenomena 'embedded' within organisational theory as argued by Borg and Söderlund (2014). Organisations lack universal definition as they *"have evolved within the context of various cultural values and institutions throughout history"* (Wren, 1972, p. 13). Nevertheless, they can be defined broadly as *"social unit(s) with some particular purposes"* (Shafritz *et al.*, 2005, p. 1).

The history of how organisations can be explained is rooted in the early work of Adam Smith, i.e. *The Wealth of Nations* (1776). By providing an example about a pin factory, he identified the concept of division of labour as a source of productivity gains. This concept relates productivity to the specialisation of the labour force. It suggests that efficiency can be increased if a task was broken down into smaller parts and then carried out by different specialised workers. In 1911, Taylor's *Principles of Scientific Management* were published in response to the calls to increase the United States national efficiency by then-President Theodore Roosevelt. Taylor worked systematically and was one of the first researchers to study the work process scientifically, introducing four principles, namely:

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[2] The terms "chaos" and "noise" are used interchangeably in this thesis.

- Using scientific methods to determine the most efficient way to perform specific tasks;

- Training and developing of the workman;

- Monitor performance and providing instructions and supervision; and

- Equal division of the work and the responsibility between the management and the workmen.

Taylor's scientific school, however, conceptualises organisations as machine-like distinct activities, giving very little research into the use or effects of social activities.

The post-World War II economic expansion led to introduction of new products and industries. This was accompanied by a higher recognition of the 'informal' aspects in project management thinking. For example, the work of psychologist Maslow (1943) formulated a theory of human motivation. He proposed a five-tier model of human basic needs, namely: physiological; safety; love/belonging; esteem, and self-actualisation. He stated that individuals are motivated to achieve certain needs and that some of these needs take precedence over others. Similarly, around 1960s, the psychologist Fredrick Herzberg developed his Motivation-Hygiene Theory (Herzberg *et al.*, 1959; Herzberg, 1966). He suggested that certain characteristics of a job are related to job satisfaction (e.g. achievement, recognition, advancement), whereas different factors are associated with job dissatisfaction (e.g. salary, status, supervision, work conditions). He further highlighted that the factors leading to job satisfaction are separate and distinct from those that lead to job dissatisfaction. These studies, however, are quite generic in explaining human behaviour and they regarded social interactions as an additional 'informal' activity rather than as being at the very core of what humans do.

Blau and Scott (1962) presented a new focus of interest - types of organisations. They examined the social structure of work groups, highlighting that organisations are structured along informal channels of interaction. These informal organisations are largely influenced by the formal structure of an organisation, yet they are distinct from each other. The idea of informal organisation is built on the work of the German sociologist Simmel (1908) concerning relational method of social research. Simmel defined these structures as emergent social forms, arising from the interaction between individuals to satisfy their needs. Simmel's ideas of interconnections among social actors have been influential in forming a foundation for the conceptualisation of organisations as networks and thereafter social network analysis (SNA). According to Scott (2017), this branch of knowledge was developed by three main schools of academic endeavour:

- A U.S.-based group working in the field of social psychology and psychotherapy during 1930s. They were explaining group dynamics in terms of their structure and information flows. This was explicit in the work of Moreno (1934) who investigated the field or space of social relations, referring to it as 'sociometry'. He invented the sociogram as a way of visually representing social networks with lines and points.

- The 'Harvard Group', comprised a team of anthropologists and sociologists. They were exploring the informal interpersonal relationships and formation of sub-groups in the workplace. Their contribution is considered critical due to their use of sociograms.

- In 1950s, a group of social anthropologists at the University of Manchester who studied African societies. They were interested in analysing the tribal conflict and divisions within communities. This work proposed exploring community relations when looking at the structure of large groups.

In 1960s, SNA developed into a coherent body of knowledge. It is essentially a form of structural analysis, employing a number of mathematical and graphical tools to study what otherwise might be regarded as largely qualitative data (Pryke, 2017). Initially, development of SNA paradigm was led by Harrison White (1963) who used algebra to represent kinship structures, outlining a method to reduce family types to their primary roles. Network theory was developed further by a group of White's students and associates. The most prominent one is Granovetter (1973) who distinguished between strong and weak ties. His article *"The Strength of Weak Ties"* (1973) investigated the topic of job search. The empirical findings showed that weak ties are important for obtaining professional-level jobs. This was quite counterintuitive, but he argued that weak ties play a crucial role in bridging social distance and thus achieving system integration. They can provide access to different and unfamiliar circles of information. At the same period, major contributions to the mathematical side of social network theory were made, such as the work of Barnes (1974) on graph theory and Kruskal's (1964a and 1964b) work on multi-dimensional scaling, hence providing the mathematical techniques to network and cluster analysis. Later, a number of graph measures were introduced such as the work of Freeman (1979) who proposed the three groups of centrality measures - degree (captures an actor's communication activity), closeness (reflects an actor's ability to access independently all other members of the network), and betweenness (reflects the potential for control of communication). He defined these as a function of direct and indirect connections and explained how they can be applied and understood. More importantly, his work provided new insights into the definition of network roles.

Another example, is the work of Laumann *et al.* (1989) on how network boundaries are defined, addressing a particular methodological problem in social networks. They made a distinction between realist approaches (based on the subjective perceptions of actors) and nominalist approaches (taking an observer's standpoint). Another fascinating work is Burt (1992) who introduced the concept of structural holes of social capital. He suggested that, in social networks, access to advantageous structural positions is not equally distributed across all actors. Therefore, individuals with more structural holes (i.e. those who are positioned at the interface between multiple groups) benefit from access to nonredundant sources of information originating in hard-to-reach noninteracting parts of the network. Structural holes also provide control benefits as a result from the ability to either play two unrelated parties out against each other or to bring them together. In order to reap these benefits, structural-hole concept assumes that actors are strategically and proactively creating and manufacturing their social network.

The work of Wasserman and Faust (1994) provided what amounts to an encyclopaedia of social network terminologies and their mathematical formulae. This is a recommended reference text for a novice reader. This period also brought about a wealth of software programs enabling the fast calculation of a wide range of SNA measures and visualisation of social network data.

Network theories have often been criticised for not being able to explain the emergence of collective action (Salancik, 1995). This turns the attention to a discussion of systems theory, as the foundation of Complexity Theory.

2.3 Systems Theory as the Predecessor of Complexity Theory

The notion of systems is as old as European philosophy. This is reflected by Aristotle's statement that *"the whole is more than the sum of its parts"* (von Bertalanffy, 1968, p. 55), highlighting the definition of the basic system problem. However, systems theory has only become established by the middle of the twentieth century. Systems theory was first introduced in the 1940s by the biologist Ludwig von Bertalanffy. It lacks a universal, formally agreed upon definition because it has been used in a variety of disciplines; hence leading to have multiple meanings (Stichweh, 2011). However, the central concept it embodies is the idea of a set of elements connected together, which form a whole with emergent properties that are distinct from its component parts (Walby, 2003). For example, vision is an emergent property of different interacting organisms (i.e. the eyeball, brain and nerves) but none of these organisms alone can see (Chapman, 2011). The emergent properties can be described by the following aspects:

- Collectively, a system, that is comprised of connected interacting components will have qualities and features that cannot be represented by the sum of its components in silo (Chapman, 2011);

- Such properties are not possessed by the individual components and will be lost once the system is disintegrated/destroyed (Fern´andez *et al.*, 2013);

- The type of properties is unique from the types of the underlying components (Auyang, 1999);

- The behaviour of emergent properties is not a function of the patterns of the underlying components separately, and thus they are inherently unpredictable or deducible (Gloag *et al.*, 2015);

- Before encompassing the whole system and becoming its global patterns, emergent properties are brought about as a result of the interactions between the system's components at their local/micro levels. Nevertheless, emergent properties are not cumulative and not proportional to the underlying interactions (Helbing *et al.*, 2009);

- The future of the system is determined by such properties, not by studying its components and their interactions (McMillan, 2006).

Systems theory was introduced as a general conceptual field of inquiry (commonly referred to as General Systems Theory) in response to the increasing fragmentation and duplication of scientific research approaches in the first half of the 20th century (Stichweh, 2011). At this time, Lilienfeld (1978) highlighted that a bundle of new theories was introduced to the study of organisations, such as information theory, theories of games, theories of decisions, systems analysis, systems engineering. In reality, however, research problems usually involve investigating different areas and disciplines. Therefore, it was difficult to compartmentalise these problems into a large number of tightly bounded theories. Acknowledging this issue, Ludwig von Bertalanffy (1968, p. 38.) highlighted the need to develop *"unifying principles running vertically through the universe of the individual sciences"*. These individual theories might have different assumptions, mathematical techniques and aims, but they are all concerned, in one way or another with the study of systems. He suggested, therefore, that *"integration seems to be centered in a General Theory of Systems"* (von Bertalanffy, 1968, p. 38.). General Theory of Systems provides an overarching body of systematic theoretical constructs rather than seeking to establish a single, self-contained general theory of everything, or replace all the special theories of particular disciplines (Stichweh, 2011). As described by Boulding (1956, p. 208) *"General Systems Theory is the skeleton of science in the sense that it aims to provide a framework or structure of systems on which to hang the flesh and blood of particular disciplines and particular subject matters in an orderly and coherent corpus of knowledge"*.

The key advantage of systems theory in problem solving is that *"it does not require a priori understanding of the detailed mechanisms of the underlying processes in the system"* (Jayawardena, 2014, p.1). Therefore, it has the potential to provide a knowledge framework that can be applied across various disciplines to study heterogenous and diverse types of systems, focusing on structures, relationships, and interdependencies between elements (Katz and Kahn, 1978). Another important aspect of General Systems Theory is the distinction between open and closed systems (Stichweh, 2011). Theories of organisations embracing the closed systems approach assume that the main features of an organisation are limited to its internal elements. This view, therefore, considers most of the interaction between the external environment and the organisation as inconsequential (Walby, 2003). This approach is more relevant to the study of mechanical systems (Stichweh, 2011). Systems theory, on the other hand, views organisations as open systems whose interaction with the external environment is vital for their survival and success (Walby, 2003). For example, organisations depend on their environments for several essential resources, such as customers, suppliers, investors, and governments. Open-systems approach is more relevant to the study of biological and social systems (Stichweh, 2011). This perspective stipulates that a system comprises individual elements or sub-systems that exhibit patterns of interconnection and interdependence (Chapman, 2011). Systems theories are based on the premise that individuals do not operate in isolation, but rather grow and develop in interaction with their environment. That is, *"the behaviour of each element has an effect on the behaviour of the whole; the behaviour of the elements and their effects on the whole are interdependent; and while subgroups of the elements all have an effect on the behaviour of the whole, none has an independent effect on it"* (Amagoh, 2008, p. 2). This leads to a discussion of 'Social Systems Theory', which is explained next.

2.4 Social Systems Theory

The use of 'system' as a concept was largely limited in sociology until the time of Talcott Parsons. This is due to the early belief that system-led explanations are inherently incapable of addressing human actions (Walby, 2003). Nevertheless, there were still few theories which implicitly or explicitly *"addressed the social within a large framing, invoking some kind of concept of social system"* (Walby, 2003, p. 2). For example, Marx (1954) viewed capitalism as a system that consists of two parts – the base (comprises the forces and relations of production) and the superstructure (social institutions, such as the law or politics, that are determined by the economic base); Durkheim (1966) was concerned with a society, theorising that the social level was not to be reduced to that of individuals, but constituted a level in its own right; and Weber (1958) who was interested in religion as a distinct world from the political and economic systems.

Talcott Parsons was the first to ground sociology in systems thinking in an attempt to formulate a systematic theory in the study of human activity, sometimes referred to as grand theory (e.g. Mills, 1959). This was driven by the need to come up with an alternative approach to understanding social and psychological phenomena that tend to resist quantitative modelling given the difficulties with boundary identification (Laszlo and Krippner, 1998). That is, the line that separates the aspects of a system from those of its environment tends to blur as the unit of analysis moves from natural and physical systems to human social systems (Laszlo and Krippner, 1998). This is because social and human activity systems usually do not have clear-cut and agreed upon aims or purposes; they tend to have multiple and overlapping purposes and even when agreed upon, these may change over time (Walby, 2003). Parsons found systems theory suitable for accommodating the multiple interaction of components by abstracting from certain details of structure and component (Stichweh, 2011).

Parsons' work (1949, 1951) conceptualised systems as nested structures, i.e. the characteristics, functions, properties, and relationships are studied without distinguishing whether they are internal or external to the system. More interestingly, he presupposed a general four-function scheme (AGIL) that all social systems must perform to survive, maintain and form social systems (Stichweh, 2011). These are as follows: adaptation to environment (involves search and acquisition of resources), attainment of goals (the setting and achievement of goals), integration of parts (cooperation and coordination among the parts of a system) and what Parsons calls latent pattern maintenance (the ability to maintain and reproduce the common values and practices over succeeding generations). Additionally, Parsons defined social systems as a network of subsystems (in terms of parts and wholes) that are decomposable in terms of action units (Heckscher, 2009). This view postulates the subsystems are interrelated thanks to the exchange (input-output) processes between them; without which systems cannot procure the resources necessary for their stability and functioning (Amagoh, 2008). He further suggested having an exchange medium which facilitates the transfer of resources (e.g. money in economic systems, power in political systems, and information in communications system). Parsons also suggests that there is a connection between a system and other systems within its environment. He called this "interpenetration" or what Maturana and Varela (1980) called "structural coupling" and it implies that one system provides another system with structural support (Görke and Scholl, 2006). For example, the economy (as a system) has to take laws (as another system within the same environment) into consideration for their own operations, but laws do not determine economic operations.

Parsons' article "*Some Ingredients of a General Theory of Formal Organization*" (1969) explains how his theory can be applied in the study of organisations. He specifies that organisations are open systems but differentiated from other social systems by their orientation towards the attainment of a specified goal; which goes beyond the limits of individual actors. His theory is concerned with ''structural-functionalist'' model of organisations, i.e. starting with the structure of a system and then exploring which part functions to maintain the structure (Görke and Scholl, 2006). In this view, individuals are discussed as taking on various roles and carrying out actions to fulfil certain system functions. Parsons (1960) further conceptualises organisational structures as hierarchical systems, classifying them into three levels of analysis, as follows:

- **The technical system:** this is the bottom level. It is concerned with tasks and activities used for the development of goods and services. It comprises people, machines, and processes. It is heavily dependent on information and resources to acquire new technologies and ensure goods and services are compliant with client's requirements, quality and other standards.

- **The managerial system:** this comes above the technical system, mediating between the organisation and task environment. This level is concerned with tasks of analysis, design, and redesign of the organisation, such as strategies, rewards and recruiting.

- **The institutional system:** this is the top level and relates the organisation to its function in the larger society. It is concerned with the social, political, cultural, and economic contexts of the organisation's environment.

In the broader sense, Parsons suggests that the technical system is controlled by the managerial system, which is in turn managed by the institutional system. However, given the functional differentiation, this control is not a one-way relation but rather every system supports the needs of other systems within the organisation (Casey, 2002). It, therefore, theorises that *"no organisation is ever wholly independent"* (Parsons, 1969, p. 199).

Having reviewed systems theory in detail, its critique is presented next.

2.5 Critique of Systems Theory

Parsons' systems-based thinking applied to sociology was primarily focused on the problems of order, stability, control, and continuance (Stichweh, 2011). As a consequence, the concept of 'system' in sociology was mired in the notion of a self-balancing equilibrium, i.e. returning to balance after being under pressure to change (Amagoh, 2008). This perspective has a difficulty in sufficiently dealing with conflicts, power inequality, diversity, possibility of dysfunctions, and sudden change (Walby, 2003). These issues relate to uncertainty and thus Parsons theory does not nurture organisations with appropriate responses under ambiguous and uncertain situations (Walby, 2003). Parsons theory also requires specifying precisely what is meant by a system and the level of analysis; it assumes that boundaries between the organisation, its sub-systems and its environment are distinct but, in reality, these boundaries usually overlap each other.

Parsons' hierarchic view is rigid and static; it fails to give a sufficient account of change and does not recognise the fact that social organisations are contrived systems. This is because it is based on a literal analogy between living organisms and organisations (Stichweh, 2011). Systems thinking, therefore, largely understates some characteristics which are vital for social organisations, such as that organisations can be established for a variety of reasons and do not necessarily follow the life-cycle patterns of birth, growth, maturity, and death as biological systems (Walby, 2003). Parsons theory suffers from a macro-bias in the sense that the notion of systems stands for the enforcement of a special kind of top-down hierarchy control rather than for the individuals and their freedom to act (Görke and Scholl, 2006). From this perspective, management in organisations is identified as the control centre, overestimating their power to control events and actions and manage change (Amagoh, 2008). Additionally, the dichotomy between closed and open systems is difficult to apply to social organisations. Most of these systems are "partially open" and "partially closed", i.e. "open" and "closed" are a matter of degree (Walby, 2003).

Recognising the shortcomings of systems theory, Luhmann shifted the focus from the conditions of stable systems to the dynamics of the emerging structures. This is discussed next.

2.6 Social Theory of Niklas Luhmann

The work of Luhmann (1985, 1990, 1995, 2000) marked the second wave of social systems theory and provided the researchers with a theoretical framework to study less hierarchical organisations. Luhmann published his major theoretical framework in 1984 under the title *Social Systems*[3], highlighting his rejection of the assumption of self-balancing equilibrium and focusing on dynamic processes. The two key contributions to the re-theorisation of systems by Luhmann is the distinction between a system and its environment together with the understanding of systems as self-organising and self-reproducing[4] (Walby, 2003). The key implication of this for empirical research is the shift towards analysing the function of a part for the reproduction of the whole system instead of focusing on functionally presumed structures.

Luhmann re-identified the relationship of a system to its environment in the sense that he does not acknowledge any external position or control (Görke and Scholl, 2006). Drawing upon the concept of order-from-noise coined by von Foerster (1981), Luhmann stated that *"without noise, no system"* (Luhmann, 1995, p. 116). Noise (or sometimes referred to as chaos) can, therefore, be seen as the space in which order is both possible and improbable (Görke and Scholl, 2006). This means that systems constitute themselves by partially overcoming meaningless noise/chaos, i.e. through differentiation from their environment and other systems rather than unity (Stichweh, 2011). From this perspective, noise/chaos is not just an outside to orderly systems, but the unstable ground of always changing orders (Nassehi, 2005). The formulation of social systems can be understood as specific selections of possibilities (Görke and Scholl, 2006). Luhmann's approach therefore is different than Parsons' as it does not presuppose a set of prerequisite basic functions (i.e. AGIL).

In contrast to Parsons' (1951) concept of 'part and whole' and Marxist (1967) concept of 'base-superstructure' that suggest some kind of hierarchical relationships and the necessity that sub-parts of systems are nested, Luhmann does not entail a presumption of hierarchy between inter-connected systems. This was facilitated by adopting the concept of 'encompassing systems', i.e. each system has, as its environment, all other systems (Stichweh, 2011).

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[3] The book took 11 years to be translated into English (cf. Luhmann, 1995).

[4] Luhmann was inspired by the work of Maturana and Varela (1980) that proposes systems have internal processes to internally connect and reproduce the system. These features are called autopoietic. Autopoiesis is *"a network of processes, in which each component participates in the production or transformation of other components in the network. In this way the entire network continually re-makes itself. The system is produced by its components and in turn produces those components"* (Walby, 2003, p. 6&7).

Following a dialectical logic, Luhmann suggests that systems can be described as operationally closed but they are open to their environment (Görke and Scholl, 2006). In this context, closure *"does not mean that such systems are not able to experience contact with their environments but that the only mode to get in contact is based on their own operations"* (Nassehi, 2005, p. 181). External contacts, therefore, cannot determine the operations of and within the system unless they are related to the internal processes (Görke and Scholl, 2006).

Luhmann started systems theory anew, following ''functional-structural'' model (Stichweh, 2011). This is because, unlike Parsons, structure has a secondary status within Luhmann theory; systems are characterised as heterarchically[5] organised and have a functional orientation to solve specific problem (Nassehi, 2005). Luhmann defines hierarchy as a special case of differentiated systems. As a result, social phenomena, such as interactions, organisations or societies, can be decomposed as autonomous systems with specific function (Stichweh, 2011). Luhmann conceptualises social systems as operating units that produce both their problems and functional solutions; hence moving from the conception of systems in terms of parts and wholes that often regards problems as an external framework (Nassehi, 2005). Functions themselves are not ontologically given entities but serve to solve problems (Walby, 2003).

Organisations, in view of Luhmann, are defined as networks of decision communication which reproduce themselves, emerging in time from one event to another (Görke and Scholl, 2006). That is, the only mode of operating for an organisation is communication but with the condition of connectivity (Nassehi, 2005). The latter means in order for an organisation to emerge and persist, each new decision must be connected to previous decisions and also enable subsequent decisions. Organisations, therefore, can be designated as decision machines (Nassehi, 2005). However, they do not depend on actors within them because individuals, as decision makers, can leave their organisations but their decisions continue to influence subsequent decisions and shape their systems for long periods of time (Görke and Scholl, 2006). Luhmann further clarifies that individuals are not the organisation itself because organisations as social systems are different from human beings who are considered psychic systems. The presence of individuals, however, is a necessary condition for interaction systems (Nassehi, 2005). Luhmann, therefore, does not reject the participation of human actors in the process of communication but gives emphasis to the conceptualisation of organisation as social processes.

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[5] To put it simply, a heterarchy is a system with elements that are unranked (non-hierarchical) or where they possess the potential to be ranked a number of different ways (Crumley, 1995).

Luhmann integrated notions from Complexity Theory into social theory (Knodt, 1995). However, the toolkit of complexity thinking that Luhmann used was quite limited and sometimes not explicitly expressed (Walby, 2003). Furthermore, the high level of abstraction at which his work was pitched meant that there is a lack of practical application (with some exceptions such as Luhmann 1985 and 2000 that studied law and art respectively). Walby (2003) argues that post-Luhmann there has been a hiatus in the development of social thinking about large scale processes and systems. She further argues that Complexity Theory within the natural and mathematical sciences has proceeded apace on these issues. The original contribution of this study is to apply Complexity Theory to the study of large projects. Nevertheless, it is acknowledged that Complexity Theory is not a single coherent body of knowledge but is constituted by a range of different traditions and approaches, and thus the focus of this study is on conceptualisation of systems as self-organising. This is discussed next.

2.7 Complexity Theory Leading the Paradigm Shift

Complexity Theory has grown enormously since the mid-twentieth century, evolving from several major knowledge areas, such as: mathematics, physics, biology, economics, social science, and computational intelligence (Mitleton-Kelly, 2003). It is a broad theory that comprises numerous concepts and tools. It was initially developed from systems theory, but then underwent a series of modifications (Heylighen *et al.*, 2006). Figure 2.1 summarises, in a chronological order, the leading theories and emerging paradigms within complexity science. For example, the early discovery of the principles of chaos by French mathematician Henri Poincare showed mathematically that *"small differences in the initial conditions produce very great ones in the final phenomena. A small error in the former will produce an enormous error in the latter. Prediction becomes impossible, and we have a fortuitous phenomenon"* (Crutchfield *et al.*, 1986, p. 48). This was followed by the "butterfly effect" which reflects the findings of meteorologist Edward Lorenz (1963), explaining the weather modelling based on chaos. Langton (1989) and Kauffman (1993) have used the same principles to enhance understanding of cell behaviour and population ecology. Despite the momentum of Complexity Theory (CT), it has no universally accepted definition (van Eijnatten, 2004; McMillan, 2006). Heylighen (1999) criticised this:

> *"Complexity has turned out to be very difficult to define. The dozens of definitions that have been offered all fall short in one respect or another, classifying something as complex that we intuitively would see as simple, or denying an obviously complex phenomenon the label of complexity. Moreover, these definitions are either only applicable to a very restricted domain, such as computer algorithms or genomes, or so vague as to be almost meaningless".* (Heylighen, 1999, p. 3)

The key benefit of adopting Complexity Theory lies in its ability to offer a new set of conceptual tools that can help explaining the diversity of and changes occurring in large-scale systems. It focuses on how parts at the micro-level can affect emergent behaviour and overall outcome at the macro-level (McKenzie and James, 2004). Complexity Theory rejects the Newtonian/mechanical ontological models, which assume linear causality between events and effects (Ferlie, 2007). It postulates that reality is characterised by discontinuity, anomalies and continuous change, given the involvement of many interacting parts (Carroll and Burton, 2000). These fundamental underlying assumptions entail the predominance of disorder, instability, nonlinearity, and unpredictability, as governing forces, over the simplified view that suggests reality is controllable, linear, and predictable (Helbing *et al.*, 2011; Heylighen *et al.*, 2006).

Another core feature of Complexity Theory is its rigorous ability to provide a platform that facilitates theoretical integration and an interdisciplinary approach to the problem, leading the existing paradigm shift from the reductionism and determinism-based[6] approaches that view situations as a product of simplified, limited and isolated causes and effects (Cooke-Davies *et al.*, 2008; Fern´andez *et al.*, 2013; Geraldi, 2008). Unlike systems theory that tends to privilege just one ontological level, whether the system, discourse or individual, Complexity Theory provides an ontological depth to engage analytically with several ontological levels within a single explanatory framework (Walby, 2003). This is because it is concerned with processes of 'emergence' at different levels and modes of abstraction. For example, it combines an understanding of both individuals and system structures that does not deny the significance of the human subject while yet theorising changes in the social totality (Walby, 2003). The underlying idea to link different levels of analysis is that all complex systems have an inherent tendency to spontaneously self-organise into new forms of order as a result of the individuals' local interactions (Heylighen, 2013). This provides a much more fluid conception of the mutual impact of systems. It enables both keeping the notion of system and the notion of systematic inter-relatedness without pre-specifying, in a rigid way, the nature of their inter-connections. By doing so, Complexity Theory can grasp the dynamic processes in organisations (McElroy, 2000), providing new developments in the conceptualisation and theorisation of systems.

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[6] Reductionism can be defined "*as epistemology that explains new properties of a system and the whole as the agglomeration of its parts*". On the other hand, determinism can be defined as "*a mechanistic and rigid epistemological approach that argues that an event or a sum of events necessarily results in a certain way and in a certain output*". Hence, no autonomy or some degree of freedom is granted to the system under study and open-endedness and indivisibility are not accounted for (Tsoukas and Chia, 2002), suggesting a generalisable linear relationship of causes and effects (Fuchs, 2003, p. 135).

Theories

1. Chaos theory - Butterfly effect
2. Strange attractors

1. Self-organizations, Dissipative structures
2. Self-organizations, Evolution and complexity

1. Edge of chaos
2. Increasing returns in economics

1. CAS
2. Emergence

1. Complex responsive process of relating

1960s 1970s 1980s 1990s 2000s onwards

Key Researcher

1. Edward Lorenz
2. Edward Lorenz and David Ruelle

1. Ilya Prigogine
2. Stuart Kauffman

1. Chris Langton
2. W. Brian Arthur

1. John Holland
2. Murray Gell-Mann

1. Chris Langton and Ralph Stacey

Figure 2.1: Summary of leading theories and emerging paradigms of complexity science.
(Source: Developed from: Mitleton-Kelly, 2003; Heylighen et al., 2006)

2.8 The Core Concepts in Complexity Theory

In this thesis, it is accepted that Complexity Theory (CT) is concerned with "*the study of the dynamics of complex adaptive systems which are nonlinear, have self-organising attributes and emergent properties*" McMillan (2006, p.25). Its core concepts are discussed as follows:

2.8.1 Complex Adaptive Systems (CAS)

The concept of CAS or multi-agent systems is a crucial pillar of CT. There is no consensus about its paradigm (Gell-Mann, 1994), but Mitleton-Kelly (2003) highlights that these systems are characterised by complex behaviours that emerge as a result of nonlinear interactions among a large number of systems' components at different levels of organisation. Stacey (1996) further suggests that such systems consist of a large number of autonomous individual components called agents, which have the flexibility to represent any range of diverse systems regardless of their internal structure or any mental quality (Heylighen *et al.*, 2006). In other words, the system's behaviour is not determined by its ingredients but rather by the nonlinear interactions between its components. Such interactions are decided by sets of rules that are derived from the local knowledge available at the individual levels rather than the holistic system-wide knowledge (Heylighen *et al.*, 2006; Mitleton-Kelly, 2003). The rationale for these interactions varies according to the situation, however, their primary drive is to satisfy internal needs such as exchange of resources and/or information, and/or in response to an external stimulus in the environment (Cilliers, 1998; Mitleton-Kelly, 2003). Depending on the level and richness of the connections and interdependencies between these agents, the effects of such interactions at the local levels could lead to unpredictable/large-scale change at the system level (Anderson, 1999; Carroll and Burton, 2000). This is because, in complex systems, the effects of such interactions are looped through iterative, nonlinear, recursive, and self-referential feedback networks (Kelly and Allison, 1999; Pascale *et al.*, 2000). This means that any agent's action could stimulate the performance of subsequent action either by the same or other agents (Goldberg and Markóczy, 2000); thus eventually leading to an unexpected change in the overall system (Loosemore and Cheung, 2015; Stacey, 2003). Due to time lags occurred by the feedback networks, the system behaviour cannot be inferred simply from the behaviour of its parts (Padalkar and Gopinath, 2016). This perspective sets up tensions around commitment of resources, including social capital and its related politics. This is because time lags may stimulate competition rather than cooperation in linear processes and perceptions of linearity.

Indeed, such continuous dynamic change could impair the system's internal balance, especially if it happens at short intervals and large number. However, generally speaking, it has been evident that systems do have some internal control processes that can adjust and self-regulate to keep the system's overall equilibrium and stability (Stacey *et al.*, 2000). Interestingly, when there is a profound effect, the system can be pushed towards operating at a state that lies just between order and disorder, called the 'Edge of Chaos' (Kauffman, 1993, 1996). This is a transition phase at the crossroads of either falling into true chaos, which means a full system disintegration (destruction) or reshaping the system by an inner "anti-chaos" force and pulling it back towards order (Stacey, 2003). Reshaping the system, involves a different way of thinking, leading to a fundamental change, creativity and innovation (Stacey, 2003). Figure 2.2, adapted from Stacey (2003) complexity matrix, illustrates the landscape of systems' complexity space based on the degree of uncertainty and level of requirements.
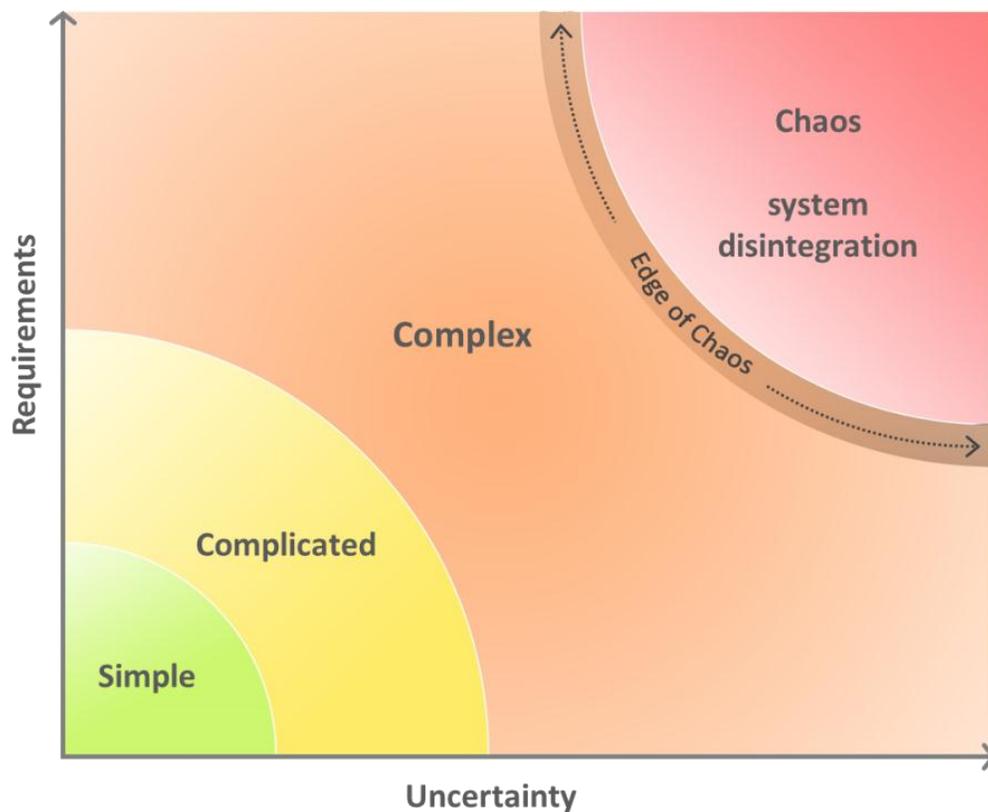
Figure 2.2: The Systems' Complexity Space Landscape Based on the Degree of Uncertainty and Level of Requirements. (Adapted from Stacey's complexity matrix, 2003)

To simplify the concept of 'Edge of Chaos' and work of the inner force for a novice reader, Kauffman (1996) descried it by giving an example of a solid ice cube (which represents a system). When the cube is exposed to heat (external force), it starts to melt. This is because such a living system would not be able to sustain its state, and the only way to survive will be to melt into water, the fluid area. Similarly, if a project's viability and/or its high priority goals were seriously threatened (e.g. by legal action and/or, in extremis, struck by a natural disaster - floods, earthquakes), there would be a high probability for innovation and change to flourish in order for the project to continue to exist (Comfort, 1994).

2.8.2 Chaos

Recently, Project Managers have taken to using the U.S. military acronym VUCA – Volatility, Uncertainty, Complexity, Ambiguity – to describe the environment in which they operate at (Bennett and Lemoine, 2014). "*Volatility reflects the speed and turbulence of change. Uncertainty means that outcomes, even from familiar actions, are less predictable. Complexity indicates the vastness of interdependencies in globally connected economies and societies. And ambiguity conveys the multitude of options and potential outcomes resulting from them*" (Espina *et al.*, 2018, p. 23). From this perspective, chaos is a function of these four distinct challenges. What this thesis tries to pull out is the need for Project Managers and practitioners to think and re-orient themselves in different ways that make no assumptions about basic stability; unfortunately, this is the current way in which knowledge is created and reality is seen.

In project management literature, chaos is also defined against other related yet different concepts, such as turbulence and disruption, whereby the system is challenged yet not at the point of disintegration (Grossmark, 2007). This is similar to the concept of volatility, which is very different from uncertainty and ambiguity in the sense that it does not pose systematic challenges (Carson *et al.*, 2006). Chaos can be usually understood as the negative effect of risks and uncertainties (*known-unknowns* and more radically *unknown-unknowns*) (Winch, 2002). More specifically, in construction projects, chaos is defined as a state "*where the future development of the system is not predictable or only poorly predictable*" (Bertelsen and Koskela, 2003, p. 2). Based on their potential effects, events causing chaos have been traditionally classified into two groups - absorbable events and system-changing events (Bertelsen and Koskela, 2003). The former includes most common events happen in construction projects which, though may result in cost/time overruns and/or compromise quality, are considered a nuisance of short-term nature and can be lived with (Bertelsen and Koskela, 2003).

On the other hand, system-changing events, as the name suggests, affects the overall project functionality and value. They are characterised by a high degree of uncertainty that triggers a change in the system structure as a whole (Bertelsen and Koskela, 2003). Project management practitioners refer to such events as 'critical events' and are viewed as the conditions for change and opportunities to re-negotiate governance (Fabianski, 2017).

However, from a CT perspective, it can be said that there is a built-in problem with such classification - it ignores the transformational nature of the absorbable events. That is, any event, even if it seems minor, can end up being fatal. Events, therefore, should be viewed as a continuum varying by minute degrees but with no obvious tipping point that determines their ultimate potential ripple effect (cf. Repenning *et al.*, 2001; Bertelsen and Koskela, 2003). Hence, this reflects different epistemological and methodological issues to that closely associated with positivism approaches (i.e. the project management paradigm manifested, for example, in the Project Management Body of Knowledge (PMBOK) and the Association of Project Managers (APM)).

2.8.3 Co-evolution[7]

Within Complexity Theory, the concept of co-evolution replaces the notion of a system having a simple impact on another system (Walby, 2003). This is because a system is conceptualised to take all other systems as its environment (Kauffmann, 1996). Systems, therefore, are structurally coupled; they interact with each other and hence co-evolve as they complexly adapt to their environment (Kauffmann, 1996). For empirical research, the concept of co-evolution implies the need to study the mutual impact between systems as a result of their interaction rather than presuming a one-way direction of causality (Walby, 2003).

The key mechanism to enable co-evolution is communication (Nassehi, 2005). A CT perspective of communication considers "information" to be the basic building unit for any system and hence both information and systems have an intertwined existence, i.e. they cannot exist separately or independently (Ying and Pheng, 2014).

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[7] Emergence can be explained as the rise of a systematic phenomenon that cannot be reduced to the individual properties of the system's parts. For example, coordination can be classified as an emergent property. This, however, should not be confused with 'Evolution' which means a system changing its state from one order to another order, usually in order to cope with new requirements or in response to higher levels of uncertainty and complexity. For example, a system evolves its decision-making from centralised to decentralised processes.

Furthermore, CT does not require individual comprehension for co-evolution to take place, i.e. it is not about the acceptance or rejection of a specific meaning that was communicated, but rather it requires systems to cope with their self-made forms of understanding (Görke and Scholl, 2006). This is to say CT necessitates communications to be connected, regardless what is understood or by whom. In light of this underlying simple but radical assumption, the transfer and translation of information are considered as self-referring dynamic iterative systems, rather than viewing them as processes or distinct activities (Ying and Pheng, 2014). Rejection of a specific meaning, nevertheless, may have the consequence of conflict or it just implies the end of communication; thereafter potential disintegration of some systematic forms.

CT suggests that the interactions between individuals produce patterns of inescapable dynamics which influence not only other people in the system but also the originators are being formed by these interactions in a reciprocal manner (Stacey, 2010; Mitleton-Kelly, 2003). This means all involved individuals learn over time through loops of feedback that are introduced at the microscopic levels. Eventually, this leads to having a collective adaptive capacity where the system is able to re-organise itself and hence evolve into another form of order (Stacey, 2003). The concept of co-evolution is, therefore, predicated on communications and interactions between the parties in social systems which usually involves a simultaneous use of implicit and explicit language (Mitleton-Kelly, 2003). This complex interplay could create new information, lead to a reciprocal influence, and result in unpredictable changes in any agents' behaviour, status or ideas, etc. (Stacey, 2010). In essence, complexity nature of large-scale systems entails a reflexive role for both the sender and receiver. That is, a receiver can become a sender when they reply and/or provide feedback. Similarly, a sender can become a receiver when they use the feedback to adapt their messages and learn from the act of consuming the messages. Parties involved in communication being introspective is another key basis for co-evolution. This means both sender and receiver create and interpret the message taking into account the context of their perspectives of, and relationships with each party. The message itself is considered an imperfect representation of what the creator would like to convey. This is because of the expressive limitations of the channel selected and the meaning space provided by the language used. For the same reasons, interpretation of the message is also highly subjective and influenced by the context.

2.8.4 Self-Organising Attributes

"Self-organisation" has been a buzzword in many research fields recently (Heylighen, 2011). Intuitively, it implies that a system not only tends to maintain its stability, but may even evolve and transform itself into a higher degree of complexity and order (Capra, 1996; Kauffman, 1996; McMillan, 2006). It is a unique feature which can be defined as the emergence of global patterns out of the agents' local interactions in a truly collective and coordinated way and without any single agent being in control of the process (Heylighen, 2013; Mitleton-Kelly, 2003). This makes the resulting self-organised configuration more flexible to cope with any internal and external changes/events and have a more stable, yet not static but a dynamic structure that is resistant to damage (Heylighen, 2011).

"Self-organisation" concept has been far-reaching with many applications in different fields of science (e.g. biology, robotics, social networks, telecommunications, and opinion formation). A salient example in economics is the process of balancing demand and supply, which is referred to as the "invisible hand" by Adam Smith (Hülsmann *et al.*, 2007; Helbing *et al.*, 2009). Similarly, CT recognises human communication as a self-organised system in view of its aim to reduce uncertainty and increase mutual understanding, leading to creation of new language and knowledge and enabling problem-solving and decision-making (Stacey, 2003; Weick, 1983). This is because CT suggests an inherent evolving capacity in communication process supported by an intertwinement between information and systems, which in turn leads to emergence of a chain of patterned responses that is known as coordination (Stacey, 2003).

An extensive review of relevant literature suggests the following common characteristics for self-organising systems:

- The process to self-organise is driven intrinsically and collectively, as a joint action by the system's constituents to self-regulate through feedback loops, and does not involve any external intervention (Auyang, 1999; Capra, 1996);
- It plays a critical role in systems' survival and evolution (Cooke-Davies *et al.*, 2008; Goldstein, 1994);
- It requires the internal components to adhere to the system's abstract values and principles which are usually embedded in generally accepted norms, cultural aspects, traditions and customs, e.g. higher level of trust, honesty, openness, mutual understanding, communication (Hülsmann *et al.*, 2007; Prokopenko, 2013);

- It generates a coordinated activity in order to achieve a shared goal and be resistant to any damage (Comfort, 1994; Heylighen, 2011);

- Self-organisation happens spontaneously, i.e. natural by action without any preplanning, controlling, and/or design (Kauffman, 1993; Mahmud, 2009);

- Its consequences are unpredictable as each system is capable of exercising choice differently and behaves uniquely (Ulrich and Probst, 2012);

- It leads to the emergence of new structures, patterns, and/or forms of behaviour from randomness but at a higher level of order (Stacey, 2003).

Against this background, this thesis argues for the importance of insights from Complexity Theory in the study of large construction projects. This is discussed next.

2.9 Knowledge Gap in The Study of Large Construction Projects

The UK construction industry has faced significant criticism for not performing to its full potential and delivering skewed results, in respect of risk management, that deviate from the original estimates and/or stakeholders' expectations (Egan, 1998; Latham, 1994; Morledge *et al.*, 2009). This has been explained by recognising the inherent complexity and uncertainty of the construction environment that arise from the need to manage the relationships between a large number of actors, with multiple interests and objectives, as well as the existence of many different interrelated risks and constraints that are usually subject to change over time (Flyvbjerg, 2009; Winch, 2002). Despite the growing recognition of the inherently complex nature of large construction projects that led to the introduction of new initiatives in the industry, many project teams still fail to deliver 'customer delight' (Latham, 1994); an objective *'to which the construction industry's clients aspire but which they are so often frustrated in achieving'* (Pryke, 2012, p. 44). This failure is because implementation of recent reform initiatives fell short of the target to reduce complexity and uncertainty in the construction projects which eventually resulted in a continued emergence of large client's satisfaction gap (Egan, 1998; Pryke and Smyth, 2006).

Bakhshi *et al.* (2016) conducted a systematic literature review in relation to the key developments concerned with defining complexity in the context of project management. Figure 2.3 below summarises their findings which covered the period from 1990 to 2015. Chronologically, development milestones to study project complexity started with the organisational theorists focusing solely on the structural complexity of the project and/or organisation and its environment. The findings highlight that research orientation was dominated by deterministic[8] paradigm approaches and continued to be instrumentalist while seeking success/failure factors and/or decision-theoretic models as prescriptions for project performance (Padalkar and Gopinath, 2016). More importantly, Complexity Theory and its concepts have been applied to a broad spectrum of disciplines, especially in organisation management field (Mitleton-Kelly, 2003). However, as far as construction industry is concerned, Walker (2015) argues that research relating to complexity of large projects still does not appear to rely on Complexity Theory and its underpinning ideas but rather on a systems approach. The difference between both perspectives is subtle and predicates on the biological originality of systems approach that assumes parts act in a predictable and determined manner (Walker, 2015).

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[8] This approach is the basis for most popular project management textbooks (e.g. PMBOK) and methodologies (Winter *et al.*, 2006). This has been termed the 'hard systems' model, emphasising the planning and control dimensions of project management.

This underlying assumption excludes the free-willing and open-endedness attributes of human behaviour that heavily determine the fabric of construction environment settings (Stacey *et al.*, 2000; Fincham and Rhodes, 2005; Mitleton-Kelly, 2003). A salient example where systems approach fails in managing large construction projects is its inability to explain the issue of conflict or opportunistic behaviour (Blockley and Godfrey, 2000). This issue arises by information asymmetries, as risks are inherently allocated in an unbalanced structure, leading to optimisation of individual goals rather than shared ones (Blockley and Godfrey, 2000; Stacey *et al.*, 2000). Attending to this gap in knowledge, Walker (2015) asserts that Complexity Theory has the potential to develop a holistic approach to manage large construction projects more effectively. That is by providing rigorous adaptive solutions that take into account the ever-changing nature of the environment over time and help to understand the social behaviours of the complex human system (Mitleton-Kelly, 2003; Jackson, 2000).
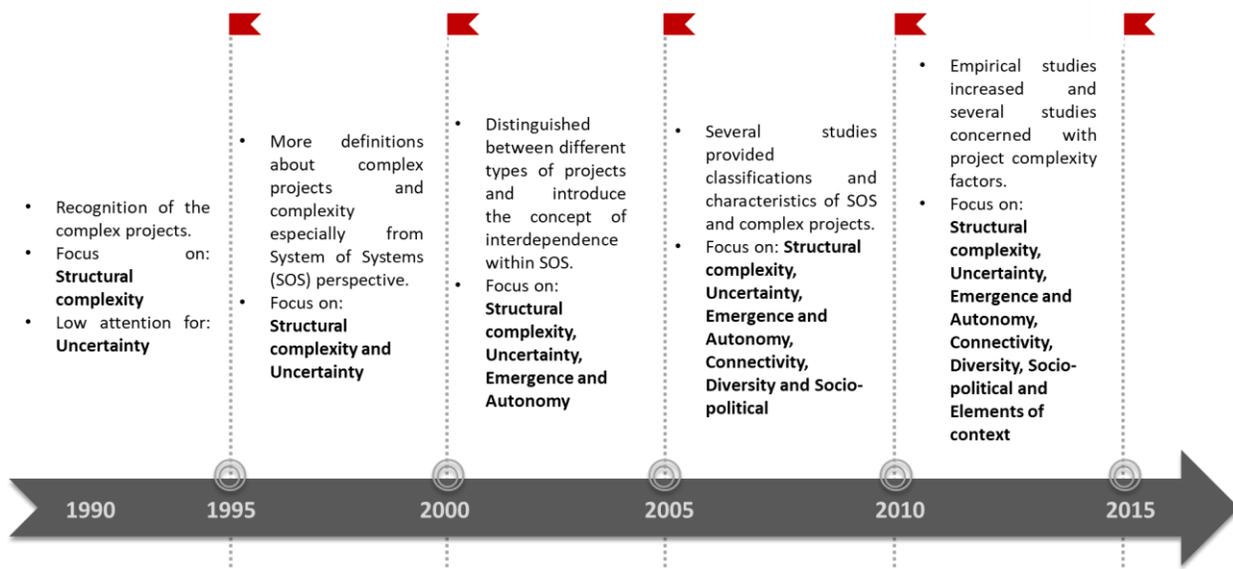
Figure 2.3: Milestones of Project Complexity History.
(Source: Adapted from Bakhshi *et al.*, 2016, Figure 1, p. 1200)

Due to the project management weak theoretic nature (Padalkar and Gopinath, 2016) and lack of relevance to practice (Winter *et al.*, 2006), the post-2000 period witnessed the growth of non-deterministic research that tried to model project phenomena under complexity-related assumptions (Bakhshi *et al.*, 2016; Padalkar and Gopinath, 2016). It represents the start of a paradigm shift that has the potential to provide alternative explanations through different ontological and methodological approaches (Padalkar and Gopinath, 2016). At the same period, particularly 'post-Latham' (Latham, 1994) and 'post-Egan' (Egan, 1998) a lot of energy and emphasis in the construction industry was put on relational contracts, focused upon the collaborative behaviour of actors beyond the duration of individual contracts/projects (Pryke, 2009). Additionally, in 2003, the UK's Engineering and Physical Sciences Research Council (EPSRC) has funded an inter-disciplinary research network of academics, researchers and practitioners to rethink project management. The initiative aimed to enrich and extend the project management field beyond its current conceptual foundations and connect it more closely to the challenges of contemporary project management practice (Winter *et al.*, 2006). As a result of the slow uptake by clients to the relational standpoint, Pryke (2017, p. 15) advocates:

> *"The construction industry has effectively remained in transition – recognising the*
> *need for flexible and collaborative day-to-day relationships but not feeling confident*
> *in casting aside the comfort [……] that a formal project-based contract provides".*

The non-deterministic research trend continued until the current status was reached, focusing on a broad spectrum of views of project complexity (Bakhshi *et al.*, 2016), that interestingly fits with Complexity Theory. Having said that, until today, a comprehensive theoretical framework, that is capable of integrating and describing these different research focuses and complexity-related assumptions, is still needed.

In the same way, the term 'self-organisation' and its current use have been systematically reviewed by Anzola *et al.* (2017), covering the years from 1990 onwards. It was highlighted that the inclusion and popularity of the self-organisation concept into the complexity paradigm has only settled around this period. The findings of Anzola *et al.* (2017, p. 222) review reveals that:

> *"In spite of its potential relevance for the study of social dynamics, the articulation and use*
> *of the concept of self-organization has been kept within the boundaries of complexity*
> *science and links to and from mainstream social science are scarce and rarely attempted"*

Table 2.1 below summarises the three types of explicit usage of the concept identified by Anzola *et al.* (2017), these are - terminological, analogical and literal. The paper reveals that the concept of self-organisation has been mostly used in a terminological way with no reference to complexity science. This means the word have been used with its "common sense" understanding words without further explanation. In the analogical type, a loose analogy to the term used in complexity science is made. Finally, in the literal use, full awareness and reference to complexity science is given when the term is used.

Anzola *et al.* (2017) systematic review serves as a contextualisation of the use of 'self-organisation' concept both explicitly and implicitly in studying social systems. The studies of self-organisation in the Construction Project Management (CPM) context remains mostly analogical (e.g. Pryke *et al.*, 2015, 2017), except for Pryke *et al.* (2018) as more explicit reference to complexity science has been made. Following this review, it is believed that this thesis is the first to address the concept literally in construction project Temporary Multi-Organisations (TMOs), aiming to provide a more robust exploration of the phenomena in project networks.

Table 2.1: Explicit approaches for using 'self-organisation' concept in social sciences.
Summarised from: Anzola *et al.* (2017)

Characteristics	Terminological	Analogical	Literal
Usage	It is the basic linguistic meaning provided by the constituent words 'self' and 'organisation' that inspires its use, rather than any reference to the concept from complexity science. That is, the concept has been arrived at independently of its use in complexity science.	No explicit acknowledgement of complexity science or the scientific background for the study of self-organisation is made. However, process is taken into account rather than only considering self-organisation to be a static characteristic of an entity.	Implies an explicit awareness of or reference to complexity science, adopting all characteristics of self-organisation described above.
Self-organising characteristic discussed	**Autonomy:** this deals with the controlling force or mechanism behind the process. As the prefix 'self' suggests, the concept deals with processes without coordination or central control. In such studies, a distinction is made between top-down and bottom-up control mechanisms.	Stronger reference to the characteristics of self-organisation, as discussed earlier, is made. Particularly "dynamics".	There are no areas in social science where literal use is widespread and established. This creates a knowledge gap that is aspired to be addressed in this research.
Field of Application	• Group/organisation formation in political science; • Scientific collaborations in sociology.	• Studies from geography on the spatial organisation of societies and economies; • Management and its related disciplines suggest allowing and encouraging self-organisation is positive for achieving management goals.	• Evolutionary economics: the use varies from analogical to literal translations from complexity science; • Psychology: the emergence of leadership and decisions in small groups in a relatively literal way; • Crisis management: applies the term to the process of response to crises, suggesting that self-organised responses are a potentially desirable policy goal.

2.10 Application of Complexity Theory to The Study of Large Projects

This thesis extends the understanding and application of self-organisation concept to the study of large construction projects. It recognises the conceptualisation of "large projects as self-organising systems" being the norm rather than the exception. It postulates that this phenomenon naturally occurs at any given point in time to respond to any challenges and may start when these challenges are seen to the system yet are not risking its overthrow of disintegration.

Next sections will explore how CT can be applied to the study of large projects, focusing on:

- Explanation of key characteristics from the CT perspective;
- Forms of project organisations through the lens of CT;
- The conceptualisation of projects as evolving self-organising systems;
- Decision-making process in project-based self-organising systems.

2.10.1 Large Construction Projects through the Lens of CT

The notion of organisations, from the Newtonian perspective, has been long viewed as machine-like distinct activities that produce predictable outputs through prescribed stable linear processes (Hamilton, 1997; Taylor, 1911). However, this view was relatively effective only in the past where organisational environments were quite stable, simple, and exposed to low levels of uncertainties (Mulgan, 1998). Given today's ever-increasing complexity and uncertainty, such view is unrealistic (Chapman, 2011; Hamilton, 1997). As a result, the mechanical understanding of organisations has been challenged over the recent years by many researchers (e.g. Handy, 1994; McMillan, 2006; Morgan, 2006; Pedler *et al.*, 1996; Priesmeyer, 1992; Senge, 1990). Of particular interest, the work of Stacey (1996, 2003, 2007), Englehardt and Simmons (2002), Lewin and Regine (2000) and Pascale *et al.* (2000) who argued that organisations are Complex Adaptive Systems (CAS) with emergent properties that result from the numerous interactions between its employees and/or other stakeholders and external environment. This perspective is heavily grounded in the Complexity Theory and provides a better insight into the structure and dynamics of the evolving organisations.

As far as construction firms and projects are concerned, CAS, being an agent-based perspective governed by simple rules, can genuinely represent the unpredictable reflexive nature of humans and their adaptive/learning ability through feedback loops (McMillan, 2006; Stacey, 1996). However, in practice, construction firms have the tendency to "freeze" themselves into a fixed stable state, in order to eliminate any potential additional costs and/or delay in time that can arise from innovation, development, and/or introducing change (Ive, 1996). That is, both the low-income margin and time pressure, as negative consequences of competitive tendering, have meant that construction firms view changes to their plans as uninsurable risks and hence refrain from them (Ive and Gruneberg, 2000). Additionally, Pryke (2017) explains that project governance in construction suffers from dangerous assumptions that are mainly associated with "the freezing" of client needs' identification and allocation of project participants roles' over time. This static view fails to recognise the dynamics and long-term nature of complex projects, ultimately leading to difficulty in achieving 'client delight'.

Complexity Theory suggests that any well-fragmented coordinated activity with an inherent diversity, such as large construction projects (Tavistock, 1966), has a natural evolutionary capacity that is sufficient enough to trigger the self-organising process (Stacey, 2003). This process is a function of the transition between the pre- and post-contract phases of projects (Pryke, 2017). This is inevitably underpinned by the fact that construction projects involve several parties with multiplicity of authority power but each with different interests and values (Wild, 2002). That is to say, the existence of large number of conflicting forces and consensus problems (mainly relating to resource allocation and methodologies used to achieve the desired results) will loom large over time and eventually push the system towards a transition phase that is not governed by the contractual project life cycle (Stacey, 2003; Pryke *et al.*, 2018). Thereafter, survival and success of the projects will be highly reliant on the ability to manage unpredictable and nonlinear interactions (Bertelsen, 2003; Geraldi, 2008). For clarity purposes, in reality, the *modus operandi* can be described as follows: each agent, in the absence of holistic knowledge, will act based on his/her past experience and/or expectation in order to deal with the uncertainty (Arthur, 1994). If his/her action was proved to be right, then it would be reused and reinforced next time; otherwise, it will be replaced by a new set of thinking and actions, i.e. to evolve into a higher state (Arthur, 1994)[9]. In this way, unpredictability and nonlinearity could also be the result of autonomous human choice, i.e. individuals develop their own purposes, choose their own goals and the actions to achieve them (Stacey *et al.*, 2000).

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[9] This is linked to the concept of path dependence and self-reinforcing mechanisms (e.g. Arthur, 1994).

Applying Complex Adaptive System (CAS) perspective to the study of large construction projects challenges the long-lived top-down agent-based models. The radical change here is that instead of having a concentrated authority that requires a detailed pre-planning, CAS implies having a dispersed authority where individual agents enjoy some sort of shared control (Coleman, 1999; Ford, 2008). This goes hand in hand with the earlier discussion of the agents' inherent ability to self-organise swiftly and freely without referring to any central or governing control, but just based on the local knowledge available at such micro levels (Heylighen *et al.*, 2006). Putting such model with a total freedom of action into operation could result in extreme unpredictable outcomes and hence to maintain the balance it is recommended that a composite of guidelines should be applied (Bertelsen, 2003). This is also rather than just following a pre-engineered rigid approach with a series of checklists or templates as it is usually the case with the pre-planned model (Bertelsen, 2003; Geraldi, 2008). Hence, CAS perspective challenges the detailed planning approach to project management which assumes constant project goals over time (Fabianski, 2017).

The common misunderstanding in self-organisation concept is the belief that there is no role for managers or leaders in self-organised networks/teams (Foerster, 1984; Mahmud, 2009). This belief stems from the traditional Newtonian paradigm that proposes that leaders'/management's role in organisations is limited to maintaining equilibrium/stability (Foerster, 1984; Mahmud, 2009; van Eijnatten, 2004). However, in reality, each individual can potentially be agent of change, i.e. considered the catalysts and cultivators of self-organising process (Foerster, 1984; Mahmud, 2009; Stacey, 1996; Stacey, 2010). Following this argument, Heino and Anttiroiko (2015, p. 306) advocate *"a self-organizing system seems to require a critical human component, some individual who can identify problems, inspire others, and implement the feasible actions required".*

However, adopting a balanced approach is not as easy as it sounds in view of the nature of construction projects (Geraldi, 2008). That is, professionals involved in the industry face a dilemma over how to manage tensions between control and flexibility as well as to draw order out of chaos in order to encourage optimisation (Szentes and Eriksson, 2015; Geraldi, 2008). In this respect, lean construction and agile project management have been adopted as strategies to cope with projects' complexities in construction industry (Cooke, 2012; Sohi *et al.*, 2016). Also, Systems Integration has been used, which is, on its own merits, heavily grounded in the 'command and control' approach that views projects as tightly coupled systems. The key weakness in systems integration is its focus on control and coordination rather than on achieving flexibility, resilience and adaptability – qualities that are more needed to achieve survival and success in today's business environment.

A careful scrutiny of the widely used initiatives over the past three decades to enhance cooperation and trust in projects (such as introducing performance incentives, adopting a system with a range of rewards and sanctions, and/or embracing a pain-gain risk sharing model) suggests that these measures appear to be very effective in changing agents' behaviour (Pryke, 2012). However, they still have profound adverse side effects such as rise of disputes and contractual disagreements (Ashley and Workman, 1986). According to Anvuur and Kumaraswamy (2008), the latter is due to the fact that such measures operate at the high level of the relationships, i.e. the beneficiaries of such incentives are the contracting firms and not the individuals – hence focusing on formal contractual links. Also, these measures have been criticised for concealing 'competition' especially in the view of the rewards being limited; thus potentially giving rise to opportunistic behaviour (Anvuur and Kumaraswamy, 2008).

Another key problem with the multi-agent structure in large projects is that the negative attitudes of self-interest and group-interest will arise as emergent properties rather than the desired team work spirit and cooperation (Bertelsen, 2003; Walker, 2015). This means the involved parties in large projects, though contractually should work together as a one team, cannot be considered totally autonomous independent agents (Bertelsen, 2003). This is because they have a strong sense of belonging to their original organisations rather than to the recently established bespoke project team (Walker, 2015). This challenge is known as the principal-agent problem, caused by information asymmetry (Blockley and Godfrey, 2000; Walker, 2015). In this situation, only few involved parties are better informed than others and in which incentives and interests between them are not perfectly aligned and/or allocated (Walker, 2015). Consequently, opportunistic behavior may arise; in this case informed parties are tempted to act in their interest rather the project owner (Cerić, 2014). Another example for this problem is: if a party bears the full cost of putting effort into a task but usually does not receive the full benefit that results from these efforts, then this may give an excuse for that party to put in less effort into the task than he/she would do if acting on his/her own behalf. This is further exacerbated by the fact that information asymmetry makes it difficult or even impossible for the project owner to know whether the parties have acted in their best interest (Cerić, 2014).

While the principal-agent problem has been widely addressed by many scholars (e.g. Müller and Turner, 2005; Ive and Chang, 2007; Cerić, 2012), most solutions still focus on aligning the incentives between the two parties through carrots and sticks mechanisms (Pryke, 2012). Ideally, this problem is best understood in the broader context of other issues as well, such as addressing fragmentation and boundary issues across multiple interrelated interfaces as well as why different people perceive different things about the same situation.

Complexity Theory can offer such integration capacity, opening up for a new perspective, rather than having a piecemeal approach to the problem (Bertelsen, 2003). That is, dealing with the rise of opportunistic behavior, Complexity Theory postulates that this adverse phenomenon is counterbalanced by another form of cooperative relationships which emerges as the project progresses (Anvuur and Kumaraswamy, 2008; Bertelsen, 2003). These emergent relationships are coined by the term "parallel or informal organisations/networks" which have been found to rise above the prescribed contractual boundaries (Anvuur and Kumaraswamy, 2008; Bertelsen, 2003; Dainty *et al.*, 2007). They aim to increase collaboration, coordination and goal alignment in the temporary project team and also help to improve problem solving, communication, fast track the processes, and expedite decision-making, regardless of any financial incentives (Anvuur and Kumaraswamy, 2008; Bertelsen, 2003, Coleman, 1999).

Next section describes such parallel/informal relationships in more detail.

2.10.2   Forms of Project Organisations

The structure of an organisation can be defined as patterns of interaction rather than in terms of the organisation chart (Emmitt and Gorse, 2009). Like the top of an iceberg, contractual relationships that are usually defined by way of hierarchical lines of responsibilities and reporting structure are only the visible part of an organisation which represents a small portion of the entire organisational functions and ties (Shaw, 1997). As illustrated in Figure 2.4, what lies beneath these formal ties is a sea of informal ties that are much larger with usually more powers – this part is called "parallel or informal organisation" (Simmel, 1908; Powell *et al.*, 1996; McGuire, 2002; Dainty *et al.*, 2007).

Figure 2.4: Organisation Structure as Patterns of Interaction
(Source: developed from: Emmitt and Gorse, 2009)

Organisational theorists have well appreciated the existence of parallel/informal organisations (e.g. Simmel, 1908; Schein, 1965; 1985), but this concept has been generally considered as an enemy that resists legitimate change efforts because of their unpredictable nature (Allen and Pilnick, 1973; Stacey, 1996; Walker, 2015). Because of this, many organisational studies and strategies have been focused on controlling and defeating them (Allen and Pilnick, 1973; Stacey, 1996; Walker, 2015; Coleman, 1999). On the contrary, Complexity Theory argues that large number of organisations do not understand how contractual/formal activities can be buttressed by informal ties (Cross *et al.*, 2002). CT goes beyond that widely acceptable argument to claim that navigating these 'informal/parallel networks' can be the subtle difference between surviving and succeeding, especially in large construction projects, given their greater adaptability (Bertelsen and Koskela, 2003). To be clear, from a CT perspective, the word "parallel" refers to the set of emergent unofficial informal relationships that influences how things are done in reality, behind the firm planned chart (Powell *et al.*, 1996). It consists mainly of what people actually do to get the work done, by a way of informal behaviour, rather than what their official mandate dictates (McGuire, 2002; Stacey *et al.*, 2000).

An interest in informal and emergent features of construction industry organisation has grown rapidly over the past two decades, particularly in the UK (Rooke *et al.*, 2009). This has entailed extending the analysis and research scope beyond the usual economic attributes of organisational effectiveness (for example, strategy, culture and operations) and their associated legal obligations towards focusing on the social dimensions at the individuals' micro levels (Ruan *et al.*, 2013). This paradigm shift is attributed to the fact that the individuals' micro levels set the foundation for such informal and emergent features in the industry (Rooke *et al.*, 2009). This is further underpinned by the fact that construction industry is essentially multi-disciplinary people-intensive arena which exhibits a high reliance on face-to-face informal conversations and interpersonal communications in order to coordinate and facilitate daily activities, problem solving and decision making (Hastings, 1998; Pietroforte, 1997; Middleton, 1996).

The classification between 'formal' and 'informal' project organisations can be traced back to Tavistock report issued in 1966. This implied that "*drawings, contract documents, contractors' programmes and other information represent the formal management control systems, and that day-to-day communications represent an informal organisation*" (Pryke, 2012, p. 16). The word informal is also referred to, by many scholars, as 'non-contractual', 'non-hierarchical' or 'embedded' networks versus 'contractual' or 'arm's length' networks (Rooke *et al.*, 2009; Uzzi, 1997; El-Sheikh and Pryke, 2010). Informal activities would include corridor talks, chit chats (Middleton, 1996), unofficial channels, such as the 'grapevines' (Dainty *et al.*, 2007).

They are considered as communication shortcuts, unofficial ways to receive required (and sometimes critical) information, in order to avoid overly bureaucratic channels and/or organisational gatekeepers and mazes that are commonly found in complex structures. More importantly, gaining information through informal communication is connected to help-seeking behaviour and forming informal cabals (support groups) which emerge, as a legitimate need, when the established structure is not working efficiently (Emmitt and Gorse, 2009). By strengthening informal relationships, supportive communication can be encouraged allowing for better alignment in interpretation, sustainable personal relationships, and break down of defensive communication (Emmitt and Gorse, 2009).

In this respect, Pryke (2012) illustrated that formal organisational and contractual models do not reflect the magnitude of complexity and/or the need for effective management of relationships inherited in complex infrastructure project delivery. Indeed, despite the significant attention placed on establishing formal organisational and contractual hierarchies in such projects, much of the decision making related to project uncertainties and risks are made through non-contractual multi-functional networks of individuals temporarily brought together by project-related common interests or tasks (Pryke, 2012; Pryke *et al.*, 2018).

In a similar vein, forms of organisations can be classified, from a CT perspective, by a two-by-two grid, as illustrated in Figure 2.5 (inspired from Goldstein, 1999, p. 66).
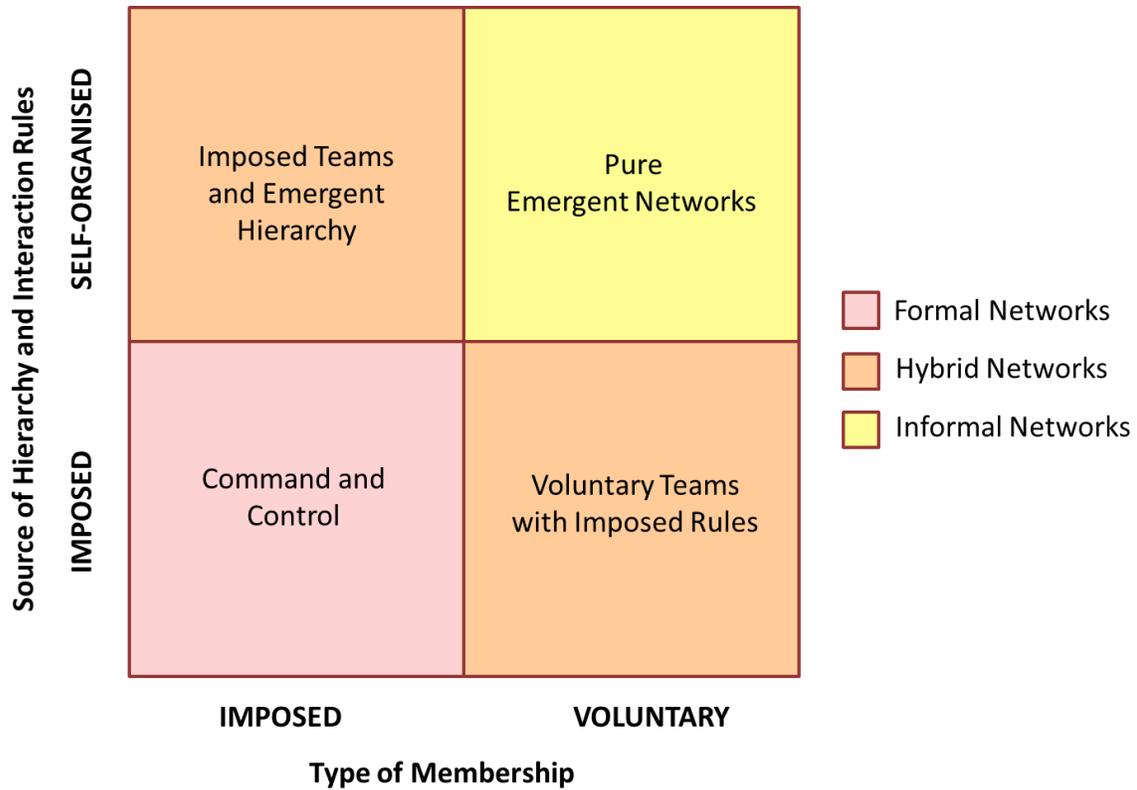
Figure 2.5: Forms of Organisations from a CT Perspective
(Source: Adapted from: Goldstein, 1999, Figure 3, p. 66)

This matrix maps type of membership (imposed or voluntary teams) against the source of hierarchy and interaction rules (imposed or self-organised). The lower left quadrant displays the pure hierarchical type of structure, such as traditional top-down agent-based models or command and control management. Here, teams' members are formally pre-identified, and they strictly follow the officially sanctioned rules. The upper left quadrant is a hybrid case, representing imposed teams but who can self-organise and evolve. Apparent applications for this are the Total Quality Management (TQM) and Supply Chain Management (SCM) work clusters. A practical example of the latter is "technology clusters" (Winch, 2000) which involves the grouping of actors in relation to specific critical interfaces within the production phase of the project (Pryke, 2001). Such form of organisation in projects have been adopted by several large client organisations and used in several complex projects. This includes British Airports Authority (BAA) project at Heathrow Terminal Five, Slough Estate project and the Building Down Barriers project at Aldershot (Pryke, 2009). In such situations, participatory work environment was encouraged in order to allow for improvements/introduction of changes to the followed processes and procedures.

Another hybrid case is the lower right quadrant, where people join voluntarily in order to achieve specified objectives that are entrusted by a central authority. Typical examples in this case include communities of practice and builders' associations. The upper right quadrant, which can overlap with the hybrid quadrants, denotes the authentic/pure type of emergent networks. These signify the evolutionary and adaptable nature of the informal/parallel networks in complex and multi-agent systems, coupled with a decentralised decision-making process. Another key feature of these networks is their ability to evolve from a lower degree of complexity to a higher one, rather than being pre-formed on an ad-hoc basis to deal with specific problems tactically.

From a CT perspective, a more holistic picture of organisation necessitates inclusion of the informal/parallel networks that are usually established based on cohesion and open communication (Bechky, 2006). Of particular importance, an organisation that is generated through self-organisation should be considered as an ongoing and provisional emergent accomplishment which is 'always in the making' (Gherardi and Nicollini, 2000; Gkeredakis, 2008; Stacey, 2010; Grove *et al.*, 2018). It is naturally-driven rather than being classically viewed as a deliberate effort, action, activity and/or process (Stacey, 2010). This profoundly asserts that projects and organisations are not "found"/ "imposed" but "invented" and co-created (Smyth and Morris, 2007; Blomquist *et al.*, 2010).

Although Complexity Theory allows local interactions to not obey any fixed laws or mathematical equations, this does not mean a full empowerment or freedom for individuals to do anything they like as this could lead to disintegration/destruction of the system (Stacey, 2010; Mitleton-Kelly, 2003). Alternatively, the interdependence of the local interactions means individuals enable each other but one can only respond in a certain way that is constrained by the self-organisation process itself, exhibiting some kind of social control and order. Another misunderstanding about self-organisation is that it could means creating some kind of despair in managers who think they can do nothing as the new form is inevitably going to happen (Stacey, 2010). The truth is self-organisation is subject to a wide range of possibilities as it is a hybrid product of many "done and not-done" interactions and "the good and the bad" actions. Its occurrence depends on diversity and spontaneous interplay, i.e. local interactions evolve simultaneously as the collective patterns are evolving.

Fuchs (2003) suggests that this cycle of dynamic interplay and co-evolution between actors and structure is the basic process of self-organisation in social systems[10]. The implication of such perspective is that the current dominant management approach of staticity, sameness and harmony does not resonate with the organisational reality to achieve success (Stacey, 2010). Rather, understanding of tensions/disagreements and local interdependence lie at the centre of firms' success or failure.

Having said that, this study aims to fill the gap in knowledge around the self-organising networks and their evolution in the construction projects. This is because, in the field of construction project management, an understanding of self-organising process in projects is still lacking, let alone an articulated model of the dynamics of this process. Hence, this research uses the theoretical framework developed from CT as a signboard to achieve the aims and objectives of this research.

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[10] This can be related to Gidden's (1984) structuration theory that suggests "*social structures do not exist outside of actions*". That is, "*according to the notion of the duality of structure, the structural properties of social systems are both medium and outcome of the practices they recursively organise*" (Gidden, 1984, p. 25) and they both enable and constrain actions Fuchs (2003, p. 140). The concept of agency focuses on the knowledgeability of the agent and the fact that the agency cannot exist or be analysed separately from its structure (Fuchs, 2003). Here agency reflect that agents engage in goal directed activity (i.e. intentional action, which is in this thesis the communication process to respond risks/issues in the project), reflecting that actors are proactive and reflexive, hence self-organising. The latter is constrained at actors' local level without full awareness and understanding of the larger network structure in which they act (Scott, 2017).

2.10.3 The Conceptualisation of Projects as Evolving Self-organising Systems

Self-organisation can be defined as a nonlinear process of pattern formation that emerges from the interactions between the agents at the local level in a bottom up fashion (Heylighen, 2013; Mitleton-Kelly, 2003). The latter implies an environment with a weak command, i.e. the process usually happens out at the organisational fringes where connectivity is dense with existence of many local interactions. The key engines behind self-organisation are the feedback loops as they can work to amplify some small events into global systemic phenomena (McMillan, 2006; Stacey, 1996). These loops define a relationship of interdependency between two or more components where the change in state of one element/actor effects that of another with this effect then in turn feeding back to alter the source element/actor (McMillan, 2006; Stacey, 1996). Adding the timing effect to these feedback loops, system dynamics can be established. That is, a relationship of interdependence over time will mean what happens now is going to affect what happens in the future (Stacey, 2010). The scope of the analysis of this study does not deal with timing effect, however the discussions in later chapters touch briefly upon impact of time lags.

The central role that feedback loops play in self-organisation is their ability to change the correlation between agents' states within the system in order to coordinate them (Stacey, 2010). This type of mechanism is nonlinear and grows in an exponential fashion, through self-reinforcing. As this process of change continues, the system then will reach a point in time where all agents involved have correlated their states in some way, leading to some form of global coordination based on the dynamic between competition and cooperation (Gherardi and Nicollini, 2000; Gkeredakis, 2008; Stacey, 2010). This is an important feature of the concept of self-organisation as it can transform systems to accommodate higher levels of complexity (McMillan, 2006; Capra, 1996). This is especially relevant to the context of project activities, as projects transition from procurement stage that is usually aligned with contractual conditions to delivery stage that is largely reliant on non-contractual networks of individuals working together to realise project-related common goals (Pryke, 2012).

This process can be illustrated as in the below phase change diagram (Figure 2.6 below). It is suggested that a complete evolutionary cycle of system structures in large construction projects goes through three phases – Phase 1 in the diagram represents the initial structure which largely mirrors the prescribed contractual lines of reporting and responsibilities. This formal structure suggests a "static" mode of dyadic interactions between the contracted firms or individuals (Pryke, 2017). However, over the time, involvement of complex and very tightly coupled systems in large construction projects lead to inevitable changes due to higher levels of uncertainty (Geraldi *et al.*, 2010).

These in isolation, probably would not have detrimental effects, but due to unanticipated interaction of multiple factors, the system will be forced to enter into a transition phase (Phase 2 in diagram) through co-creation process or otherwise to disintegrate/get destroyed. From CT perspective, this is the self-organising phase poised at the Edge of Chaos (EC) and will be referred to as 'transition phase' from this point onwards. At this point, project actors cultivate on their informal relationships and power positions to support the design and delivery of projects on a daily basis. The lower order system will collapse or bifurcate[11], and the result will be a new structure with a greater level of adaptability and complexity (Phase 3 in diagram).
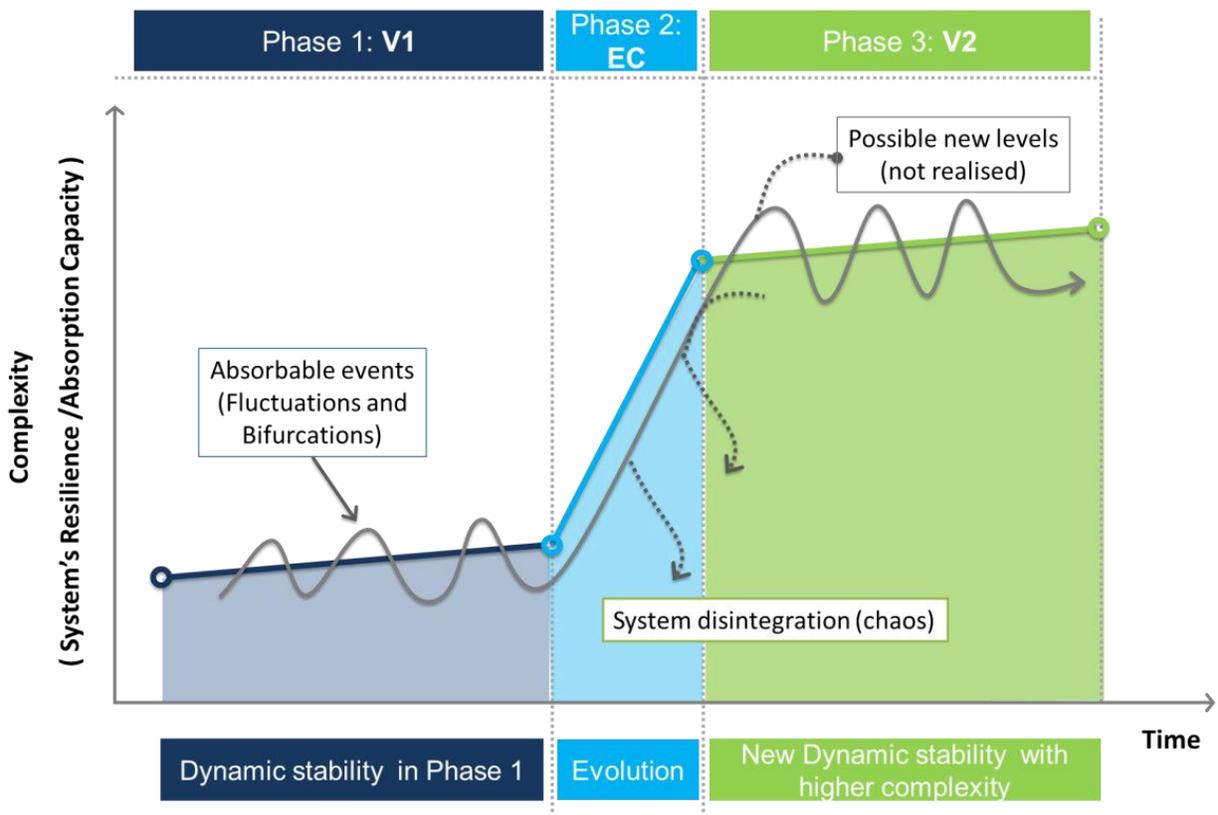
Figure 2.6: Phase Change Diagram: A Complete Evolutionary Cycle of System Structures
(Source: Adapted from Saynisch, 2010, Figure 7, p. 32)

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[11] Bifurcations: "*These points occur because of accumulated flaws or problems within the system and refer to a system's conditions or behaviours suddenly dividing or branching into two different or merging part behaviours*" (Ying and Pheng, 2014, p. 63).

In project management research, the previous emphasis has been mainly on Phase one, which focuses on procurement and contractual relationships and the pattern of interaction from a "static" perspective (Borgatti *et al.*, 2014). The current literature suffers significant limitations in understanding evolutionary behaviour in the project environment. Therefore, this research focuses on understanding the processes of self-organisation and their dynamics in a large infrastructure project.

2.10.4 Decision-Making Process in Project-based Self-Organising Systems

The evolving nature of communication systems over the project life cycle suggests that individuals usually carry-out multiple roles, and thus are confronted with a sheer magnitude of situations begging for quick decisions (Pryke, 2012). Human cognitive capacity and resources, however, are limited and individuals do not have the luxury of spending adequate time in all situations (Jager and Janssen, 2012). This is just not practical. To cope with such challenges, individuals employ a number of strategies to allocate their limited cognitive capacity, resources and time over the multitude of decisions (Jager and Janssen, 2012). The critical question therefore is *what these decision strategies are and how individuals decide on which one to employ in a given situation?*

There are three broad theories dealing with the decision-making process (Padalkar and Gopinath, 2016). These are summarised briefly as follows:

> ➢ **Experimental Behavioural Economics:**

This theory is concerned with the study of economic decisions, using experimental methods (Baddeley, 2013). It combines experimental and field evidence with insights typically from psychology, to develop a greater understanding of the decision-making process (Anzola *et al.*, 2017). It views individuals as rational goal seeking optimisers and therefore naturally it is aligned to the deterministic approaches (Padalkar and Gopinath, 2016). It requires designing carefully controlled conditions in order to capture the real drivers of decision-making behaviours (Baddeley, 2013). Critics of behavioural economics typically stress that its results may have limited external validity and may not be generalisable to real-work decisions. In view of its deterministic perspective and limited application, experimental behavioural economics theory is dismissed in this thesis for the study of self-organising systems that give precedence to ongoing change.

➢ **Network Theory**

This theory is concerned with the study of connectivity between discrete agents (Cross *et al.*, 2002). It plays a central role in understanding large systems by providing graphs as a representation of relations (Pryke, 2017). It also provides a set of techniques for analysing graphs that are often deployed to examine complex systems (Wellman, 1988; Mazzocchi, 2016). Given its capacity to recognise the principles of Complexity Theory, Network Theory is used as the analytical framework in this thesis. It can provide a greater insight into understanding social interactions and human behaviour as interrelated elements in the complex dynamics taking place within the self-organising project systems (Padalkar and Gopinath, 2016). Further details on Network Theory are given in next chapter.

➢ **Game Theory**

Game theory is rooted in economics and concerned with the study of strategic interaction between rational decision-makers using mathematical models (Pryke, 2017). Originally, it addressed zero-sum games, in which one person's gains result in losses for the other participant (Anzola *et al.*, 2017). The key assumptions of game theory cast several challenges in modelling competition and collaboration and the emergence of collective behaviour in project (Kay, 2005; Pryke, 2017). In his recent book, Pryke (2017, p. 78) studied Game Theory and provided a review of its application in construction industry, elucidating how its principles are "*important in understanding individuals' behaviour and effectiveness in networks, and how some networks function well while others are slow or dysfunctional in some way*". However, Pryke (2017) concluded by highlighting several limitations in applying game theory in the study of project performance and predicting emergent self-organising behaviour. These limitations are worth mentioning and thus summarised as follows:

- **Finite number of participants and possible course of actions:** game theory assumes a finite number of participants and a finite number of possible course of actions available to each participant (Pryke, 2017). On the contrary, construction projects involve several parties with multiplicity of authority power and each with different interests and values (Wild, 2002). The complexity nature of construction projects means underlying interactions among actors could be more than the expected number of participants, as there is a large number of stakeholders and factors tend to influence the decision-making process. This is particularly true in large complex infrastructure projects and other public projects in which politics, for example, will probably influence the decisions (Fabianski, 2017). Additionally, the actors' interests and values are considered key factors in determining the decision-making strategy followed, for example whether to collaborate or compete, leading to infinite number of strategies that have either synergetic or destructive effect on system effectiveness.

- **Rationality:** game theory is based on rational choice theory (Scott, 2000) which assumes that actors are knowledgeable, rational, and have unlimited information processing ability. Their choices, therefore, can be predictable (since they are maximising their pay-off), suggesting a controlled and static environment that fails to acknowledge risk and uncertainty. This perspective is limited and will not suit the study of highly complex and interdependent environments such as construction projects, where project systems are dynamic and decisions are usually made with imperfect time-sensitive information.

- **Trade-offs:** The underlying assumption of zero-sum game fails to acknowledge the cooperative behaviour in self-organising project systems. This is because trade-offs must be made by individual actors after weighting utility of the various interdependent and conflicting project functions.

The limitations associated with Game Theory calls for exploring alternative techniques to study self-organisation in construction projects. This study, therefore, proposes making use of Complexity Theory principles and putting uncertainty at the centre of the discussion, being the key characteristic of temporary organisations, such as construction projects (Addyman, 2019). An explanation is given next on how this thesis would advance the work of Pryke *et al.* (2017) on decision-making process in project-based self-organising systems.

In his pursuit of developing the theory of social networks in project-based organisations, Pryke (2017) has advocated Winch (2002) concept of dynamic uncertainty, conceptualising project organisations as information processing systems. Winch (2002) affirms that the main problem in the management of construction projects is the lack of information required for decision-making at any given time. He further suggests that uncertainty is progressively reduced through the project lifecycle as project information become available (e.g. statutory approvals are gained, design ambiguities are resolved, geotechnical survey are completed). This concept implies that actors engage in information gathering relationships to aid the process of reducing uncertainty at the project. Uncertainty is high at inception and then it decreases as the project develops. Uncertainty therefore is a function of time structured around a predefined life cycle model, consisted of timebound sequential stages (Addyman, 2019).

Winch (2002) concept of dynamic uncertainty is depicted in Figure 2.7 below.
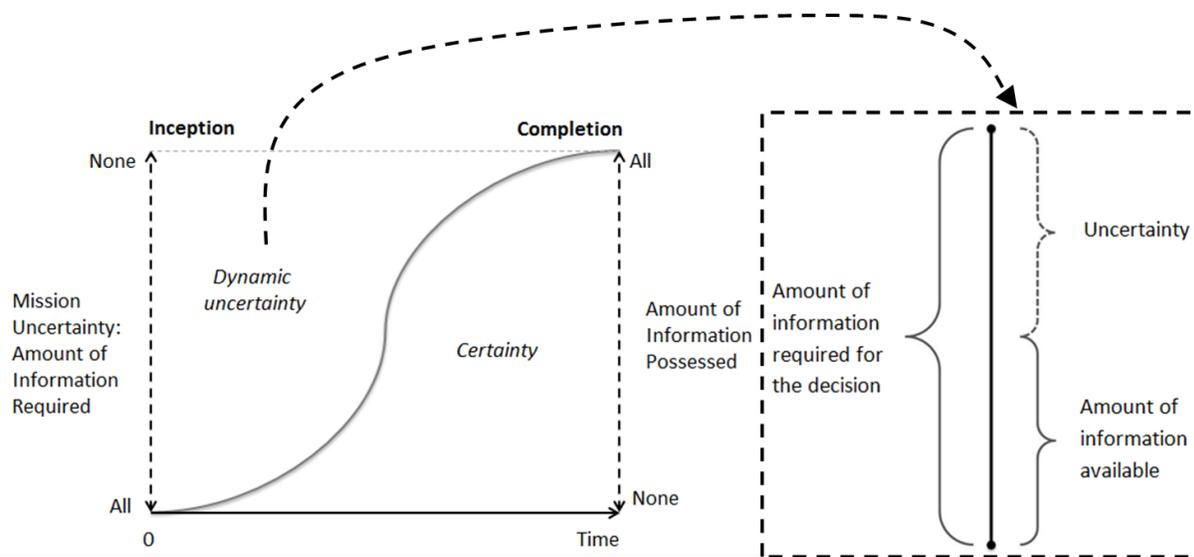
The Definition of Uncertainty: "The lack of all information required
to take a decision at a given time" (Source: Galbraith, 1977, Figure 3.1)

Figure 2.7: The Dynamic Reduction of Uncertainty over Time. (Source: Winch, 2002)

While this thesis recognises the crucial role of uncertainty in the decision-making process of construction projects, the notion of time-bound uncertainty gives Winch (2002) model its prescriptive and deterministic ill-nature. In other words, the dynamic uncertainty concept proposed by Winch (2002) assumes that at any given point in time, uncertainty is relative to earlier and later points in the project lifecycle. He referred to these points in the 'information flow' as stage gates, that are governed by a predetermined set of outputs and assurance process, primarily led by the production of a checklist of items (e.g. a design, a risk register, etc.). This kind of governance focusses on the role of contracts in getting the job done. It contradicts with self-organising concept that is built on informal relationships and nonlinearity.

In order to understand the decision-making strategies employed by actors in large projects, this thesis suggests reconceptualising uncertainty by adopting Jager and Janssen (2012) model. The fundamental difference between these two perspectives is that uncertainty is defined as an emergent state of social process (under Jager and Janssen's model) rather than as a state of nature (time), under Winch model. Viewing uncertainty as a social process means it continually changes as a consequence of an individual or collective behaviour. The advantage of this perspective is that it acknowledges the complex multi-level dynamics between the behavioural (local/individual) and structural (global/social) levels, taking place within project Temporary Multi-Organisation (TMO) teams (Lettieri *et al.*, 2017; Madey *et al.*, 2003).

Uncertainty, being a social process, means actors will refer to their own previous experiences and abilities when they are certain of themselves and will refer to others when they are uncertain (Jager and Janssen, 2002). Moreover, in recognition of actors' limited resources, Jager and Janssen (2012) suggest that individuals optimise the use of resources that are associated with making a decision. That is, individuals are not only concerned with maximising the outcomes. It further means an individual may decide a certain problem is not worth investing a lot of resources in whereas another problem requires more attention. The argument here is that individuals in projects use a number of decision rules, called "heuristics"[12], that help to simplify the complex decisions (Myers, 2010).

By adopting Jager and Janssen (2012) model, this thesis postulates that decision-making process in construction projects involves use of heuristics that can be organised on two dimensions, as follows:

1. **First Dimension:** The resources that are associated with making a decision, e.g. the amount of cognitive effort involved for the individual agent/actor;

2. **Second Dimension:** Uncertainty/'information gathering' as a social process. The information gathering process involves two levels of focus, namely individual or social focus. That is, a higher level of uncertainty requires more focus on social information-gathering process and hence reaching out to other actors. This approach is aligned with Winch and Maytorena (2009) 'social sensemaking' approach for decision-making that is argued to be more appropriate to deal with conditions of uncertainty and ambiguity. Both sense and subsequent decisions are principally based on the interaction with others and deployment of one's judgment. Individuals make sense of their work environment by negotiating their own perceptions based on their previous experience and knowledge (Koskinen, 2013). Inter-subjective meanings are therefore created through series of interpretations and actions (Fellows and Liu, 2017). When an actor's subjectivity is internalised by others, it could lead to enforcement of certain behaviours and thus creation of a status quo (Koskinen, 2013), which in turn influences subsequent decision-making process.

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[12] Heuristics are powerful techniques in reducing complexity, defined as any approach to problem-solving that employs a practical method that is not guaranteed to be optimal, perfect or rational, but instead sufficient for reaching an immediate goal (Myers, 2010). Heuristics are shortcuts to speed up the process of finding a satisfactory solution; examples for methods that employ heuristics include using trial and error, a rule of thumb, an intuitive judgment or common sense (Myers, 2010).

In order to organise the various heuristics into simple distinct categories, it is instructive to use the above two dimensions as graphically depicted in Figure 2.8.
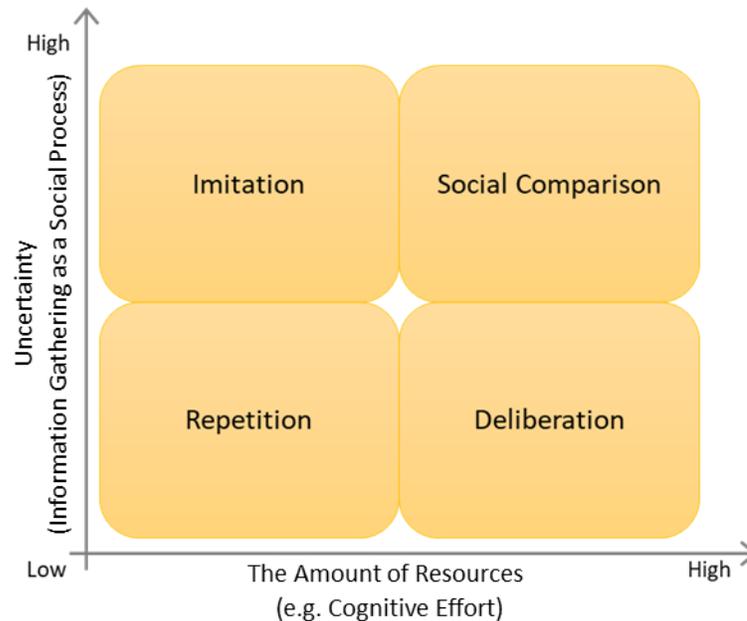
Figure 2.8: Decision-Making Heuristics Organised in Terms of Uncertainty and Cost.
(Source: Adapted from Jager and Janssen (2003), Figure 3, p. 45)

Referring to Figure 2.8 above, the various decision-making processes are organised into four heuristics as follows:

➢ **Repetition:** this is the lower left quadrant with low uncertainty and low amount of resources to be invested (e.g. low cognitive effort). In this case, the actor will use their own previous experiences and simply repeat what he/she has been doing so far, because it seems to be a successful strategy. The actor is satisfied with the outcome of this strategy and thus no need to waste any further resources. This is the simplest type of heuristics. Actors therefore will be highly concentrating on their own work but paying less attention to interaction with others. Repetition is behind habitual behaviour and routines in projects (Jager and Janssen, 2012).

- ➢ **Deliberation:** this is the lower right quadrant with low uncertainty but high amount of resources to be invested. He/she will evaluate various potential options and then select one of them. An individual in this case will rely on social processing for their decision-making. That is, for any fixed time frame, the consequences of all possible decisions are determined, and the "best" perceived possible way is acted upon, which is a form of optimising behaviour.

- ➢ **Imitation:** this is the top left quadrant with high uncertainty but lower amount of resources to be invested. When confronted with an unexpected issue, actors will imitate the behaviour of those agents with similar abilities, without giving too much thought about the issue. In this case, an individual will employ the behaviour and experiences of others in their decision making. This is an economical way of allocating resources to a decision in case of a higher uncertainty. However, it requires more effort than the repetition strategy because one should be attentive to the behaviour of others and be able to reproduce the same behaviour (Bandura, 1977).

- ➢ **Social Comparison:** this is the top right quadrant with high uncertainty and large amount of resources to be invested. Social comparison involves the same procedure as the imitation, but, before adopting a new strategy, the actor checks whether the new activity has a better expected output/value than the current one. It also involves the fact that actors consciously compare their opinion, performance and abilities to those of similar abilities. Jager and Janssen (2012) acknowledge that this approach involves a strategy of "inquiring" by asking other actors about their behaviour, i.e. investing larger resources to acquire information about possible alternatives.

To avoid falling into the trap of being just descriptive, operationalisation of the above model will be discussed in the Methodology chapter.

At this point, the theoretical part of Complexity Theory comes to an end. Next chapter presents a comprehensive theoretical framework for the methodological approach.

2.11 Summary

Complexity Theory, originated from systems theory, could be portrayed as a multifaceted space where different research pathways (e.g. chaos theory, CAS) come to merge (Mazzocchi, 2016). It was originated by mathematicians and physicists and underwent a series of modifications before it found its way into many areas of inquiry since the mid-twentieth century. Modern Complexity Theory is rooted in and arises out of the seminal work of authors such as Parsons and Luhmann, who were reviewed along with those who have critiqued these bodies of work. Therefore, this new way of thinking is still an "amalgam" of principles, methods and concepts (Heylighen *et al.*, 2006), but mainly concerned with the study of the dynamics of complex adaptive systems (CAS) which are nonlinear, have self-organising attributes and emergent properties.

The possibility of applying these underlying concepts to construction industry was discussed in depth in this chapter. It was highlighted that these ideas impose several challenges for the widely-accepted reductionism and determinism-based project management that views situations as products of simplified, limited, predictable and controllable isolated causes and effects. Of particular importance is that Complexity Theory is leading the paradigm shift, by providing greater insights into social systems, especially its capacity to explain the inherent risks and characteristics of construction industry. It suggests that the notorious features of large construction projects should be recognised as the norm rather than the exception, given the numerous human and social multidisciplinary interactions.

While project management literature has placed great emphasis on technical issues such as planning, scheduling, risk analysis, and project management techniques (Winter *et al.*, 2006; PMBOK, 2004; Rubinstein *et al.*, 2016), there have been recent calls for more attention to be placed on the "relational" and "social" dimensions of project management (Müller and Martinsuo, 2015; Zhang *et al.*, 2015). Consequently, based on the fundamental principles of Complexity Theory, this chapter challenges the foundation of managing large construction projects, by proposing a new and uncharted proposition. That is, large construction projects should be perceived as complex adaptive systems that self-organise themselves in response to higher levels of uncertainty, allowing dynamic "parallel or informal networks" to emerge in order to adapt to the ever-changing environment. This proposition comes in line with the growing recognition of "informal" and "relational" forms of governance in projects with management scholars increasingly viewing projects as complex networks of multidisciplinary interdependent actors (Dubois and Gadde, 2002, Pryke *et al.*, 2018).

From CT perspective, therefore, organisation is defined as an emergent property derived from the micro self-organised communication systems. In this process, the feedback loops play a central role due to their ability to change the correlation between agents' states within the system in order to coordinate them. That is to say, communication process triggers the formation of self-organising networks in complex settings. This is uncharted area in construction industry that holds considerable promise for addressing complexity and delivering better outcomes for clients and stakeholders. The discussion led to categorising the decision-making approaches that can be employed in self-organising systems in order to reduce the uncertainty of complex projects.

This research aims to extend the knowledge of Complexity Theory to the study of the informal networks in project environment. This approach has the potential to make bedfellows around the concept of managing networks within a context of managing projects. The link between the two concepts can be established based on Stacey's (1996) argument that self-organising networks are to be found primarily in the invisible area of organisational structure. Network approach is discussed next.

3

A Network Approach to
Understanding Projects
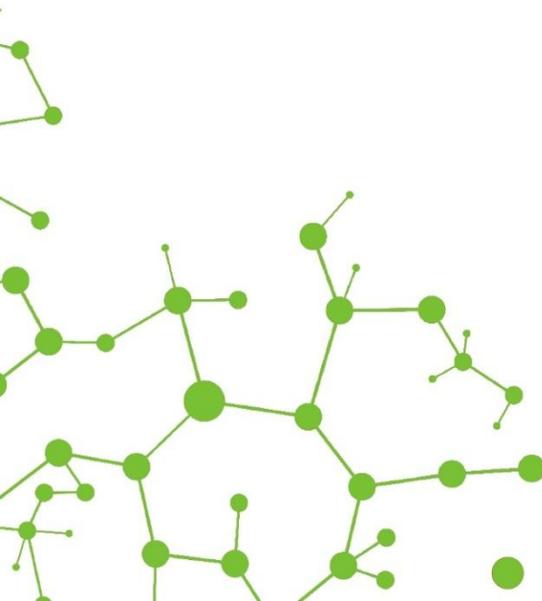
3.1 Introduction

This chapter proposes and justifies the theoretical framework for the methodological approach of this thesis. It starts by reviewing the key reports about the UK construction industry since 1930s in order to highlight the fundamental issues to the management of construction projects. The frequently repetitive findings of these reports emphasise on the need to find a new approach to the analysis and management of project systems. Building on Pryke's (2012; 2015; 2017; 2018) work on rationalising the use of networks, this chapter proposes adopting a network approach and hence deals with the benefits that social network analysis (SNA) might bring to the understanding, representation and analysis of construction projects. Self-organising networks are defined as a special type of networks; they form when project actors are under pressure to gather and disseminate information and exhibit a number of distinct structural properties. In turn, this highlights that there is a mismatch between what is contractually procured in terms of roles and the roles that are acquired through project actors' network positions. The chapter reviews previous research on both network approach and SNA, highlighting that self-organisation phenomena in construction projects and network actor roles remain underexplored, thereby posing a knowledge gap.

3.2 Fundamental Issues to the Management of Construction Projects

The continuous client dissatisfaction with the UK construction industry has a long history that can be tracked back at least since 1930s (Cain, 2004). In order to understand the fundamental issues to the management of construction projects, this section presents a list of key reviews of the UK construction industry, as follows:

- **Building to the Skies: The Romance of the Skyscraper, by Alfred Bossom (1934).** This is considered one of the early books that criticised the UK construction industry (Cain, 2004). Drawing on his experience in the US in the design of skyscrapers, Bossom proposed that construction should be treated as an engineering process, i.e. it can be planned in advance and then carried out to an agreed schedule. He highlighted the deficiencies in the UK construction industry by saying: '*The process of construction, instead of being an orderly and consecutive advance down the line, is all too apt to become a scramble and a muddle*' (Bossom, 1934, p. 69). The recommendations of Bossom, however, were made through the use of descriptive text (Cain, 2004).

- **The Simon Report (1944):** it was the first major report commissioned by the UK Government into the way projects were procured by clients (Pryke, 2012). It investigated how the placing and management of contracts and documentation could improve the efficiency of the construction industry. In particular, the report proposed for the abolition of open tendering, i.e. allowing any firm to tender for a contract rather than using a pre-qualification process to ensure only suitable companies are invited to tender. The report also recommended better training of construction managers and the use of a more collaborative approach to design and construction with earlier contractor involvement. Unfortunately, the Simon Report had little impact as attempts to implement its recommendations were overshadowed by the demand for rapid reconstruction in post-war Britain (Murray and Langford, 2003).

- **The Emmerson Report (1962):** In the immediate aftermath of World War II, there was an obvious need for a massive programme of reconstruction, which kept the industry away from the necessary scrutiny (Murray and Langford, 2003). During this time, the government was using the construction industry as an instrument to regulate the economy. Following the development of the welfare state and pressures of inflation and exchange problems, the UK economy was in deficit in 1960 (Murray and Langford, 2003). There was a need, therefore, to conduct a national reassessment of efficiency on critical economic cost centres, such as construction industry. Emmerson report highlighted that the governmental interference in the industry created an inefficient system for arranging and placing contracts and how the relationships between the players in the construction process were managed. The scope and depth of the report, however, were limited because it was to be delivered in a relatively short time frame and missed out on the participation of local authorities, which were a key influence on the construction industry at the time (Pryke, 2012). It did, nevertheless, act as a preamble to the more detailed Banwell Report that was to follow.

- **The Banwell Report (1964):** it was commissioned in response to the findings of the Emmerson report, aiming at presenting an agenda-setting report supported by a more detailed and analytical findings. The Banwell Report focused on team relationships, construction contracts and documentation. It criticised the industry for separating design from construction, lacking a common form of contract for building and civil engineering, appointing the project contractors based on lowest price, and operating at a slow pace. The recommendations of the report were adopted by some local authorities but not widely supported. In particular, they were not taken up by the Ministry of Works (Pryke, 2012). In 1967, the Potts Report, therefore, was published, in order to implement some of the findings of the Banwell Report.

- **The Wood Report (1975):** it is a product of a working party formed between the government, trade unions and industry. It was presented at a period of political and economic crisis. It was at the end of the post-war construction boom and the start of cuts in government spending (Murray and Langford, 2003). At the same time, construction costs experienced a sharp rise whilst some of the country was working a three-day week[13] (Murray and Langford, 2003). The report focused on how to yield better value for money by advocating some reforms to procurement of consultants and contractors, such as to move away from lowest-price tendering, use of pre-approved lists of suppliers, and development of a rolling programme of public sector projects to stabilise demand for construction. Wood's recommendations presumed a future return to the 'normality' of the 1960s, but the worsening economic conditions led to a new government policy based on cutting public sector expenditure rather than using it as a lever to shape the construction industry (Murray and Langford, 2003). The report, therefore, had only a modest impact.

- **The British Property Federation Report (1983):** this was initiated and delivered by a group of predominantly private sector clients (Pryke, 2012). The objective was to produce a manual that sets out a procurement system to address the issues that caused overruns and disputes. Recommendations of this report were very specific and adopted widely by the private sector developers. This included the creation of a new role of client's representative and publication of a standard building contract reflecting the system described in the manual. Outside the private sector, the recommendations of this report were largely ignored (Pryke, 2012).

- **The Latham Report (1994):** it was commissioned by the UK government to investigate the perceived problems with the construction industry, which the report's author described as 'ineffective', 'adversarial', 'fragmented' and 'incapable of delivering for its customers'. The report was carried out at a very difficult time for the industry; it had just experienced the heights of economic growth a few years earlier and was currently experiencing a significant decline (Murray and Langford, 2003). The report dealt with procurement of consultants and contractors and contractual conditions. Latham advocated a thorough overhaul of the present standard forms and promotion of a non-adversarial culture. He argued that a fresh approach was required to introduce better working practices in the construction industry. To this end, he suggested putting the client at the core of the construction process and adopting partnering, as a more integrated approach to reduce conflicts and disputes.

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[13] A measure introduced by the government following the oil embargo imposed by the Arab members of the Organisation of Petroleum Exporting Countries (OPEC). Commercial users of electricity were limited to three specified consecutive days' consumption each week and prohibited from working longer hours on those days.

The Latham report led to the creation of the Construction Industry Board (CIB) to oversee implementation of its recommendations, but CIB was disbanded few years later owing to clients withdrawing support in the belief that this organisation was failing to promote their strategic business goals (Murray and Langford, 2003).

- **Rethinking Construction (Egan Report, 1998):** it was the output of the Construction Task Force (CTF) set up by an incoming UK Labour government with the scope of improving the quality and efficiency of UK construction industry (Pryke, 2012). The composition of CTF was criticised for exclusively representing private sector construction clients and in specific biased towards house building (Murray and Langford, 2003). The background of Egan was in manufacturing and thus his report was not entirely welcomed by the industry; there was some perception that applying experience in manufacturing to an industry as different as construction was unrealistic (Murray and Langford, 2003). Nevertheless, the major clients on the CTF agreed to lead the way by supplying a number of demonstration projects that would be used to develop and illustrate the ideas in the report. The objective of these demonstration projects was to pursue innovative approaches, disseminate knowledge and promote best practices to other firms operating in the industry. This entailed coming up with an industry-wide performance system to measure performance. Ten years after publication of Rethinking Construction, Egan said, 'we have to say we've got pretty patchy results. And certainly nowhere near the improvement we could have achieved, or that I expected to achieve'…..'I guess if I were giving marks out of 10 after 10 years I'd probably only give the industry about four out of 10' (Egan: I'd give construction about 4 of 10, 2008, p. 1 and p. 4 respectively).

- **Recent Government Construction Strategies:** the government has recently published a series of documents relating to construction industry. For instance, the Construction Strategy for 2011-15 which acknowledges that 'the UK does not get full value from public sector construction; and that it has failed to exploit the potential for public procurement of construction and infrastructure projects to drive growth' (Government Construction Strategy, 2011, p.3). It has therefore called for a profound change in the relationship between public authorities and the construction industry. To this end, it suggested using performance specifications rather than prescriptive specifications to define client needs, use of standard forms of contract, using benchmarking to enable government clients to challenge the market on cost without sacrificing value, and creating a digital economy for infrastructure, buildings and services. The overarching aim was to reduce the cost of public sector construction projects by up to 20% (i.e. £8.8 billion); cost reductions which can then be reinvested in further projects, stimulating economic growth.

In March 2016, however, the strategy was superseded by the Government Construction Strategy 2016-2020. This revealed that only £3.3 billion had been saved over the past five years, clearly well below the target. The new strategy sets a much less ambitious target of just £1.7 billion over the whole period 2016-2020. It sets out ambitions for smarter procurement, fairer payment, improving digital skills, reducing carbon emissions, and increasing client capability. As part of the strategy, Building Information Modelling (BIM) was defined as one of a range of tools that will be used to digitise the industry to better understand the needs of clients and enable 'right first-time' delivery. These themes are consistent with the wider long-term strategy policy paper, Construction 2025, which was jointly delivered by industry and government in 2013.

It is clearly evident from the above historical review that there is a significant number of recurring themes; they are not just a shot term aberration. With hindsight, Pryke (2012) argues that this is mainly because these reviews have highlighted the shortfalls of construction industry but failed to implement the recommendations effectively to achieve tangible change within the industry. He further explains that implementation effectiveness is highly related to the analysis and presentation approaches used. This is discussed further next.

3.3   Network Approach

Since 1965, Tavistock Institute had encouraged the construction industry to 'find out how the system works, the functions of its different parts, their interrelationships… the main centres of control and coordination' (Higgin and Jessop, 1965, p. 56). More importantly, it acknowledged that information and communications in projects do not flow linearly in the direction of the hierarchy reflected in contractual conditions. Pryke (2012) highlights that these noble ideas suggested by Tavistock Institute were not addressed by a large number of the industry studies; for example:

- The work of Higgin and Jessop (1965) adopted task-dependency approach, where processes were presented through the use of simple Gantt charts and information flow charts. Although interdependence was identified as a key issue, the study lacked the detailed quantitative analysis;
- Cleland and King (1983) highlighted the need to quantify the relationships between actors and to identify the key actors for a given task or process. However, it lacked the analytical tools to investigate prominence within organisations and interdependencies were not readily identifiable;

- Curtis *et al.* (1991) uses cognitive-mapping approach to study the roles and responsibilities in projects. This involved mapping communications between actors. However, it failed to equate this mapping to any form of processes and hence added little to our understanding of the way in which projects are delivered;

- The work of Turner (1997) and Masterman (2002) on functional relationships adopted structural analysis but it was essentially based on contractual communications. Similarly, Coggin (1974), Stoner *et al.* (1995), and Davis and Newstrom (1993) adopted a simple structural approach but they did not deal with the roles of the actors and the interpersonal relationships;

- Franks (1999) adopted a process modelling approach, mapping the procurement stages of a construction project as a flow chart. However, the analysis of actors, their functions and the communications between them was inadequate; and

- Walker (2015) adopted linear responsibility analysis to the modelling of process, providing a classification of responsibilities in matrix format. This approach, however, failed to provide any detail about how the responsibilities were executed by those to whom they were allocated.

Pryke (2012), therefore, advocates bringing human relationships to the fore by highlighting that project activities are essentially the output of networks of interpersonal relationships. Furthermore, actors' roles in projects are best understood as a function of their positions acquired within a given network, i.e. they do not follow the official reporting structures prescribed in contractual documents (Pryke, 2017). Adopting a network perspective, therefore, entails that actors can change their positions in the networks, providing representation of a dynamic system rather than a static representation of an authority relationship structure (Nohria and Eccles, 1992). This network approach focusses on the relationships among the actors in order to understand the overall properties of the system and determinants of its outcome (Wellman, 1988; Mazzocchi, 2016). It is believed to have the capacity to overcome the limitations imposed by reductionism by focusing on "connectivity" and thus aid in understanding the "whole again" (Mazzocchi, 2016). Of particular interest, adopting network perspective can generate insightful analysis to project organisations/teams by explaining the organisational phenomena from a social dimension rather than business benefits (Ruan *et al.*, 2013; Pryke *et al.*, 2015). Therefore, it provides managers with the tools necessary to shift their focus from boundary protection towards underlying relationships, regardless of the hierarchies.

3.4   The Knowledge Gap in Network Analysis

Over the past two decades, the area of network analysis has established itself as a major theoretical framework across a variety of disciplines, as evidenced by the exponential growth rate[14] of the publications referencing Network Approach (Borgatti *et al.*, 2014). This growth is illustrated in Figure 3.1 below.
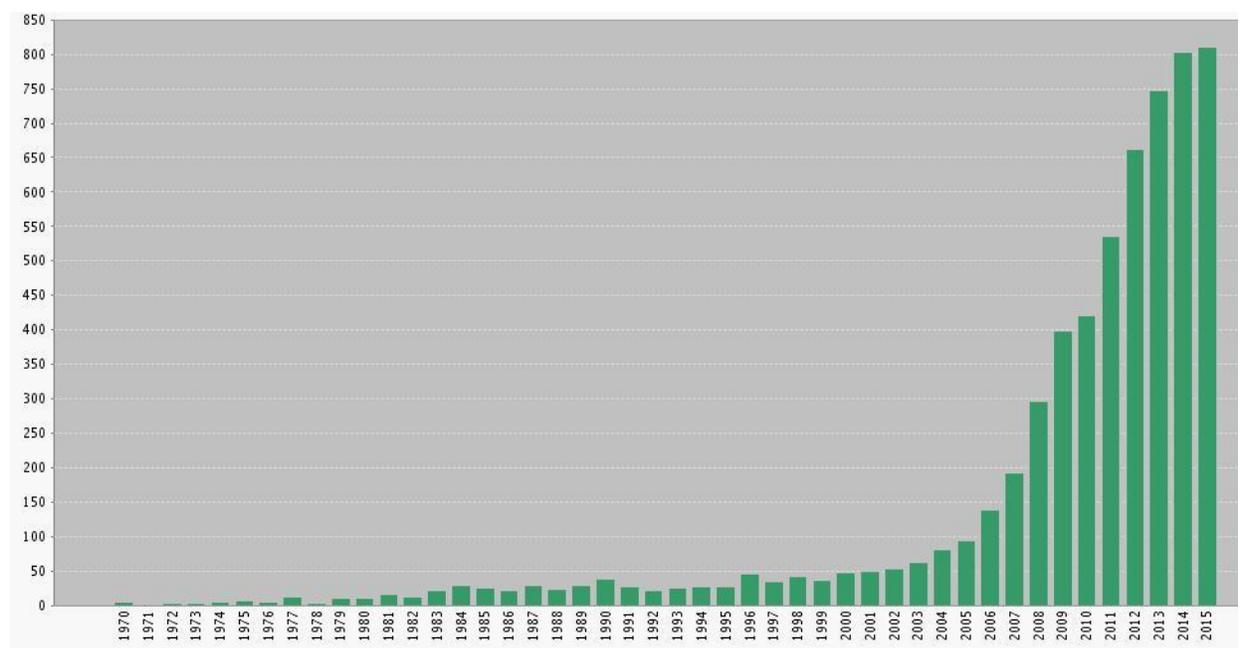
Figure 3.1: Number of Publications Indexed in Web of Science Core Collection with "Network Approach" in the Title in the period "1970-2015".
(Source: Original- Extracted from Web of Science)

Despite this growth, Borgatti *et al.*, 2014 suggest that there is a knowledge gap in the literature relating to network approach. This is because its applications have been limited to the "static-oriented" systems where the network data is often cross-sectional, collected at one specific point in time rather than investigated over long periods of time (Borgatti *et al.*, 2014). Additionally, ties are conceptualised merely as conduits that enable things (e.g. resources) or contents (e.g. information) to flow between actors in order to define their position in the structure (Borgatti *et al.*, 2014; Lizardo and Pirkey, 2014).

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[14] An Exponential Growth: "Growth whose rate becomes ever more rapid in proportion to the growing total number or size; e.g. the exponential growth of the world's population" (Pearsall and Trumble, 1996).

Following such discussions, Havlin *et al.* (2012) assert that large number of network studies failed to take into consideration the realistic features of networks, such as: the coupling between networks that is by assuming the networks are isolated, the dynamics of networks by taking a static view of networks, interrelationships between structure, dynamics and function of networks, co-evolution and interdependencies of networks, and finally the spatial properties of the networks.

In a similar vein, Borgatti *et al.* (2014) asserts that when theorising about the dynamic effects of network structures, researchers seem to ignore the continual adjustment and negotiation in networks' structure such as the possibility of new ties being added, or existing ties being dropped. In response to this critique, there have been recent calls to enrich network theory by suggesting a model of "dynamic stability" (Lizardo and Pirkey, 2014). This conceptualises networks as '*Complex Adaptive Systems (CAS) that exhibit both persistence and change*' (Kilduff *et al.*, 2006, p. 1032). As Shaw (1998, p. 29) postulates the potential paradox inherent in the phrase 'dynamic stability' or '*stability in flux is fully exposed, putting our dualistic minds in a spin*'. In this view, stability is manifested by the persistence of core structural properties whereas dynamic is manifested by the interplay between the actors and the system, and the changes that emerge from such interaction (Kilduff *et al.*, 2006). This concept links back to the importance of the duality of micro-macro analysis and postulates that '*at certain levels of analysis, stability can be seen, and yet at other levels, high degrees of dynamism are apparent*' (Grove *et al.*, 2018, p. 9). In essence, such 'dynamic stability' approach is capable of addressing the paradox of recursiveness of networks, i.e. the routine creation and re-creation of relational patterns as necessary to accomplish goals (Kilduff *et al.*, 2006). The latter is at the heart of this thesis discussion and will be investigated and reflected on throughout the chapters.

A number of studies with a large variety of datasets, such as collaboration and citation networks (Berlingerio *et al.*, 2013), online social games (Szella *et al.*, 2010), and transportation networks (Cardillo *et al.*, 2013; Cozzo *et al.*, 2013; Kaluza el al., 2010), have found that networks exhibit a significant overlap of ties between its different layers. This entails moving beyond the simple 'single-layer' networks towards conceptualising the project as multi-layered networks, as depicted in Figure 3.2 below (Dickison *et al.*, 2016; Boccaletti *et al.*, 2014). Thus, what happens at a single level or layer of interaction affects the structure and function of the network at another interconnected layer (e.g. Padgett and McLean, 2006). In turn, the topological structure of a whole network can be explained as emerging from the simultaneous presence of these multiple layers (Cardillo *et al.*, 2013). This new concept in network studies is thought to be the next step towards a better and full comprehension of modern social systems (Dickison *et al.*, 2016).

Unfortunately, for so long the study of interactions has been deduced and investigated through the single-layered perspective (Borgatti *et al.*, 2009). To address this gap, this thesis, therefore, will adopt the multi-layered framework developed by Pryke (2012). This research method will be explained further in the Methodology Chapter.
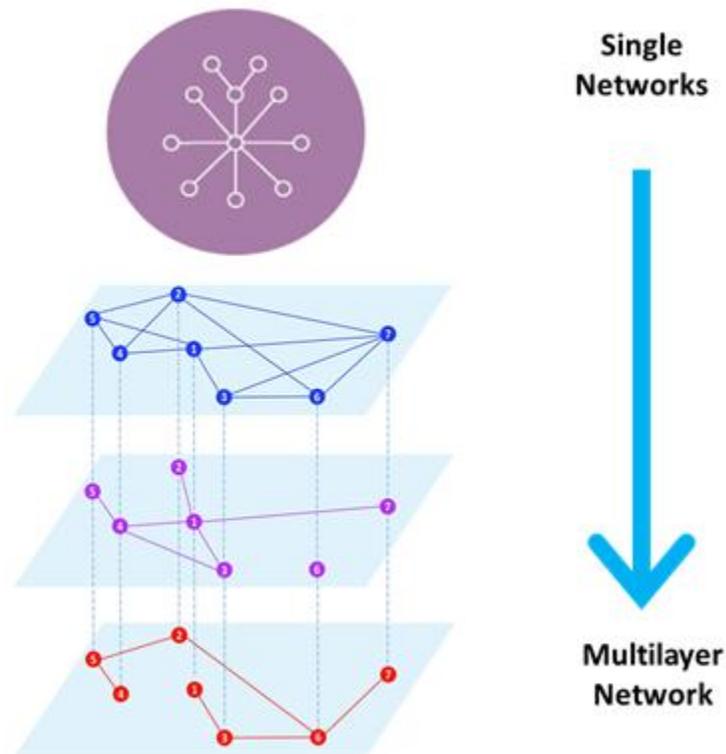
Figure 3.2: The Multi-Layered Network Perspective.
(Source: Developed from: Boccaletti *et al.*, 2014)

Next section introduces the analytical approach Social Network Analysis (SNA) and the benefits it might bring to the understanding, representation and analysis of construction projects.

3.5   Social Network Analysis (SNA)

Pryke (2012) suggests using Social Network Analysis (SNA) as a new analytical approach to better understand the multiple concurrent and interdependent systems that comprise the construction project. SNA is the '*product of an unlikely collaboration between mathematicians, anthropologists and sociologists*' (Pryke, 2012, p.77). It offers an alternative powerful formal language to investigate complex systems, by understanding how structure defines the overall social system. Its central axiom is not focused on the actors and their attributes and properties but instead on how they are interconnected (Wasserman and Faust, 1994; Borgatti *et al.*, 2014). It is further argued that such analytical approach entails to turn our thinking from artificial boundaries that were imposed by traditional hierarchies and procurement terms (such as project phases, contracts and subcontracts, organisational charts) towards the idea of viewing value delivered to clients and stakeholders as a product generated by networks of relationships that usually span organisational and project-related boundaries (Pryke, 2012).

SNA provides an opportunity to better analyse, both graphically (using sociograms) and mathematically in a more common and accessible terminologies, the nature of the inter- and intra-relationships and their function between individuals and firms seamlessly without any boundaries, and hence accurately describe success and failure by providing better focus for delivery of superior value that can achieve client 'delight' (Pryke, 2012). According to Pryke (2012), SNA can overcome the following key problems confronting construction industry:

- **Interdependence:** by relating networks to specific functions and hence reflecting the roles of the individual actors in the project network, rather than what their job titles designate. This confronts the appropriateness of traditional project management tools, for example flow charts and critical path analysis, in reflecting the specific roles played by individuals in projects.

- **Non-Linear, Complex Iterative and Interactive Processes:** SNA is sophisticated enough to provides more interactive means to deal with the complex, concurrent and interdependent systems. For example, by taking a multi-layered network perspective (i.e. the whole network constitutes other sub-networks, in which these are interdependent), such processes could be understood by analysing interactions of different types of ties among the same set of individuals (Dickison *et al.*, 2016; Boccaletti *et al.*, 2014). Additionally, complexity of the design process entailed the involvement of specialist sub-contracts and manufactures early in the process. This confronts the linearity and time-related approaches that are used to plan and describe the design and construction processes.

- **The Need for a Single Graphical Representation:** by providing one systematic format to represent the different conflicting systems and hence easily compare between them using the same language.

- **The Need to Make Analysis at an Appropriate Level of Detail:** by enabling an analysis to be made at any selected level (individuals, groups of actors or whole network level) and hence presenting construction systems appropriately where decisions are processed on a concurrent and interdependent basis by groups of actors.

- **Quantification of Differences:** by representing the differences between systems, projects, and the actors' positions in a mathematical manner.

- **Non-Hierarchical and Non-Dyadic Representation:** by providing a quantifiable measure for the actors' centrality that reflects its role importance, prominence, or power within the project/organisation network rather than related to a dyadic contractual relationship. Additionally, SNA enables to cite more than two parties and hence represents more closely the team-based nature of construction systems.

- **Inter-firm Relationships versus Inter-personal Relationships:** SNA has the ability to represent relationships between project actors in a comparable format to contractual relationships by gathering data from individuals and representing them as relationships between firms. Additionally, SNA has the strength to analyse and compare variety of governance, procurement and management forms in a simultaneous, uniform and systematic manner that is readily understood by both academic and practitioner.

- **Explicit Formal Statements and Measures:** SNA provides very precise meanings to social terms, such as 'networking', 'webs of relationships', and 'social position' that might otherwise be defined only in metaphorical terms (Wasserman and Faust, 1994). It also allocates mathematical definitions/formula to each of these terms.

3.6   The Key Features of Social Network Analysis (SNA)

The mathematics behind the measures and a comprehensive review of SNA data collection procedures, methods and application is beyond the scope of this section and can be referred to in standard textbooks (e.g. Wasserman and Faust, 1994; Borgatti *et al.*, 2018; Prell, 2012). This section, however, will highlight the key features that distinguishes SNA from other existing (linear) management and analytical methods, as follows:

- **A Topological Space:** by appreciating the connectivity between project actors, SNA suggests a new kind of space that is different than the one conceptualised by linear Euclidean geometry[15] (Namatame and Chen, 2016). The space created by connectivity is called a topology, which is of a nonlinear nature and can be used to abstract any inherent connectivity between any set of agents, regardless of their detailed form (Scott, 2017). This implies an ability to have different set of global rules for different sets of agents (Wasserman and Faust, 1994).

- **Flow:** connectivity in SNA entails along every connection there is a flow of something (Scott, 2017). That is, if there is no flow, then there is no network. In communication networks, information flows; in financial networks, assets flow, and so on. Additionally, a multi-layered network perspective entails accepting the fact of the simultaneous flows between project actors (Pryke, 2012). Accordingly, it is important to recognise the changing relationships between project actors and thus their changing roles within these multi-layered networks. The project communication network is the focus of this research; hence the flow of information between any two participants represents the connection/tie.

- **Social Agents:** these are the different forces (such as individuals/firms) acting within the typological space where an exchange of flow happens between them, representing the connections (Wasserman and Faust, 1994). Establishment of the connections between these agents is based upon the perceived return which is expected to be higher than the investment of time energy, interest, social capital or any other resource that of value (Pryke, 2012). In this thesis, social agents are represented by the individuals that have been involved in the project communication networks.

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[15] Euclidean geometry: "*Relating to or denoting the system of geometry based on the work of Euclid and corresponding to the geometry of ordinary experience*" (Pearsall and Trumble, 1996). In nutshell, this is the study of flat space. Namatame and Chen (2016) argue that many social interactions are beyond the common sense of Euclidian geometry, hence spatial modelling is far too limited in capturing the different levels of social interactions.

- **Micro/Macro Analysis:** SNA has the capacity to analyse a network, by either taking a micro level bottom-up perspective or a more global perspective (Wasserman and Faust, 1994). In the former, the focus is on the agents/actors, why and how they make connections, whereas, in the latter, the focus is on the overall network and the environmental context to see how these shape the system of connections (Scott, 2017).

- **Environment:** Although SNA provides a quite abstract representation, this does not mean researchers will lose sight of the fact that these networks exist within some context (Pryke, 2012). Actually, SNA can still help in contextualising and understanding the nature of the whole network and the kind of environmental forces that it is under.

Having discussed the general features of SNA, next section explains self-organising networks within which actors organise and facilitate the design and delivery of projects.

3.7 Self-Organising Networks

Self-organising networks are a special type of networks. They can be viewed as *'complex [adaptive] networks that are not regular, but they are not random either: their linking patterns do obey certain regularities, albeit not strictly' [emphasis added]* (Heylighen, 2011, p. 12). In the study of projects, self-organising networks represent the systems for project delivery, comprising the non-contractual information exchange relationships (Pryke, 2017). They form in response to different pressures (e.g. uncertainty, time and financial constraints) on project actors to connect and collaborate, particularly for information gathering, processing and dissemination (Pryke, 2017).

There is a common misunderstanding prevails in relation to the self-organising networks, in that they may not be suitable, as a management tool, to operate within a goal-oriented framework, such as a project. This misunderstanding is grounded on the Newtonian paradigm, which stipulates maintaining stability and equilibrium to achieve successful project delivery (Foerster, 1984; Mahmud, 2009). However, in reality, project actors need to obtain information from other actors with whom they have no contract. They also face a number of unpredictable problems. In the context of the complexity paradigm, projects are therefore transient; they are seen as a social function and hence formation of non-contractual self-organising networks is considered inevitable (Pryke, 2017).

Thompson (2003) argues that the focus of a group of individuals on common project-orientated goals requires establishing 'mutual orientation'. He further argues that this can be achieved through complementarity and accommodation, i.e. reciprocity, mutual exchanges and a desire to assist others. While 'mutual orientation' is recognised to have a detrimental effect on project delivery, it is typically not managed in any way (Thompson, 2003); and thus Pryke (2017) suggests that self-organising networks can be used for achieving this objective. This is because self-organising networks are flexible and adaptive; they evolve and decay as a response to the need to process information in an efficient manner (Foerster, 1984; Mahmud, 2009; Stacey, 2010).

This premise is essential as it sets the ground for discussing the nature of the adaptive capacity that gives the self-organising networks their distinctive features (Comfort, 1994; Kauffman, 1993). This capacity is also sometimes called systems' robustness or resilience. It is an essential quality to have in order to cope with the uniqueness of each issue faced in projects. This can be achieved by replacing the traditional project communications of regular reports and other 'one size fits all' strategies with a more tailored methodology that considers the complexities of each stakeholder involved (Bourne, 2015). It also entails carefully designing targeted information exchange strategies, which are characterised by using highly particularistic forms of knowledge that match the context-specific of the issue in question and addressed to the right parties (Bourne, 2015). The induction of self-organising networks may require changing the actors' positions in the communication network structure, but the overall characteristics will remain unchanged. Such quality helps in having a network structure with a smaller number of bottlenecks, and hence facilitating the dissemination of information in a more efficient and effective way.

Despite their intrinsic unpredictability, self-organising networks were found to inherently settle into small groups/communities of recognisable behaviours (Heylighen, 2011). This represents a model of "dynamic stability" that is equivalent to system equilibrium state, where bifurcation processes can take place in response to any sub-system changes/events but tolerated within the adaptive capacity of the system (Lizardo and Pirkey, 2014). This may include changes occurred in any project phase, where relational patterns are being re-created to reduce the perceived complexity and uncertainty, but without any core structural changes. From a multi-layered network perspective, these bifurcation processes can be understood as the multiple functioning modes of these different layers as the uncertainty and complexity of the project and/or its environment increase (Kivelä *et al.*, 2014). These events are described as "absorbable", as the system continues to fluctuate between the boundaries of chaos and order, and between stability and dynamics, before a new network structure is fully shaped.

From the SNA perspective, "absorbable events" can be manifested, for example, by having resistance to change in the largest component of the network and/or overall attributes, such as density, average path length. However, positions of the actors, and hence their relational patterns, in the network structure can vary from one time to another as necessitated by the triggering events (e.g. change of project focus, scope, technologies used, and political and/or governmental support). The evolutionary transformation into a new dynamic stability with higher levels of complexity, adaptation, organisation and quality may occur gradually or in jumps, through a transition phase (Comfort, 1994). This is usually accompanied with the achievement of key deliverables (e.g. moving from design to construction phase which is commonly recognised as an important life-cycle shift in large construction projects); or otherwise as a result of major events (e.g. change in management, natural disasters) that again pushes the system towards a transition phase and therefore requires major restructuring (Comfort, 1994). Figure 3.3 below illustrates the evolutionary cycle of network structure in reference to the overall project life cycle, using the project phases outlined in the Royal Institute of British Architects (RIBA) Plan of Work 2007.

Next section outlines the key SNA structural properties pertaining to self-organising networks.

RIBA Outline Plan of Work (2007)

Preparation		Design			Pre-Construction			Construction		Use
A	B	C	D	E	F	G	H	J	K	L
Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion

Absorbable events (Fluctuations and Bifurcations)

System disintegration

– – – – – Phase Transition

Figure 3.3: Projects as an Evolutionary Process.
(Source: Inspired by Saynisch, 2010, Figure 8, p. 33)

3.8 The Key SNA Structural Properties of Self-Organising Networks

Complexity researchers (e.g. Hassas *et al.*, 2006; Heylighen, 2011; Saha *et al.*, 2015; Jackson, 2010) have observed that the complex and self-organised networks typically exhibit a number of distinct structural properties. These can be defined statistically using SNA and described as follows:

- **A "Small-World" Property:** This resonates the famous 'six degrees of separation' theory which suggests that average distance between everyone on the planet is only six handshakes/steps (Powell *et al.*, 2005). That is to say self-organising networks are characterised by a relatively short average path length and a high clustering, i.e. the tendency of actors to concentrate their ties within certain groups (Baker, 2014; Watts, 1999). These characteristics result in networks with unique properties of regional specialisation and efficiency (Watts, 1999). This property also entails that a change in one node can rapidly propagate to the rest of the network. As a result, the network can swiftly react to perturbations or innovations. Although these characteristics make a given network surprisingly robust in facing random removal of nodes in counterpart, they make it extremely vulnerable to any strategic removal directed to nodes with a high connectivity and multiplexity of ties[16] (Hassas *et al.*, 2006; Lizardo and Pirkey, 2014). The latter eventually could lead to network dysfunction (as have been identified in Pryke *et al.*, 2015). This means small-world property can also be viewed as "dyadic liability" rather than just a "diffuse strength" (Lizardo and Pirkey, 2014; Prell, 2012). The concept of small-world is crucial to our investigation of self-organising project networks. It will be utilised to study the dynamics of self-organising networks in terms of efficiency and costs.

- **Clustering:** High clustering is the reason behind small-world property. This stems from a distance-based cost structure, i.e. nodes that are closer or more similar (e.g. co-location, co-membership, co-participation, sharing attributes) find it cheaper to maintain links to each other leading to high clustering (Borgatti *et al.*, 2014). Borgatti *et al.* (2014) assert that such property provides the conditions to maintain the system functionality as well as its holding capacity by creating 'inertia' to resist change.

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[16] Following Lizardo and Pirkey's (2014) definition, multiplex ties are redefined as cluster-spanning ties, that is, by their membership in multiple clusters.

Having said that, Project Managers should be mindful that excessive connectivity and interdependence could lead to negative results of repetitive and uniform behaviour i.e. constrains (Granovetter, 1973). This, in turn, can result in the emergence of 'groupthink' phenomenon, for example, where feelings of obligation and friendship may cause an increased communication load, poorer performance, missed deadlines, suppressed creativity, more rework, and compromised quality, hence hindering the resolutions of particular issues (Robbins *et al.*, 2010).

- **Network Density:** This is the primary determinant in the makeup of any network (Wasserman and Faust, 1994). It simply about asking how many connections are there relative to the maximum possible number of connections (Wasserman and Faust, 1994). Mathematically, it can be calculated as follows:

$$\text{Density} = \frac{\text{Actual Number of Ties}}{\text{Maximum Possible Ties}} \qquad \text{(Equation 3.1)}$$

However, maximum possible ties are a function of number of nodes (N) which is calculated as follows:

$$\text{Maximum Possible Ties} = \frac{N \times (N-1)}{2} \qquad \text{(Equation 3.2)}$$

Density, as defined under Equation 3.1, therefore can be calculated as a function of number of nodes as follows:

$$\text{Density} = \frac{\text{Actual Number of Ties}}{N \times (N-1)} \times 2 \qquad \text{(Equation 3.3)}$$

From Equation 3.3, it can be inferred that density decreases as number of nodes increases (assuming the result is not counterbalanced by the numerator, i.e. actual number of ties).

Network density can be understood in terms of interaction cost, i.e. the easier it is for agents to make connections, the more connections are likely to be made. Self-organising networks follow the famous saying "*it is not what you know but who you know*". Therefore, these networks have been found to be sparse with dense local clusters, thus what network knows collectively will weigh more than what individual knows in isolation (Pryke, 2012). In construction projects, this can be done by exploiting the existence of diverse actors, encouraging various views and aligning them to the core values. This should inculcate a culture of positive chaos rather than

seeking unified information and repetitive actions (Stroh, 1998). Additionally, it implies that managers should harness the various cultures and beliefs instead of avoiding them (Walker, 2015).

- **Degree Distribution:** it is a measurement of how evenly or unevenly the degree of connectivity is distributed out among the agents. This is important because it can measure how equal or unequal resources are distributed out in a system, which can be used as an indicator for the nature of power within that system. Given the fact that in construction project communication between agents are usually conversational in nature, exercised level of power will act as a constraint to either exclude or include actions and hence determine the patterns of collaboration (Stacey *et al.*, 2000). Self-organising networks are considered distributed systems, i.e. they have a decentralised structure where every agent is involved in the decision-making and are often the product of informal relationships. This indicates a higher social integration and hence stronger channels through which a lower level of power can be exerted globally.

- **Closeness and Path Length:** This is about how close any two agents within a given network are to each other on average. This closeness is obviously a very important factor in terms of cohesion and interdependence. As the number of components to a social system is scaled-up, path lengths between members will be longer, which can adversely impact social cohesion. That is, a longer average path length acts like an outward force disintegrating the social system since it puts people at a longer distance from each other with a lower sense of interdependency. On the contrary, if the average path length was turned down (e.g. through better transportation or communication technologies), individuals will interact more often making it easier for them to synchronise their states and recognise their interdependence and common identity.

- **Scale-free:** A less intuitive feature of complex networks is that their distribution of links tends to follow a power law; i.e. there are many nodes with few links/connections, and few randomly distributed nodes with many links (Hassas *et al.*, 2006; Heylighen, 2011). Such heavily skewed nodedegree distribution is known as scalefree. Here concepts of major hubs and high degrees of social inequality emerge. That is, nodes which are extremely well connected tend to function as network 'hubs/cross-roads'. This is where many different connections come together thus acting as 'shortcuts' or 'wormholes' that reduce the distance between the clusters and bringing them suddenly within easy reach (Hassas *et al.*, 2006; Heylighen, 2011). On the other hand, the

common nodes have few links. This means a greater differentiation between degrees of connectivity in scale-free networks. This inequality can be explained by two different reasons: firstly, some people are simply better at doing certain things than others; secondly due to a preferential attachment process (Heylighen, 2011). The latter is explained next.

- **Preferential Attachment:** this is likened to "rich-get-richer" rule. It provides potential explanations for growing inequalities in the process of network expansion/growth (Powell *et al.*, 2005). That is, new nodes joining the network preferentially establish links with nodes that already have a large number of links (Heylighen, 2011; Powell *et al.*, 2005). This means that such network has a high level of centrality, is vulnerable to targeted attacks on the nodes that function as hubs but robust to the random removal of links. This is extremely dangerous in communication networks as the removal of hubs may deteriorate the network by splitting it up into separate "islands" that no longer communicate with each other (Heylighen, 2011).

Pryke (2017) advocates that preferential attachment in project networks is expected to be driven by the needs of project actors to discharge their project responsibilities. That is, in projects, actors pursue connections to facilitate the efficient accomplishment of their roles under complex and uncertain conditions (Pryke, 2017). However, such behaviour may lead to hubs being overloaded with many connections, reaching saturation level that may constrain efficiency.

Self-organising can be defined as a process to transform the dyadic contractual relationship to complex information exchange networks. This entails project actors acquiring new roles for themselves within their networks which are usually different than their contractually prescribed roles (Pryke, 2017). The identification and management of these roles is essential for effective project organisations. Next section discusses network actor roles and how they can be defined using SNA.

3.9 Using SNA to Classify Network Actor Roles

Pryke (2017) argues that roles allocated by contracts at the procurement stage are often incomplete and less important than network roles, as they are usually subject to redundancy over the project lifecycle. This argument stems from the fact that procurement usually focuses on contractual relationships, which are dyadic and inflexible. In this sense, roles acquired through contracts are usually defined by using frameworks such as the accepted body of knowledge (for example, the Institute for Project Management (IPM) and the Association of Project Managers (APM)), or a system of competences (for example, the Royal Institution of Chartered Surveyors (RICS) and the Chartered Institute of Builders (CIOB)) (Pryke, 2017). These frameworks are unable to capture the hidden self-organising networks that emerge spontaneously to support the design and delivery of projects on a daily basis (Pryke *et al.*, 2018; González-Bailón *et al.*, 2014).

The 'incompleteness' and inability to fully define the project in the contract documents at early stages, creates an uncertain environment in which self-organising networks emerge (Pryke, 2017). The implication of this is that the quest for more effective project management approaches should move away from focusing on project outcome and monetary rewards, which are heavily rooted in the 'iron triangle'. The focus instead should be on the evolving nature of project governance, based on actors' individual and collective behaviours as a consequence to this incompleteness (Jones and Lichtenstein, 2008; Grove *et al.*, 2018).

Pryke (2017, p. 29) argues that: *"the project is delivered by network of individuals with reference to a formal set of contract documents, but these documents are peripheral because the project functions evolve through iterative information exchange relationships in an environment which is essentially transient".* Consequently, Pryke (2017) calls for a move away from traditional terms, such as architect, quantity surveyor and main contractor, towards redefinition of project actor roles using social network terms. Such redefinition would reflect on reforms in the procurement and management strategies prevailed in the construction industry, as he argues these kind of network roles are currently not procured in projects. The traditional roles' classification eventually could restrain self-organising as it introduces rigidity in managing large complex projects and hence potentially stifles the interactions (as processes) and efficiency and effectiveness (as outcomes/consequences). This is exacerbated by changing key or powerful individuals as the network structure changes, through the different project lifecycle and through the different issues/risks encountered. Duggal (2018) explains that project

managers and actors are frustrated, and sometimes even confused, by these unclear lines of authority and poorly defined roles. Grove *et al.* (2018) and Stacey (2003) echo the same and explain that formal project documentations such as process maps may lead to negative consequences, such as confusion and frustration, rather than facilitating the intended shared meaning.

Pryke (2012, p. 60) suggests that *'the position that actors occupy within networks… provides a measure of quantifiable change in both organisational form and actor roles within that form'*. This is because, in project networks, the structural positions and the potential roles played by actors constrain or enable actions of others and in turn the overall network topology is re-shaped by them (Pryke, 2017), affecting the emergence of coordination both positively and negatively. For comparative analysis, Pryke (2012) suggests investigating prominence as a measure of asymmetry in relationships within a given network and the extent to which decision-making process is concentrated among a few actors. This implies that actors' position in the network is a result of the quantity and quality of their ties, rather than being imposed by organisational protocols and contractual relationships (Pryke, 2017). In network studies, prominence is determined by various centrality measures and is key to the discussion of network outcomes/consequences (Wasserman and Faust, 1994).

Concept of centrality was first developed by Bavelas (1948) and Leavitt (1951) at the Massachusetts Institute of Technology (MIT). It is also used as a measure for power[17] when groups of people are studied in problem-solving environments, such as the activities within the project environment (Mizruchi and Potts, 1998; Pryke, 2017). In this thesis, therefore, the structural positions and the potential roles played by actors in the overall network structure will be investigated and quantified by the three commonly used SNA centrality[18] measures, namely:

- Degree Centrality: a measure of Connectivity;
- Eigenvector Centrality: a measure of Influence; and
- Betweenness Centrality: a measure of Brokerage.

Figure 3.4 illustrates these three prominent roles in networks which are explained in more depth below.

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[17] Within an organisational context, power is defined as *"the ability to get things done the way one wants them done; it is the latent ability to influence people"* (Shafritz *et al.* 2005, p. 284).
[18] Methodologically, centrality is calculated by quantifying the number and quality of connections that an actor has within a network (Pryke, 2012).

1
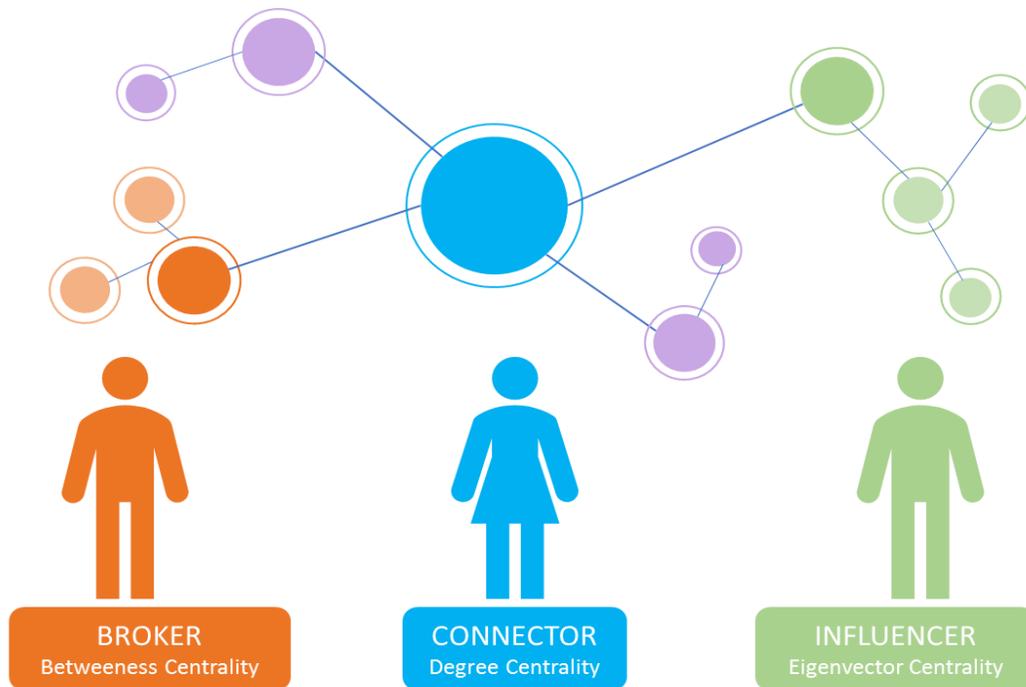
Figure 3.4: Network Roles Based on Three Actor Centralities; Betweenness, Degree and Eigenvector Respectively. (Source: Adapted from Kstoolkit, 2016[19])

3.9.1 Connectivity

The term connectivity means the number of links or connections incident upon a given node and the weight of those connections (Freeman, 1979). In a directed network, a distinction needs to be made between in-degree (incoming links) and out-degree (outgoing links) centrality. The former is often an indication of prominence (or prestige), whereas the latter signifies influence and expansiveness (Pryke, 2012; Prell, 2012). In undirected network, it is a measure for "*an actor's level of involvement or activity in the network*" (Prell, 2012, p. 97). Hence, it does not reflect popularity or influence of actors (Prell, 2012). Normalised centrality measures enable comparing actor's centrality from one network to another (Freeman, 1979; Prell, 2012).

In communication networks, high-degree nodes (hubs) are highly visible to other actors, and considered to be important (Borgatti *et al.*, 2018). Decisions in such communication networks are usually taken by the prominent actors and then communicated to other project members for them to implement. Actors with a high level of incoming links have the ability to gather information from others, that is necessary

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[19] http://www.kstoolkit.org/Social+Network+Analysis. [Accessed on: 20th September 2016]

for decision-making (Freeman 1979; Bertolotti and Tagliaventi, 2007; Steen *et al.*, 2018). On the other hand, actors with a high out-degree typically communicate and disseminate either the information required to take a decision, or the results of the decision to those who will implement it (Freeman 1979; Bertolotti and Tagliaventi, 2007; Steen *et al.*, 2018).

3.9.2 Influence

Influence is the sum of an actor's connections to other actors, weighted by their degree centrality (Prell, 2012). It is a measure of an actor's ability to influence the network due to their popularity and prestige. It is a measure of whether an actor is connected to the well-connected, and it works best when centrality is driven by differences in degree (Bonacich, 2007). Such measure reflects the extent of the effects of secondary connections, which is important to note when dealing with complex communication networks (Pryke, 2017).

3.9.3 Brokerage

Brokerage reflects how often an actor lies on the path between other nodes in the network (Freeman, 1979). Betweenness can be interpreted as a measure of potential control over information as it quantifies how much an actor acts as an intermediary to others (Freeman, 1979; Borgatti, 2006; Prell, 2012). Actors with high levels of betweenness are usually regarded as 'brokers' or 'gatekeepers', as they act as critical bridges, reducing the distance between any two nodes (Freeman, 1979; Borgatti, 2006). They can help to hold the network together significantly by reducing transaction costs, but at the same time, they can control the flow of information and communication (Freeman, 1979; Borgatti, 2006; Prell, 2012) by retaining or biasing the information (Freeman, 1979; Hossain and Wu, 2009) and creating unnecessary iterative interactions (Pryke, 2017). The latter may lead to an actor having a "dysfunctional prominence" and may then lead to disruptive functioning of the network (Pryke, 2017). Cross *et al.* (2002) suggest that project teams may become over-reliant on these specialised, knowledgeable individuals. As a result, they become overloaded, leading to poor project performance. Additionally, this affects continuity where actors change over the project lifecycle.

It is important to note that the intention of this thesis is to provide a broad picture of the types of roles that are expected to be acquired in networks, both globally and locally. This comes to reflect the transitional nature of project networks and the interdependency of network actors. In this sense, global

roles, for example, are those acquired to collaborate, gather and/or disseminate information and connect different clusters/groups (i.e. inter-cluster roles). While local roles are those acquired in intra-clusters, as illustrated in Figure 3.5 below. By classifying brokerage roles based on their influential levels, this analysis can extend previous network studies with the aim of providing a deeper understanding of the dynamics of networks. This is discussed next.
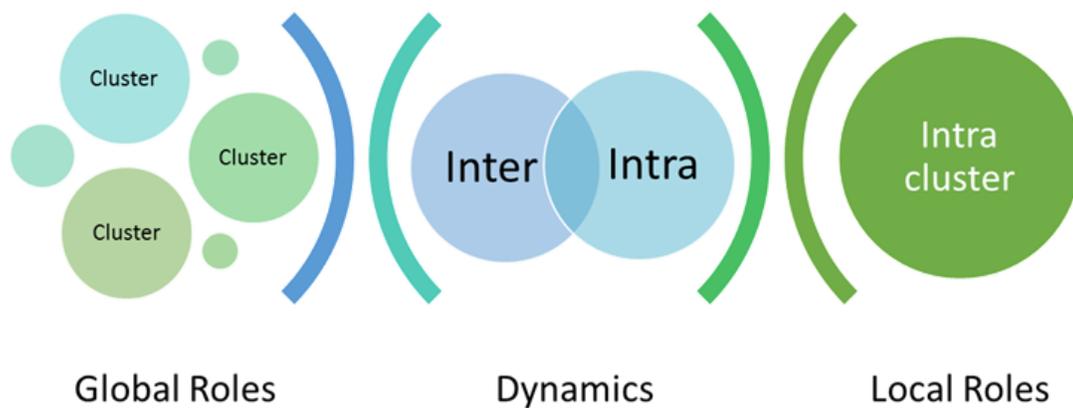
Figure 3.5: Interplay Between Global and Local Roles as A Function of Network Dynamics. (Source: Original)

3.9.3.1   Classification of Brokerage Roles

Gould and Fernandez (1989) introduced the concept of brokerage typology in order to categorise brokerage roles. They were interested in understanding the reasons behind individuals crossing their group boundaries to work with others, and if it is related to the perceived influence in the network. This typology divides brokerage activities into five different roles, that can be classified as either global or local roles, depending on the outcome of the brokerage (Prell, 2012). That is, if the broker connects actors from the same cluster, this is considered to be carrying out a local brokerage role. On the other hand, connecting individuals from different clusters is considered as a global role.

These different brokerage roles are illustrated in Figure 3.6, below. The shading of the node, specifically red, blue, or yellow, indicates to which group the node belongs, where the boundary of the group is defined by dotted lines. The broker is always the node in the middle of the 'chain' - the one that both sends and receives information (represented by a directional arrow).
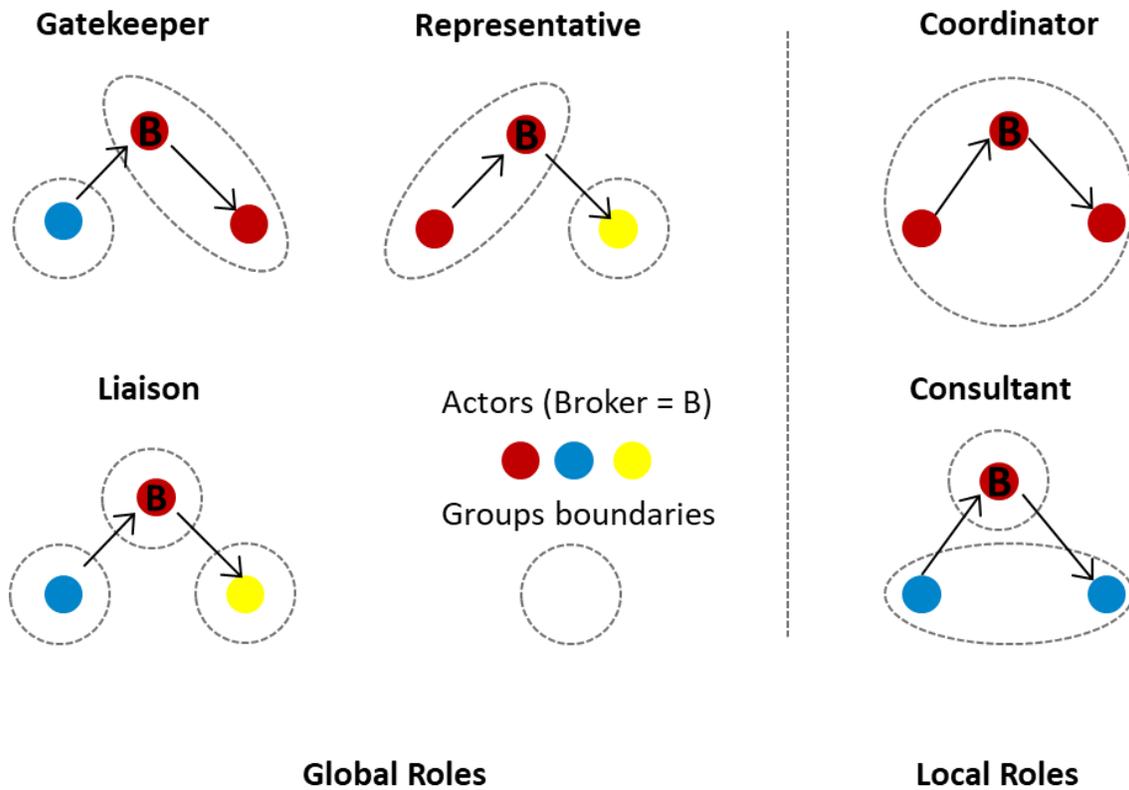
Figure 3.6: Brokerage Roles' Classification.
(Source: Adapted from Gould and Fernandez, 1989, Figure 1, p. 93)

These different roles are described as follows (Prell, 2012):

1. **Local Roles:**

   - **Coordinator:** brokerage is occurring within one defined group. The broker is coordinating the activities of group members who share similar interests, aims, and goals;
   - **Consultant:** brokerage is occurring locally within a defined group. The sender and the receiver of information are from the same group, while the broker is from a different group;

2. **Global Roles:**

   - **Gatekeeper:** the broker receives information from a node in a different group, then communicates it to a node in his/her group. This role is perceived negatively in networks as gatekeepers can gain power by filtering, controlling and delaying the information exchange;
   - **Representative:** the broker represents his/her group to a member of a different group;
   - **Liaison:** all the three nodes in the brokerage chain are from different groups.

This classification links naturally with Merton's (1968) research on brokerage roles. This research distinguished between local roles, oriented towards the promotion of social integration, and the cosmopolitans, working to create social differentiation (Täube, 2004). Gould and Fernandez (1989) brokerage analysis has been proved useful in understanding different network roles, but it is often criticised for disregarding the directionality of connections (Prell, 2012). Directionality is crucial to communication networks; and if direction is neglected the distinguishing between gatekeeper and representative roles cannot be made (González-Bailón *et al.*, 2014). Hence, this is a limitation in Gould and Fernandez's (1989) classification that needs to be highlighted.

Next section provides some discussion of previous applications of SNA. While the focus of this thesis is construction industry, few examples of studies from other industries/disciplines have also been given with the aim to present a reasonably well-rounded summary.

3.10 Previous Applications of SNA

Management scholars have increasingly viewed construction projects as networks of social relationships by adopting network approach. For example, Pryke (2006) who showed that pressure for reform in UK construction procurement has led to a move towards relational contracting under the public sector procurement strategy known as 'prime contracting'. He suggested that this innovative approach has led to a radical change in traditional construction roles and relationships and supported this argument by examining the emergent roles and relationships using SNA tools. However, his study was focusing on the legal issues associated with the new procurement strategy. Pryke and Smyth (2006) dealt with management of complex projects, defining added value to projects through the relationships surrounding the client. It showed how to create and maintain effective relationships between the client and the project team, as well as intra-coalition relationships. It concluded by highlighting how crucial good relationships are to the successful management of projects. Pryke and Ouwerkerk (2003) studied post completion risk transfer audits. They underlined the benefits of adopting a network approach to map project relationships for effective risk identification and management. Styhre (2008) explored the role of social capital in knowledge sharing. His study investigated the interpersonal relationships of a Swedish specialist rock construction company. His analysis demonstrated how social networks, built by each professional, are activated when unexpected events occur. The conclusions of the study highlighted that, in the absence of structured practices, the knowledge sharing and learning of blue-collar workers largely depend on word of mouth and personal contacts. While these studies have recognised the crucial roles played by social relationships, they lack application of SNA tools and techniques.

According to Ruan *et al.* (2013) there is a scant application of SNA in the UK construction industry. At best, there is a limited use of measures mostly relating to the general attributes (e.g. degree centrality and density). This is because despite the importance of informal networks and its contribution to performance, they are rarely recognised and understood by the organisations they are embedded in (Cross *et al.*, 2002). This explains why majority of the SNA applications in construction industry remain concerned with the relationships that are formally prescribed by hierarchical organisational structure and/or contractual functions/obligations (Pryke, 2012; Ruan *et al.*, 2013). For example, the work of Chowdhury *et al.* (2011) highlighted the benefits of using SNA in bridging the gaps in understanding the complex structure of Public Private Partnership (PPP) arrangements and identifying main structural features and the influential actors. Their analysis, however, was limited to the formal contractual relationships between parties involved in the PPP agreements.

In response to the calls to focus on the relational and self-organising aspects of projects, a stream of research has emerged recently conceptualising construction projects as networks. A prominent example in the construction literature is the work of Pryke, Badi & Bygballe (2017a). They presented a special issue in the Journal of Construction Management and Economics that included eight articles examining a wide range of issues concerning the construction industry, such as time-saving through knowledge sharing networks, improving financial returns through network position in equity markets, and increasing business competitiveness through inter-firm network relationships. Collectively, the articles highlighted the potential of social network theory and SNA to enrich the area of project management. The work of Pryke, Badi & Bygballe (2017a) concluded by outlining a research agenda for social network research in construction industry that is predicated on three key issues, as follows: 1) understanding of the role of individual actors; 2) exploration of relationships in delivering project outcomes; and 3) dealing with transitions in projects and in particular the transformation from contract award to project delivery. This thesis stands in this tradition and builds on such emerging body of work with the aim to provide further insights into the study of the formation of self-organising networks and understanding their role within the context of complex infrastructure projects.

Some network-analytical studies have investigated the informal ties; however, they are not without shortfalls and limitations. For instance, Loosemore (1998) explored interpersonal communication networks but he focused on crisis management in the UK construction industry under what is defined as 'crisis conditions'. His work, also, did not explore the use of sociograms for the representation of communication networks. Another example is the work of Hossain (2009a, 2009b) and Hossain and Wu (2009), who investigated the correlation between actors' centrality in a project-related e-mail communication network and organisational coordination. The findings revealed the importance of centrally positioned actors in coordinating large proportion of project activities. However, the study exhibited limited use of SNA measures and was based on organisational process theory. The work of Soda and Usai (1995) studied networks of construction firms in northern Italy, competing for public sector work. They highlighted that interorganisational collaboration is embedded in networks of social relations; a quality that allows smaller construction firms to win large size projects. They, however, defined centrality in relation to the possession of work permit, focusing on actors with the same attributes. The work of Hagedoorn on strategic alliances (e.g. Hagedoorn, 1993; 1996; Hagedoorn and Schakenraad, 1991; 1994; Hagedoorn and Narula, 1996) who studied the behaviour of firms but focused

on the relationships between corporate bodies; hence largely ignoring the daily interpersonal activity within these alliances.

SNA has also been employed by a number of Space Syntax studies. For example, Wineman *et al.* (2008) highlighted the crucial role of spatial configuration in shaping the formation of co-authorship networks within a university department. Definition of closeness in this case, however, can be influenced by departmental policies on how staff are placed. Peponis *et al.* (2007) studied work processes of a design firm, before and after moving into new premises. They drew a relationship between knowledge-related processes and space; hence underlying the impact on efficiency. However, they highlighted difficulties in measuring performance. Sailer (2010) studied the relationship between spatial configuration and organisational behaviours, focusing on collective patterns and physicality. However, she highlighted that *'the structure of social networks in relation to spatial configuration, or the importance of choice-related configuration measurements are only just discovered as relevant topics in the respective research communities of Social Network Analysis and Space Syntax'* (Sailer, 2010, p. 342).

As part of SNA literature on loosely structured systems, Glückler (2008) explored the evolution of a strategic alliance network in the context of German stock photography. This sector experienced fundamental technological, institutional and organisational changes in a very short time, giving rise to new forms of sales alliances. This new phenomenon was largely explained by multi-connectivity which theorises that multiple indirect linkages between any two firms enhance the formation of direct ties between them. He further found a strong association between geography and alliance behaviour.

Albert *et al.* (1999) studied the topology of the World Wide Web (WWW) and calculated its diameter. He found that development of WWW follows a scale-free power-law distribution, indicating it is governed by self-organising phenomena. This feature is supported by the addition of new nodes, in this case the HTML documents connected by links pointing from one page to another, which in turn attach preferentially to sites that are already well connected.

In their study to analyse virus and worm infections, Balthrop *et al.* (2004) explored the structure of several computer networks and explored their epidemiological characteristics. They suggested a dynamic throttling mechanism to control contagion for different computer network types. This mechanism would slow the spread of computer infections while leaving normal network traffic unconstrained.

Another study is Xu *et al.* (2006) who applied SNA to the study Open Source Software (OSS) development community. They found that the social networks of the OSS community represent a self-organising system which obeys scale-free behaviours. The inclusion of the co-developers and active users triggers the emergence of the small-world phenomenon, turning the OSS community into a fast communication network. The study concluded by giving recommendations on how the topological network properties can be used to potentially explain the success and efficiency of OSS development practices.

Recently, the investigation of actual/informal roles and positions played by project actors has received some attention with the aim to generate useful insights into the functioning of projects. For example, the work of Kratzer *et al.* (2010) underlined the importance of informal ties in project teams. The study analysed a group of engineers involved in a new product development and concluded that the informal relationships are positively correlated with creativity.

Also, Pauget and Wald (2013) investigated relational competence[20] in a large construction project of a French hospital. Using the communication/information exchange networks and qualitative interviews, they compared the actors' formal prescribed roles and positions to their actual ones. The observations revealed several mismatches between the two. Interestingly, this acknowledges the contribution of the informal roles to achieve effective coordination as well as the evolutionary nature of these relational competencies in order to overcome the project network dysfunctions and failures. Calls for further studies to investigate and understand such dynamics have been raised by the researchers.

Complexity researchers have examined a diverse set of complex self-organising real-world networks, using SNA. For example, Wagner and Fell (2001) studied metabolic networks that present in the biological organism of E. Coli (a type of bacteria that normally lives in the intestines of people and animals). They found that this network has properties of small-world which can be exploited to minimise the transition time between metabolic states; hence lowering the risk of experiencing illness caused by E. Coli. Newman (2001) investigated scientific collaboration networks in the disciplines of physics, biomedical research, and computer science. The actors are authors of scientific papers and a tie between two actors represents co-authorship of one or more papers. A strong 'funnelling' effect was observed, i.e. for most authors the bulk of the paths between them go through one or two of their collaborators. They also highlighted a number of differences between the fields studied; for example,

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[20] Relational Competence: defined as "*characteristics of the individual that facilitate the acquisition, development, and maintenance of mutually satisfying relationships*" (Hansson and Carpenter, 1994, p. 75).

they found that researchers in experimental disciplines have larger numbers of collaborators on average than those in theoretical disciplines. Braha and Bar-Yam (2004) studied engineering problem-solving networks and showed that they have properties of sparseness, small-world, scaling regimes. They highlighted that the efficiency of information transfer can be increased by investigating actors' capacity to process information as a function of incoming and outgoing links. More recently, Pryke *et al.* (2018) offered a case-specific illustration of self-organisation in complex infrastructure project. The findings have shown that, the existence of these 'hidden' informal channels challenge the 'command-control' strategies, which in turn suggests the ability of project members to self-organise themselves and adapt to the dynamic changes of their environment. This underlined the need for these non-contractual networks to be identified and sponsored, allowing them the space and capacity to evolve (Pryke *et al.*, 2018).

To summarise this section, the review of previous research on network approach and SNA highlights that networks are ubiquitous and permeate many aspects of human-made and natural systems. These networks are increasingly complex and dynamic; a characteristic that opens new opportunities to analyse and advance our understanding of the topography of the underlying systems. The review also demonstrates the huge potential offered by SNA, as a powerful analytical tool, especially in the context of construction research. It provides an innovative means of analysis to reveal additional knowledge about the operation of the systems comprising the project organisations that otherwise cannot be known. Network approach is now thriving and gaining large amounts of attention, both in academic and practice circles of project management. This rapid interest growth for applying SNA in project management has mainly been driven by the fledgling conceptualisation of a construction project as a temporary network. However, it is perhaps surprising that relatively little is still known about the formation of these networks, how various functions-related systems operate, and how they might evolve and be managed over time. This conclusion sets up the research gap of this study to stand out clearly as an area where further research is certainly needed.

3.11 Summary

This chapter sets out to demystify the key issues to the management of construction projects; which have been found to be repetitive and not just a shot term aberration. As an ever-growing approach, projects are conceptualised as networks of social relationships; an approach that has huge potential for application within the field of construction research. Methodologically, project communication networks can be investigated using social network analysis (SNA), which enables the researcher to deal with a wide variety of variables using one common method. Unlike other analytical approaches (e.g. task-dependency; cognitive-mapping; process orientated modelling and structural analysis), SNA provides the construction researcher with a rigorous analytic method that allows focusing on emerging ties rather than prescribed ties; hence the opportunity to deal with a number of the issues confronting an increasingly complex industry. For example, SNA places great emphasis on the importance of interdependencies between project actors, reflecting the complexity of the systems that projects constitute. Furthermore, SNA involves no assumptions about hierarchy, which is important and informative when trying to understand how things are done in reality. Of particular interest, SNA offers the possibility of more effective comparative study in a field where it could be argued that each project is unique.

Complex construction projects are increasingly delivered by iterative information exchange relationships that do not relate to linear processes. Research and practice, therefore, need to shift from a focus on project-based firms to project-based relationships. This entails understanding the invisible self-organising networks in projects. These networks support the systems for project delivery; they are flexible and adaptive, constituting a process to transform the contractually procured roles to transient network roles. Self-organising networks represent a model of "dynamic stability"; they exhibit distinct structural properties that can be measured quantitatively using SNA.

The chapter concludes by reviewing previous research on network approach. Despite the increased momentum of adopting network approach to investigate the structure of project networks, its application remains limited in the construction industry. Furthermore, the literature review reveals that project management scholars have not exploited the full potential of SNA, confined themselves to a handful of widely used measures.

Except for few studies (e.g. Pryke, 2017), it is argued that, at present, little is known about how self-organising networks evolve and decay, and how they are managed in construction projects. Arguably, this is problematic for successful project delivery, as it means human interpersonal relationships are underexplored in the discussion of project management. This highlights a knowledge gap in the study of self-organising networks within the construction industry; hence informing the research question of this thesis.

Next, Chapter Four presents the research philosophical perspective, methodology and methods. It demonstrates how the theoretical stance of this thesis affects the philosophical and methodological approach that will be applied to study a complex infrastructure construction project.

4

Research Methodology

4.1   Introduction

This chapter starts by briefly discussing the philosophical reasoning that informs this study, followed by a discussion on the research methods. It emphasises the conceptualisation of construction projects as social networks and how this might aid in understanding project actualities. The chapter also provides an introduction to the key Social Network Analysis (SNA) methods and software packages used for data analysis and visualisation. These quantitative methods are complemented by a number of qualitative methods in order to inform the research findings. The Bank Station Capacity Upgrade (BSCU) Project was chosen as the focus for this study. A case study approach is, therefore, adopted, reasoning for which is highlighted. Furthermore, the key challenges and ethical considerations in relation to conducting this research and those which are unique to SNA studies are discussed. The chapter concludes by proposing a road map for the analysis chapters to follow, organised by the main units of analysis.

4.2   Research Philosophy

Research philosophy can be viewed in two ways, either in terms of its ontological or epistemological nature (Hatch and Cunliffe, 2013). Interrelation between these two views provides the basis for shaping the appropriate research methodology (Hatch and Cunliffe, 2013; Smyth and Morris, 2007). Having an appropriate research methodology is crucial because it "*affects what we come to know*" (Smyth and Morris, 2007, p. 423) and ultimately how knowledge is constructed and the intellectual disciplines' frameworks (paradigms) are created (Smyth and Morris, 2007).

This research challenges the efficacy of the predetermined formal structures, giving precedence to ongoing change over stability (Tsoukas and Chia, 2002). It studies informal communication and presents self-organising as a generative mechanism that influences stability and change, and so the (re)creation of organisational informal structure over time. The broader ontological debate of this research proposal is, therefore, that project organisations are actually structured as networks. Its epistemology is how the structure of project organisations can be understood as a self-organising network.

The key challenge in the construction industry is that it has no fixed or specific research approach (Knight and Ruddock, 2009). The primary object of this study is informal self-organising networks that are concerned with 'how to get the work done'. This study, therefore, adopts a 'practice-centred epistemology' to the generation of new knowledge, seeing practice and theory as mutually constituted (Jarzabkowski *et al.*, 2010; Sandberg and Tsoukas, 2011).

Practice-centred methodology recognises the interdependent and context-creating relationships between macro- and micro-levels in organisational settings (Knorr-Cetina, 1981). The underlying interactions at the local levels are spontaneous and contribute to the co-creation of the whole context as it is folding. That is, actors always are working together in a dynamic relationship to co-create their world "for first time" (Garfinkel *et al.*, 1981).

Drawing on project management context rather than management *per se*, Pryke and Smyth (2006) identified four research paradigms: **(1)** The traditional project management approach; **(2)** The information processing approach; **(3)** The functional management approach; and **(4)** The relationship approach. The paradigm of this research proposal is placed within the last category in view of the earlier literature review and discussion on importance of relationships in managing projects. This approach:

> "*views managing social relationships as a means to manage and add value to, and through, projects. It is based on social theory and tends to focus upon effectiveness […]. The approach is theoretically diverse and certainly not linear in thinking, and arguably has the broadest definition of managing projects of all the paradigms*"

<div align="right">(Smyth and Morris, 2007, p. 425)</div>

Having discussed the underlying philosophical reasoning of the study, next section discusses the choice of research methods.

4.3   Quantitative Research Methods

Three main quantitative methods are used in this thesis, namely: Social Network Analysis (SNA), multi-level decision-making, and small-world network models. These are discussed in detail next.

4.3.1 Fundamental Concepts in Social Network Analysis (SNA)

SNA is concerned with understanding the relations/linkages between different social entities and the implications stemming from network structural properties (Wasserman and Faust, 1994). It was chosen as the analytical tool of this study because theoretical framework proposes viewing projects as products delivered mainly through informal relationships. The mathematical foundation of SNA is developed based on Graph Theory, in which the qualitative patterns of interactions are expressed in abstract equations (Scott, 2017). For this reason, it uses matrix principles and operations to calculate different network's properties and characteristics (Wasserman and Faust, 1994).

This section introduces some of the basic terms used in SNA[21], based on their relevance to the study. This is particularly important in order to provide a core working vocabulary and remove any ambiguity concerning the way they are applied in this research:

- **Actors:** are "*discrete individual, corporate, or collective social units*" (Wasserman and Faust, 1994, p.17). Graphically, these are represented by nodes. For the purpose of this study, this term is given to individuals involved in the project communication networks rather than firms. In particular, next analysis chapters are structured around individuals and their associated relationships (rather than firms). This is because analysis of the informal (i.e. interpersonal) communication project networks entails focusing and collecting data on the individual level rather than firms or organisational level. This is further underpinned by the fact that construction industry is essentially a multi-disciplinary people-intensive arena which exhibits a high reliance on face-to-face informal conversations and interpersonal communications in order to coordinate and facilitate daily activities, problem solving and decision making (Hastings, 1998; Pietroforte, 1997; Middleton, 1996).

- **Relations:** are "*the collection of ties of a specific kind among members of a group…The defining feature of a tie is that it establishes a linkage between a pair of actors*" (Wasserman and Faust, 1994, p. 20). Graphically, these are represented by links/connections. This research project seeks to look at a number of different types of relationships between construction project actors involved in the resolution of issues encountered at the detailed design stage of the BSCU project. This is needed in order to establish an understanding about the roles that individuals enact within project networks. Additionally, roles that are acquired through actors' network positions will be compared between the two stages of the BSCU project in order to explain the evolving nature of project networks in response to the changing events and circumstances. The following relational measures are relevant to this study:

    - **Evaluation of Communication:** includes evaluating the quality of the communication links between individuals;

    - **Flow/Transfer of Resources:** includes information exchange, discussion, advice and instruction, being the key communication types as defined by Pryke (2012);

    - **Formal Relations:** include functional relationships and contractual (line) responsibility or authority between individuals and their respective organisations.

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[21] The SNA terminologies used by Wasserman and Faust (1994) are adopted throughout this study.

- **Dyads:** consist a subset of two actors and the ties between them, respectively. The dyad is the simplest form of a 'network' between two actors and will be most relevant in analysing the contractual relationships or lines of authorities within the project networks (Pryke, 2001).

- **Modularity:** this is a measure for detecting community structure in networks, by dividing the graph into modules/groups/clusters, based on concentration of ties and how a node can be easily grouped with other sets of nodes (Blondel *et al.*, 2008). There are different methods for calculating modularity; however, the one relevant to this study is concerned with detecting group of nodes that are densely connected among themselves but they maintain sparser connections with other groups in the network (Pryke, 2012).

- **Tie Strength:** this is a *"representation of the strength of a tie between two actors…. [it] should relate to the perceptions of the actors at each end of the tie"* (Pryke, 2017, p.56). Graphically, this is illustrated by linkages' thickness, i.e. the thicker the line, the stronger the relationship is and vice versa. Following the methods set out by Pryke (2012) and Pryke *et al.* (2017), a reasonable proxy for tie strength is calculated by multiplying the normalised frequency and quality scores. Pryke *et al.* (2018) validated this formula for approximating the tie-strength by performing a Multiple Regression Quadratic Assignment Procedure (MR-QAP).

- **Network Density:** "*a concept that deals with the number of links incident with each node in a graph*" (Wasserman and Faust, 1994, p.101). It can be expressed as the total number of links present between nodes in a given network in relation to the maximum number of links theoretically possible for that network (Pryke, 2012). Remarkably, this measure indicates network connectivity - i.e. the degree of network integration or fragmentation (Goddard, 2009) and thus provides a comparability measure between networks of comparable sizes (Pryke, 2012; Scott, 2017). It also indicates the speed at which a spill over effect or information diffuses within a network, degree of reciprocity, trust, and cooperation between actors, and hence whether they have high levels of social capital or constraints. That is, the flow of information and exchange through multiple channels, allows the cross-checking of information as a basis for establishing reliability and trust, and thus supports their adaptive resilience through multi-connectivity (Lizardo and Pirkey, 2014).

- **Actor Centrality:** "*a characteristic of a node rather than a network, and relates to the prominence, and possibly power, that an actor has in a particular network depending on the nature of the relationships being measured*" (Pryke, 2012, p.72). It indicates how extensively a given actor is involved in relationships with other actors (Pryke, 2012). It is worth highlighting that the centrality terms are not just affected by number of interactions but also by quality of communication. This is already embodied in the respective centrality measures and sometimes referred to in literature alongside spatial (geographical) and social distances. These distances reflect degree of acceptance/closeness and arise from differing cultural norms (Matthews and Matlock, 2011).

- **Actor Attributes:** the fundamental attribute used in this study is the function or role of the actor that is influenced by his/her network position. This is a very important variable because there is a mismatch between formal roles, dictated by contracts, and those that are acquired in projects as a result of the informal self-organising behaviour (Pryke, 2017).

4.3.2 Multi-level Decision-Making

Investigation of the decision-making processes is essential to provide a deeper understanding of foundational issues in the design and delivery of construction projects (Lettieri *et al.*, 2017). This will be conducted as part of the empirical analysis using the model developed in the theoretical framework. This model is adapted from Jager and Janssen (2003), validation of which is confirmed by Holzhauer (2017). This model organises various decision-making processes into four distinct heuristics, based on the degree of uncertainty and amount of resources associated with making a decision. For the reader's ease of reference, this model is illustrated as below:
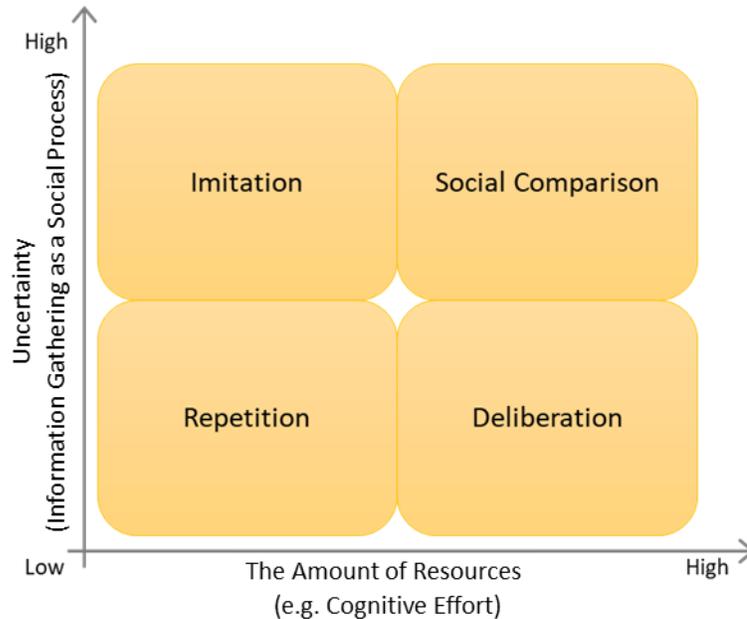
Figure 4.1: Decision-Making Heuristics Organised in Terms of Uncertainty and Amount of Resources. (Source: Adapted from Jager and Janssen (2003), Figure 3, p. 45)

The model will be operationalised as follows:

➢ **First Dimension:** Uncertainty as a social process

The framework developed in theoretical chapter suggests that individuals will depend on their own experiences and abilities if they are certain; and on others/social level if they are uncertain. Level of focus (local/global) therefore will determine the degree to which social information is used in the decision-making process.

The variable "Frequency of Communication", collected as part of the study questionnaire (see Appendix Three), will be used as the parameter to assess how often an actor reaches out to others to communicate and obtain information. The low frequency therefore means less communication activities and hence actors are satisfied with their local level of experience (i.e. low uncertainty requires a low degree of social information and hence an actor relies on his/her local level). On the other hand, the high frequency means high communication activities, i.e. actors reaching out to others to seek for information (i.e. high uncertainty requires a high degree of social information and hence an actor refers to the social level).

➢ **The Cut-Points of Uncertainty and Level of Focus:**

The cut-point is determined by using the dataset of frequency variable. The mean value of frequency data, therefore, is calculated and used as the value for the cut point. These are at 0.126 for stage one and at 0.133 for stage two. As part of the questionnaire (see Appendix Three), the participants were asked to assign frequency scores based on a unified seven-points Likert scale to enable like-for-like comparison.

➢ **Second Dimension:** Amount of Resources Associated with Making a Decision

The basic idea of this dimension is that actors have limited resources and thus they would optimise their utility over various decision problems. This means an individual may decide a certain problem is not worth investing a lot of resources in whereas another problem is of more importance, hence requiring more attention and resources. The decision on how much resources to be allocated is determined based on the nature, importance and purpose of the problem in hand as well as the expected value (Jager and Janssen, 2002).

In the study of communication networks, the perceived quality of communication per link can be used as an approximate for the amount of resources to be allocated (Pryke, 2017). In his explanation of networks, Pryke (2017) has justified this by describing the links between the actors as conduits or pipes through which resources can flow. He further asserts that the characteristics of the resources/flows (e.g. amount) are quantifiable, *"frequently expressed in terms of value as perceived by the actors at either end of the flow"* Pryke (2017, p. 17).

Perceived quality of communication (as an approximate for the amount of resources associated with making a decision) will therefore be operationalised by using the following five questionnaire parameters (see Appendix Three): importance, accuracy, timeliness, clarity and trust. The high quality of communication will need lower amount of resources (e.g. a lower cognitive effort) for an individual to make a decision and vice versa.

➢ **The Cut-Points of Resources associated with Making a Decision:**

The cut-point is determined by using the dataset of importance, accuracy, timeliness, clarity and trust. Amount of resources associated with making a decision is calculated as the sum of these scores per communication link. The mean value of these data, thereafter, is calculated and used as the value for the cut point. These are at 0.488 for stage one and at 0.493 for stage two. As part of the questionnaire (see Appendix Three), the participants were asked to assign scores based on a unified seven-points Likert scale to enable like-for-like comparison.

It is worth highlighting that this framework does not claim that decision-making strategies are limited to these four types only, but rather it serves as a practical analytical method, using simple measures that are easy to quantify and interpret. The subjectivity is also accounted for in this method since all the questionnaire scores essentially represent the perceptions of project participants involved. Decision-making strategies will be investigated at both the local level (cluster levels) and at the global level (whole network level). The results of the same will be presented in Chapter Seven: Self-Organising Clusters, as part of the intra-relationships analysis (refer to Figure 7.4). This involves defining the decision-making strategies employed by each actor and then grouping them based on their cluster affiliations. The results of each cluster are then expressed in relative terms, i.e. "Total of each type of decision-making strategy in a given cluster" / "Total of all decision-making strategies for the same cluster". The percentage values are useful in presenting the results in a more convenient way and hence easily produce comparable and interpretable findings. Results derived from this method will be cross-validated by qualitative evidence (as presented in Section 4.4.2).

4.3.3 Small-World Network Models

Historically, the small-world phenomenon was studied using two simple network models (Watts and Strogatz, 1998). The first model is a regular structure lattice structure that has an array of nodes connected solely through their adjacencies (Watts and Strogatz, 1998; Scott, 2017). This suggests that all connections are local, resulting in both a high clustering coefficient and a high path length (since travelling from one link to another requires crossing a large number of nodes). The second model is formed by nodes that are connected through randomly placed links (Watts and Strogatz, 1998; Scott, 2017), resulting in few local connections, a low clustering, and short path lengths.

Watts and Strogatz (1998) have argued that these two models represent two extreme cases and thus are not true representatives of real-world networks, which lie somewhere in between (as illustrated in Figure 4.2). This particular network topology can be created by performing a rewiring procedure. This procedure is used to study network dynamics and involves lattices forming shortcuts; hence reducing the average path length whilst maintaining high clustering (Watts and Strogatz, 1998). This network model has been dubbed the small-world property and found to be ubiquitous of seemingly disparate complex networks such as social systems. Next section examines the original mathematical formulation proposed by Watts and Strogatz for small-world networks and thereafter introduces a formalism based on Complexity Theory concepts.
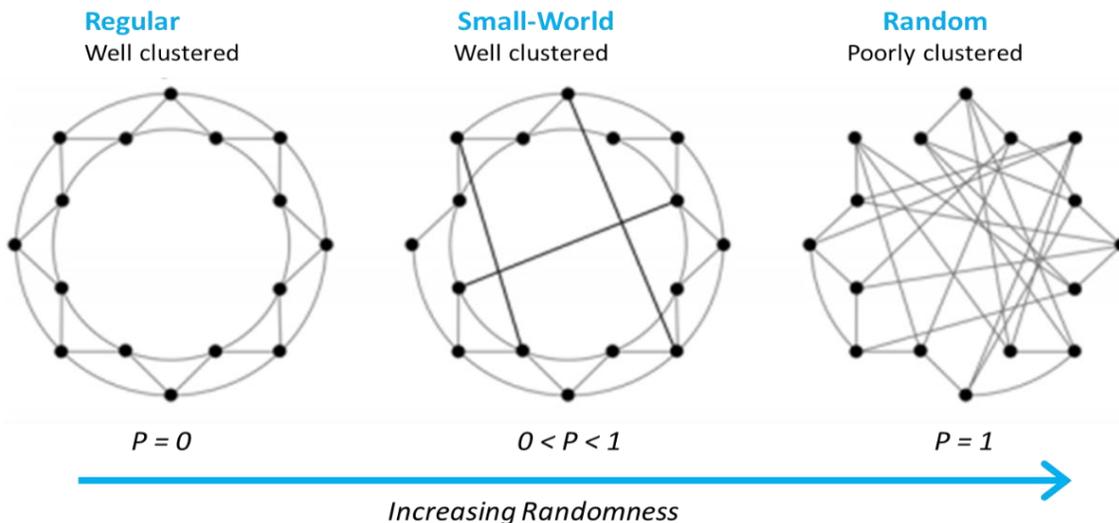
Figure 4.2: Network topologies: The two traditional classes of network models (lattice and random graphs) and the "small-world". Source: Original adapted from Watts and Strogatz (1998).

4.3.3.1 Mathematical Formulation of Small-World Networks

Watts and Strogatz (1998) suggest that small-world behaviour can be defined in a more general way by considering how efficient a system is in propagating information on both global and local scale. That is, the key characteristics of such networks are: their ability to be simultaneously segregated (high clustering coefficient), and integrated (short path lengths).

The mathematical characteristics of the small-world behaviour, identified by Watts and Strogatz (1998), are based on the evaluation of two different quantities, applied separately based on the level of analysis/interactions in a given network (G), as follows:

1. **Global Level:** measured by Path Length (L). This can be defined as the average of the shortest path lengths between two nodes (N). It can be calculated based on the below formula:

$$L(G) = \frac{1}{N \times (N-1)} \times \sum shortest\ path\ length\ between\ any\ two\ nodes \text{ (Equation 4.1)}$$

2. **Local Level:** measured by the Clustering Coefficient (C). This indicates how much, locally, a network is clustered (how much it is "small-world", so to say). It refers to the enhanced probability that the existence of a link between any two nodes implies the existence of another link with a third node. In other words, in a social system, there is a strong probability that a friend of your friend is also your friend. This is formulated as below:

$$Local\ Clustering = \frac{Number\ of\ Linkes\ at\ the\ local\ level}{max.\ possible\ links\ at\ the\ same\ level} \quad \text{(Equation 4.2)}$$

$$Average\ Local\ Clustering = \frac{1}{N} \times \sum Local\ Clustering \quad \text{(Equation 4.3)}$$

From a Complexity Theory perspective, Watts and Strogatz's balance of localised specialisation and global efficiency means that the global properties of any complex system are a function of its local interactions, which can be formulated as:

$$Global\ Properties \leftrightarrow Local\ Interactions$$

According to Complexity Theory, there is a nonlinear, unpredictable relationship between the two. This, therefore, can be shown by arranging the above function, as follows:

$$Global\ Properties = Local\ Interactions \times Complexity\ Factor \quad \text{(Equation 4.4)}$$

The complexity factor is a cornerstone for any complex system, but this was not taken into account by Watts and Strogatz (1998) formulation. Their formulation suggests that rewiring a network requires shifting one end of the link to a new node, chosen randomly with a uniform probability, but avoiding multiple links (that is, more than one link connecting the same couple of nodes), self-connections (a node is connected to itself), and disconnected networks. This assumes existence of equally weighted, direct, unique connections only. It eventually reduces the total possible number of links in a network and ignores indirect links formed by traversing through multiple nodes. It, therefore, adds linearity components in the formula. These very same assumptions were used to formulate the mathematical models of many research papers over the past years, including Pryke *et al.* (2017).

In a similar vein, Opsahl *et al.* (2017) acknowledge that management scholars have recognised the limitations of the method used to assess the small-world networks based on Watts and Strogatz's (1998) model. Limitations are predicated on recognising the discrepancy of the evidence on the positive effect of small-world networks to organisation performance. Literature, therefore, suggests that research on small-world networks is far from complete. Consequently, Opsahl *et al.* (2017) propose that there is a substantial variation in the properties of small-world networks that needs careful considerations, and therefore sub-classes - efficient and non-efficient small-world networks - have been introduced. Keeping these limitations in mind, next section will discuss and propose a different formulation, grounded in Complexity Theory.

4.3.3.2 A Mathematical Formulation Grounded in Complexity Theory

Latora and Marchiori (2003) presented a way to extend Watts and Strogatz's small-world analysis with the aim of covering complex networks whilst catering to the limitations of the original model. Latora and Marchiori (2003) introduced a unified global and local measure (efficiency) and identified the cost of a network, as follows:

1. Introduction of a single variable, efficiency (E), to define small-world behaviour on how efficiently the nodes exchange information. This is evaluated on both global and local scales, playing the role of Path Length (L) and Clustering Coefficient (C). This is explained further below:

The efficiency measure for global scale defines Path Length (L) as the smallest sum of the distances throughout all the possible paths in the network from any two nodes. It is determined as an inverse of the shortest distance, as follows:

$$Global\ Efficiency\ (E) = \frac{1}{N \times (N-1)} \times \sum \frac{1}{shortest\ path\ lengths} \qquad \text{(Equation 4.5)}$$

This can be normalised to be in the interval [0, 1] by considering the respective ideal/random case of the network, which will have all the possible links N × (N − 1)/2, i.e. information is propagated in the most efficient way.

$$Normalised\ Global\ Efficiency\ (E) = \frac{E(G)}{E(G\ "Ideal")} \qquad \text{(Equation 4.6)}$$

On the local scale, the efficiency measure is determined as an average of the local efficiencies, in a similar fashion to Clustering Coefficient (C), and thus the formula will be as follows:

$$Normalised\ Local\ Efficiency\ (E) = \frac{1}{N} \times \sum \frac{E(G)}{E(G\ "Ideal")} \qquad \text{(Equation 4.7)}$$

The appealing feature of using efficiency is its ability to be applied on the both scales, as a one unifying concept for information exchange. The most efficient small-world networks will have high Global and Local Efficiency (Latora and Marchiori, 2003). In contrary, when efficiencies equal zero (or are at a minimum), globally this means having a disconnected network which potentially could lead to disintegration of the system. This disintegration will ideally lead to dividing the network into local clusters that communicate only locally, with highest possible local efficiencies.

The path length defined by Watts and Strogatz's model assumes sequential processing of information, i.e. only one packet of information travels along the network at any given time (Latora and Marchiori, 2003). This depicts the traditional communication model discussed in the literature review. Efficiency, on the other hand, has the capacity to measure parallel or concurrent processing, i.e. all the nodes in the network exchange multiple packets of information between themselves at the same time (Latora and Marchiori, 2003).

2. Identification of the network cost on a weighted basis. Assuming that everything else is constant, the efficiency of a network will increase as the number of links also increases. However, in real world networks, this is countered by the price that is paid for the number and weight (length) of the links to be established (Latora and Marchiori, 2003). Therefore, cost of communication in a given network is quantified in terms of building and the operational cost of each link or connection relative to the size of the network.

$$Weighted\ total\ Cost\ of\ a\ Network =$$

$$\sum(\text{Building Cost of each connection} \times \frac{its\ length}{Total\ length}) + (its\ operating\ cost \times \frac{its\ efficiency}{Total\ efficiency})$$

(Equation 4.8)

This can be normalised to be in the interval [0, 1] by considering the cost of the respective ideal/random network where all the possible links are present. The relative cost overrun, therefore, can be calculated as follows:

$$Normalised\ \Delta\ Weighted\ Cost = \frac{Cost(G) - Cost(G\ "Ideal")}{Cost(G\ "Ideal")}$$ (Equation 4.9)

This formalism is based on a unified measure that can be used at the local and global scale with an additional measure for network cost; all defined in the range of [0,1]. The cost is an intuitive variable that takes into account the fact that, in real-world, resources are not unlimited but somehow a compromise between the search for a higher performance and the need for less cost (Latora and Marchiori, 2003). The interaction between these three measures provides a quantitative explanation for the dynamics of complex networks as they evolve (Latora and Marchiori, 2003). Hence, this study proposes adopting a mathematical approach that provides a different perspective to understand the reasons behind the substantial variation in the properties of previously researched small-world networks (cf. Opsahl *et al.*, 2017). It perceives the properties as an outcome of the interplay between global, local, and cost variables, all of which are function of the interactions at the micro level.

Similar to most of the statistical analysis, SNA can provide meaningful information and holistic understanding only when combined with qualitative data (Loosemore, 1998; Fuhse and Mützel, 2011). This shall set the scene to our discussion on the research qualitative methods in the following section.

4.4 Qualitative Research Methods

The researcher was not present at the BSCU project to witness and hence infer the daily actors' interactions and decision-making processes. However, a coherent overview is formed with the support of key project "informants" (Yin, 2018) as well as by having access to a number of project-related documents. These two main qualitative approaches are discussed in more detail below:

4.4.1 Key Project "Informants"

In his book on case study research, Yin (2018) distinguishes between research participants and research informants. The former is a person from whom case study data are collected, whereas the latter is not a subject of study, but he/she plays a supportive role in providing critical information or interpretations about the case (Yin, 2018). In terms of techniques adopted to seek source of evidence, interviews are usually used in case of having access to research participants. This often involves putting an interview guide with a set of prepared questions, screening the profile of the interviewees, and thereafter having the interviews transcribed and evaluated (Eisenhardt and Graebner, 2007). In contrary, discussions with research informants usually involve a smaller group, follow a less structured approach, and take place over an extended period of time (Yin, 2018). Key informants are often used to support single-case studies or analysis of secondary data (Yin, 2018).

This study uses secondary data and therefore the researcher did not have access to the original research participants. However, four key informants were identified, namely: the TfL Project Manager and the Knowledge Transfer Partnership (KTP) team, who were based at UCL campus. Both had firsthand experience of the BSCU project (design stage), as they were directly connected to the project actors and their lived experiences and actions. This provided them with insights into the events leading to emergence of change in communication patterns, as they unfold in time. The KTP team consisted of three research associates, led by Professor Stephen Pryke from The Bartlett School of Construction and Project Management at UCL. Two of the members are PhD holders, specialised in the area of project management and social networks. The other member is a PhD candidate, specialised mainly in SNA and related analytical tools. The KTP team spent almost six months in collecting the data, whereas the TfL Project Manager was involved, among others, in a total of one hundred and thirty-one management meetings and a total of seventy-nine interviews (Addyman, 2019).

These meetings and interviews were held with different individuals from the client and contractor companies, discussing various issues such as: corporate governance, progress reports, protocols, contract change, commercial challenges, organisational conflicts, forecasts, client funding, statutory obligations and requirements, critical paths of the project, roles and personnel changes, and other types of bespoke issues (Addyman, 2019). This brief description of the study informants is necessary in order to highlight the level of their engagement in the project and hence how crucial their views are in explaining the case study background and results.

In order to have a good grasp of the issues and events, researcher was involved in clarifying different aspects of the project and dataset with the key informants. This took place over a period of three months. However, it is worth highlighting that, at the time of conducting the analysis of this thesis, the TfL Project Manager was already enrolled at the Bartlett School of Architecture (UCL) for one of the PhD programmes. The researcher, therefore, found the key informants (both TfL Project Manager and KTP team) easily accessible, i.e. they were mostly available at UCL campus as and when required. The discussions conducted with the key informants were largely open and unstructured, conducted in a collegial atmosphere and sometimes involved group discussions. As a result, this promoted more in-depth discussions regarding various situations and helped researcher to see things from different perspectives. Initial discussions usually resulted in inevitable follow-up questions that were tailored to a specific informant or context (Yin, 2018). Questions raised were mainly to inquire about project specifics, such as: the context of the project, the issue of complexity and uncertainty, data collection strategy, people involved in the BSCU project and key events and challenges encountered.

The chances of having informal and unplanned encounters with the key informants were high since they resided on the UCL campus. This, therefore, eliminated the need to observe some formalities, e.g. having pre-designed interview guides for each discussion, and booking meeting rooms for specific time and date. In fact, some discussions took place at the main corridor or at the common areas. This is considered acceptable in such situations, especially when the role played by the informants is considered secondary (Yin, 2018). That is, for this study they were mainly to confirm the understanding of the researcher on a number of quantitative results, filling few gaps, and/or to provide some guidance and directions. Having the interviews transcribed, date stamped, and evaluated, therefore, is considered irrelevant to this study as it will add little value. This is because, unlike findings drawn from research participants, data collected from informants are usually not sufficient enough by their own right to develop distinct themes and hence pursue a research objective (Williamson and Johanson, 2018).

This is also to say, this case did not meet the criteria to apply a qualitative systematic methodology, such as content analysis or following routines of the Grounded Theory[22]. Nevertheless, the research benefitted from a number of *ex post facto* reflections that were crucial to explain the quantitative results of social network analysis and hence establish a better understanding of underlying interactions between project actors. To a large degree, this helped in 're-constructing' the reality of the project from the perspective of those involved in the discussion and data collection; enabling the researcher to understand the behaviour of individual actors and relate to their perceptions. Findings drawn from the discussions with project informants will be presented as part of the analysis and discussion chapters.

4.4.2 Organisational and Project-related Documents

The researcher was granted access to a suite of project-related documents. These included governance documentation, internal periodic meeting reports of the BSCU project, the TfL Project Manager case study narrative on the project and other TfL and KTP published and unpublished reports (e.g. inspector's report; TWAO[23] application; planning drawings; elements of the development; project effects; cost and funding). These documents were reviewed by the researcher to gain a holistic understanding of the project wider context, specific practices, organisation, and understand how the project was performing during the different project stages.

It is worth noting that these documents constituted a large amount of data that was unreasonable to be systematically analysed (e.g. using content analysis), given the limited timeframe of the PhD study. These documents, therefore, were prioritised based on their relevance. In particular, the project periodic reports helped in understanding the project formal organisational structure and provided a timeline of the changes in personnel/human resources. Findings drawn from these documents were presented as part of the BSCU project narratives, which enabled the researcher to understand the context and events featuring main actors, actions and thus implications.

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[22] This is an inductive method, developed by Strauss (Strauss, 1987; Strauss and Corbin, 1998). It involves a number of routines such as open coding procedure to break content of the interviews into conceptual components with the aim to identify the main topics/categories (Dick, 2005). Thereafter, this is usually followed by axial coding, the process of relating codes to each other, in order to make links and find relationships between the concepts and categories derived from open coding (Dick, 2005).

[23] A TWA Order is a statutory instrument made under the Transport and Works Act 1992. In brief, it is the usual way to authorise the construction or operation of railways or tramway schemes in England and Wales.

Overall, the qualitative research methods offered a post-rationalised perspective on the project at the "relevant time", largely depicting the way project actors made sense of the events as they unfold and then affirmed these observations in retrospect with the key informants (Fabianski, 2017). These methods, such as TfL published reports, periodic project progress reports, and reflections after the event, provided rich sources of indirect evidence. In particular, the statements given by the TfL Project Manager provided insights into decision outcomes (Section 4.3.2). This is entirely in line with self-organising concept, which emphasises that the value is embodied in the outcomes (Smyth *et al.*, 2018). This, therefore, means a qualitative weight of evidence is provided to build a reasonable picture (Lakatos, 1970). This way of results interpretation is justified because decision-making events are difficult to research, especially where there are various competing factors and high levels of sensitivity, such in the case of BSCU project.

The next section explains the single case study approach, being the research method adopted in this thesis.

4.5   A Case Study Approach

Case studies constitute an important research tool in the field of organisational management (Yin, 2018). They are commonly used to conduct an empirical in-depth analysis, "*especially when the boundaries between phenomenon and context may not be clearly evident*" (Yin, 2018, p. 15). In this way, case studies offer a level of detail, enabling researchers to answer the 'how' and 'why' questions (Yin, 2018). This method involves mainly two approaches, namely: a single case study and a multiple case study (Donmoyer, 1990). Multiple case studies are used mainly to analyse data across different situations, whereas single case studies are used to provide a greater understanding of a specific subject or when the research is constrained by cost and time (Dyer and Wilkins, 1991). Although the researcher of this thesis did not have the choice to decide on which case study approach to follow (since analysis was conducted using an existing dataset), the KTP being focused on a single case study approach found to be justifiable in view of the following:

1. **Case Selection:** Eisenhardt and Graebner (2007, p. 27), suggest that single cases are chosen when the case is "*unusually revelatory, extreme exemplars, or [offers] opportunities for unusual research access*". This is particularly true for the BSCU project in that it is an award-winning project, it exemplifies the 'management of complex relationships' paradigm (Pryke, 2017), introduces a novel procurement methodology focused primarily on the creation of value for the

project sponsor (Morris, 2013), and its data allows for conducting a long-term empirical investigation of self-organising networks, specifically in the infrastructure sector which suffers from a dearth of research. Next chapter provides full details on the BSCU project, highlighting why it warranted selection as a case study for the empirical inquiry in its own right.

2. **Data Points:** Authors such as Donmoyer (1990), Kennedy (1979) and Yin (2018), believe increasing the number of data points in a single case would mitigate the issue of generalisation, i.e. the difficulty of extending the findings to a larger population (Donmoyer, 1990; Kennedy, 1979; Yin, 2018). This is called a single case study with embedded units (Yin, 2018). The KTP dataset is an example of this approach, as data was collected at two different stages and hence enabled conducting analysis not just from a holistic view but also between the embedded units to make a cross-case analysis (Gustafsson, 2017).

3. **Exhibiting Specificity:** Criticism of generalisability is of little relevance when the intention of the research is one of particularisation, i.e. the researcher is not concerned about understanding the general laws that operate in a particular field but to provide a better explanation (Tsoukas, 2009) or study existence of a certain phenomenon within a specific population (Siggelkow, 2007). This is particularly relevant to this study, since research question is to investigate self-organising networks within large construction projects.

4. **Theory Enrichment:** Theory building is usually not possible with a single case or few cases (Yin, 2018). Nevertheless, it is the selection of strategic cases rather than seeking a general feature shared among many yet random cases that brings to light the most valuable insights about a given situation (Siggelkow, 2007). Dyer and Wilkins (1991) argue that single cases are more useful to build a higher-quality theory and thus enable conducting a more careful study. That is, the researcher can critically question old theoretical underpinning of the subject matter and explore new ones (Dyer and Wilkins, 1991; Gustafsson, 2017). Yin (2018, p. 85) takes matters further and advocates "*such a study even can help to refocus future investigations in an entire field*". Eisenhardt and Graebner (2007, p. 30), who generally advocate the superiority of multiple cases over single cases, recognise that: "*somewhat surprisingly, single cases can enable the creation of more complicated theories than multiple cases, because single-case researchers can fit their theory exactly to the many details of a particular case. In contrast, multiple-case researchers retain only the relationships that are replicated across most or all of the cases*".

4.6   Research Dataset

This section discusses the sources of data used in this study as well as its key challenges and ethical considerations. It also outlines the collection and retrieval process and research design.

4.6.1 Data Sources

For this research, the data collected for the Knowledge Transfer Partnership (KTP) research project will be used. The KTP was partly founded by Innovate UK (formerly Technology Strategy Board) as a joint effort between UCL Centre for Organisational Network Analysis (CONA)[24] and Transport for London (TfL). Datasets were gathered over a two-year period and involved a number of pilot projects (Bank tube station capacity upgrade program, Hammersmith flyover road project, and Blackwall Tunnel Northbound refurbishment project). The initiative aimed to contribute to Infrastructure UK (IUK), by promoting collaborative working arrangements in order to drive down the cost of risks associated with successful project delivery. For TfL, the purpose of KTP was to enhance the company's competence in design, implementation and evaluation of collaborative teams, through use of SNA. In return, the partnership offered CONA the opportunity to gain greater insights into the operation of project systems within several major infrastructure projects[25].

By the end of the KTP initiative, enormous quality data were gathered, but these were not extensively studied and analysed. In fact, the subsequent studies (Pryke *et al.*, 2015; Pryke, 2017; Pryke *et al.*, 2018) used only a small portion of the collected data while the majority part still requires further data mining, indicating a larger value and insights waiting to be unlocked. This is far more data than the author would expect to collect personally within the time constrains of a PhD, and most probably would have not been able to get hold of the same size as the CONA research team has done. In particular, it would be very hard to get access to such large project without UCL support or be successful to collect SNA data at this level of granularity with 100% response rate (see Table 4.1 for the sample size). The collected data, as described by TfL Project Manager, probably the finest data in terms of granularity that have been ever collected on TfL. Also, because of the KTP, TfL was very engaged in the process and the CONA team had a degree of leverage, as employees were motivated by their line managers to participate in the process.

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[24] CONA is led by Professor Stephen Pryke from *The Bartlett School of Construction and Project Management*. It is an interdisciplinary centre for training, research, knowledge transfer and consultancy, focusing on the use of Social Network Analysis (SNA).

[25] Further information on KTP can be found at: UCL CONA website, TfL and UCL KTP advert and Pryke *et al.* (2015).

This research will be focusing on exploiting the existing KTP data to a greater extent than it has already been achieved. The author applied new analytical methods on the data, pursued and built on what the CONA team had already done, and hence taking the study into new directions. The analytical originality and contributions of this study in comparison to existing work will be highlighted at the respective analysis chapters.

The key challenges and research ethical considerations that may arise from using an existing KTP dataset are discussed next.

4.6.2 Key Challenges in Conducting Secondary Data Analysis

Despite availability of the dataset, management and analysis of secondary data is easier said than done. The key challenges mainly relate to the substantial effort needed in data mining, data cleaning process, and achieving the same level of comfort and familiarity as if data was obtained directly from first-hand sources on a primary basis (Smith *et al.*, 2011; Bryman, 2016). It crucially requires assessing the data validity as well as knowing and understanding its variables inside out, project/events' details and profiles of the actors involved. In other words, to achieve a comprehensive understanding of the strengths and weaknesses of the dataset and to ensure there are enough events/cases to generate meaningful findings about the subject of interest. This involves, among others, "*obtaining detailed descriptions of the population under study, sampling scheme and strategy, time frame of data collection, assessment tools, response levels, and quality control measures*" (Cheng and Phillips, 2014, p. 373).

In adopting secondary data analysis, the researcher of this thesis focused on understanding the social construct of the dataset. This includes ensuring the dataset is appropriate to generate meaningful results that in turn can provide answers to the secondary research questions. Researcher, therefore, needed to understand the variables and outcomes of the dataset, including where it came from, how it was collected and by whom. Furthermore, other qualitative resources were defined, such as project-related documents and post-fact discussions, in order to complement the existing dataset. Such combination (i.e. using both qualitative and quantitative data) has strengthened and enhanced the richness of the research compared to one-source-data-based approaches. This is also necessary in order to validate data, facilitate cross-verification from as many sources as possible, and provide explanation to any context-based findings (Barratt *et al.*, 2011; Steen *et al.*, 2018). This approach, coupled with the fine-grained structure of KTP dataset, has increased the credibility and validity, and subsequently supported the mathematical analysis, giving a boost to confidence in the research findings (Steen *et al.*, 2018).

After weighing the opportunity costs and taking into account the commonalities between the subject PhD study and involved projects in KTP initiative, it was concluded that the existing data offers an accessible solution to break through the complexities of BSCU networks. The research, thereafter, was successfully upgraded from MPhil to PhD status based on this justification. The most obvious advantage in gaining a complete access to KTP rich dataset is the possibility to explore new research questions, using important yet hard-to-access network constructs at a lower cost and shorter time. This allowed spending more time on data analysis and interpretation, hence revealing more valuable findings regarding project actualities.

It is important to stress on the fact that the use of existing KTP dataset offers the opportunity to conduct a long-term research, since it was collected at two different stages. The rare use of such research approach in SNA studies to understand development and evolution of organisational networks have been highlighted recently by several researchers (e.g. Williams and Shepherd, 2015; Jackson, 2010; Borgatti *et al.*, 2014; Steen *et al.*, 2018). To bridge such methodological research gap, they have suggested making up for lost time by using 'secondary data' in organisational social network studies. In fact, Borgatti *et al.* (2014) acknowledge the increased popularity of long-term network data to the point that some reviewers seem to regard it as mandatory. This trend is expected to increase as longitudinal electronic archival data is increasingly becoming available to the public and easy to obtain (Borgatti *et al.*, 2014; Mazzocchi, 2016). This places a great emphasis on using such secondary data, so "*researchers can inductively identify new network measures that offer contributions to the network and organisational literatures*" (Williams and Shepherd, 2015, p. 4).

4.6.3 Ethical Considerations

The UCL ethics regime has changed in recent years, for example to account for the EU General Data Protection Regulation (GDPR). However, it remains principally the same. Under the UCL regulations[26], research students can only receive their upgrade from MPhil to PhD status after fulfilling the consideration of research ethics. This can be obtained by either exemption or submission for approval by the UCL Research Ethics Committee (REC). As outlined in the UCL Academic Manual, the Head of Department is responsible for ensuring that the staff and students of the Department are apprised of UCL's arrangements for research governance and the associated procedures, the main components of which include the UCL REC.

This study was upgraded to PhD status in 2016, after satisfying the criteria required for ethics. At that time, it was concluded that the research did not require an ethical approval from the UCL Research Ethics Committee (REC). This is because the used KTP dataset is of non-sensitive nature; its ethics' dimensions are governed by the Knowledge Transfer Partnership (KTP), arranged separately between TfL and the Centre for Organisational Network Analysis at University College London (CONA@UCL). Used data is further supported by information freely available in the public domain and findings drawn from follow-up interviews are presented anonymously.

The non-disclosure agreement, governing information collected as part of the KTP partnership, allows CONA@UCL to use the dataset for further research. Being sponsored and part of CONA@UCL, researcher of this study therefore enjoyed a full access to the KTP dataset. Nevertheless, extra care is observed in how information is presented in this study to give identifying data a high degree of anonymity. In this respect, data and network diagrams are displayed in a way that does not allow identification of the participants by way of reverse engineering. Some de-identification techniques were applied (Borgatti and Molina, 2003), such as using disguised names, untraceable identification numbers or characteristics, and removal of any direct identifiers (i.e. address, photo and the like). Moreover, participants are sometimes identified in reference to their organisational/functional affiliation after obscuring their specific titles/roles. Instead, only commonly used titles or pseudonyms are presented in this study, which is considered a randomisation method for privacy-preserving data mining, adding noise to the data so that they are masked (Breiger, 2005).

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[26] Please refer to below link for further details:

https://www.ucl.ac.uk/students/sites/students/files/mphil_phd_upgrade_guidelines.pdf

For the sole purpose of the study, TfL management will have the opportunity to see the research output in order to benefit from its findings and recommendations. However, any information to be shared or published will conform with the ethical principles and standards. This process is observed by CONA@UCL who also enjoys the support of UCL Legal Services in case of need. The participants are, therefore, not considered "vulnerable", their personal identities are not exposed, and their participation does not induce any kind of undue psychological stress or anxiety. At all times, data will be treated with full confidentiality and anonymity, i.e. whether at analysis phase, storage, or in any subsequent publications, ensuring no harm is caused to the research participants.

It is worth highlighting that participants at the KTP surveys have been informed about the nature, purpose and process of the research project. This was outlined at the participants' information sheet, as confirmed by the KTP project team. A written informed consent was obtained from each participant prior to his/her participation in the KTP study. They have also been given the right to withdraw from the study at any stage of the research. None has been withdrawn thus far. This is encouraging because otherwise it could have resulted in having skip patterns, which will need to be addressed as part of the data validation to ensure data quality is not compromised or to confine any ramifications for network construction and analysis (Borgatti and Molina, 2003).

It should be noted that there are several key ethical considerations that are unique to SNA studies, which should be recognised by both academic research and managerial practice (Borgatti and Molina, 2003; Breiger, 2005). That is, the fundamental nature of network analysis has the power to make the invisible visible and thus can easily run into ethical problems (Borgatti and Molina, 2003). Simply, SNA "*may have become a victim of its own successes*" (Breiger, 2005, p. 139). As data in SNA can only be meaningful by recording links/relationships between different participants, the identity of one participant can often be deduced using such relational information and hence his/her associates (Borgatti and Molina, 2003; Breiger, 2005). This feature poses a unique risk for SNA researchers and it is minimised in this study by applying several de-identification techniques as highlighted earlier.

4.6.4 Data Collection and Retrieval

Surveys and questionnaires are commonly used in collecting data for SNA studies (Edwards, 2010; Prell, 2012). The data collected in the KTP project were gathered using an online questionnaire[27] in two different stages of the BSCU Project. It covers in total almost half of the phase time since completion of concept design. In particular, they represent networks of actors involved in the resolution of issues/events relating to the detailed design of the station box and the new ticket hall.

The data collected through the online questionnaire (see Appendix Three) was stored in a NoSQL database called MongoDB. This is a document-oriented database that has a flexible structure that can be easily modified and extended (i.e. it structures data into collections of documents rather than tables and rows) (Hows *et al.*, 2014). The data was retrieved from the database, entered in igraph package in RStudio software (Csardi and Nepusz, 2006) for network construction and analysis and then exported to Microsoft Excel, Gephi and UCINET for further analysis and visualisation.

Figure 4.3 below illustrates the data collection timeframe:

Data Collection Stage	Duration
Stage One	Nov 2014 – Jan 2015
Stage Two	Mar 2015 – May 2015
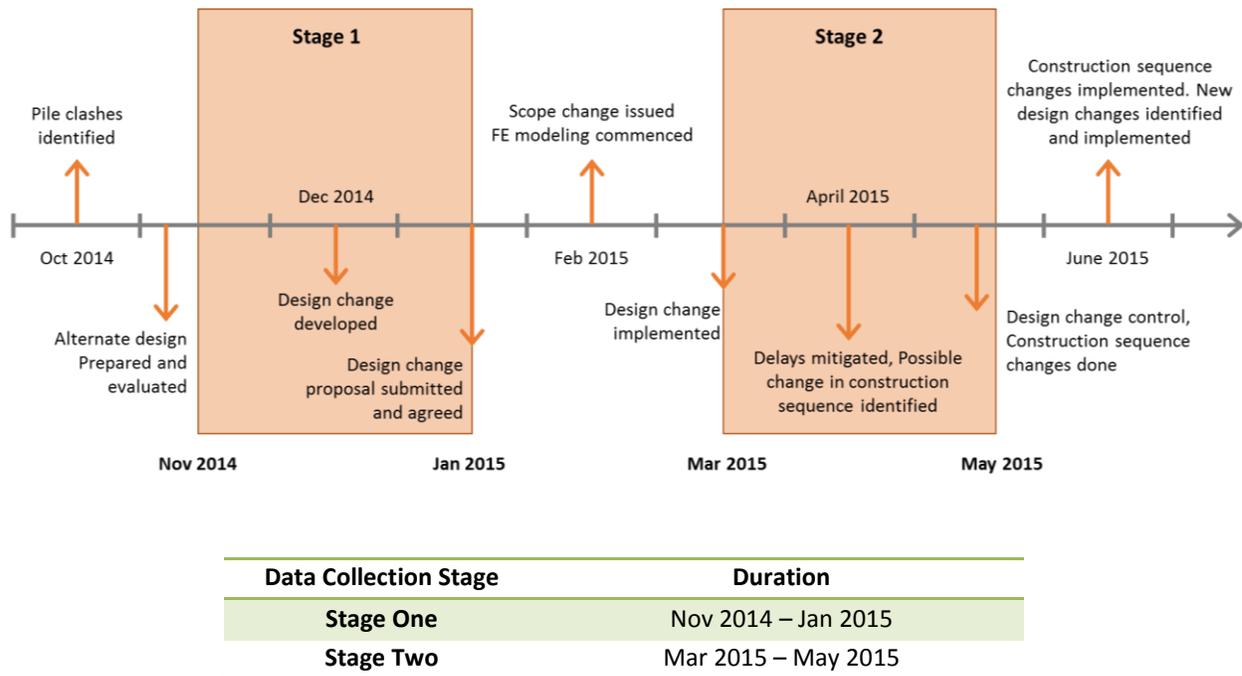
Figure 4.3: Data Collection Timeframe.
(Source: Adapted from Pryke et al., 2017, Figure 3, p. 34)

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[27] Screenshots of the questionnaire are provided in Appendix Three.

Table 4.1 below summarises the sample size of the study:

Table 4.1: The Sample Size of the Study at Stage One and Stage Two of the BSCU Project, Organised based on their Organisational Affiliation (Source: Original)		
Organisation	**Stage One**	**Stage Two**
Alan Auld Engineering Ltd	7	6
Byrne Bros	2	2
Dr Sauer & Partners	10	14
Dragados	42	51
Fourway Communication	2	2
Geocisa	2	2
Geotechnical Consulting Group	1	1
Hyder Consulting	3	4
Keltbray	1	1
McNicholas	0	6
Munellys	0	1
Robert Bird Group	12	16
Scott Lister	3	4
T Clarke	16	21
Transport for London (TfL)	45	51
URS Infrastructure & Environment UK Ltd	7	4
Vision Survey	1	2
Wentworth House Partnership	1	1
Wilkinson Eyre	7	8
Total Number of Participants	**162**	**197**

4.6.5 Research Design

The used questionnaire (see Appendix Three) was intended to identify the relationships between the actors in the project coalition and to classify the direction, quality and type of communication (whether an informal or formal contractual ones). Participants were asked to identify the individuals with whom they communicated in relation to issue-resolution within the last four weeks. Emails, telephone calls, letters, and face-to-face conversations are collectively represented as relationships between two actors. Actors were also asked to describe and quantify the nature of their communication. Likert scales were used to quantify the frequency and quality of communication (as perceived by actors based on their professional judgment). The quality of communication was in turn operationalised using five parameters. These were: importance, accuracy, timeliness, clarity and trust; each one of these parameters to be quantified using a seven-points Likert scale.

Discussions with the KTP research associate, who at that time collected the data, revealed that in line with research best practice, the questionnaire was piloted at the commencement of the fieldwork from January 2014 to April 2014. Pryke *et al.* (2017, 2018) acknowledge that the pilot study was crucial in informing the procedures used for data collection and analysis, and to ascertain which variables were important and then determine their level of importance (Yin, 2018; Larsen, 2011). As a result, some questions were rephrased and clarified. Some of social-science and network-related terms were deleted. The feedback obtained from the pilot testing allowed the questions to become clearer, more user-friendly and jargon-free, whilst the objectives remained constant throughout the development stages (Pryke *et al.*, 2017).

The questionnaire (see Appendix Three) was divided into four sections, as summarised in Table 4.2 below:

Table 4.2: Summary of the Four Sections of the Questionnaire
(See Appendix Three for screenshots of the questionnaire)

Section	Questions
Section 1: Participants to verify information available in the database	Photo, name, job title, organisation and contact numbers
Section 2: Participants to provide information on their functional and contractual links in the project [select from drop-down menu]	• Which 'functional discipline' do you consider yourself to belong to? • What is your employment status? • Who is your functional manager? Add the name if it is not available in the database. • Who is your line manager? Add the name if it is not available in the database.
Section 3: Participants to select the people they communicate with regarding the issue-resolution	Were you involved in the ongoing development of all aspects (design, commercial, planning, reporting, operation, maintenance, construction) of the detailed design of the station box and ticket hall, as defined by the boundaries in the 3D CAD Model, the cost account codes, activity codes and risk codes in the terms of reference within the last four weeks? (it is worth noting that these were provided to the participants as a guide) [Yes/No] **If [Yes]** Please identify the people with whom you have exchanged information with (either to or from) from the identified list. If there is anyone who is not in the list, please add them.
Section 4: Participants describe the nature of communication links with the people selected	• **Purpose**: what is the predominant purpose for which you exchanged information with the person? [select from dropdown menu] • **Nature**: what is the predominant nature of the information sent to the person or received from them? [select from dropdown menu] • **Frequency**: Please select the appropriate number based on how often you communicate with the person (6 = more than once a day, 5 = daily, 4 = several times a week, 3 = a few times a week, 2 = once a week, 1 = less than once a week, 0 = once or twice in total). • **Quality:** Please assess the quality of the communication, in terms of importance, accuracy, timeliness, clarity and trust (6 = strongly agree, 5 = agree, 4 = somewhat agree, 3 = neutral, 2 = somewhat disagree, 1 = disagree, 0 = strongly disagree).

4.7 Programs Used for SNA Data Analysis and Visualisation

The data of this study was analysed using different software packages, namely: RStudio, Gephi and UCINET 6. Results were visualised mainly by using NetDraw and Gephi. This combination of software packages facilitated a powerful and comprehensive data analysis and thus gave a deeper understanding to the issues/events being investigated. In particular, network visualisation allowed highlighting the characteristics and patterns of project communication networks (Pryke, 2012), i.e. the quantitative results were explained using the qualitative data. The different programs used in this study are briefly described as follows:

- **Gephi:** is an open-source software used for both network analysis and visualisation. It provides a powerful interactive capability for exploring and interpreting networks through filtering, navigating and dynamic network visualisation (Bastian *et al.*, 2009). Gephi was mainly used to visualise the BSCU networks presented throughout the thesis. Giving its powerful filtering capability, it was not only used as an analytical method but also as a mean to export the multi-layer network files to other programs, such as UCINET 6 and NetDraw, for further social network statistical analysis and visualisation.

- **UCINET 6:** is a one-stop software package that provides a number of mathematical routines for performing analytics on the data. It allows conducting sophisticated statistical analysis relating to social network data and presenting them in an intelligent way. It comes with NetDraw, a network visualisation tool that is used for producing sociograms from the social network data (Borgatti *et al.*, 2002). Additionally, UCINET 6 contains multivariate techniques, such as multi-dimensional scaling, correspondence analysis, and correlation and regression. Both multi-dimensional scaling and correspondence analysis were used in this thesis as visualisation tools to represent the patterns of change observed in the BSCU project network, as it moves from stage one to stage two. These tools were applied at both global and local scales.

- **RStudio / R (Programming Language):** RStudio is a set of integrated tools designed to help with R. It was used in this thesis as a platform to configure igraph, a collection of open-source network analysis tools (Csardi and Nepusz, 2006). These tools in turn were used for some data analysis and graphical representations. The other key objective of using R was to export the KTP archived data in a tabular/matrix format to Microsoft Excel, UCINET and/or Gephi. It was also used to perform the re-wiring simulations to model the BSCU project network's dynamics and investigate its small-world properties (Scott, 2017; Jarman *et al.*, 2017).

4.8 Network Boundary Definition

In social network analysis, an accurate and clear boundary definition is important to delineate an appropriate assessment of network structural properties (Pryke, 2012; Borgatti *et al.*, 1992). However, defining the network boundary, which is the population for the study, can be difficult because social networks are potentially infinite and transitory (Pryke, 2012). Although sampling is theoretically possible and administratively convenient, validated network studies require a well-defined and complete inclusion of all actors involved, rather than the sampling of actors from larger populations (Wasserman and Faust, 1994; Pryke, 2012). In trying to approximate the network boundary, three main possible approaches have been identified by Laumann *et al.* (1989) and Wasserman and Faust (1994), as follows:

1. **The realist approach:** the actors define the boundary of the network themselves (Pryke, 2012), i.e. actors identify other actors with whom they need to interact to achieve the project objectives).

2. **Snowball sampling (or chain-referral sampling):** the researcher identifies the network boundary through a chain referral process (Prell, 2012). This technique is used when other sampling methods are infeasible (Bryman, 2016), e.g. when trying to sample highly sensitive and/or hard-to-reach populations.

3. **The nominalist approach:** the network boundary is defined by the researcher (Pryke, 2017), who relies on his or her theoretical justifications (or other justifications) for defining the network boundary. This is particularly relevant when actors can be pre-identified through formal or published documents (e.g. formal contracts, academic papers). With regard to information exchange networks, Pryke (2017) elucidates that this approach entails considering the incoming and outgoing information links (i.e. receivers and senders of information). In case that a project actor has been identified as either a sender or a received of information who was not part of the pre-identified list, then that actor will be included in the network.

The nominalist approach was adopted to network boundary definition of BSCU project. Further details are given next.

4.8.1 Application of the Nominalist Approach to BSCU Project Networks

Due to the extensive organisational scope and complexity of the BSCU project, it was infeasible to generate a complete information exchange or communication network between all actors involved. Therefore, the nominalist approach was adopted to define boundaries of BSCU project networks. The scope narrowed to focus on a particular work package - the detailed design phase of the project, which falls within the timescale of the KTP initiative. This focuses on the communication between the actors involved in all aspects of the detailed design of the BSCU station box and the new ticket hall. There is a clear delineated boundary in terms of design accountability within design packages. The project is multi-disciplinary in terms of design, construction, operation and maintenance and has specific cost, time and risk codes associated with it (Pryke *et al.*, 2017). In addition to the cost, time and risk codes, a 3D-CAD model was used to clarify the physical boundaries of the work package to all participants (as illustrated in Appendix Two). This approach assisted in delineating a clear network boundary definition, and also had the ability to capture the maximum number of inter-organisational interactions.

A total of 162 actors in stage one and 197 actors in stage two were identified as meeting the criteria. Their communication networks, therefore, were studied. This approach required obtaining some information on target respondents (e.g. the names of their organisations, roles, and contact details) along with pre-listed answers. This has made completing the questionnaire easier. A 100% response rate was achieved, and the problems of respondent recall were addressed. For details of the problems encountered in data collection during the BSCU pilot study, please refer to Pryke *et al.* (2017). The latter has established the parameters for the following KTP case studies, including the data used in this thesis, and provided some focus for data gathering processes and methodology.

Reflecting on the challenges encountered in data collection and how the KTP team tried to encourage the participants in filling the survey, Pryke (2017, p. 149) asserts:

> *"To enter an environment where individuals are working on a technically and procedurally highly complex project and convince them of the value of completing a survey aimed at analysing their work-related social networks was a challenge. Designing a questionnaire that gathered sufficient data while not being perceived as overly complex was important"*

In a similar vein, TfL Project Manager echoed these challenges by providing the following comments[28]:

'The main problem we encountered is getting people to fill in the survey, that's the real challenge'.

'[……] I don't think collecting the data was difficult because people were resistant, I think probably some people were, I think it's just the nature of we trying to collect that much data when people are doing their data or kinda thing. I think during the KTP its very productive in terms of: we put the networks on the TV screen in the entrance to the office, I think people liked that, we showed them updates on the breakfast meetings, so there is kinda whole thing effect, people kinda feel connected [collective participation and reflection]'.

The BSCU Project Manager continues to provide some recommendations, given the advantages of using network data from his perspective, to analyse communication in project environments:

'The disappointment about this, if you collect this data every month as you collect cost and time data you will build up such an amazing picture, it's just getting the people to fill in the data every month that's kinda the challenge!'

The latter remark could be further developed as a recommendation for project managers, particularly those interested in network analysis, in order to develop routine data collection methods. This should become increasingly attainable in light of the growing technological capabilities that can embed for example sensors to measure and provide a real-time data. Consequently, this can be used to provide timely feedback and adjust any potential negative or dysfunctional behaviour in the network.

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[28] Comments provided for TfL Project Manager in this thesis are dated 15/11/2018. This represents the date of which the remarks from TfL Project Manager were agreed in their finalised version for the use of this thesis.

4.9   Multi-Layered Networks

The combination of interdependence and uncertainty provides a challenging environment for successful project delivery (Tavistock, 1966). Pryke (2017), therefore, argues that networks in projects form as a response to such conditions. These networks tend to evolve and decay, i.e. they move from one structure into another, primarily due to the interactions among their parts at the micro-level (Ferlie, 2007; Kauffman, 1993).

The evolving nature of BSCU networks is described in this thesis by highlighting the structural changes between the two stages of the project, i.e. how the project actors and their interactions are co-created and/or terminated. These changes start at the local level and cascade to affect the global network structure, its functions and outcomes (Scott, 2017). This implies there is a complex interplay between individual behaviour and structural characteristics. The distinction between micro, meso and macro levels of analysis are therefore made clear in this thesis. These terms are adopted from Lukes (1974) and used to come-up with a multi-level analysis framework, organised based on the fundamental units of social network analysis, i.e. individuals, clusters, and the whole network. By doing so, this thesis aims to provide insights into understanding of the interdependence and interactions between network components at different levels. Figure 4.6 summarises the roadmap of the research analysis, highlighting the key areas of focus in the analysis chapters and key measures used.

The global structure refers to features that can only be determined by examining the entire network, e.g. small-world properties. On the other hand, local interactions refer to individual nodes and/or their immediate network groups, i.e. clusters. The properties emerging from the relationships between these clusters are referred to as network 'meso' structures. In this way, meso-level serves as the link between global and local levels. That is, global structures can be described as the emergent properties of the local micro interactions (Anderson, 1999). Figure 4.4 below illustrates the different levels of analysis and the corresponding units/key network components.

Taking this further, the BSCU project will be studied as a synthesis of multi-layered networks. That is, the whole network comprises different types of smaller networks, which are interdependent in nature. This approach opens a new perspective in understanding network evolution, dynamics and the 'dysfunctional prominence' (Pryke *et al.*, 2015) that may emerge from the interplay between different components/layers. Dickison *et al.* (2016) and Boccaletti *et al.* (2014) further suggest that the multi-layered approach may unlock new insights that are otherwise considered hidden under the single-layer approach.

Following Pryke (2012) analytical approach, the research questionnaire (see Appendix Three) sought to categorise BSCU interdependent networks into four types or layers, namely: information exchange, discussion, instructions and advice. This is justified since informal human relations might be classified by the nature of the interaction (Kilduff and Krackhardt, 2008). In turn, the interaction between these layers can be described by the changing actor roles, i.e. same individuals using different types of communication ties in order to satisfy a particular need (Dickison *et al.*, 2016; Boccaletti *et al.*, 2014).

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[29] Available at: https://www.slideshare.net/Cloud/sp1-exploratory-network-analysis-with-gephi. [Accessed on: 24th July 2017]

The complexity of these layers can be exacerbated by further categorising each layer into several types, based on the purpose of communication. The questionnaire (see Appendix Three) sought to gather this data by asking the participants to specify the purpose of their communication with other actors, by selecting from a pre-defined drop-down list that contains fourteen types of communication purposes (the full list of these categories and details of their shares in the communication networks can be seen in Appendix Four). Having said that, this study will focus on the whole network level and the four communication networks in level two, as illustrated in Figure 4.5 below. Reference will be made to the third level, where possible, to highlight any changes in communication as BSCU network shifts from stage one to stage two of the project.
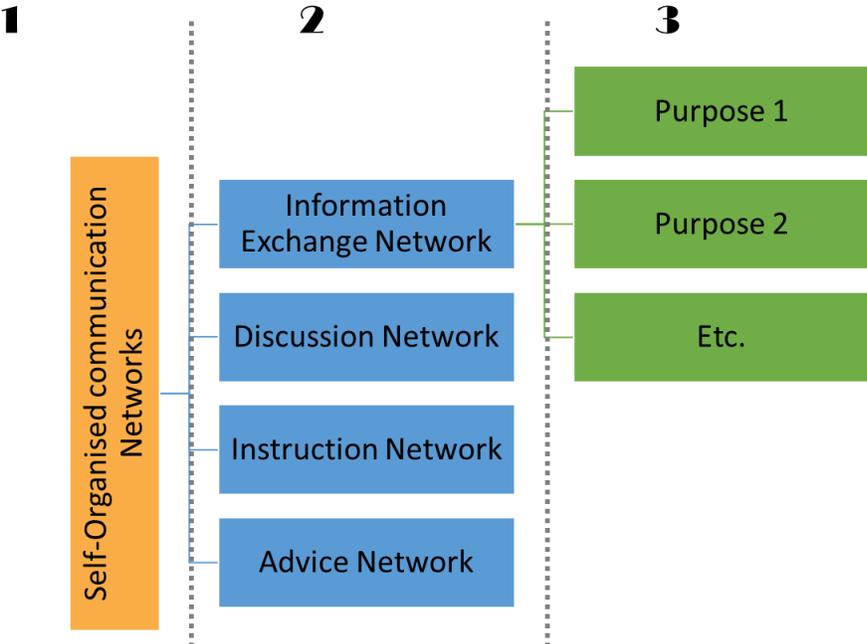
Figure 4.5: The structure of BSCU Project Multi-Layered Networks.
(Source: Original)

Level of Analysis

Structure of the Analysis Chapters: Areas of Focus

Key Measures/Concepts

High-level Analysis → Introduction to BSCU Case Study
- SNA Basic Measures
- Multi-Layered Networks
→ Nodes and Links / Density / Path Length / Clustering Coefficient

Detailed Analysis
Organized based on the Main Units of Social Network Analysis

→ Micro-level *(Roles of Individuals)*
- Centrality Measures
- Multi-level Roles *(based on direct and indirect connections)*
→ Degree Centrality / Eigenvector Centrality / Betweenness Centrality

→ Meso-level *(Self-Organising Clusters)*
- Identification of Clusters
- Identification of Multi-Functional Themes
→ Inter- and Intra- Relationships / Decision-Making / Clusters Pairing

→ Macro-level *(Whole Network Advantages)*
- Efficiency and Cost Measures
- Network Dynamics and the Interaction between Local and Global levels
→ Small-World / Global Efficiency / Local Efficiency / Cost of Communicating

Figure 4.6: The Roadmap of the Research Analysis (Source: Original)

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4.10 Summary

This chapter discusses the research methodology, providing a high level philosophical reasoning and outlining the key methods and measures to be employed later in analysis. These were linked to the earlier theoretical chapters, emphasising on viewing construction projects as evolving self-organising networks that form in response to the ever-changing nature of project requirements and environment. The chapter proposes using SNA as a quantitative method in order to understand network roles, behaviours and emergent outcomes of BSCU project. The latter is a single case study, whose interpretive context is informed by both project informants and review of project-related documents; hence constituting a mixed method approach. The chapter also deals with data sources, highlighting several analytical and ethical issues relating to use of an existing KTP dataset. It concludes by setting the scene for the analysis chapters to follow, highlighting that the synthesis of BSCU self-organising networks will be investigated using a multi-level framework (micro-level: individual actors; meso-level: clusters; and macro-level: the whole network).

Next chapter is the start of the analysis, introducing the case study and employing research methods and techniques discussed in this chapter.

5

Introduction to BSCU Case Study
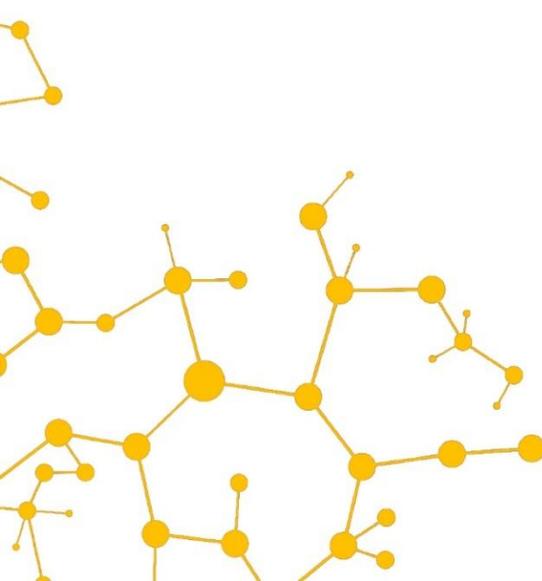
5.1   Introduction

This chapter provides a description of the BSCU project and the context in which it operates. It aims to familiarise the reader with the key features of the project. It also conducts some high-level analysis, as an introductory for the detailed analysis that will follow in next chapters. It will make use of the data collected via the questionnaire, TfL published reports and the periodic project progress reports that were gathered through the KTP project.

5.2   Project Context and Background

The case study of this thesis is centred on the Bank Station Capacity Upgrade (BSCU) project. It is a complex inter-organisational infrastructure project and was fourth in line of a programme of major station capacity projects for Transport for London (TfL)[30]. The project was led and managed by London Underground Limited (LUL), a wholly owned subsidiary of TfL. The primary purpose of the BSCU project was to accommodate a significant increase in passenger demand (over 50% since 2003) and expected further growth at Bank underground railway station. Bank Station is the fourth busiest interchange on the London Underground Network and is considered to be one of the world's most complicated subterranean railway stations. It is a key gateway into the City of London, especially the financial district, which is a densely populated and heavily congested area. It is located in a designated 'conservation area'[31] and interfaces with over sixty properties, ranging from brand new commercial office developments to 17th century churches and tunnelling within meters of the Bank of England. More than 250 engineers and staff were working at BSCU project on a daily basis while the station stayed open to customers throughout the work. Most of the construction work was taking place below ground to minimise construction impact on the historically significant site which is bordered by 31 listed buildings. To illustrate this complexity please refer to the existing London Underground (LU) infrastructure of Bank Underground Station in Appendix One.

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[30] Transport for London (TfL) is the statutory body accountable for all public transport within the City of London in the United Kingdom. Its remit covers all modes of transport – road, river and rail - within Greater London.
[31] The term 'conservation area' applies to an area of special architectural or historic interest, the character of which is considered worthy of preservation or enhancement. It creates a precautionary approach to the loss or alteration of buildings.

The cost of BSCU project was estimated at £563m and launched in 2003. The proposals for it were the result of an iterative design process informed by a detailed understanding of the wider Bank area (its past, present and future) and the existing station. The scope of the work included the purchase and demolition of a number of properties, construction of 600m new rail tunnel (to be connected to the existing 120 years old tunnel), construction of new station entrance, passenger walkways and passages, completion the engineering works for additional escalators, lifts, power supply and communication systems. The initial concept design suggested that BSCU project will exceed its budget and will be completed in late 2023 (as compared to statutory approved completion date of end of 2021). These challenges led LU to implement an innovative procurement model. This is discussed next.

5.3   BSCU Innovative Procurement Model

Besides its complexity (e.g. in terms of task interdependency and surrounding interfaces), large scale and strategic importance to the UK railway infrastructure development, the BSCU has been chosen as the case study for this thesis because it is considered a unique project for Transport for London (TfL). That is, "*it is part of a number of pilot projects that aimed to promote collaborative working arrangements in order to drive down the cost of risks associated with successful project delivery*" (Pryke *et al.*, 2015, p. 4). The project team pioneered a novel procurement approach, Innovative Contractor Engagement (ICE). This approach was first of its kind, developed from the lessons learnt from previous projects with the aim to reduce project uncertainty that was causing the time and cost overruns (TfL, 2014).

ICE procurement model is a key feature of BSCU case study, focusing primarily on the creation of value for the project sponsor through a relational approach. The project has won a number of industry awards in recognition to its innovative approach. Contrary to the current industry practice, ICE requires pre-qualified contractors to divulge their innovative ideas to the client in a protected dialogue phase (TfL, 2014). This happened early in the project life cycle at the front-end, even prior to invitation to tender, through a negotiated dialogue phase governed by a joint confidentiality agreement. Project information is shared in advance of formal issue of the tender documentation, in order to minimise information asymmetry and maximise potential value of the design and build ideas and their long-term social benefit. The wining tender was awarded based on the added value brought by innovation to the project's business case.

The BSCU project in its own terms was complex, involving a large number of stakeholders and interfaces. By adopting the ICE procurement approach, management of the BSCU project has been made even more complex. Arguably, the most important task was to create and enable a project team with the capability to support the uncertainties of the project as well as of the ICE process (Addyman, 2013; TfL, 2014). Additionally, the governance structure for the ICE novel approach went through multiple iterations as it was being implemented, and thus could be considered to be an emergent feature of an evolved structure. Such process undeniably contrasted with the traditional iron triangle (cost-time-quality) to focus on trade-off the value criteria within the client business case against procuring the most "effective product" and "efficient method" (TfL, 2014). This meant that the solutions proposed by the bidders can vary in contrast to the fixed project requirements and design solutions imposed in the traditional procurement approaches (TfL, 2014). Reflecting on the ICE collaborative procurement philosophy that focuses on relationships, the TfL Project Manager states:

> *'The type of procurement that we have done [referring to the ICE methodology report, and the adopted strategy of 'collaboration through integrated team'] as a result of that we had quite strong relationships once we started the project, the nature of that procurement we did, doing the network studies was a part of enhancing that relationship as much as possible, and probably we should have done more with the network stuff afterwards. But I think it's kinda tough to introduce too many things at the same time'.*

A public and stakeholder consultation was conducted before a base case (concept design) was arrived at in 2011 (TfL, 2014). LUL began the ICE process in April 2012 by issuing formal invitations to four pre-qualified contracting consortia to improve upon the base case design (developed by LUL) as part of their tender proposal (TfL, 2014). In September 2014, BSCU conceptual designs were submitted to Transport and Works Act Order (TWAO[32]) to gain construction and operation permissions (TfL, 2014). The design process completed in January 2016, whereas construction stage commenced in April 2016.

The ICE implementation involved five phases, namely: a pre-dialogue phase for establishing the business case, ICE dialogue phase for bidder engagement, an interim review, an invitation to tender (ITT), and finally an evaluation and contract award. Figure 5.1 illustrates these phases against the BSCU project timeline and the three-stage approvals for the TfL Board.

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[32] A TWA Order is a statutory instrument made under the Transport and Works Act 1992. In brief, it is the usual way to authorise the construction or operation of railways or tramway schemes in England and Wales.

The ICE approach was successful in exceeding 15% increase in project's value target (TfL, 2014; Addyman, 2013). This included a 45% increase in the project's business case, £62m cost reduction, enhancement of social benefit and an increase in revenue over the life of the project (TfL, 2014; Addyman, 2013). The focus on improvements in social benefits included: reduction in closure duration of the Northern Line, reduced journey time through the station, effective step-free access solution direct from street to platform on both the Northern and the Docklands Light Railway (DLR) lines and finally a more efficient fire and evacuation strategy throughout the whole station (TfL, 2014). A summary of the ICE approach and the benefits realised is illustrated in Figure 5.2 below. The illustration was developed by TfL's Benefits and Value Functional Lead and provided by him on the side of Dubai International Project Management Forum, 2018.

2011 | **2012** | **2013**

| Q4 | Q4 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 |

OCT NOV DEC | JAN FEB MAR | APR MAY JUN | JUL AUG SEP | OCT NOV DEC | JAN FEB MAR | APR MAY JUN | JUL AUG SEP

Pre Dialogue

- Business Case
- Invitation to Participate
- Information Agreement
- ICE Governance & Execution Plans
- External Expert / IIPAG – Corp Gate C Review
- TfL Board Approval
- ICE Launch Day – 20 April 2012

ICE Dialogue

- Confidential Bidder engagement
- The Independent Observer
- Request to Proceed Statements
- Draft Scoring & Criteria
- Negotiating and evaluating

Interim

- De-constraining the Works Information
- Scoring & Evaluation Model
- External Expert / IIPAG – Interim Review

ITT

- D&B Tender queries
- Tender evaluation plans and governance

Evaluation & Award

- Specialist Evaluation teams
- Preferred Bidder negotiations
- External Expert / IIPAG – Corp Gate D Review
- Contract document preparation
- TfL Board Approval
- Contract Award

Strategy approval | Invitation to tender | Contract award

Figure 5.1: ICE Implementation Phases. (Source: TfL, 2014, Figure 2, p. 27)

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Figure 5.2: A summary of the ICE approach and the benefits realised (Source: TfL's Benefits and Value Functional Lead)

5.4   BSCU Project Formal Organisational Structure

According to Pryke *et al.* (2017) the project's formal organisational structure at the detailed design stage was hierarchical and linear, with a limited degree of mixed teams and responsibilities. The client (TfL) had a single contract with a Main Works Contractor (Dragados) who was responsible for both the design and construction works. The Main Contractor in turn had several contacts with other sub-contractors in separate dyadic relationships, forming the project supply chain. The project was managed internally by the client supported by external consultants responsible for managing all external stakeholders' relationships, especially in gaining statutory planning authority through the TWAO.

Overall, the contractual structure consisted of the client (TfL) and three tiers of contractors, involving the contributions of more than ten organisations and more than two hundred and fifty personnel across various teams and roles. Figure 5.3, below, illustrates the three main tiers of the project supply chain. The diagram below places firms within the project contractual hierarchy, giving an indication of the lines of formal authority within the project organisation (Pryke, 2012). A brief description of each firm role is given next.
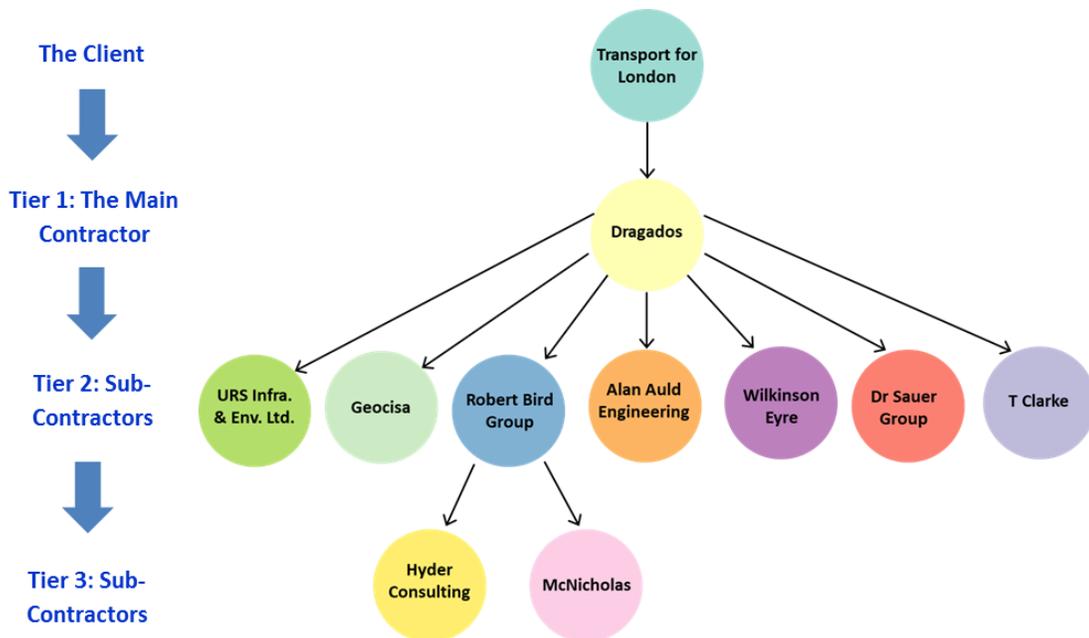
**Figure 5.3: Contractual Network Between Organisations Involved in the BSCU Project – 2015.
(Source: Pryke *et al.*, 2017, Figure 3.1a, p. 35)**

- **Tier 1 - The Main Contractor (Dragados):** It was the successful bidder in the ICE procurement process and accountable for both the design and construction works. It has developed the BSCU scheme along with London Underground Limited (LUL), aiming to reduce congestion and provide improved access to Bank Station. The Main Contractor is supported by their external supply chain of designers and works sub-contractors. This approach enabled integration and coordination for the design of BSCU project, capitalising on the expertise from the second and third tier firms as well as LUL engineers.

- **Tier 2 - Sub-Contractors:**
  - **URS Infrastructure & Environment:** responsible for planning, environment and engineering services;
  - **Geocisa:** responsible for the design of the instrumentation and monitoring works for both the above and below ground elements;
  - **Robert Bird Group:** they are the structural engineers responsible for the design of civil structures;
  - **Alan Auld Engineering:** Mainly responsible for the detailed design of the proposed tunnels and shafts. This involved using Building Information Modelling (BIM) and Computer Aided Design (CAD) resources to produce the digital representation of physical and functional characteristics of BSCU facilities;
  - **Wilkinson Eyre Architects:** responsible for architecture and design;
  - **Dr Sauer Group:** responsible for tunnelling works; and
  - **T Clarke:** responsible for Mechanical, Electrical and Public Health (MEP) works.

- **Tier 3 Sub-Contractors:**
  - **McNicholas:** responsible for the utilities' diversion design;
  - **Hyder Consulting:** this sub-contractor was nominated by McNicholas in October 2014 to improve design capability, especially in relation to the infrastructure of statutory utilities. This included a different team from Hyder Consulting that was already offering consultancy services to the client.

In contrary to the usual procurement practices in construction industry that tend to emphasise on achieving lowest cost, the ICE procurement helped to establish strong relationships between the client, the main contractor, designers, and sub-contractors (including the engineering and sponsor teams in the LU). This was further fostered by the fact that all of the project participants were located in a single worksite. The TfL Project Manager reflected on this saying:

> *'Those visiting the worksite found it difficult to tell which participant was from which organisation. It had become a feature to easily hold team events or workshops to take stock of where we were. In addition, monthly breakfasts meetings were organised for the teams, allowing sharing of information'*

However, the meeting of the joint management team took place on the 29th June 2015 highlighted that there was lack of formal communication between the functional teams of the project, especially at the senior managerial level (Addyman, 2019). They were not yet ready for the transition from design stage to construction stage. This conclusion came as a complete surprise. The management focus on completion of the public inquiry and TWAO submission had diverted attention away from identifying early warning signals in relation to communication effectiveness.

In light of this context, this study will conduct a post-mortem for the period preceding the discovery of lack of formal managerial communications, i.e. the detailed design phase of the Whole Block Site (WBS), the location where the new entrance on Cannon Street will be installed. The purpose is to understand how the strong informal relationships among project participants had helped the project to self-organise in absence of adequate formal managerial communications. The data collected from the Knowledge Transfer Partnership (KTP) presents a good source to conduct the analysis, as they extend over two time periods, covering in total almost half of the phase time since completion of concept design. Moreover, they capture the key events encountered in the detailed design phase, described as "some of the toughest challenges" by the Project Manager. These datasets, therefore, lend themselves to being crucial in understanding the self-organising concept and how actors behave to respond to BSCU project issues and risks/uncertainty faced at WBS.

The details of the key events encountered through the two stages of BSCU project is provided next.

5.4.1 Main Context Surrounding BSCU Project at Stage One

Around October 2014, while conducting the detailed design of the Whole Block Site (WBS)[33], possible pile clashes were identified. This issue was classified as a major risk as it could ultimately reduce the bearing capacity[34] of the piles, leading to potential cracking of the structural slabs and therefore serviceability and safety issues. This had requested the development of an alternative design and construction sequences. Consequently, discussions with Tier two sub-contractors were held to determine possible solutions and mitigating actions. This was carried out over the rest of the year, resulting in some delays to key design dates. The general focus in this stage, therefore, was re-directed to provide sound structural solutions and mitigate the risks associated with progressing in the conceptual design. Some detailed description of this period, assimilated from the BSCU project progress reports, is provided next in a chronological order.

- **November 2014:**

The most significant event of this period was the change to the Whole Block Site (WBS) lift shaft design, from piles forming a rectangular shaft to a circular shaft in either segmented rings or Sprayed Concrete Lining (SCL)[35]. This change is the result of Robert Bird Group's (Civil and Structures engineers) assessment of the Compliance Design Submission (CDS) design which raised questions about pile load-carrying capacities. A base option for the proposed alternative design was developed, utilising a circular Persons with Reduced Mobility (PRM) shaft constructed using precast concrete segments. This was deemed appropriate as it alleviated geotechnical issues and allowed reducing the construction time, removal of propping requirements, and reduced complication of excavation and construction. The lack of clarity of this potential conflict resulted in various issues, particularly programme and design delays of the other interface parts.

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[33] Whole Block Site is located at Cannon Street London. It is the location of the entrance to Bank Tube Station on completion of the BSCU project.
[34] The bearing capacity is the maximum load which a pile can carry without failure or excessive settlement of the ground.
[35] Sprayed concrete is a construction technique used to provide support for tunnels, e.g. through weak rock.

- **December 2014:**

Pile interception design was significantly delayed as a result of MEP contractors (T Clarke), who faced shortage in resources. Additionally, during this period a design change proposal was being developed for the upper PRM shaft. The main contractor (Dragados) was managing this with support from other designers. In this regard, resources were mobilised and work was re-prioritised on several activities to recover time and get back on programme. As a result of the experienced delays, the first design-freeze[36] milestone date (15th December) was not met.

- **January 2015:**

A number of activities were delayed, mainly surrounding the change of the PRM shaft design. Resources were increased and work was re-prioritised on these activities in order to recover time and get back on programme. This is to ensure there is no impact to the Compliance Submission. A design change proposal was submitted and agreed in principle for the upper PRM shaft. Issues associated with pile capacity had also delayed the programme. Progress was hindered further due to: abortive work on the Compliance Design Submission (CDS), concept design options considered for detailed design, definition of scope split, and determining the preferred construction methods. Dragados was finalising the scope definition with Dr Sauer group (Tunnelling engineers) and Robert Bird Group (Civil and Structures engineers).

The main context of this stage relates to a civil engineering and structures event/issue with regard to the pile load capacity. This was mainly managed by Dragados, supported by other designers. When the Project Manager was asked to discuss the main issue/risk at this period in the project, he stressed on its civils and structural nature by stating:

> *'from the concept design, we understood there was a pile clash. We had a square design for the box and that clashed at the bottom of the lift shaft technically. So, we had to re-design that to a circular shaft'.*

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[36] Design Freeze is a method used during design development stage to mitigate the risks associated with change. It involves organising and compiling the design process and control changes, forcing the completion of design stages on time.

He also shed the light on the organisational challenge at this stage, which again relates to the civils and structures discipline, that necessitated the client (TfL) to step in and exert some power. In this regard, the Project Manager made the following comment:

> *'the civil engineering company that were doing the detailed design was different from the civils engineering company that did the concept design. Separately, we had tunnel designers that were doing the main running tunnel, but the civils designers went and get their own tunnelling sub-contractors in and we didn't want them to use these new contractors. We wanted to use the organisation that was already in the project. So, we had to make that change and say that you can't use those. Eventually they agreed to use the ones already there'.*

February 2015 was the time gap between the two studied stages. Reflecting on the context is therefore crucial to gain a deeper understanding to the change in network structure. During this time, a number of activities were in delay, mainly surrounding the PRM shaft design and MEP services being re-routed. Overall design coordination was impacted by the ongoing consideration being given to the shaft and room layout. This resulted in a three months delay. As a result, the main contractor along with sub-contractors were drafting recovery plans. These included increasing resources, mainly for MEP works, and commencing Finite Element (FE) modelling to assist in solving problems of structural engineering.

5.4.2 Main Context Surrounding BSCU Project at Stage Two

The context of this stage was mainly concerned with the project control and management. By January 2015, the final decision on design changes, resulting from the identified pile clashes, was made. These changes were sent through change control by May 2015. In addition, around April 2015, new information on the sub-structure was received from London Underground, requiring the re-design and re-sequencing of the construction works to make time savings.

The changes introduced in stage two were carried out in May 2015 and implemented by June 2015. Some detailed description of this period, assimilated from the BSCU project progress reports, is provided next in a chronological order.

- **March 2015:**

The main delays identified during last period (i.e. the PRM shaft design) were mitigated through resources re-location. Other arising issues relating to track design and pile interceptions were also identified and addressed. Additionally, 3D FE modelling was progressing and the clash detection review, developed through BIM, aided the design team to identify key outstanding items yet to be coordinated. Work in this period also focused on finalising proofs of evidence for submission to objectors and other parties in the public inquiry. This was an enormous amount of work and a significant achievement that required support and input from the whole project team. This, however, meant that key resources within the design and construction teams were redirected to support the TWAO process, particularly in the preparation of proofs of evidence and rebuttals. Additional CAD resources, therefore, were brought to support with the 2D drawings production.

- **April 2015:**

This is a busy period with significant activities, including the start and finish of the public inquiry (14th-30th April). This meant that the work in this period was concentrated on finalising inquiry documents. Additionally, the earlier identified pile interceptions were instructed to Dr Sauer (tunnelling engineers), who accelerated the work to mitigate the reported program delay. A base case design for the track was developed by London Underground (LU) Track Engineering. However, basement drawings sent by LU differed from the site information, requiring construction of additional piled retaining walls. This required re-design and re-sequencing of the construction works again. Finally, Robert Bird Group delays (regarding the 3D FE modelling) were mitigated to achieve the design key dates, thanks to the additional Architecture and MEP resources joined the project during this period.

- **May 2015:**

As a result of the changes associated with the construction sequence and basement design, Alan Auld (BIM/CAD designers) continue to be in a program delay. Additionally, their lack of transparency over the buildability, operational disruption, infrastructure protection and CAD model integration resulted in being more closely monitored and supported by both the main contractor (Dragados) and LU Engineering.

In this period there were three main areas of concern that required re-working and thus resulted in consequential delays to the delivery programme. These have been re-located to the contractor's (Dragados) main office in order to reduce the delay impact and give a greater certainty on delivery:

- **DLR PRM shaft works:** required a major re-design to address previously reported delays with the design of the Northern line cross passages and DLR PRM shaft;
- **DLR Cross Passages:** works delayed by changes introduced upon identification of new information during intrusive surveys; and
- **Central line MEP shaft:** re-design of the shaft required to address space issues.

Reflecting on the context from several sources and particularly from the project periodic reports (October 2014 – June 2015), it is revealed that the identified pile clashes in stage one weighed heavily on the delivery programme. This issue was, however, eventually solved. Remarkably, when the TfL Project Manager was asked to comment on this, he explained:

> *'My reflection is that the engineers and the designers sorted it out, once they have kind of clicked, it was sorted. As a senior management team, we weren't really that kind of worried about the issue [i.e. pile clash identified in stage one], as we had the confidence in the engineers that they will get on with it'.*

This reflects the emergence of coordination and increased level of trust between the project participants. Particularly, the disengagement of project management team in resolving the pile issue suggests that they have trust in the competence of the designers and engineers to self-organise. The Project Manager continued to explain the shift in focus of this stage, from being a Civils and Structures relating event/risk to a Project Control and Management relating event, by saying:

> *'If I remember the date, that was April 2015, we were finishing the statutory planning of that stage, so we had a public inquiry about the statutory planning, now that particular design issue [i.e. pile clashes] didn't really impact the statutory planning. The management of the design team and us the senior management team, our focus was more oriented towards getting the statutory planning, as without it we couldn't do the scheme'.*

He continues saying:

'Initially, the design was planned to be generally completed around October time and there will be three or four months of assurance reviews and checking of everything and formal submission to sign off the design in February. However, late June we realised that actually there was a quite disconnection between the design and construction and the design wasn't going to be completed on time.

We had one design package that going to be submitted and signed off for a milestone date in February 2016, which had a fixed lump sum fee associated with it. We realised we couldn't do that. So, we split it up into five separate packages, so that particular design issue was fine. It could sit on one of the civils packages but of course once you start splitting the design packages there are different sort of issues to go through. I think that came in a time when we may be felt that the design was running okay and the focus had shifted'.

Having discussed the BSCU project context and the series of events encountered at the detailed design stage, it is appropriate to discuss the high-level characteristics of BSCU contractual reporting network (i.e. formal) before conducting any analysis on the informal BSCU networks. It is to this subject we turn now.

5.5   BSCU Contractual Reporting Network

Formal networks are dictated by contracts that are deliberately designed to coordinate and control organisational activities in pursuit of collective goals (Aldrich, 1976). BSCU contractual reporting hierarchy is visualised as a network graph using the NetDraw program[37]. The produced network is illustrated in Figure 5.4. It was established by asking the participants to identify whom they formally report to in the BSCU project on a daily basis. Hence, the contractual (line) managers could be from different organisations than the one the participant is employed by.

From the graph, it is observed that there are several well-connected parties with large nodes size. This indicates their contractual authority and power based on the reporting hierarchy. It is obvious that the managers from the main contractor (Dragados) followed by the MEP contractors (T Clarke) and Civil and Structures engineers (Robert Bird Group) were the most prominent actors in this network. This is expected given the scope of the work in this phase as well as the fact that the main contractor was procured on a design-and-build contract where in turn it had dyadic relationships with the rest of the project supply chain. This graph also reflects that tier two sub-contractors, in particular, played a key role in managing day-to-day activities alongside the main contractor.

It is also noticeable from the graph that managers form the client organisation (TfL) are ubiquitous in all parts of the network, reflecting their hands-on involvement. This is unsurprising given that ICE contract had a nested structure based on risk-sharing, requiring completion of the works within target arrangements (Addyman, 2019). This was further supported by a 'management protocol' to govern the behavioural relationship between the client and the contractor (Addyman, 2019); hence reducing the likelihood and impact of uncertainty. TfL is, therefore, had contractual authority in terms of resource allocation, budget allocation and decision making. Additionally, this could be attributed to the fact that at the tendering stage, the existing LU's engineering consultants joined with contractors to form a bid team. This core design-delivery team had been initially ring-fenced at the front-end and continued to be part of the project as the design was being developed (TfL, 2014). Overall, the network is quite dense around the core design-delivery team, suggesting a fairly centralised formal structure. Interestingly, the investigation of the BSCU informal network (to be discussed later) revealed that the same core design-delivery team continued to occupy prominent network positions, being identified as 'go-to' team. This shows how critical the front-end is in shaping the subsequent project phases.

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[37] NetDraw program is integrated with UCINET and used mainly for visualising networks.

It is worth noting that the BSCU contractual reporting network shows several less connected nodes, some of which have just isolated dyads. These nodes represent mainly tier three sub-contractors, actors designed to perform specific tasks and/or actors reporting to managers in their home organisation who might not be directly involved in the BSCU project.

The detailed examination of 'formal' network is beyond the scope of our discussion in this thesis. This study is concerned with informal networks that are self-organising in nature and hence of paramount importance to understand how things are actually done. The thorough investigation of BSCU informal networks will be performed in the coming three analysis chapters, involving inspection of network sociograms. As a high-level analysis, basic measures and characteristics of BSCU informal networks are discussed next. This is essential to set the scene for the detailed analysis.
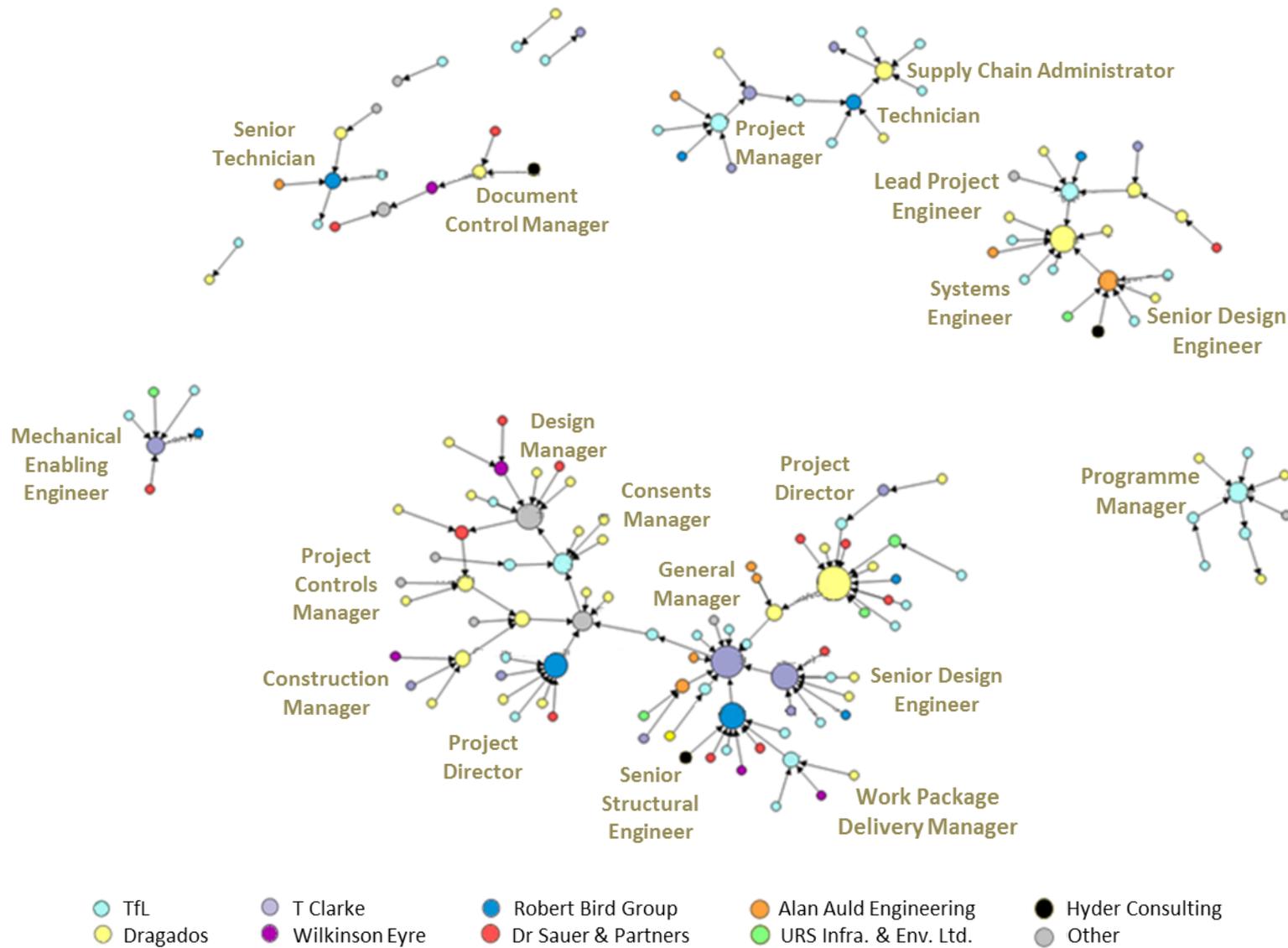
Figure 5.4: Contractual Reporting Network. Nodes are Sized by Degree Centrality and Coloured by Organisation. Titles of the Line Managers (have largest nodes) are given for key teams (Source: Original)

5.6   The Basic Measures of BSCU Informal Networks

Probability distributions are one of the basic quantitative methods used to study complex systems, providing a simplistic but effective tool with which one can describe the occurrence of regularities and characteristics of the underlying organisation (Sornette, 2009; Castellani and Rajaram, 2016). Examination of the BSCU project informal networks, at both stages, reveals a fat-tail, skewed-right degree distribution. This is most commonly observed in complex systems compared to the normal distribution usually found in the correspondent random networks (Castellani and Rajaram, 2016).

The basic SNA measures of BSCU informal networks are presented in below table, calculated using UCINET.

Table 5.1: BSCU Network Basic Measures. (Source: Original)

Measure	BSCU - Stage One	BSCU - Stage Two
Number of Nodes	162	197 *(22% growth)*
Number of Links/Ties	1440	2207 *(53% growth)*
Network Density[38]	0.055	0.057
Average Path Length[39]	2.668	2.549
Average Path Length – *Random Network*	2.6	2.5
Average Clustering Coefficient	0.384	0.416
Average Clustering Coefficient – *Random Network*	0.057	0.059

Results listed in Table 5.1 above highlight that BSCU project networks have "small-world" features. This is because, as per Watts and Strogatz (1998) model, their average clustering coefficient found to be significantly higher than that for a random network constructed on the same number of nodes. Also, they have approximately the same average path length as its corresponding random network. These small-world structural patterns have been consistently observed in a diverse set of self-organising networks (Watts and Strogatz, 1998). BSCU networks are no exception.

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[38] Density reflects the extent to which the network is connected. Generally speaking, high density means an overall good connectivity or cohesion while low density could indicate network fragmentation (Pryke, 2017).

[39] Path Lengths refers to the number of connections between actors. It is an important measure in project communication and information exchange networks, as it affects the speed of communication and problem resolution (Wasserman and Faust, 1994; Pryke *et al.*, 2018). Long path lengths imply that information go through several intermediaries and take more time to be delivered. Hence, the potential for information bias, hoarding, filtering and controlling increases and affects negatively the information flow (Wasserman and Faust, 1994; Scott, 2017).

The growth between stage one and two in terms of number of actors (nodes) was approximately 22%, increasing from 162 actors in stage one to 197 actors in stage two. This was associated with the appointment of new resources mainly from project controls and commercial management disciplines, particularly to support the input for the public inquiry and to mitigate the reported design delay from several disciplines. The growth in number of nodes was accompanied by a growth in connectivity. This is 53% increase in number of links. These measures indicate introducing changes to network topology and resources. Density, however, remained flat, which means network actors adapted quickly to the new structure. This was achieved through maintaining and/or establishing new connections with those actors that can help in getting the work done.

As part of the research questionnaire, participants were asked to categorise their communication activities into four types namely: instructions, advice, information exchange and discussion. This is the same framework suggested by Pryke (2012) to study multi-layered networks. The basic measures of the BSCU sub-networks/layers, in terms of size (i.e. number of nodes and ties) and density, are summarised in Table 5.2 (see Appendix Five for the full-size versions of the sociograms). These high-level results visually illustrate the uniqueness of each communication layer and help to understand the multi-layer nature of project networks that co-exist simultaneously in a non-linear self-organising system.

Apart from the Instruction layer, the measures of BSCU sub-networks highlight that the increase in nodes was associated with an increase in connectivity while density remained almost flat. This is in line with the earlier results for the whole BSCU network. It suggests topologies of sub-networks have changed between stage one and stage two, given introduction of new actors who have adopted quickly to the new environment, establishing new connections with the rest of the team. Information and Advice layers reported the highest growth scores. This is explained by their crucial role in situations requiring problem-solving techniques, such that encountered at BSCU (Pryke, 2012).

Instructions layer stood out from the rest in the sense that growth in nodes was associated with reduction in connectivity and hence density. This is an interesting result. Pryke (2017, p. 96) explains this by arguing that "*the issuing of 'instructions' is one of the few types of communication referred to in forms of contract for delivering construction or engineering projects*"; hence suggesting a formal approach to communication. Actors involved in Instruction layer are usually assuming managerial positions, given nature of their order-based communications (Pryke, 2012). It can be concluded therefore that other actors at stage two were resistant to engage through formal channels. They preferred establishing more informal relationships in response to the higher uncertainties/risks faced.

Such disengagement by the managers also indicates a shift in decision-making power from formal/contractual arenas towards making more deliberations at the junior (local) levels. The overall results at stage two therefore imply less reliance on formal communication channels, moving towards establishing more collaborative and trusted informal relationships.

The high-level analysis of BSCU sub-networks demonstrates the non-linearity of BSCU project communication networks. This arises from the non-additive nature of these different communication layers when combined and studied as a single-layer network. It is also an indication of co-existence, where actors are simultaneously engaging in different layers to satisfy their communication needs. Moreover, a non-linear growth between stage one and stage two was observed across the different communication layers. That is, the number of nodes or links increases nonlinearly with time (Bauer and Kaiser, 2017).

Table 5.2: Basic Measures of BSCU Multi-Layered Networks at Stage One and Two, Nodes are sized by Betweenness Centrality and Coloured by Organisations. See Appendix Five for the full-size versions of the sociograms (Source: Original). *Table continued on the next page.*

Name of the Layer	Sociograms of Stage One and their Basic Measures						Sociograms of Stage Two and their Basic Measures					

Information Exchange Layer

| | No. of Nodes | 128 | No. of Links | 571 | Density | 0.035 | No. of Nodes | 172 *(34% growth)* | No. of Links | 1080 *(89% growth)* | Density | 0.037 |

Discussion Layer

| | No. of Nodes | 121 | No. of Links | 506 | Density | 0.035 | No. of Nodes | 144 *(19% growth)* | No. of Links | 726 *(44% growth)* | Density | 0.035 |

Legend:
- TfL
- Dragados
- T Clarke
- Wilkinson Eyre
- Robert Bird Group
- Dr Sauer & Partners
- Alan Auld Engineering
- URS Infra. & Env. Ltd.
- McNicholas
- Other

Less Brokerage ● ● ● More Brokerage   Weaker Relation ||| Stronger Relation

Table 5.2 *[Continued]*: **Basic Measures of BSCU Multi-Layered Networks at Stage One and Two, Nodes are sized by Betweenness Centrality and Coloured by Organisations. See Appendix Five for the full-size versions of the sociograms (Source: Original)**

Name of the Layer	Sociograms of Stage One and their Basic Measures						Sociograms of Stage Two and their Basic Measures					
Instructions Layer												
	No. of Nodes	107	**No. of Links**	269	**Density**	0.024	**No. of Nodes**	119 *(11% growth)*	**No. of Links**	251 *(7% decrease)*	**Density**	0.018
Advice Layer												
	No. of Nodes	70	**No. of Links**	94	**Density**	0.019	**No. of Nodes**	98 *(40% growth)*	**No. of Links**	150 *(60% growth)*	**Density**	0.016

○ TfL ○ T Clarke ○ Robert Bird Group ○ Alan Auld Engineering ○ McNicholas   Less Brokerage ● ● ● More Brokerage   Weaker Relation ||| Stronger Relation
○ Dragados ○ Wilkinson Eyre ○ Dr Sauer & Partners ○ URS Infra. & Env. Ltd. ○ Other

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Additional basic measures are calculated for BSCU multi-layered networks at both stages, as follows:

Table 5.3: Key Characteristics of BSCU Stage One and Two Multi-Layered Networks.
(Source: Original)

Layer Name	Ave. Weighted Degree		Ave. Path Length		Ave. Clustering Coefficient		Density	
	Stage 1	Stage 2	Stage 1	Stage 2	Stage 1	Stage 2	Stage 1	Stage 2
Whole BSCU Network	0.661	0.885 (↑)	2.668	2.55 (↓)	0.384	0.416 (↑)	0.055	0.057 (↑)
Information Exchange	0.326	0.5 (↑)	3.098	2.75 (↓)	0.209	0.225 (↑)	0.035	0.037 (↑)
Discussion	0.298	0.382 (↑)	3.001	2.93 (↓)	0.213	0.252 (↑)	0.035	0.035 (-)
Instruction	0.209	0.181 (↓)	3.557	3.65 (↑)	0.092	0.071 (↓)	0.024	0.018 (↓)
Advice	0.098	0.121 (↑)	4.001	4.68 (↑)	0.03	0.03 (-)	0.019	0.016 (↓)

(↑) *indicates a growth between the two stages;* (↓) *indicates a decrease between the two stages;* (-) *indicates no change*

The basic measures of the BSCU communication networks indicate that network characteristics are quite comparable for both stages at the overall level. However, a closer look at the sub-networks reveals that each single layer has its own specific characteristics that represent a specific social dynamic. Interpretation of these results are given below, out of which several discussion themes will be developed to be included later in the Discussion Chapter.

Table 5.2 shows that Information Exchange and Discussion layers had the highest network sizes (i.e. number of nodes and links). It means the BSCU communication in both stages was concentrated at these two layers. This is expected as Information and Discussion layers usually prevail in projects since they are centred on problem-solving (Pryke, 2012) and conceptualised as information processing systems (Winch, 2002). Apart from Instruction layer that largely represents formal communication, BSCU stage two networks also reported an improved connectivity. This is evident by the higher degree scores. Given the relational nature of ICE approach, the results support those demonstrated in Pryke (2012), stressing on building collaborative relationships to facilitate knowledge transfer and exchange in response to project complexity/uncertainty. The low degree score of Instructions layer, on the other hand, implies that this form of communication was discouraged to be used as the main method because it could defeat the purpose of adopting a collaborative procurement model. These findings are opposed to those envisaged by the Joint Contracts Tribunal (JCT) which promotes the use of standard form of construction contracts in the UK, that are structured around allocation of risks between the parties and using Instructions as the primary form of communication (Pryke, 2012; Higgin and Jessop, 1965).

The scores for average path length were found to be below 5 degrees across all BSCU networks and layers. In fact, the whole BSCU network remarkably scored just above 2.5 degrees at both stages. This is lower than the 6-degree average path length between two nodes in a random network (Watts and Strogatz, 1998). This finding means that ICE model was successful to bring BSCU actors closer to each other, enhancing access to resources. This is a key benefit for adopting a relational model because project teams must make decisions in a constant manner given the ongoing internal and external developments (Tsoukas and Chia, 2002). That is, in large projects, actors usually do not have the luxury of time or the capacity to go through a lengthy process or carefully analyse all the issues involved (Tsoukas and Chia, 2002).

Table 5.1 shows that BSCU networks have clustering coefficients much larger than those of their corresponding random networks of equal size (i.e. equal number of nodes and links). This highlights the network inherent tendency to form tightly knit groups characterised by a relatively high density of ties (Watts and Strogatz, 1998). Investigation of clustering coefficients at the sub-networks level highlights that Information Exchange and Discussion layers have comparatively high scores compared to others (refer to Table 5.3). This is an indication of higher nodes' embeddedness at these two layers. It means that adoption of the ICE model helped to foster collective participation and collaborative decision-making. This is a key benefit as it implies that different views can be heard, control and authority are better distributed, and every agent therefore can take part in the process (Stacey, 2010). The increased level of average clustering coefficients in stage two also indicates that actors have evolved to operate relying more on the collective participation and knowledge. This finding is supported by the increased level of trust observed at stage two, as highlighted by the questionnaire results. On the other hand, the relatively low clustering coefficient at Instruction layer, which consists largely of formal communication, indicates to some extent existence of so-called structural holes. This can be understood as a gap between two individuals who have complementary sources to information (Pryke, 2012). It means that formal communication was inadequate at both stages of BSCU, adversely impacting its effectiveness. The same was confirmed at the BSCU joint management team took place on the 29th June 2015.

The high clustering coupled with high connectivity of Information Exchange and Discussion layers indicates that actors at BSCU project tend to discuss and exchange information in (more or less) stable groups (Borgatti *et al.*, 2018). Such groups provide a forum in which actors can shape the rules and norms of engagement, deliberate and articulate their agendas to solve the encountered issues (Stacey, 2010).

This also may indicate the success of the ICE approach in bridging the gap between project participants (and supply chain tiers) through the integrated team approach. It facilitated a more collaborative and collective approach to decision-making and problem solving. In other words, through the ICE approach, the client managed to facilitate the co-creation of a project culture designed to encourage shared practices and decision-making (Silvius and Karayaz, 2018). This led to the creation of project collective power emerging organically from the core design-delivery team involved in the front end as part of ICE approach and grows stronger the more it is put to use (Gaventa, 2006). Such collective approach creates new possibilities from the very differences that might exist in a group and find a common ground among different actors, reducing social conflict and promoting equitable relations (Gershenson, 2007).

Results have shown that project networks, from both a single-layer and multi-layer perspectives, are characterised by very low density (i.e. they are sparse networks). This clearly reflects the relational basis of the ICE collaborative approach where global non-hierarchical nature of communication is expected to succeed. These low scores also indicate a fragmented communication and decision-making processes (Goddard, 2009). Given their non-hierarchical nature, BSCU networks therefore can be considered loosely coupled systems (Weick, 1976). This is an interesting finding. It suggests that there is no single group or actor in full control and thus managers, for example, have low levels of power to exert on the network as a whole. This is in line with the definition of self-organising systems highlighted in the literature review earlier. BSCU networks found to be no exception. When unexpected issues/events are encountered, responsibilities will be distributed among the loosely-coupled actors, functions, and network layers, despite the tightly-coupled nature of tasks and interdependencies in large complex projects (Duggal, 2018). The same characteristic of low density has also been observed by Pryke (2012) when partnering arrangements were investigated. The latter are known for having non-hierarchical project networks, promoting trust, long-term relationships, openness, etc. which are desirable behaviours comparable to those proposed to be found in self-organising project networks. Furthermore, it is observed that the density scores of Information Exchange and Discussion layers are the closest to the whole network's density score. However, overall density is not determined by a simple addition of the sub-networks/layers. This finding supports the nonlinearity of the project networks as the whole is greater than sum of its parts (Aristotle, 350 B.C.E.)[40].

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[40] Aristotle, Metaphysics, Written 350 B.C.E., Translated by Ross (1924).

At this point the high-level analysis comes to an end, following chapters will discuss and reflect on these features in more depth.

5.7 Summary

This chapter essentially sets the scene regarding the empirical analysis in preparation for the detailed analysis that will follow in next chapters. It provides a high-level description of the BSCU case study and its basic measures, making use of the questionnaire data, TfL published reports and the periodic project progress reports that were gathered as part of the KTP project.

The chapter starts by highlighting the project background, its objectives and importance, the key parties involved and their roles, and project complexity in terms of size, task interdependency and surrounding interfaces. The ICE procurement model was highlighted as the key feature of the project. It is an innovative model based on a relational approach, focusing primarily on the creation of value for the project sponsor. The process of ICE happened early in the project life cycle at the front-end, even prior to invitation to tender. This was found to play a crucial role in shaping the communication networks as they emerge. From this line of thought the following discussion theme is developed: *the crucial role of relational approaches in creating a nested governance for the front-end that is able to shape project environment as it progresses.*

Main context surrounding BSCU Project at both stages along with several key events were identified. These events are crucial to understanding the structure and functions of self-organising project networks. Both of BSCU formal and informal organisational structures were then studied. Investigation highlighted that formal project organisation diagrams (i.e. the dyadic contractual relationships) pose relatively little value in terms of explaining, analysing and understanding the way in which projects are managed. The attention was then turned to self-organising project networks, giving reference to both single-layer and multi-layer perspectives.

Finally, the key measures and characteristics of project communication networks were presented, together with reflections on those results. These suggest that self-organising project networks are sparse (i.e. characterised by low density), suggesting that BSCU networks can be considered as loosely coupled systems (Weick, 1976) with a non-hierarchical nature, in which low levels of power can be exerted on a macro level.

Additionally, communication networks are concentrated on Information Exchange and Discussion layers when confronted with uncertainty and risks. This sets these networks apart from traditional procurement systems and practices, in which Instruction and Advice are the primary forms of communication. BSCU communication networks indicate an environment that relies on collective participation and collaborative decision-making, reflecting the aims of the adopted Innovative Contractor Engagement (ICE) approach.

Next chapter will study the role of individuals in self-organising networks being the key unit of analysis at the micro level.

6

Micro-Level Analysis

**The Roles of Individual Actors
in Self-organising Networks**
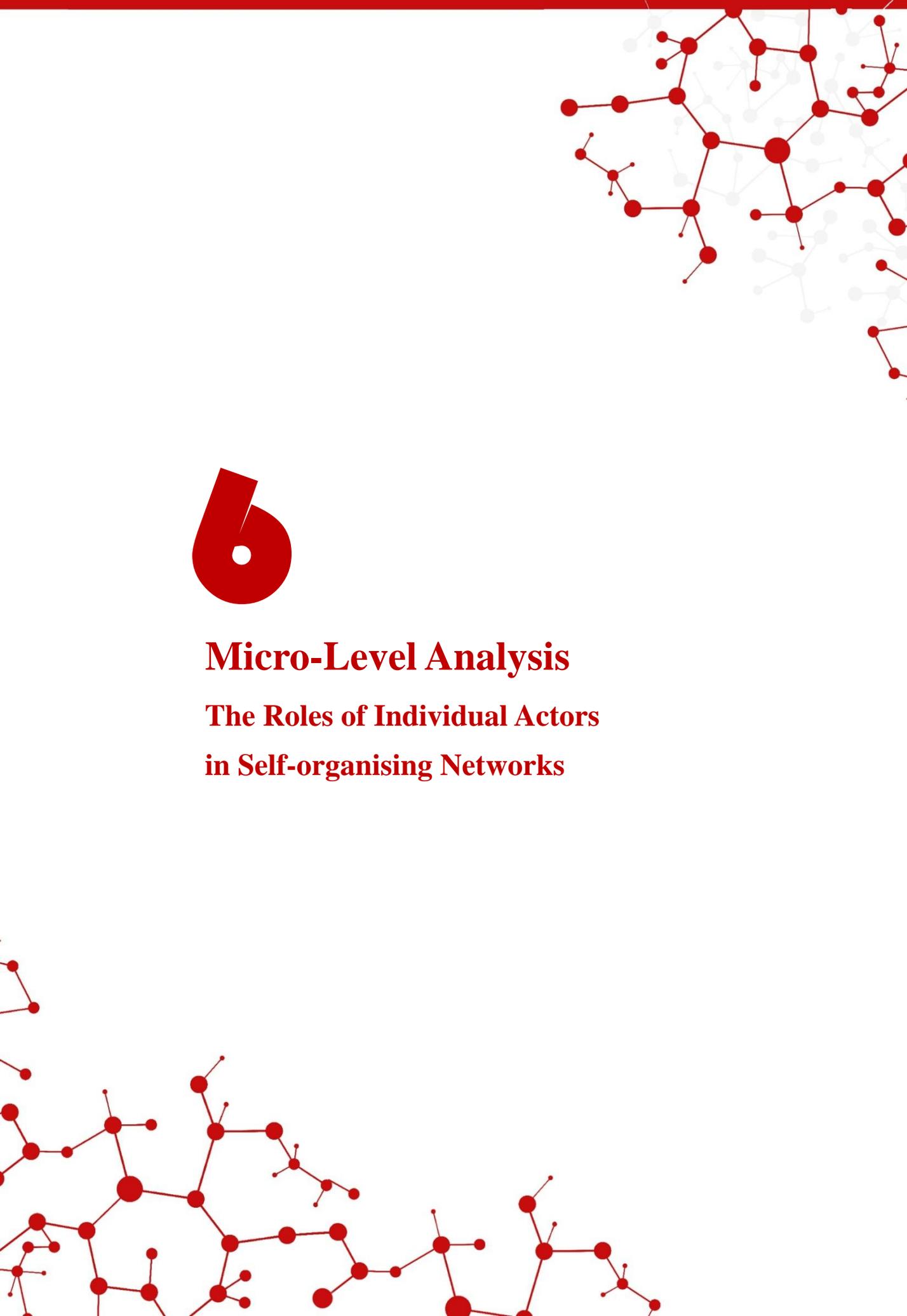
6.1   Introduction

This chapter aims to investigate the roles of individual actors in project-based self-organising networks, being the most basic element in forming relationships. The adoption of social network analysis in recent years has brought new insights to this area of inquiry. However, the analysis of this chapter is different from previous studies in view of the following:

- SNA approach was previously used to map network configurations alongside the characteristics of the links between actors (e.g. Pryke, 2012). This way of analysis places relatively low emphasis on the social interactions and human behaviour.

- Alternatively, this chapter suggests defining the roles of individual actors based on the degree to which social processes are used. This approach therefore can relate an actor's participation in a network to a multi-level framework (see Section 4.9), i.e. in reference to actors' influence on local and global levels. This is an advancement from the work of Pryke *et al.* (2017) and (2018) in relation to investigating roles in project-related networks.

- Focusing on linking the roles of individual actors to their social context (i.e. local/global levels) is also helpful in analysing and breaking power[41] into different categories. In particular, this is crucial for grasping the rationality of decision-making process, given the fact that self-organising networks, as an invisible structure, have generally remained mostly concealed from project managers and clients (Stacey, 2010; Pryke, 2017).

- The reader is reminded that human actors are more than simply 'resources' to be placed within a system as they sometimes could be unpredictable or even irrational. This chapter, therefore, acknowledges that the roles of individual actors are not just a function of their network position but rather that project actors are also influential in network contextual terms – their behaviour affects the way in which the network functions and changes the behaviour of other actors. This additional distinction is important in moving forward the way in which how projects are managed – towards a greater emphasis on understanding and managing the networks contextual underpinning.

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[41] Methodologically, power is measured by centrality.

6.2   Roles of Individuals in BSCU Networks

Having summarised the approach of this chapter and its main objectives, the roles of individual actors in BSCU networks will be studied next using the centrality measures outlined in Section 3.9.

6.2.1 Degree Centrality: A Measure of Connectivity

Degree centrality provides a measure of the importance of an actor in a given network by quantifying its direct connections, i.e. those linked in a single path (Pryke, 2012). Generally speaking, high degree centrality of a given actor within a network indicates a high level of prominence.

Table 6.1 and Table 6.2 below display the top ten prominent actors of both stages of BSCU networks, based on their connectivity. The high-degree values suggest that these nodes are highly connected, and thus sometimes they are also known as 'hubs'. The degree centrality values were calculated using Gephi program after weighting the values of their links.

Tier	Project Role	Connectivity (Weighted Degree Centrality)
Table 6.1: Stage One: Top ten actors based on connectivity (hubs) – Whole Network (Source: Original)		
Tier 2- Lead Design	Lead Engineer	10.339
Tier 2-MEP	Mechanical Design Engineer	10.193
Tier 3 - Architecture	Senior Technical Architect	7.805
Tier 1-Contractor	Project Engineer - Civils & Structures	7.773
Tier 2- Lead Design	Senior Engineer	7.516
Client	Lead Premises Engineer	7.248
Tier 1-Contractor	Design Manager	6.342
Tier 3 - Architecture	Architect	6.073
Tier 1-Contractor	Systems Integration Manager	5.960
Tier 1-Contractor	MEP Manager	5.929

Table 6.2: Stage Two: Top ten actors based on connectivity (hubs) – Whole Network
(Source: Original)

Tier	Project Role	Connectivity (Weighted Degree Centrality)
Tier 1-Contractor	Planner	17.869
Tier 2- Lead Design	Senior Engineer	16.005
Tier 3 - Architecture	Lead Architect	13.396
Tier 2-MEP	Senior Design Manager	13.029
Tier 2-MEP	Mechanical Design Engineer	12.549
Tier 3 - Architecture	Architect	11.552
Tier 2- Lead Design	Lead Engineer	11.155
Tier 1-Contractor	Project Engineer - Civils & Structures	9.975
Tier 1-Contractor	Systems Integration Manager	9.253
Client	Lead Premises Engineer	8.255

The network sociograms of stage one and stage two of BSCU project are illustrated in Figure 6.1 and 6.2 respectively. The size of nodes is differentiated by their degree centrality scores, i.e. the larger node size indicates a higher degree centrality and vice versa. It is interesting to observe that the top ten prominent actors of the BSCU communication networks, at both stages, came from different tiers and disciplines. The key observations between the two lists are summarised as follows:

- Degree centralities of the prominent actors were higher in stage two, compared to stage one of the BSCU project. This can also be seen from the network sociogram of stage two as number of nodes with a larger size are higher. This indicates that connectivity per node is higher at stage two, i.e. the project teams became more connected and integrated (hence less power inequality/less connectivity status differentials/less hierarchies).

- The top ten prominent actors of stage two have a wider variation between its actors in terms of degree centrality. This means there is a higher diversity in levels of prominence. It is due to the different growth pace of connectivity per node, i.e. during the transition between stage one and two, some actors were able to establish more connections than others.

- The above two points suggest that the top ten prominent actors of stage two have a higher connectivity (per node) and higher variation (between nodes). These two findings generate opposite effects. Higher connectivity enhances access to resources (e.g. information). However, higher variation gives rise to risk of information asymmetry. This duality is a feature of self-organising networks and its fuels the process of negotiation and re-negotiation that gives the network its flexibility and adaptive capacity.

- Three actors have changed between stage one and stage two. All the new actors at stage two appeared at the top of the prominent actors list. They came from the main contractor and its supply chain organisations (one actor for each tier). This indicates a change in the communication activities of the contractor/sub-contractors towards achieving more connectivity.

- Client organisation (TfL), on the other hand, appeared only once at both stages. This was represented by the same actor, Lead Premises Engineer. A slight decrease is noticed in its degree centrality when the project moved from stage one to stage two. This suggests a high reliance on the sub-contractors to solve the pile clash issue that was encountered. This was further supported by TfL Project Manager who commented saying:

'My reflection is that the engineers and the designers sorted it out, once they have kind of clicked, it was sorted. As a senior management team, we weren't really that kind of worried about the issue [i.e. pile clash in stage one], as we had the confidence in the engineers that they will get on with it'.

- In terms of number of actors per each organisation, the list of top ten prominent actors at stage one is dominated by the main contractor (4 actors/10 actors, i.e. 40%), followed by Tier-2 sub-contractors (3 actors/10 actors, i.e. 30%). However, in terms of values of degree centrality, Tier-2 sub-contractors had total value of 37% compared to 35% for the main contractor[42]. Tier 3 sub-contractors had total degree centrality of 19%.

- Similarly, number of actors per each organisation for stage two list of top ten prominent actors was inspected. It is found that the Client and Tier 3 sub-contractors maintained the same number of actors. However, one actor from the main contractor was removed reducing its share to 30% (3 actors/list of 10 actors). This was replaced by an actor from Tier 2 sub-contractors, increasing Tier-2 share to 40% (4 actors/list of 10 actors). Subsequently, the total values of degree centrality for Tier 2 sub-contractors increased from 37% to 43%. The client and Tier 1 organisation reported small decreases in their overall degree centralities whereas Tier 3 (Architecture) subcontractors reported a slight increase. Overall, this suggests that the teams concerned with design (Tier 2 and 3 subcontractors) at both stages were engaged in the majority of the communication activities, reflecting the design-related nature of the issue being faced.

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[42] These percentage values are measured as "Total of degree centrality per Tier" / "Total of degree centrality for the top 10 prominent actors".

To sum up, the investigation of degree centrality measure supports Pryke (2017) findings that network roles are quite different to project roles. This discussion theme developed from this analysis confronts the traditional management which assumes prominence in large projects is held mainly by project managers, following their hierarchical structure. It also emphasises the need for project managers to recognise the potential roles that can be played by other actors in the information exchange processes. In particular, it is important to exploit prominent actors in projects as entry points to induce change and enforce certain strategies, leveraging on their high level of connectivity. Project managers, therefore, can use the network analytical measures as supporting management tools to help achieve this objective.

Taking this analysis further, the shift in roles between stage one and stage two of BSCU project is investigated next by classifying them based on their level of social engagement.
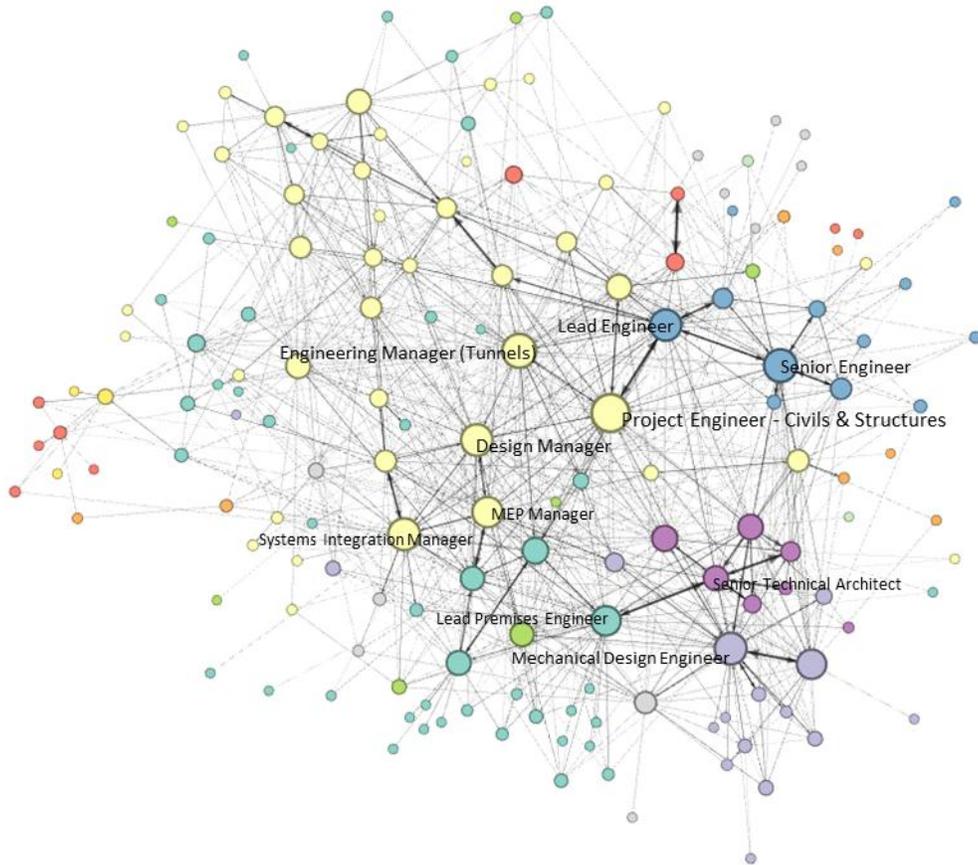
Less Degree ● ● ● More Degree   Weaker Relation ||| Stronger Relation

○ TfL ○ T Clarke ○ Robert Bird Group ○ Alan Auld Engineering ○ McNicholas
○ Dragados ○ Wilkinson Eyre ○ Dr Sauer & Partners ○ URS Infra. & Env. Ltd. ○ Other

Figure 6.1: Project Network at BSCU Project Stage One.
Nodes are Sized by Degree Centrality and Coloured by Organisation
(Source: Adapted from Pryke *et al.*, 2017, Figure 3.5a, p. 44)
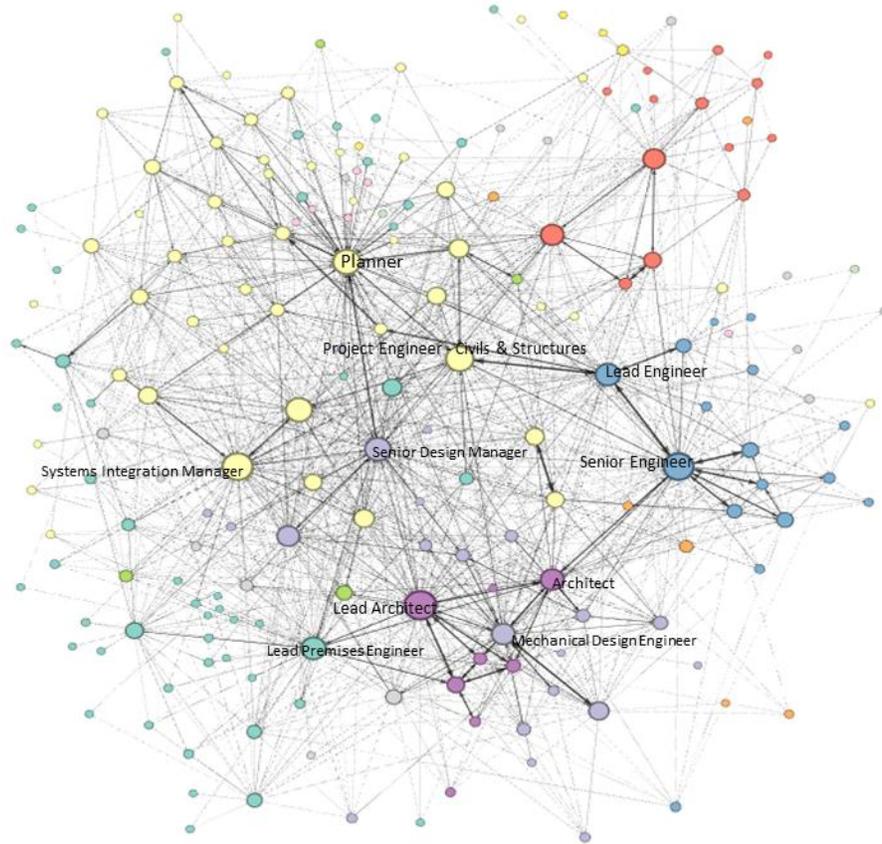
**Figure 6.2: Project Network at BSCU Project Stage Two.**
Nodes are Sized by Degree Centrality and Coloured by Organisation.
(Source: Adapted from Pryke *et al.*, 2017, Figure 3.5b, p. 45)

6.2.1.1 Multi-level Connectivity

Degree centrality is essentially a measure of connectivity, and hence can be used as an indicator of the degree to which social processes are used. At this point, the distinction between in-degree (incoming links) and out-degree (outgoing links) centrality values becomes relevant in order to describe the role of an actor in the social process. High out-degree values of an actor mean he/she is responsible for the dissemination of information whereas high in-degree values of an actor mean he/she is responsible for gathering information from a large number of other actors. A multi-level classification can therefore be developed for an actor role, based on the in-degree and out-degree centrality values, as follows:

Table 6.3: Roles of an actor based on its out-degree and in-degree measures
(Source: developed from Wasserman and Faust, 1994)

Degree Centrality Measure	High in-degree	Low in-degree
High out-degree	Prominent Actors	Disseminators
Low out-degree	Gatekeeper Hoarders	Isolated actors/Sub-groups

- **Isolated actors/Sub-groups:** *(Both in-degree and out-degree centrality values are low)*

This is concerned with the use of individual processes in order to complete tasks/obtain resources. It is represented by the actors with limited communication activities, whose prominence does not go beyond their immediate neighbouring areas (Scott, 2017). This explains why they usually remain outside the attention of project managers, hence classified as 'invisible' in most of the cases. Isolated nodes/sub-groups are usually formed based on their hierarchical authority levels, functional affiliation, physical location, qualifications or language (Pryke, 2017).

- **Prominent Actors:** *(Both in-degree and out-degree centrality values are high)*

This is concerned with the high use of social processes to complete tasks/obtain resources. It is represented by the most prominent actors in the network whose high connectivity suggests they contribute generously to information exchange and thus allowing them to play the hub/connector roles (Scott, 2017). These actors tend to have a high level of expertise in their area. They are well connected in both directions of the communication process with highest level of receiving and transmitting activities.

Given their high connectivity, they are also well known by/visible to large number of actors in the network. The functionality of complex networks relies largely on these prominent actors and their role in facilitating, enabling and coordinating activities among large number of actors. For example, they help facilitate the timely and accurate flow of information (Pryke *et al.*, 2018; Duggal, 2018).

- **Disseminators:** *(Low in-degree centrality with high out-degree centrality)*

Disseminators make a positive contribution to the promotion of effective information flows in a given network. They are the actors who transmit a high level of information to others (i.e. high out-degree values). Typically, they are the 'go-to' personnel who can provide guidance on specific or general issues.

- **Gatekeeper Hoarders:** *(High in-degree centrality with low out-degree centrality)*

Unlike disseminators, gatekeeper hoarders represent a barrier to effective project information flows within the network (Pryke, 2017). They usually enjoy the ability to control the flow of information to others and thus they can, for example, slow down/filter the movement of information. They can be a nuisance or bottlenecks, implying shortages in processing capacity (low out-degree centrality). Their negative contribution can be due to their wish to maintain their status quo or they may lack the expertise of some of the other, perhaps competing, actors in the network.

To operationalise the multi-level connectivity for stage one and stage two of BSCU project, in-degree and out-degree centrality values are mapped on scatter plots. These are illustrated in Figure 6.3 and Figure 6.4. UCINET program was used to generate the normalised degree centrality values to enable like-for-like comparison. The cut-points of x-axis and y-axis of the scatter plots are determined by the mean values of out-degree and in-degree centrality measures respectively. The plots are classified into four quadrants in order to investigate the change in individual roles between the two stages.
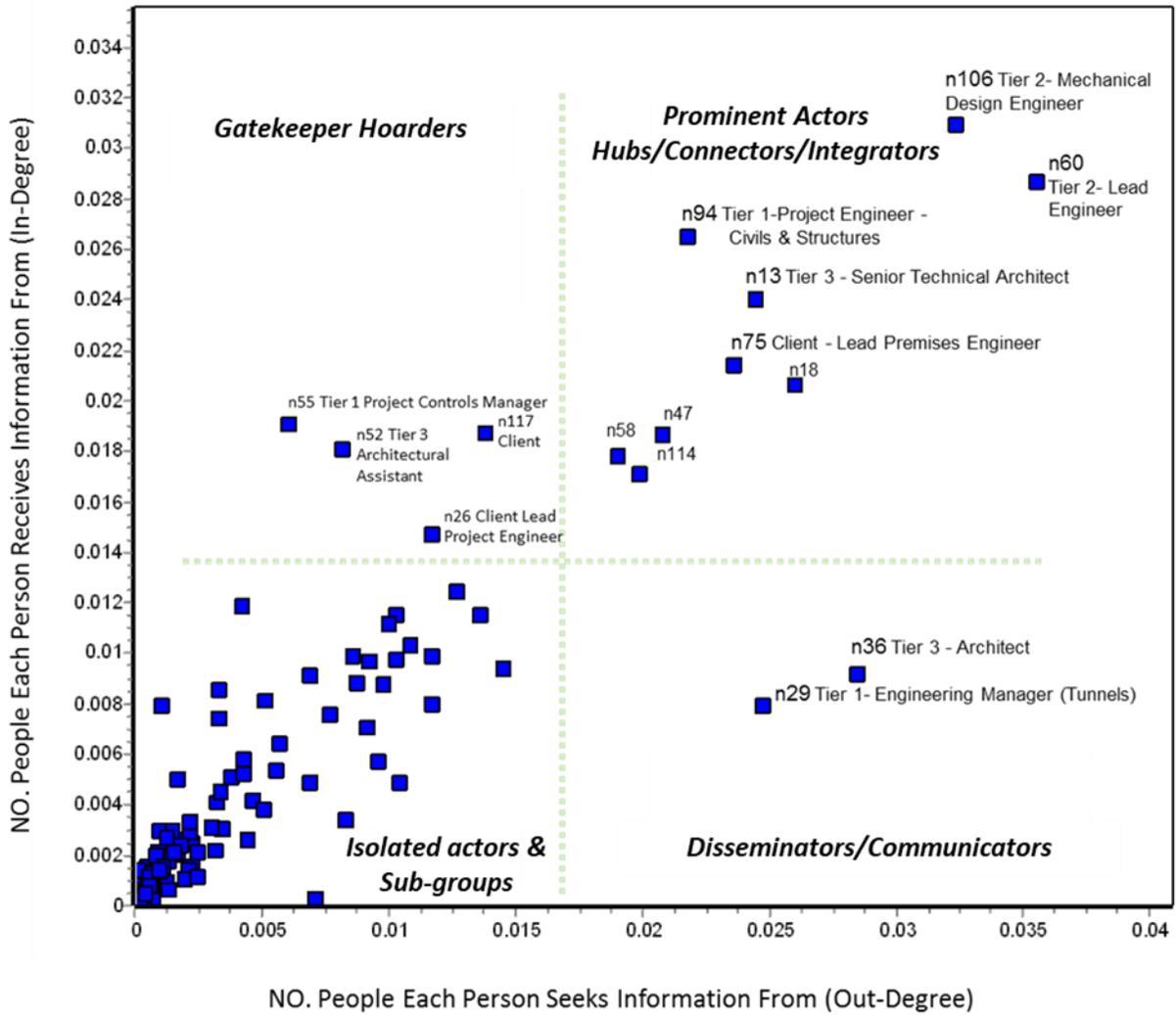
Figure 6.3: Distribution of Actor's Degree Centralities in Stage One.
(Source: Original)
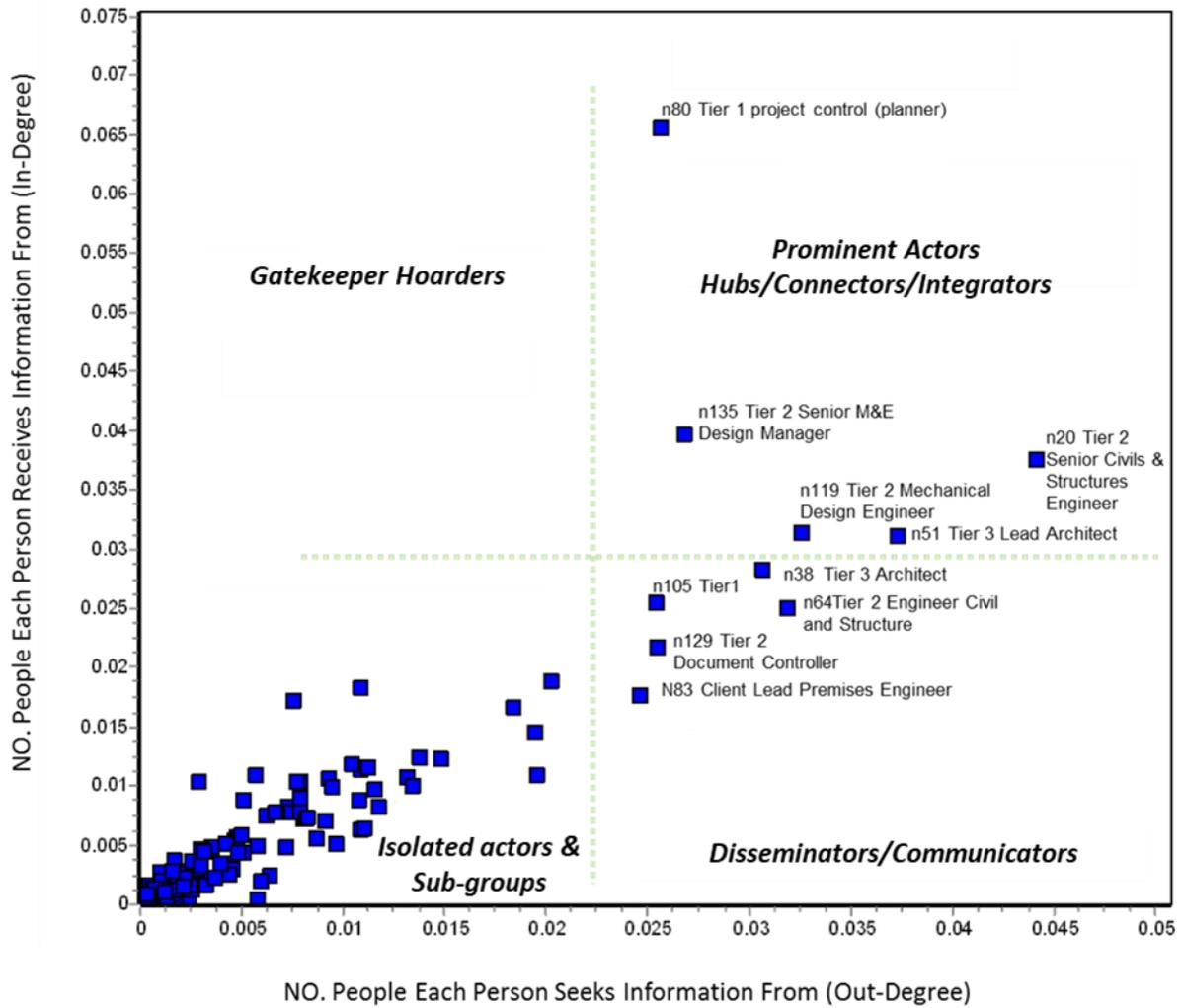
Figure 6.4: Distribution of Actor's Degree Centralities in Stage Two.
(Source: Original)

The key observations between the two degree-distribution scatter plots are summarised as follows along with their interpretations:

- The average values of in-degree and out-degree centrality measures (represented by the cut-points on the graphs) for stage two are higher than those of stage one. This suggests a higher connectivity/communication activity at stage two.

- Isolated actors/sub-groups represent the majority of the population at both stages. This implies that majority of the project actors were largely concerned with their own communities/tasks and that they did not socially engaged beyond their levels. This could be because these actors operate without awareness and understanding of the larger network structure in which they reside. This is in line with the findings of Scott (2017) and Stacey (2010). Given their limited connectivity, isolated actors/sub-groups actors are usually considered invisible in the network and thus they largely represent untapped resources. Higher social engagement (through higher connectivity) can therefore help in unpacking this resource, providing it with a greater visibility.

- Overall, the degree-distribution plot at stage one has a more scattered nodes than stage two. This is because of the wider variation between in-degree and out-degree centrality among the actors. Pryke (2017) explanation on actors' attributes suggests that wider variation between transmitting (out-degree centrality) and receiving (in-degree centrality) activities is an indication of a lower trust. Using the same argument, this means that actors at stage one have a lower level of trust among themselves[43]. The wider variation between in-degree and out-degree centrality is also an indication of the ill-distribution of power[44] in the network of stage one (Pryke, 2017), i.e. some actors are more powerful than others. Decision-making process of stage one is therefore rather centralised.

- Similarly, it can be argued that there is a lower variation between in-degree and out-degree centrality at stage two. The lower variation is largely evident by the smaller number of prominent actors and removal of the gatekeeper hoarders. The lower variation in degree centrality values suggests an improved level of trust among actors at stage two (Pryke, 2017). It also means that power is better distributed at stage two; the network structure is therefore moving to a more democratic decision-making process (Pryke, 2017).

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[43] This outcome is also confirmed by the scores reported under trust parameter in the BSCU questionnaire results (Average of 67.82% and 68.37%, for stage one and two respectively).
[44] Methodologically, centrality measures are used as a measure for power. This is particularly relevant in problem-solving environments, such as the activities within the project environment (Pryke, 2017).

- Of a particular importance, stage two has reported no gatekeeper hoarders, reducing from four actors at stage one. This is a positive improvement, enabling better information flows. Existence of gatekeeper hoarders at stage one means there was a tight control over resources and hence associated decision-making power was focused in the hands of few actors (two from the client organisation, one from the main contractor, and one from Tier-three architects).

- Additionally, there was only two disseminators at stage one. This very small number of information disseminators is a weakness which was exacerbated by the existence of a larger number of gatekeeper hoarders. This imbalance in actor roles suggests that stage one suffered from information asymmetry among its actors, and hence leading to inequality in level of power.

- Examining the degree-distribution scatter plot of stage two, illustrated in Figure 6.4, highlights that number of hubs (i.e. nodes with high degree-centrality that are represented by prominent actors) has decreased between stage one and stage two. These actors exhibit large use of social processes to gain prominence within their networks. This high prominence in turn provides them with a high degree to influence the relationships that they have with other actors, and hence impacting the overall coordination and decision-making process. The reduction of the prominent actors in stage two therefore indicates a move towards a more decentralised structure where more information exchange now exists between actors of the lower levels (e.g. sub-groups and disseminators). Following from this point, power, therefore, is more distributed at stage two, i.e. reduction of prominent actors at stage two shifted the power to the actors residing at the lower levels.

- The above point highlights that power has decreased at the prominent actors' level of stage two. The reduction in power was further supported by the introduction of a higher number of disseminators who, by definition, promote a higher level of connectivity. Simply put, the higher connectivity leads to integration that in turn reduces power inequality and hence less hierarchies achieved at stage two.

- While re-distribution of power at stage two, shifting to lower levels (i.e. disseminators), is noted, power was not entirely transferred to the level of sub-groups/isolated actors. This is particularly evident given the increased number of disseminators (from two actors in stage one to five actors in stage two). The shift to a higher out-degree centrality at this level suggests a higher processing capacity. However, it also suggests that some degree of power inequalities (and hence hierarchies), though lower, still exists between the different actors. This cannot be eliminated entirely but in fact such imbalance is necessary to ensure having a continuous

creation and recreation process. In other words, this suggests that there is a degree of fluidity in terms of how power is distributed which supports presence of some hierarchy within the self-organising project networks. This finding challenges the dominant thinking which associates better performance with a higher level of prominence (e.g. Losada, 1999). Effective management is rather about balancing rigidity and flexibility as well as continuity and change. At the end, the reality stipulates the need to have stable roles protecting the division of power, but at the same time to have the necessary flexibility to adjust to changing social and political conditions. This finding suggests that disseminators can play a key role in addressing this dilemma.

- The higher connectivity at stage two is an indication of integration and hence a move towards cultivating tightly-knit communication structure (Loosemore, 1998). The benefit of this structure is its ability to achieve a widespread supply of information through a more targeted and directed communication. The result implies that actors at stage two were able to communicate directly to those that are considered important without having to go through intermediaries. This change in the communication structure is in response to the higher level of complexity/uncertainty created by the pile clash. It enables having more flexible communication channels, i.e. actors not following the contractual links of normal multi-level hierarchy but rather communicating directly to different information sources. This change in behaviour could be a contributor to the effective project information flows at stage two.

- The shift from stage one to stage two is essentially a function of the changing requirements of the project. The network at stage one could not deal with the new requirements and thus there was a need for a re-orientation in the network structure and roles. That is, the uncertainty caused by the pile clash issue resulted in a further need for information exchange between the actors. The network structure at stage one was not able to cope with the increase in time-sensitive information flow by just relying on the existing nodes and links. This is especially relevant in view of the negative roles played by the gatekeeper hoarders who tend to form bottlenecks, constraining mobilisation of resources. The transition to stage two, therefore, constituted a change in the network structure, i.e. establishing new relationships and redefining the roles.

- To sum-up, information flow improved as a result of the shift to stage two. This is supported by introducing additional disseminators and removing the gatekeeper hoarders. Power at stage two was also better distributed (i.e. more democratic decision-making processes), as reflected by the lower variation between in-degree and out-degree centrality values.

  This is reflected in the graph of stage two by the reduction in prominent actors and the dense degree-distribution at the level of isolated actors/sub-groups (Pryke, 2012). In turn, Pryke (2017) explanation on actors' attributes suggests that an actor might seek to reduce their own in-degree centralities to deal with low-trust-value received information, and vice versa. Therefore, the removal of gatekeeper hoarders (whose in-degree > out-degree) and introduction of additional disseminators (whose out-degree > in-degree) can be considered a move towards increasing trust at stage two.

Degree centrality is concerned with the study of direct connections only (i.e. those linked to a given node in a single path). However, human communications are complex, involving multiple connections. Unlike contracts, human communications are rarely if ever just dyadic. For the study of the individual roles in a given network, it is therefore essential to study indirect connections involved (i.e. those with more than one path). Eigenvector and Brokerage centrality measures, as an extension to the degree centrality measure, are therefore studied next.

6.2.2 Eigenvector Centrality: A Measure of Influence

Eigenvector centrality will be used in this section to provide a measure of actors' ability to influence others due to their popularity and/or prestige. This measure reflects the extent of secondary connections held by an actor (Wasserman and Faust, 1994; Pryke, 2017).

Table 6.4 and Table 6.5 below display the top ten prominent actors of both stages of BSCU networks, based on their Eigenvector Centrality. The values were calculated using Gephi software. Mathematically, the scores are assigned on a relative basis, using the top node as the common factor. This is because eigenvector centrality measures a node's importance while giving consideration to the importance of its neighbours. The main principle is that links from important nodes (as measured by degree centrality) are worth more than links from unimportant nodes. Following this concept, a high eigenvector score means that a node is connected to many nodes who themselves have high scores.

Table 6.4: Stage One - Top Ten Actors Based on their Influence on the Network.
(Source: Original)

Tier	Project Role	Influence (Eigenvector Centrality)
Tier 1-Contractor	Project Engineer - Civils & Structures	1
Tier 1-Contractor	MEP Manager	0.889
Tier 1-Contractor	Design Manager	0.843
Tier 2-MEP	Mechanical Design Engineer	0.813
Tier 2- Lead Design	Lead Engineer	0.794
Tier 1-Contractor	Systems Integration Manager	0.773
Tier 2- Lead Design	Senior Engineer	0.772
Tier 3 - Architecture	Lead Architect	0.743
Client	Lead Project Engineer	0.711
Tier 2-MEP	Lead Mechanical	0.679

Table 6.5: Stage Two - Top Ten Actors Based on their Influence on the Network.
(Source: Original)

Tier	Project Role	Influence (Eigenvector Centrality)
Tier 3 - Architecture	Lead Architect	1
Tier 1-Contractor	Systems Integration Manager	0.898
Tier 1-Contractor	Project Engineer - Civils & Structures	0.886
Tier 2- Lead Design	Senior Engineer	0.844
Tier 2-MEP	Senior Design Manager	0.813
Tier 1-Contractor	Design Manager	0.808
Tier 2-MEP	Mechanical Design Engineer	0.705
Tier 2- Lead Design	Lead Engineer	0.696
Tier 3 - Architecture	Architect	0.686
Tier 1-Contractor	MEP Manager	0.655

It is interesting to observe that the top ten prominent actors (based on their influence) of the BSCU communication networks, at both stages, came from different tiers and disciplines. The key observations between the two lists are summarised as follows:

- At stage one, it is noted that the top three influential actors have one characteristic in common; they belong to the same tier (i.e. dominance in this case is hierarchical-based). That is, Tier-one contractor, Dragados, was the most influential actors. This reflects their role in driving the agenda of the project. The concept of determining influence in this case is based on indirect relationships and thus, reflecting on power at stage one, this means contractor had the ability to enforce his power indirectly. Lukes (1974) classifies this as an 'invisible power' that can become visible indirectly through the actions of other actors rather than through the contractor himself. The key benefit of the indirect manifestation is its ability to avoid using the costly formal command lines. It is therefore used to gain legitimacy and control through affiliations at reduced costs.

- At stage two, actors with design-related roles were the most influential. In this case dominance is role-based. This is not surprising as it reflects the design-related nature of the issue was faced. The client (TfL) disappeared from the list of stage two, replaced by an architect. This highlights the disengagement of TfL in solving the pile clash issue and hence the reliance on the sub-contractors. This finding is in line with the earlier analysis.

Eigenvector centrality is based on the concept of 'relative' prominence which stipulates that a node with few connections could have a very high eigenvector centrality if those few connections were themselves very well connected. Its application to multi-agent complex project environments therefore is quite sophisticated given the sheer number of actors. This is further exacerbated by the fact that many of the activities of complex project networks involve group of actors self-organising themselves into function-related clusters to solve and adapt to problems. Such group-based problem-solving clusters are usually dense and often exhibit a high degree of structural equivalence, i.e. actors almost have the same 'direct' connections to all other nodes within a given cluster. This structure therefore limits the 'indirect' influence in the grand scheme of things.

Unlike degree-centrality that measures prominence as a function of in-degree and out-degree values, eigenvector centrality, by definition, is not an absolute measure. Its 'relative' concept to study 'indirect' connections entails identifying a proper reference point for every node in order to retrofit roles of individual actors into a multi-level framework. Given the intricate web of interactions in self-organised networks, the appropriate way of studying eigenvector centrality means that every node should therefore have its own reference point that in turn could differ from those reference points identified for its peers.

Furthermore, identification of a reference point for each node is particularly difficult because of the interpretive context of centrality studies (Brass and Burkhardt, 1992; Pryke, 2017). In absence of a common reference point, the like-for-like comparison to establish a multi-level framework cannot be achieved by using the eigenvector centrality measure.

Pryke (2017) acknowledges that eigenvector centrality has its limitations in the study of complex projects. He therefore advocates using brokerage centrality to study indirect connections, highlighting the fact that the distinction between influence and brokerage centrality measures is anyway sometimes unclear and overlapping.

Brokerage measure is discussed next which is concerned with the extent to which an actor has the ability to come between communications of other actors.

6.2.3 Betweenness Centrality: A Measure of Brokerage

Betweenness centrality will be used in this section to provide a measure of 'brokerage', i.e. the extent to which an individual actor is 'between' other actors (Pryke, 2017). In the study of communication networks, betweenness centrality is used to:

- Measure actors' ability to control flow of information, by playing an intermediary role (Freeman, 1979; Borgatti, 2006; Pryke, 2012; Prell, 2012). Therefore, actors with high betweenness will have a considerable power within a network by virtue of their control over information passing between other nodes;

- Betweenness centrality is also an indicator for network resilience. That is, existence of actors with high betweenness in a given network represents a high key person dependency risk, as their removal could lead to disruption in communications between other actors or disintegration of the network structure. This is in view of their crucial role to facilitate large number of cross-communities communications;

Tables 6.6 and 6.7 below display the top ten actors based on their total brokerage roles in both stages of BSCU project. The values were calculated using Gephi program. Actors with high levels of betweenness are usually regarded as 'brokers' or 'gatekeepers', as they act as critical bridges between any other two actors/clusters (Freeman, 1979; Borgatti, 2006). Generally speaking, high levels of betweenness in a network is inappropriate and undesirable, suggesting a 'dysfunctional prominence' where actors unnecessarily hoard information in networks. The key difference between this type of hoarders prominence and the one studied under degree-centrality is that betweenness is concerned with indirect connections.

Table 6.6: Stage One - Top Ten Actors Based On their Total Brokerage Roles.
(Source: Original)

Tier	Project Role	Brokerage (Betweenness Centrality)
Tier 1-Contractor	Engineering Manager (Tunnels)	0.108
Tier 1-Contractor	Project Engineer - Civils & Structures	0.092
Tier 1-Contractor	Systems Integration Manager	0.079
Client	Lead Premises Engineer	0.079
Client	Programme Engineering Manager	0.071
Tier 2-MEP	Mechanical Design Engineer	0.071
Tier 1-Contractor	Design Manager	0.069
Tier 2- Lead Design	Project Director	0.064
Tier 2- Lead Design	Senior Engineer	0.060
Tier 2- Lead Design	Lead Engineer	0.052

Table 6.7: Stage Two -Top Ten Actors Based on their Total Brokerage Roles.
(Source: Original)

Tier	Project Role	Brokerage (Betweenness Centrality)
Tier 1-Contractor	Planner	0.146
Client	Lead Premises Engineer	0.095
Tier 1-Contractor	Systems Integration Manager	0.089
Tier 2-Tunnelling	SCL Engineer	0.081
Tier 3 - Architecture	Lead Architect	0.070
Tier 2- Lead Design	Senior Engineer	0.068
Tier 1-Contractor	Project Engineer - Civils & Structures	0.054
Tier 2- Lead Design	Lead Engineer	0.053
Tier 2-MEP	Senior Design Manager	0.052
Tier 1-Contractor	Design Manager	0.050

It is interesting to observe that the top ten prominent actors (based on their brokerage) of the BSCU communication networks, at both stages, came from different tiers and disciplines. The key observations between the two lists are summarised as follows:

- Betweenness values for both stages are very low. This is positive because it indicates that there are no overly controlling actors. Flow of information (and hence power) in the network is not concentrated at few nodes but rather distributed among many actors. That is, both stages are demonstrating a low degree of reliance on hierarchies, as actors are sourcing information from large number of paths.

- Low Betweenness values also implies a low-key person dependency risk. Removal of any nodes can be easily substituted, i.e. it has the capability to find alternative paths to ensure effective flow of information. The network therefore is resilient as it has the capacity to absorb shocks and re-organise itself. These are the key features of self-organising networks.

- The network sociograms of stage one and stage two of BSCU project are illustrated in Figure 6.5 and 6.6 respectively. The size of nodes is differentiated by their betweenness centrality scores, i.e. the larger node size indicates a higher betweenness centrality and vice versa. Overall, nodes at stage two are of a smaller size, indicating a lower brokerage level, and hence less power inequality (less brokerage status differentials).

- The network sociograms and lists of top ten actors suggest that actors with higher brokerage activities are from the contractor and client organisations. This reflects their contractual responsibilities for coordinating project activities among different sub-contractors (the supply chain) and managing relationships back into the engineering and sponsor teams in the London Underground Limited (LUL).

- Despite the reduction of overall brokerage activities at stage two, the lists of the top ten actors exhibit a slight shift in brokerage prominence from the contractor/client organisations (at stage one) to the sub-contractors (at stage two). This is evident by the introduction of Tier 3 (architect) in the list of stage two top ten actors as well as reduction in client actors (from two to one). This is in line with the earlier findings highlighting the nature of the issue at stage two being design-related and the reliance on the sub-contractors to resolve it.

- Interestingly, the cross-comparison between the lists of the top ten actors of betweenness and degree centrality measures shows that actors on both stages are very similar. In stage one, 7 out of 10 actors appeared on both betweenness and degree centrality lists. In stage two, 8 out of 10 actors appeared on both lists. This implies that prominent actors in terms of connectivity (direct links) in a given network are likely to be the same prominent actors in terms of brokerage (indirect links). This highlights the crucial and multiple roles played by the prominent actors in a given network. Prominent actors not just facilitate flows of timely and accurate information, but they can also play enabling or disenabling roles that affect the configuration and other characteristics of the network.

- The above point on potential disenabling roles stresses that an actor could be prominent in a network for negative reasons. Pryke (2017, p.176) called this 'dysfunctional prominence', highlighting that "i*n information exchange networks, and especially those involving complex design activities, high betweenness centrality scores for individual actors are disruptive to project networks*". The discussion theme developed from this point is that some formal interventions in managing self-organising networks are still needed in order to facilitate constructive interactions. It could involve embedding use of social network analysis in project management; for example, conducting periodic monitoring of betweenness centrality to look for early warnings of disruptive brokerage behaviours. Remedial actions could include actor repositioning, training and establishing service-level guidelines on timeliness of responses and information dissemination.

- The cross-comparison between the lists of the top ten actors of betweenness and influence measures shows that high influential actors have low brokerage scores. This implies that actors within BSCU networks do not rely on the most influential nodes to source their information but rather refer to various paths and nodes. This is in line with Pryke *et al.'s* (2018) finding that self-organisation structure makes the most influential individuals bypassable in terms of communication flow and hence reducing their power in the resolution of the issue being faced.
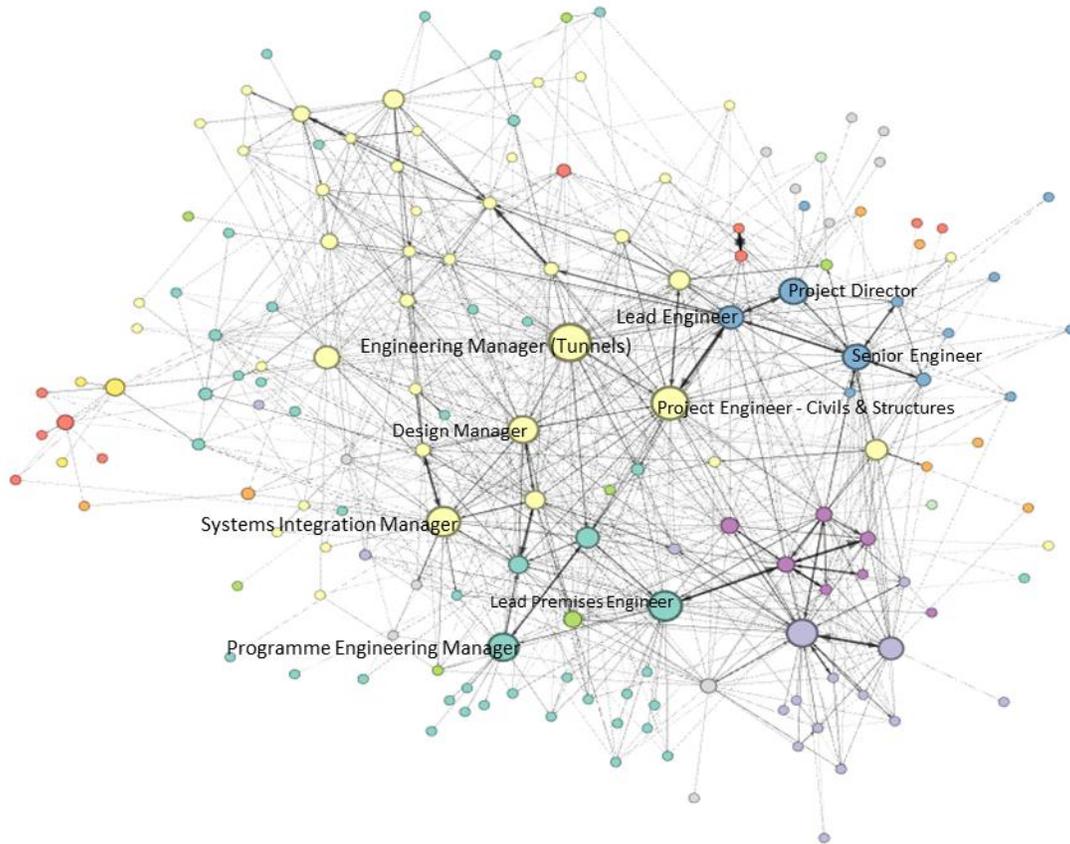
Figure 6.5: Project Network at BSCU Project Stage One.
Nodes are Sized by Betweenness Centrality and Coloured by Organisation.
(Source: Adapted from Pryke *et al.*, 2017, Figure 3.7a, p. 48)
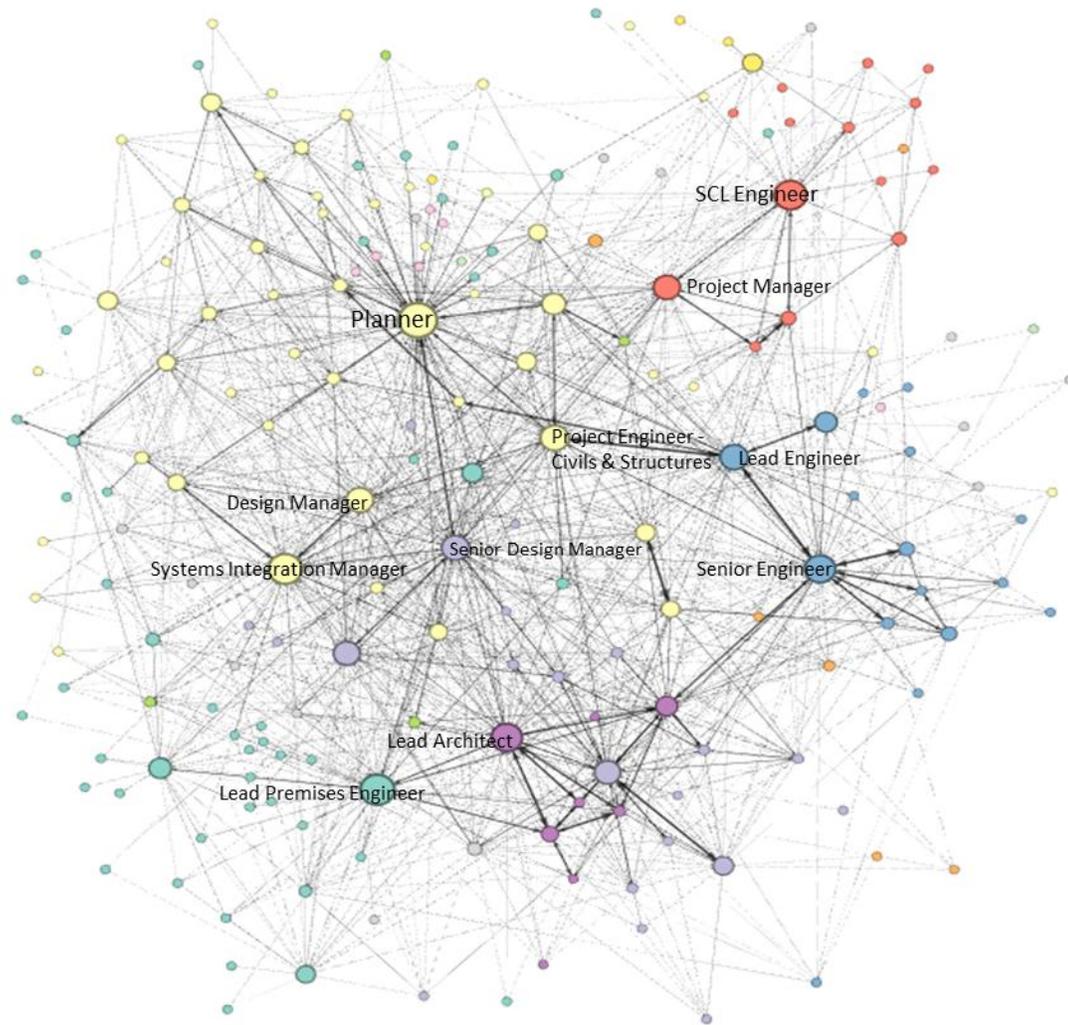
Figure 6.6: Project Network at BSCU Project Stage Two.
Nodes are Sized by Betweenness Centrality and Coloured by Organisation.
(Source: Adapted from Pryke *et al.*, 2017, Figure 3.7b, p. 49)

Legend:
- Less Brokerage ● ● ● More Brokerage
- Weaker Relation ‖‖‖ Stronger Relation

- TfL
- Dragados
- T Clarke
- Wilkinson Eyre
- Robert Bird Group
- Dr Sauer & Partners
- Alan Auld Engineering
- URS Infra. & Env. Ltd.
- McNicholas
- Other

Node labels: SCL Engineer, Project Manager, Planner, Project Engineer – Civils & Structures, Lead Engineer, Design Manager, Senior Design Manager, Senior Engineer, Systems Integration Manager, Lead Architect, Lead Premises Engineer

6.2.3.1   Multi-level Brokerage

This thesis extends the normal discussion of Betweenness Centrality (e.g. Pryke, 2012 and 2017), by categorising the brokerage roles based on their levels of brokerage influence. The terms local, meso and global levels are used in order to come up with a multi-level brokerage analysis (Lukes, 1974). Brokerage influential levels are defined based on the degree to which social processes are used in order to relate an actor's brokerage prominence in a given network. These are summarised as follows for the reader's ease of reference:

- Brokerage typologies involve three parties, based on their roles in the communication chain, namely: broker, transmitter and receiver. These parties are represented by nodes in the network which are in turn affiliated to distinct functional clusters[45].

- Cluster affiliation of each node is used as the criteria to define the brokerage influential levels, i.e. whether the broker, transmitter and receiver nodes belong to the same or different clusters. Brokerage influential levels are therefore defined as follows:

  - **Local level:** brokerage activity involves one cluster, i.e. when all of the three nodes belong to the same cluster. In this case the brokerage influence is limited to its immediate proximity;

  - **Meso-level:** brokerage activity involves two different clusters, i.e. when two of the nodes belong to the same cluster, but the remaining node belongs to a different cluster. In this case the breakage influence is extended beyond its immediate proximity, but it is still not reaching the full potential;

  - **Global level:** brokerage activity involves three different clusters, i.e. all of the three nodes belong to different clusters. In this case the breakage influence is maximised.

The brokerage roles introduced by Gould and Fernandez (1989)[46] can therefore be mapped to the above proposed multi-level influential brokerage framework, as follows:

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[45] As first step of this Betweenness Centrality analysis, the network functional clusters were identified. Cluster analysis is the subject of next chapter but for the benefit of the reader, it is worth highlighting that seven clusters were identified for both stages of BSCU network. These were defined using modularity analysis in Gephi. This approach is adopted from Pryke *et al.* (2017). Formation of BSCU clusters were further confirmed through discussions with the BSCU Project Manager. The clusters of BSCU networks are function-oriented and thus given the following names: Architectural Design and Management; Civils and Structures; Project Control and Management; Design Management; M&E Design; BIM/CAD; and Tunnelling Design.

[46] These are discussed earlier in Chapter Three (see Section 3.9.3.1 for further details).

Table 6.8: Multi-Level Brokerage Framework
(Source: developed from Gould and Fernandez (1989)

Brokerage Roles as defined by Gould and Fernandez (1989)	Definition by Nodes Position	Proposed Influential Levels
Coordinator	• Broker, Transmitter and Receiver belong to the same cluster	Local
Consultant	• Transmitter and Receiver belong to the same cluster • Broker belongs to a different cluster to that of the Transmitter and Receiver	Meso
Gatekeeper	• Transmitter and Receiver belong to two different clusters • Broker belongs to the same cluster as the Receiver	Meso
Representative	• Transmitter and Receiver belong to two different clusters • Broker belongs to the same cluster as the Transmitter	Meso
Liaison	• Broker, Transmitter and Receiver belong to different clusters	Global

With the help of UCINET 6 (Borgatti *et al.*, 2002), the brokerage roles for each node in the project network were determined. The distribution of the brokerage roles for each stage of BSCU project is then calculated and thereafter mapped to their brokerage influential level. Figure 6.7 below illustrates the share of each brokerage role/influential level at both stages in %-terms.
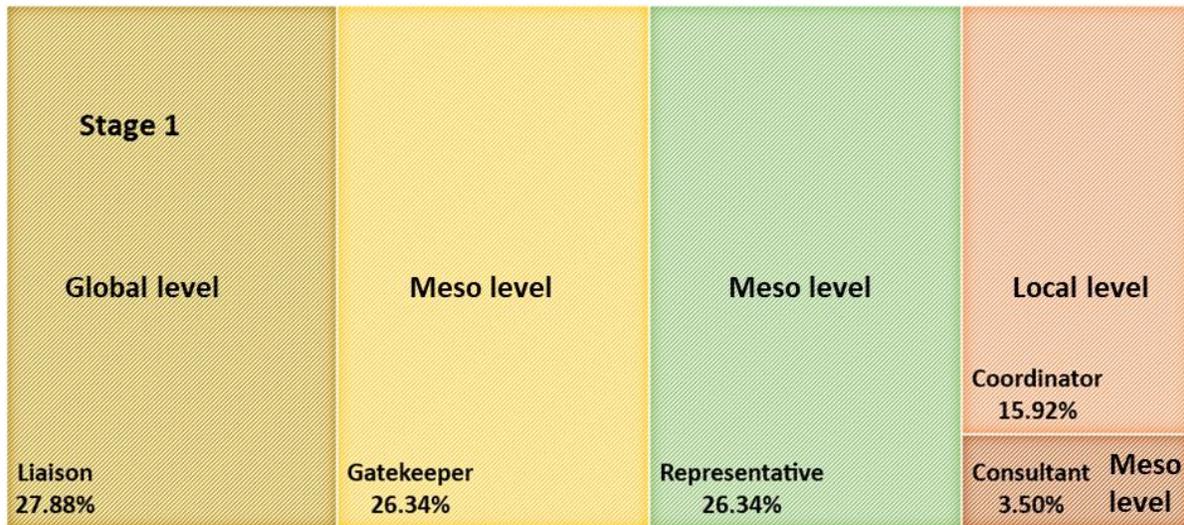
Figure 6.7: Comparison of Brokerage Roles/Influential Levels Distribution Between the two Stages of BSCU Project. (Source: Original)

The key observations from the distribution of Brokerage roles at BSCU networks are as follows:

- Brokerage roles at both stages of BSCU project are dominantly meso-based, accounting for just above 55% of the total roles. This is followed by global roles just above 25%. These two results mean majority of Brokerage activities are cluster-spanning. Local roles, on the other hand, represent just above 15% of the total roles. This is an indication that, within clusters, actors in general have a quite tightly-knit communication structure. Brokerage roles are limited at the local level as actors within clusters can communicate directly among themselves without the need to actively go through intermediaries.

- At both stages, the brokerage roles of Gatekeeper, Representative and Liaison have almost the same share (with each having just above 25% of the overall network roles). This implies an active use of various cross-functional brokerage roles. This diversity in directionality of communication is positive to ensure network is not dependent on one typology.

- Liaison role has the major share at both stages (though with a slight difference compared to Gatekeeper and Representative roles). The Liaison role brings a distinct benefit to the network configuration in the sense that it connects a chain of actors, who all belong to different groups/clusters. Burt (1992) and Granovetter (1973) stress that this type of trilateral communications (involves three clusters) carries higher benefits to the network compared to other type of bilateral (involves two clusters) or unilateral (involves the same cluster) communications. This is because it assists in establishing richer cross-functional connections (Everett and Borgatti, 2012) and hence assists in bridging structural holes[47] (disconnections) and facilitating coordination in the whole network (i.e. maximising the influential level of brokerage activities).

- At the local level of both stages, brokerage role is centred on coordination, relying on the internal actors. The slight increase in the local brokerage roles comes in response to the need to coordinate a larger level of activities within the clusters in order to address the project requirements at stage two.

- Consultant role is subordinate. It was used on occasions to extend any shortages in the local capacity base.

- Distribution of Brokerage roles/influential levels has not changed much between stage one and stage two of the BSCU project. This could be because of the very low Betweenness values at both stages. However, it means that, in complex projects, nature of brokerage roles *per se* does not explain the dynamics of self-organising networks. This finding therefore supports Pryke's (2017) argument that dynamics of networks are not governed by causal relationships.

- It can be drawn from this analysis that brokerage activities of self-organising networks require focusing on meso and global levels to foster establishment of cross-functional communication flow. While global brokerage activities bring richer influence, it is more complicated as it involves three different cluster affiliations. Meso-level, on the other hand, is less complicated (as

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[47] A structural hole can be understood as a gap between two nodes which have complementary sources to information.

it involves two clusters only) and hence can optimise use of brokerage. Furthermore, self-organisation structure makes actors in the network less reliant on local brokerage activities as their needs rather satisfied through targeted and directed communications without having to go through intermediaries.

- Actors with meso-brokerage roles can also be viewed as the network focal points that mobilise majority of resources and hence serves as the link between local and global actors. Meso-actors in this sense assist in keeping the network cohesive which is in turn related to resilience of the network.

Having discussed the multi-level brokerage framework for the whole network at stage one and stage two of BSCU project, next section investigates the brokerage influential levels of each cluster and type of communication used. The latter is based on the multi-layered networks, i.e. Information Exchange, Discussion, Instructions, and Advice, suggested by Pryke (2012) and used as a framework in this thesis.

6.2.3.2   Brokerage Distribution at Cluster Level

The results from previous section suggest that distribution of brokerage roles/influential levels of BSCU project networks was almost the same at both stages. This therefore provides a little insight into the dynamics of self-organising structures. By investigating the brokerage distribution at the cluster level, this section aims to explicitly focus on the nodes and their influential levels rather than on the whole network structure. Such approach gives precedence to contextual underpinnings. Pryke (2012) framework of multi-layered networks will also be used in order to explain different dynamics governing the patterns of communication at the various stages and layers.

The key benefit of the brokerage multi-level framework is its ability to define the brokerage roles and influential levels of each actor, i.e. the degree to which social processes are used by an actor to influence others, leveraging on its brokerage prominence. The results of the previous section, generated by UCINET 6, were used and thereafter nodes were grouped based on their functional clusters to determine their respective roles and influential levels. The same approach is applied to the multi-layered framework[48]. The data of each cluster/role are then expressed as a percentage of their respective total activity, in order to present the results in a more convenient way and hence easily produce comparable and interpretable findings. The results of brokerage distribution at cluster level are shown below[49]:

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[48] As part of the research questionnaire, participants were asked to categorise their communication activities into four types namely: instructions, advice, information exchange and discussion. This is the same framework suggested by Pryke (2012) to study multi-layered networks.

[49] The results of the whole BSCU network at each stage will be used as the benchmark when commenting on the results of individual clusters. It is also to be noted that the relationship between BSCU whole project communication networks and individual clusters is non-linear due to co-existence of nodes.
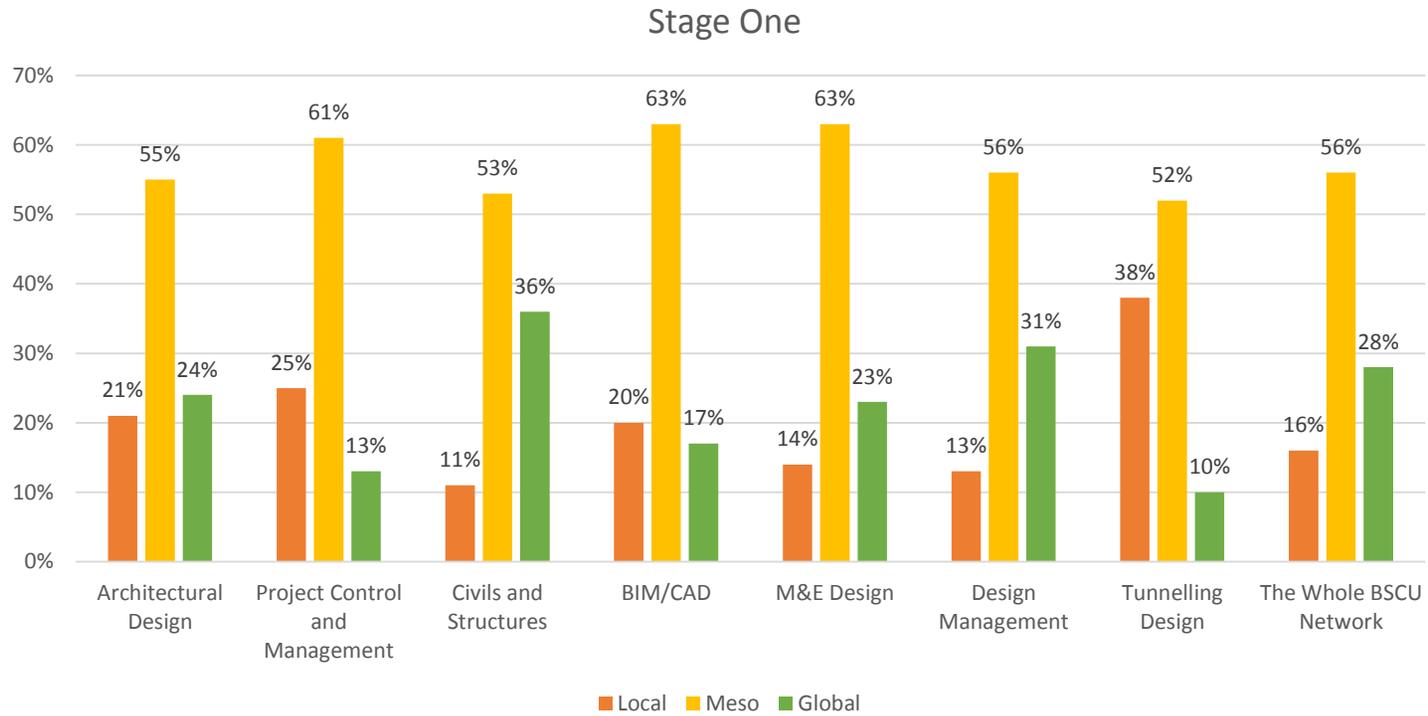
Stage One

Figure 6.8: Percentages of Brokerage Roles at Each Cluster according to their Influential Levels (Local, Meso, Global). Data is grouped based on clusters at Stage One of BSCU Project. (Source: Original)
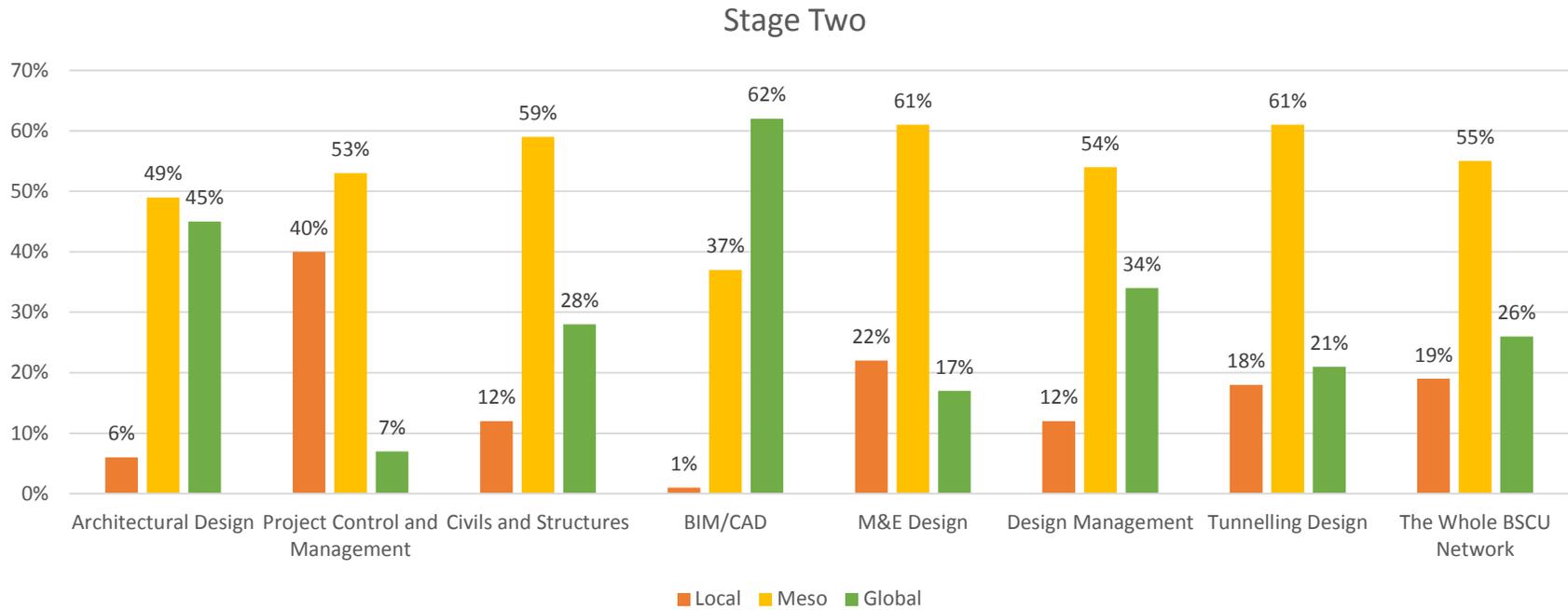
Figure 6.9: Percentages of Brokerage Roles according to their Influential Levels (Local, Meso, Global). Data is grouped based on clusters at Stage Two of BSCU Project. (Source: Original)
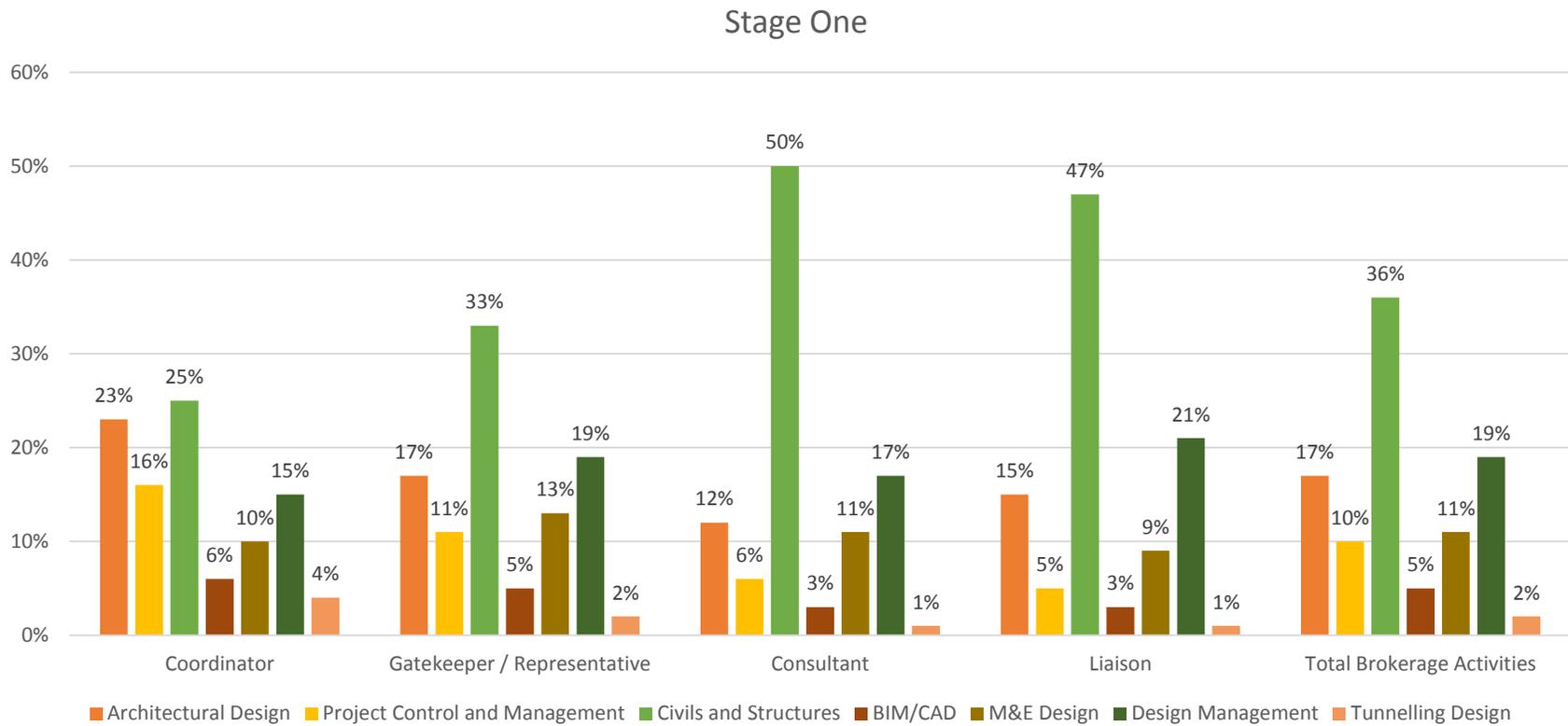
Figure 6.10: Distribution of Brokerage Roles at Stage One of BSCU Project Based on Clusters (Source: Original)
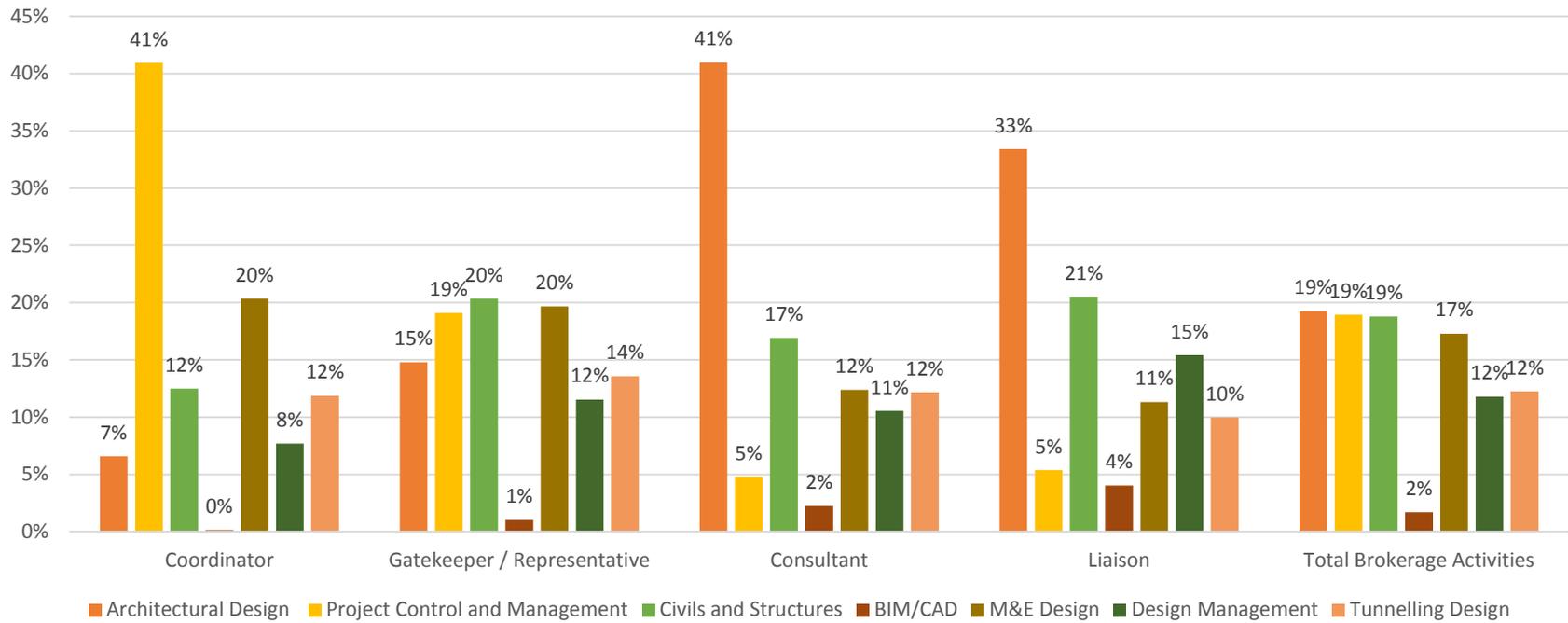
Figure 6.11: Distribution of Brokerage Roles at Stage Two of BSCU Project Based on Clusters (Source: Original)
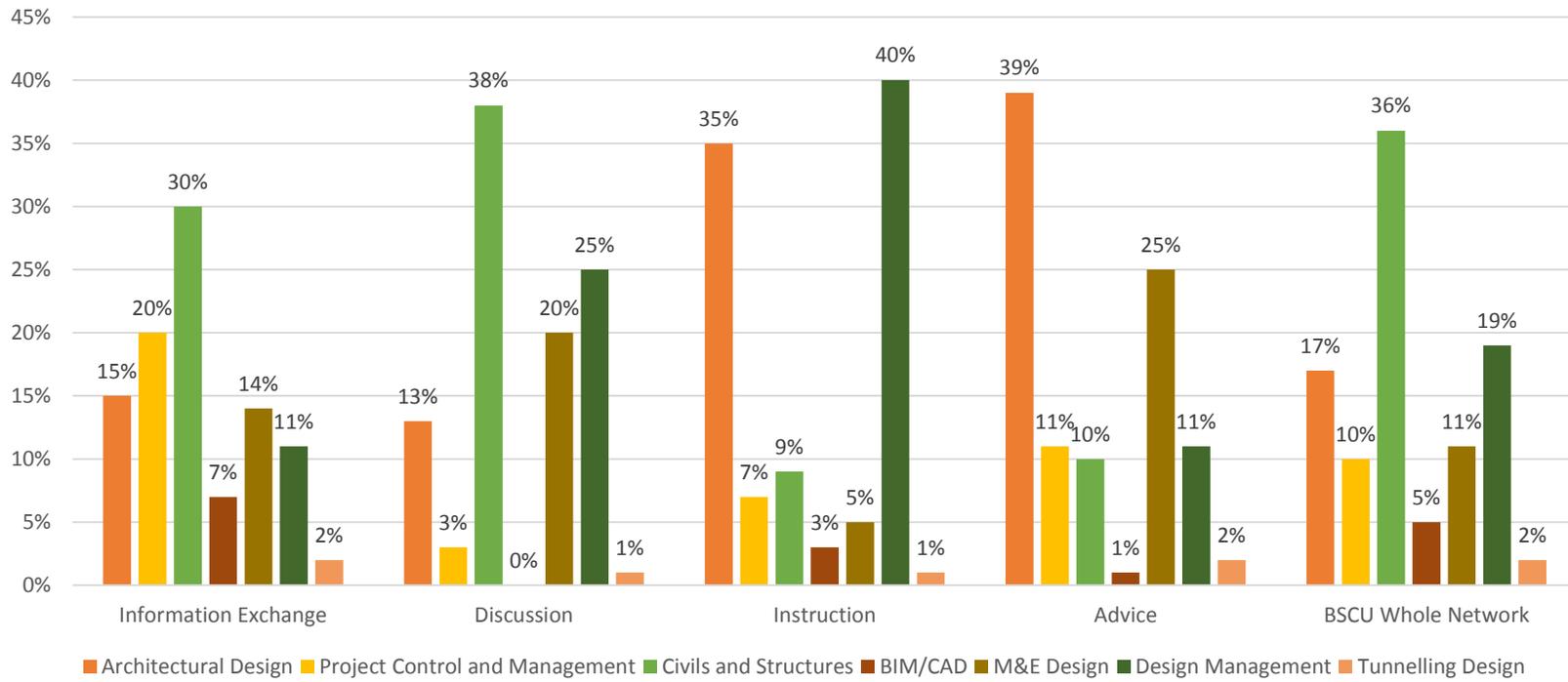
Figure 6.12: Distribution of Multi-Layered Communication Networks at Stage One of BSCU Project Based on Clusters (Source: Original)
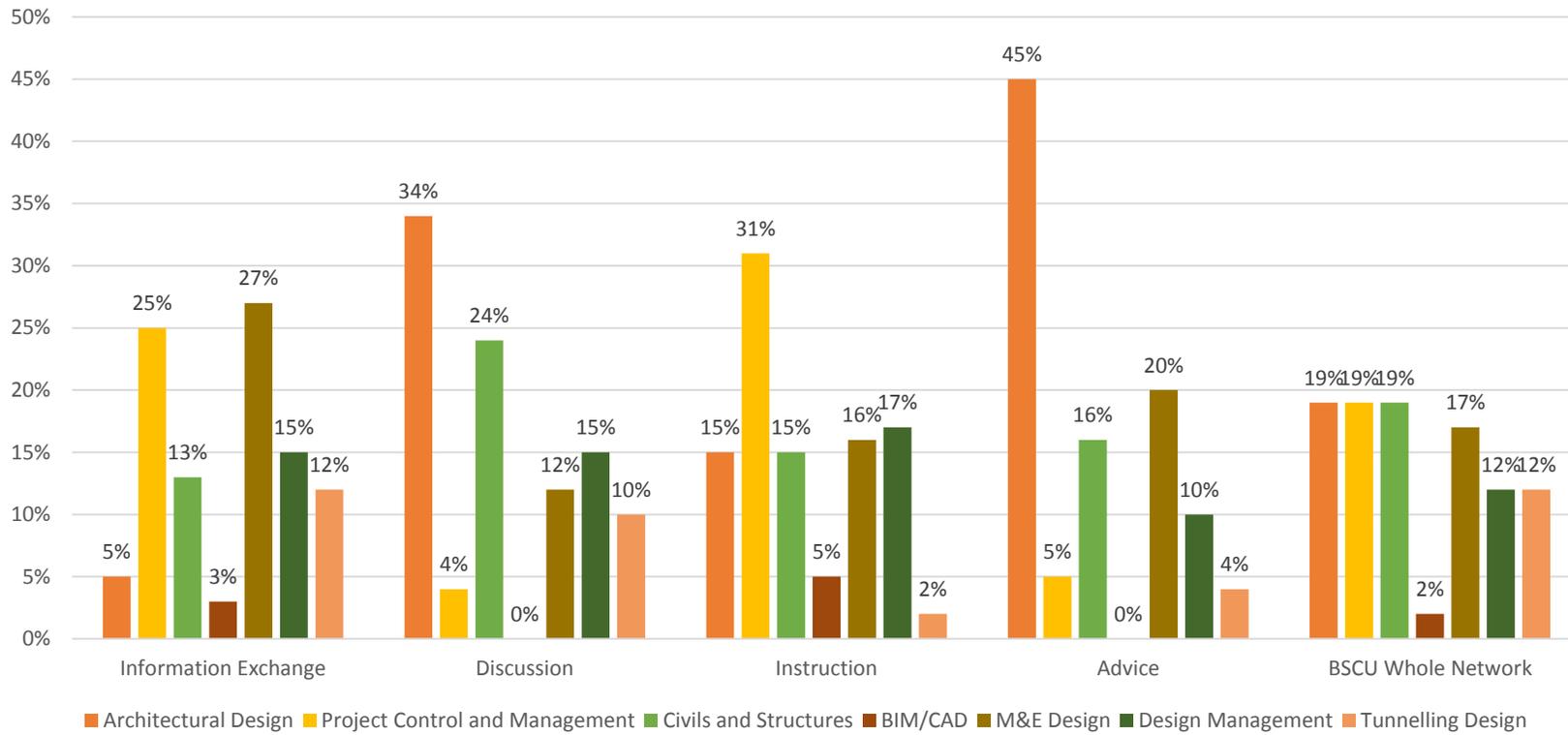
Figure 6.13: Distribution of Multi-Layered Communication Networks at Stage Two of BSCU Project Based on Clusters (Source: Original)

The key observations from the above results are as follows:

- From Figure 6.8, it can be concluded that, at both stages of the BSCU project, most of the brokerage activities, across all clusters, were observed at the meso levels (except BIM/CAD cluster at stage two). As explained in the earlier section, this finding highlights the crucial role played by meso-level in the self-organisation networks. It is mainly to foster cross-functional flows whilst optimising use of brokerage.

- Apart from the two clusters of Project Control and Management and M&E Design, all other clusters reported a higher global activity and a lower local activity. This increase in use of social processes was coupled with an increase of 68% in the informal communication (Information Exchange and Discussion) at stage two, increasing its share of total forms of communication used from 75% (at stage one) to 82% (at stage two). The increase in informal communication indicates a lower reliance on hierarchy and hence a more decentralised structure at stage two. The specific cases of Project Control and Management and M&E Design are discussed in the following bullet points. However, it is worth highlighting that both of these clusters reported a high density compared to others[50]. It can be argued therefore that high density can be used as an indication of relatively high local brokerage activities.

- **Architectural Design:** At stage one, local brokerage activities of this cluster were relatively higher than local brokerage value of the whole BSCU network (21% vs. 16% as illustrated in Figure 6.8). This has changed dramatically in stage two (refer to Figure 6.9) with local brokerage activities reducing to just 6% (the lowest score for local activities at stage two). Global brokerage activities, on the other hand, increased from 24% at stage one to 45% at stage two. This highlights a shift in the brokerage roles of Architectural Design, focusing on global activities at stage two, i.e. reaching out to larger actors from different functional affiliations. This is evident from the increased level of consultant and liaison roles which jumped from 12% and 15% to 41% and 33% respectively (as illustrated in Figure 6.10 and 6.11). Reflecting on the contextual circumstances of stage two, the increased level of global activities of Architectural Design cluster can be explained by its focus on introducing design changes and gathering evidences to support obtaining the necessary statutory approvals. This entailed involving a large number of actors/clusters. This finding highlights the importance of contextual circumstances in determining actors' social activity for treatment of uncertainty (cf. Winch, 2002).

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[50] Density values of clusters are presented in Table 7.2 in Chapter Seven.

Looking into type of communication, it is noticed that Architectural Design at stage one was primarily using Instruction and Advice forms of communication. These two types of communications, in particular Instruction, largely represent the formal communication (Pryke, 2012). At stage two, however, Architectural Design reduced its reliance on Instruction and Information Exchange. It became more active in Discussion (informal form of communication) but it is still dominant in Advice. It can therefore be concluded that formal use of communication has reduced the brokerage influence of Architectural Design at stage one whereas the use of informal type of communication has increased cluster's global status. Furthermore, at stage two, a positive relationship is observed between Advice and Consultant role.

- **Project Control and Management:** between the two stages, this cluster exhibited an increasing local brokerage activity and a decreasing global brokerage activity. It means Project Control and Management were focusing on limited activity (getting the statutory planning) and thus disengaged in resolving the technical issues being faced. As illustrated in Figure 6.8 and 6.9, local activities increased from 25% to 40% whereas global activities decreased from 13% to just 7% (lowest score for global activities at stage two). Their brokerage activities were focused on coordinating activities within their group, reaching 41% at stage two (see Figure 6.11). The limited size of brokerage activities (just 10% at stage one out of the whole BSCU network) and large local brokerage activity mean that Project Control and Management were bypassable by other actors in terms of brokerage flow. This is in contrary with their position in the organisational hierarchy. These results can be attributed to the cluster's high reliance on the formal type of communication (Instruction) at stage two, representing 31% (being the largest score for Instruction at stage two; refer to Figure 6.13).

- **Civils and Structures:** at stage one, this cluster reported the highest global brokerage in the project communication networks (36% - see Figure 6.8). This is supported by its dominance across all brokerage roles of stage one (see Figure 6.10) and their dominance in using informal communications, i.e. discussion and information exchange (Figure 6.12). This is expected, given the structural nature of the main issues encountered in this stage (i.e. the pile clashes) and the need to align other actors/clusters through integration. At stage two, the Civils and Structures lost its leading position as its total brokerage activities, across all types of roles, were reduced from 36% (at BSCU stage one) to just below 19% (at BSCU stage two). In terms of communication type, Civils and Structures reported the highest scores of informal communications at stage one (for both Information Exchange and Discussion). The reduction in

total brokerage activities at stage two was coupled with an increased use of formal forms of communications (Instruction and Advice) and a decreased use of informal forms of communications (Information Exchange and Discussion).

- **BIM/CAD:** this cluster represents an interesting case. It reported a dramatic shift in its influential level from having the largest meso score at stage one (refer to Figure 6.8) to having the lowest meso score at stage two (refer to Figure 6.9). Similarly, its local activities were among the highest at stage one (at 20%), but it was very minimal (at just 1%) at stage two. This dramatic change was translated into a substantial increase in its global activities from 17% (at stage one) to 62% (at stage two), reporting the largest global score at stage two. It also represented an exception in the sense that the meso level was the dominant across all clusters at both stages, apart from this cluster at stage two. This exceptional case can be explained by the small brokerage activities of this cluster (just 5-2%) as well as the substantial reduction in its size (from 16 actors at stage one to 4 actors only at stage two). Global status of BIM/CAD cluster at stage two can be explained due to its review meetings that were arranged fortnightly with the rest of the teams. At both stages, the cluster exhibited a mix use of formal and informal communications, using Information Exchange and Instruction as the primary forms (though they remained limited). Discussion and Advice were suppressed at both stages. This indicates their focus on information gathering.

- **M&E Design:** This cluster reported the largest meso-activities at both stages. However, similar to Project Control and Management, M&E Design at stage two reported a higher local activity and a lower global activity when compared to its scores at stage one. The increased level of locally focused brokerage activity at M&E Design can be explained by the high level of turnover among its actors; majority of them working on a contract basis. This explanation was confirmed by the Project Manager, highlighting that the large number of new joiners entailed higher requirements for coaching and supervising (locally-based activity). Distribution of brokerage roles highlights, nevertheless, that the focus on local brokerage activity was offset by the increased level of meso-brokerage activities at stage two (gatekeeping and representative roles). In terms of communication forms, it is noticed that stage two reported higher Instruction, lower but still high Advice, increased level of Information Exchange and lower Discussion. This mix use of formal and informal communication reflects the changing membership in M&E Design. That is, lower Discussion can be explained by the fact that new joiners (contract staff)

usually tend not to challenge their line managers but rather rely on Instructions. Higher Information Exchange is needed to bridge local discontinuity caused by turnover.

- **Design Management:** this cluster shows a slight tendency towards reducing its local activities and increasing its engagement with other teams. This is evident from the local scores that are found to be below the scores of BSCU whole networks at both stages. The scores of global activities are also higher than those reported by the network as a whole at both stages. This slight tendency towards global status, however, unexpectedly was coupled with a decrease in the brokerage activities at stage two, across all roles. This change between the two stages therefore was caused due to the disproportionate decrease in brokerage roles. In particular, coordination activity was lagging behind the other roles. In terms of communication, stage one exhibited a high use of Instruction at 40% (being the highest score for Instruction in stage one) as well as a high use of Discussion at 25% (the second largest score at stage one for Discussion). At stage two, the key change in communication is the substantial reduction in the formal communication. That is, Instruction reducing from 40% at stage one to 17% at stage two. Informal communication (Information Exchange and Discussion) at stage two reported slightly higher scores than those reported by the BSCU whole network.

- **Tunnelling Design:** At stage one, this cluster reported the lowest global score and highest local score (38%) which can be attributed to its very low brokerage activities at 2% (being the lowest score for brokerage activities across all clusters). The cluster's local focus can be explained due to the very technical and specialised nature of their work. At stage two, however, a shift was observed towards more use of social processes, reporting the highest meso score at stage two (61%). This was supported by an increase in the brokerage activities from just 2% (at stage one) to 12% (at stage two). While an increase in local coordination activity is noticed at stage two, the increase in both meso roles (Gatekeeper and Representative) and global roles (Liaison and Consultancy) outpaced the local growth. This shift was reinforced by an increase in use of informal communication (both Discussion and Information Exchange). Formal communication, on the other hand, was limited at both stages. The shift between stage one and two reflects the cluster's increased engagement with other teams, contributing towards satisfying stage two requirements (e.g. the public inquiry and TWAO submission).

6.3 Summary

Over the years, project management has evolved to become a self-sufficient discipline characterised by a formalised body of knowledge, with a systematic process defined to execute projects (Chapman and Ward, 2011). Such formalised processes have become bureaucratic and burdened the professionals with procedures, leading to a lack of emphasis on important issues (Chapman and Ward, 2011) and how projects are being delivered. Projects are delivered by people; they are mostly about people making decisions, optimising outcomes and being proactive in resolving issues as they arise. The way in which people perceive issues and react to them is at the heart of the success or failure of projects (Chapman and Ward, 2011). Therefore, what people do post-contract, in terms of informal interactions and communication, is critical to unveiling their effectiveness through the project design and delivery stages (Pryke, 2017; Pryke *et al.*, 2018).

The considerable pressure exerted on individuals to perform their roles in complex projects leads to high levels of self-organising, i.e. ignoring the organisational hierarchies. This chapter, therefore, illustrates a redefinition of project actor role based on Social Network Analysis (SNA) terms. As SNA involves no assumptions about hierarchy, it provides the ideal method to understand the nature of work and how it is coordinated in these self-organising networks (Pryke, 2017). Unlike the norm in studying the roles of individual actors in networks, this chapter proposes that the roles of individual actors are not just a function of their network position but rather they are also influential in network contextual terms. This is because roles of actors in a given network and social process are often inextricable. It is suggested therefore defining the roles of individual actors based on the degree to which social processes are used. By doing so, the thesis relates an actor's participation in a network to a multi-level framework.

In the pursuit of more effective management approaches capable of supporting the design and delivery of projects post-contract, SNA, as an analytical method has shown to be helpful. In particular, the investigation of centrality, as the fundamental concept to study the roles of individual actors in organisational networks, highlighted SNA has the capability to capture invisible functionality that usually cannot be obtained using traditional scientific methods of project management. Centrality was investigated considering the three main centrality measures - degree centrality (connectivity), eigenvector centrality (influence), and betweenness centrality (brokerage). These were used to retrofit individual roles into a multi-level framework.

Connectivity or degree centrality measures an actor's direct connections, representing his or her communication activity within the network. High connectivity in BSCU project translates to the individuals who are the most visible or outspoken to others in the team. A multi-level classification for individual roles was developed, based on the in-degree and out-degree centrality values. Depending on the actors' level of social engagement, four key roles were identified, namely: Prominent Actors, Disseminators, Gatekeeper Hoarders, and Isolated actors/Sub-groups. Each of these actors exhibits different characteristics, affecting the way in which a network functions as well as the behaviour of other actors. Of particular interest, the results of degree centrality measures highlight the dual role played by self-organising networks in promoting or constraining effective information flow, which can be achieved by way of introducing disseminators or removing gatekeeper hoarders respectively.

Eigenvector centrality is concerned with indirect connections and used as an indicator of influence by identifying actors who are well connected to other well-connected actors. From this perspective, high eigenvector score means an actor has the power to connect to other influential individuals and hence in return will have the power to build norms and expectations that others in their group will relate to (Wasserman and Faust, 1994). Its application to the study of self-organising networks is sophisticated, given its 'relative' concept that requires identification of numerous reference points to accommodate for complexity of large projects as well as the high degree of structural equivalence within clusters that limits indirect influence.

Betweenness centrality is an indicator of brokerage activity, based on identifying individuals on the path between most of the other nodes in the network (Wasserman and Faust, 1994). In a project context, individuals with high betweenness can filter or change information flowing to others in the network, and thus information can be delayed, changed, or stopped at these points in the network. They can also connect otherwise disconnected groups and hence can be used as indicator for network resilience as their removal may fragment the network. Using cluster affiliation of each node, this thesis extends the normal discussion of Betweenness Centrality by categorising the brokerage roles based on their levels of brokerage influence. Five roles are identified, namely: Coordinator (Local), Consultant (Local), Gatekeeper (Meso), Representative (Meso), and Liaison (Global). BSCU case study exhibits very low brokerage, implying that there are no overly controlling actors and hence a low degree of reliance on hierarchies. Interestingly, investigation of brokerage roles at clusters level reveals that higher level of global and meso activity is associated with the use of informal type of communication whilst local level activity is associated with the use of formal type of communication.

Focusing on linking the roles of individual actors to their social context (i.e. local/meso/global levels) is also helpful in analysing and breaking power into different categories. This is because, within project settings, centrality measures are used to determine power. They are quantified by either direct or indirect connections, i.e. degree centrality or Eigenvector/ Betweenness centrality respectively. It therefore makes sense to categorise power into two different types (Lukes, 1974), namely visible power (the one generated by direct connections) and invisible power (the one generated by indirect connections). Actors with visible power can exert their influence directly on their neighbouring nodes whereas actors with invisible power can exert their influence indirectly through the actions of other actors or controlling the flow of resources within the network. It is suggested that these two types of power are closely connected (i.e. prominence in terms of degree-centrality is likely to be associated with brokerage prominence).

Results from BSCU case study highlight existence of different dynamics governing the patterns of communication at the various stages and layers. These are exhibited by the different roles played by individuals in self-organising networks which can produce heterogeneous outcomes. For example, global roles are able to span the clusters/group boundaries, whereas local roles are limited in nature but they can lead to less differential status and hence dilute the invisible power. Roles at meso level, on the other hand, have a very distinct benefit in the sense that they keep the network cohesive, acting as the network focal points that mobilise majority of resources and hence serving as the link between local and global actors.

While it is noted that stage two of BSCU project has less hierarchies, some degree of power inequalities (and hence hierarchies) is still required to fuel the process of negotiation and re-negotiation in self-organising networks. Results from BSCU case study also highlights that absence of extreme levels of prominence is a key to foster the establishment and maintenance of high levels of trust. Therefore, a small number of very prominent actors, who have a wide variation between in-degree and out-degree centrality, should be avoided to move towards a 'democratic network'.

The analysis of the centrality measures reveals some facets of the duality nature of the self-organisation structures. For example, the prominence in terms of degree-centrality was found to have a positive impact on the network configuration and its connectivity. However, this type of prominence is likely to be associated with brokerage prominence which provides an actor with power to influence other actors whether in a positive or negative way. As a result, individuals who exhibit both high degree and high Betweenness centralities often gain a positional advantage to act as network coordinators/leaders, and

therefore they have the power to synchronize the activities of the different network actors (Pryke, 2017).

Self-organising networks are less formalised and should be understood as an emergent outcome that is designed, established, and maintained by the project actors involved. Interestingly, analysis of individual roles suggests that an actor could be prominent in a network for negative reasons. This finding therefore challenges the theorisation about self-organising networks which largely assumes positive outcomes. Results suggest that self-organising networks open up opportunities yet also create constraints. The latter include the emergence of negative consequences, such as dysfunctional/disruptive behaviours due to excessive betweenness, which could result in impairment in project functioning. This suggests that self-organising networks should not go unmonitored.

7

Meso-Level Analysis

Self-Organising Clusters
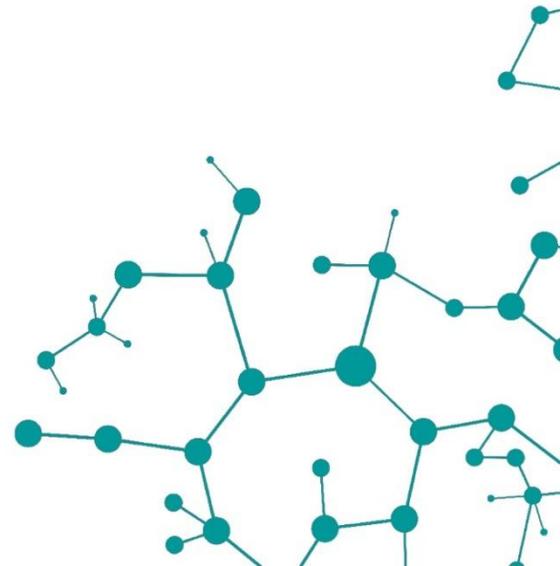
7.1 Introduction

This chapter principally deals with the identification of clusters in projects. These are defined as relatively small problem-solving groups of actors that are densely connected among themselves but in turn sparsely connected to other parts of the network (Pryke, 2012). The previous chapter on the roles of individuals in self-organising networks touched upon clusters, bringing the crucial role played by meso-level to the fore. This chapter investigates the meso-structure in further detail by studying the intra- (within clusters) and inter- (among clusters) relationships. This involves understanding the decision-making processes and exploring project functional communication themes.

7.2 How Clusters Were Found?

Clusters were found by conducting a "cluster detection" process. This was facilitated by Gephi modularity analysis (Blondel *et al.*, 2008). It is a density-based clustering method and thus looks for the actors that are more densely connected together than to the rest of the network. The function in Gephi is built on an algorithm that calculates the minimum number of nodes required to form a dense region vis-à-vis the number of connections in the dataset. It divides the communication network into modules (also called clusters) by grouping a given node with its neighbourhood (a form of proximity search) only if they were found to be a dense part of the same cluster. The process to detect a given cluster continues until all set of density-connected nodes are grouped together. Then, a new unvisited node is retrieved and processed in the same way, leading to the discovery of a further cluster.

The cluster detection process was conducted twice on BSCU dataset; one for each stage. These were completed separately since the two stages are represented by two independent datasets as well as to avoid any type of cross-influence between the different variables. Seven self-organised clusters were detected at each stage (see Figure 7.1 and Figure 7.2 for clusters found at stage one and stage two respectively). While cluster detection is essentially an algorithm-based process, the classification of the clusters was based on their functional nature. This list of project function classifications is context-specific and derived from TfL systems, namely: Architectural Design and Management; Civils and Structures; Project Control and Management; Design Management; M&E Design; BIM/CAD; and Tunnelling Design. The functional classification adopted in this thesis is in line with Pryke *et al.'s* (2017) approach and was further confirmed through discussions with the BSCU Project Manager (to ensure identified clusters properly reflect how the project was delivered). This type of classification enables

focusing in some detail on the communication networks of individual context-specific project functions and understanding the actors' behaviour behind delivery of projects.

7.3   What's New?

This chapter builds on the identified clusters in Pryke *et al.* (2017) in order to understand the driver of local interactions and formulation of clusters. Table 7.1 below summarises the key differences between Pryke *et al.* (2017) and this thesis, as follows[51]:

Table 7.1: Key differences between Pryke *et al.* (2017) Study and this Thesis.
(Source: Original)

Aspect(s)	Pryke *et al.* (2017)	This Thesis
Definition of Clusters	Function-oriented. Seven self-organising clusters were identified in both stages of the BSCU project, using modularity analysis in Gephi.	Adopted from Pryke *et al.* (2017) and confirmed by discussions with the BSCU project manager. Clusters are further challenged by investigating in detail the underlying micro level interactions.
Clusters' Description	Discussion is basic and limited to general observations.	In-depth discussion is provided for each cluster in terms of both statistical and structural characteristics. A comparison is provided between both stages of BSCU project in order to understand the structural changes in BSCU network.
Level of Analysis	Does not give reference to the level of social engagement.	A multi-level framework is adopted in reference to actors' intra- (within cluster) and inter- (cross-cluster) relationships. Analysis of clusters involves interpretation of network data and inspection of sociograms. Analysis also involves shedding the light on clusters' characteristics and investigating their inter- and intra-cluster pairing.
Study of clusters and decision-making process	Use of theoretical underpinning of self-organisation is limited.	It advances the analysis of self-organising networks by studying the decision-making strategies and exploring project cross-functional communication themes. This provides insights into how meso-level structure emerges from the actions of segregated clusters.

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[51] This comparison does not aim to dismiss value of the work presented in Pryke *et al.* (2017) but rather to highlight the additional aspects/analysis covered in this thesis.

7.4　Intra- (Within Cluster) Relationships

Network graphs (sociograms) of both stages of BSCU project were produced in Gephi. These are illustrated in Figure 7.1 and 7.2. For presentation purposes, the boundaries of each cluster were added to the produced sociograms. Each cluster is composed of a number of highly specialised individuals who emerged with a distinct function within the project communication network. Nodes are sized by betweenness centrality and coloured by their organisation affiliation. Ties represent the communication activity between the nodes and are weighted by communication strength[52]. Table 7.2 and Table 7.3 provide a summary for the general characteristics of each cluster at stage one and stage two of the project respectively.

The purpose of cluster analysis is to study the structural regularity of the network at both stages of the BSCU project. Classification of various project functions into clusters offers a tool to understand the changes occurred at each function as the project shifts from stage one to stage two. In this context, composition of the clusters will be investigated, identifying distribution of actors based on their cluster affiliation. Table 7.4 shows this information, highlighting that clusters' compositions have changed between stage one and stage two, mainly by way of new hires, leavers and inter-transfers. More importantly, the findings of such analysis can provide insights into how individuals collaborate and cultivate on informal relationships to deliver projects. Therefore, the effective project team configurations and any potential managerial interventions can be defined and replicated for managing other networks delivering projects. This is not to say that all projects will have similar structures, but certain patterns and underlying processes behind the successful design and delivery of complex projects can be generalised (Pryke, 2017). This is useful because many of the fundamental challenges in construction projects are the same whether the project in question is building a leisure centre, commercial office space or rail infrastructure.

The study of self-organising clusters provides insights into how clusters act as platforms to cope with complex interactions, leading to reduced levels of conflict between too many actors comprising the entire project team (Gershenson, 2007). That is, clusters manage the potential adversarial relationships between actors in a given network, who usually interact and make decisions locally before they reach

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[52] The questionnaire data for communication frequency and quality scores were normalised and then multiplied. The outcome was used as a proxy for tie strength. This is in line the method set out by Pryke (2012) and Pryke *et al.* (2017).

consensus globally. This is particularly important to the understanding of network functions, dynamics and the changing roles of actors within the BSCU complex project design network, as it moves from stage one to two. The analysis of this section will therefore highlight any discrepancies between the roles procured contractually and the roles adopted in the self-organising clusters that evolved to discharge their functions. This will be linked with investigation of decision-making strategies as the project and self-organising networks develop between the two stages. The decision-making strategies are studied by adopting the model explained in Methodology Chapter (Section 4.3.2), which emphasises on the project's social processes. This model organises various decision-making processes into four distinct heuristics, based on the degree of uncertainty and amount of resources associated with making a decision, namely: imitation, social comparison, repetition, deliberation (see Figure 4.1). The distribution of decision-making strategies across all clusters is illustrated in Figure 7.3. This involves defining the decision-making strategies employed by each actor and then grouping them based on their cluster affiliations. The results of each cluster are then expressed in relative terms, i.e. "Total of each type of decision-making strategy in a given cluster" / "Total of all decision-making strategies for the same cluster".

(Architectural Design and Management)

(Tunnelling Design)

(M&E Design)

(Design Management)

(BIM/CAD)

(Project Control and Management)

(Civils and Structures)

Less Brokerage ● ● ● More Brokerage   Weaker Relation ||| Stronger Relation

● TfL   ● T Clarke   ● Robert Bird Group   ● Alan Auld Engineering   ● McNicholas
● Dragados   ● Wilkinson Eyre ● Dr Sauer & Partners ● URS Infra. & Env. Ltd. ● Other

Figure 7.1: Project Functional Clusters at BSCU Project Stage One. Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Adapted from Pryke _et al._, 2017)
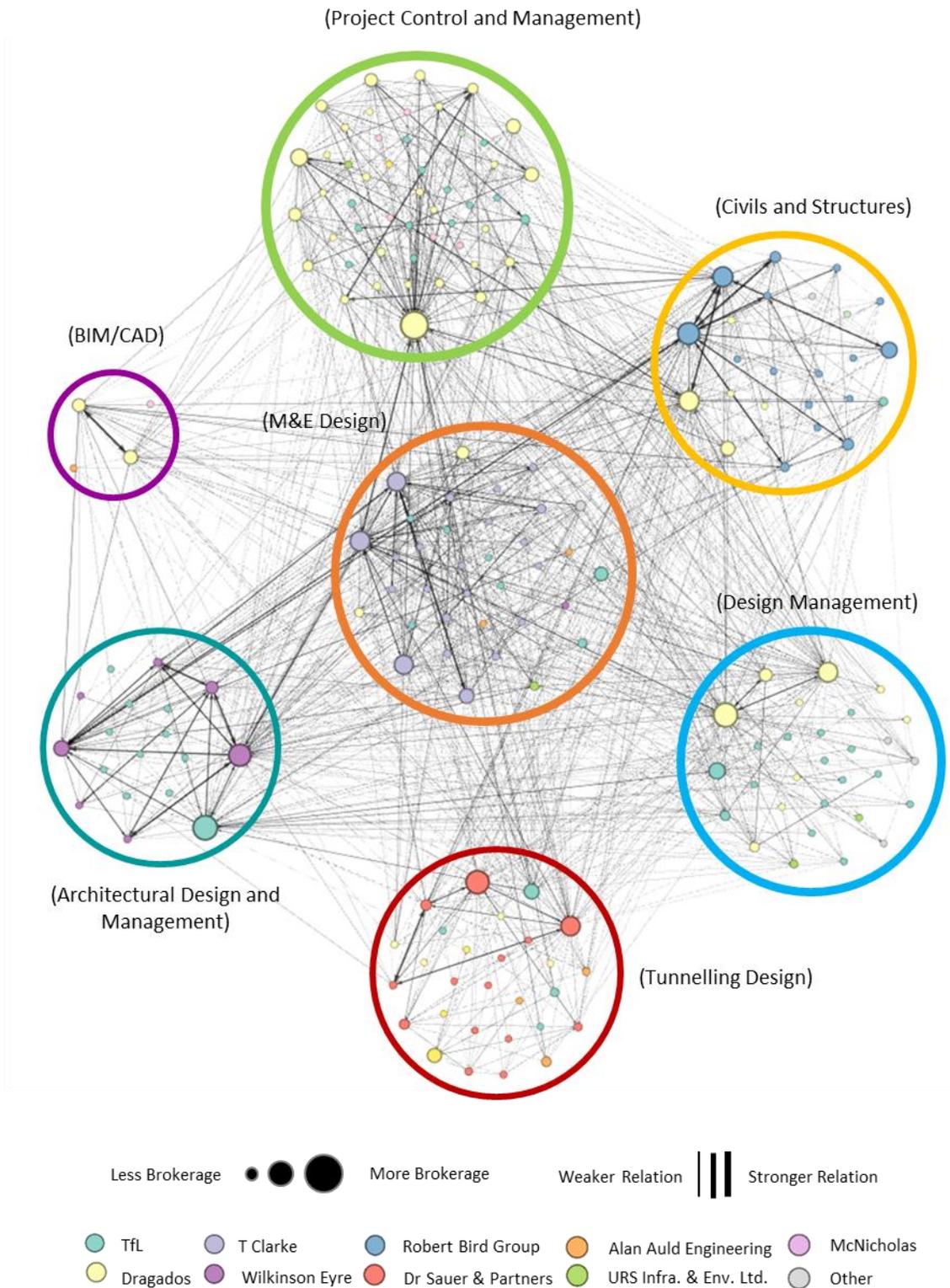
Figure 7.2: Project Functional Clusters at BSCU Project Stage Two. Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Adapted from Pryke _et al._, 2017)

Table 7.2: Stage One - Network Clusters' Characteristics.
(Source: Original)

Cluster Function	No. of Nodes	% of Nodes[53]	No. of Links	% of Links[54]	Links % intra-Cluster	Links % inter-Cluster	Cluster Density
Architectural Design and Management	32	20%	410	18%	26%	74%	0.106
Civils and Structures	30	19%	493	22%	31%	69%	0.177
Project Control and Management	26	16%	365	16%	37%	63%	0.209
Design Management	26	16%	418	19%	25%	75%	0.158
M&E Design	18	11%	307	14%	30%	70%	0.301
BIM/CAD	16	10%	126	6%	21%	79%	0.113
Tunnelling Design	14	9%	112	5%	29%	71%	0.176

Table 7.3: Stage Two - Network Clusters' Characteristics.
(Source: Original)

Cluster Function	No. of Nodes	% of Nodes	No. of Links	% of Links	Links % intra-Cluster	Links % inter-Cluster	Cluster Density
Architectural Design and Management	18	9%	413	12%	14%	86%	0.186
Civils and Structures	27	14%	593	17%	30%	70%	0.251
Project Control and Management	54	27%	666	19%	39%	61%	0.092
Design Management	29	15%	530	15%	17%	83%	0.110
M&E Design	37	19%	736	21%	33%	67%	0.181
BIM/CAD	4	2%	118	3%	5%	95%	0.500
Tunnelling Design	28	14%	413	12%	27%	73%	0.149

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[53] The percentage values for Nodes are measured as "Total of number of nodes in the cluster" / "Total of number of nodes in the network".
[54] The percentage values for Links are measured as "Total of number of links for the cluster, including intra- and inter-links" / "Total of number of links in the network".

Table 7.4: Distribution of Nodes Based on Their Cluster Affiliation (Source: Original)

Cluster Function		Where the actors come from based on their cluster affiliation at stage one							New Hires[55]	Total Actors at Stage Two
		Architectural Design and Management	Civils and Structures	Project Control and Management	Design Management	M&E Design	BIM/CAD	Tunnelling Design		
Clusters at Stage Two	Architectural Design and Management	12		1					5	**18**
	Civils and Structures	1	20				2		4	**27**
	Project Control and Management	2	5	22	6		4		15	**54**
	Design Management	10			14		2		3	**29**
	M&E Design	3		1	5	18	1		9	**37**
	BIM/CAD						3		1	**4**
	Tunnelling Design	1	2	1	1		2	14	7	**28**
Leavers[56]		3	3	1			2		N/A	**9** *(Total Leavers)*
Total Actors at Stage One		**32**	**30**	**26**	**26**	**18**	**16**	**14**	**44** *(Total New Hires)*	**162/197** *(Total Actors at Stage One/Total Actors at Stage Two)*

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[55] These are the new actors joined BSCU project at Stage Two.
[56] Actors were part of Stage One but they left the project at Stage Two.
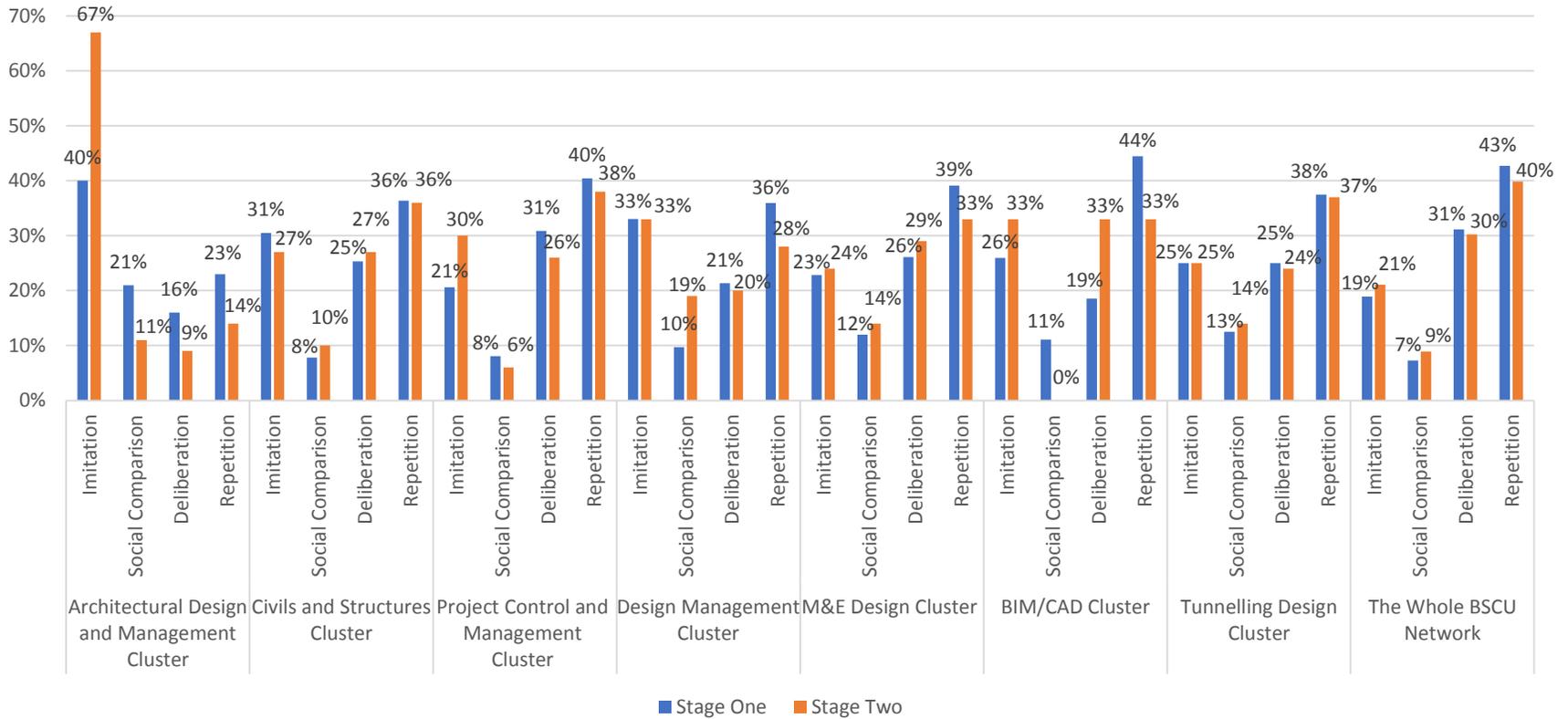
Figure 7.3: Distribution of Decision-Making Strategies across all clusters at stage one and stage two of the BSCU project. The results of each cluster are expressed in relative terms, i.e. "Total of each decision-making strategy in a given cluster" / "Total of all decision-making strategies for the same cluster". (Source: Original)

Below are the general observations from the above results:

- The defined clusters are found to be inter-organisational/cross-functional, i.e. not related to organisational/hierarchal formal chart (presented earlier in Chapter Five). This supports the argument of Pryke (2017) who advocates that a highly interdependent environment is typically found in complex construction and engineering projects;

- BSCU project networks' clusters are characterised by having low-to-medium density values (see Table 7.2 and Table 7.3). However, these values are higher compared to the density of whole network (stage one is at 0.055 and stage two is at 0.057 – see Table 5.1). This suggests that, in complex projects, individuals tend to self-organise themselves into smaller groups/clusters to get the work done and minimise uncertainty;

- Clusters in stage two reveal a different composition to that observed in stage one. That is, some actors/ties were dissolved, and new/different ones emerged. This suggests that self-organising project networks are not static, but they evolve and decay over time. Within each function-based cluster, networks evolve as project activity increases, and decay towards the end as activity reduces prior to completion or as a new activity comes onstream. The network changes its topography as necessary to adapt to the changing project requirements and conditions. As the BSCU project shifts from stage one to stage two, number of nodes increased by 22% (162 to 197 actors). Key changes are presented in Table 7.4 and summarised below:

  - 9 actors left the project. This represents 6% of stage one;
  - 44 new hires were made (i.e. new actors joined the project). This represents 22% of stage two;
  - 50 inter-transfers (i.e. actors changed their cluster affiliation). This represents 31% of stage two;
  - 103 actors maintained their cluster affiliation (i.e. without moving to another cluster or leaving the project). This represents only 52% of total nodes at stage two.

- Informal networks at both stages exhibit a wide variety of relational structures (see Figure 7.1 and Figure 7.2). For example, number of connections per node ranges from being dense to dyadic. This variety reflects the transient nature of organisations in the construction industry. It can be said that this differential is created by the continuous negotiation and re-negotiation process of power (network centrality in SNA terms) to effect outcomes through the different phases. That is, relationships develop at different rates (hence the issue of time lags/discontinuity); some relationships

are just being formed; some have reached maturity stage; others could be residual, carried forward from previous project phases.

- Communication activity (total number of links) increased by 55% between stage one and stage two (see Table 7.2 and Table 7.3). Interestingly, the inter-communication was higher at stage two across all clusters (except for Project Control and Management and M&E Design). This indicates a focus on cross-functional activities, leading to a higher level of integration. This is further supported by emergence of new strong ties, which indicates an increased level of trust and mutual cooperation as the project progresses into stage two. This finding suggests that integration is largely a human function. The TfL Project Manager reflects on this by asserting:

    'When we saw the communities' data, they are quite multi-discipline clusters, apart from perhaps the M&E one. We were delighted with this finding, that's what you are trying to achieve in the project. You are trying to achieve function to function coordination via consultation team or interface people. We want people to speak directly together'.

The TfL Project Manager further stresses on the element of path-dependence in creating a more integrated working environment:

'The main contractor, Dragados, and the tunnelling contractor have been working together since the tendering stage (late 2012- early 2013). They have a very good relationship and I think they had worked together on other projects probably overseas as well as in the UK, they knew each other.

We worked together at Victoria station, Bond Street station, Tottenham Court Road station and then Bank station. We were all part of the same organisational unit in London Underground station capacity programme'.

TfL Project Manager further highlighted, as part of the interview, that a number of interventions in the management of BSCU project were introduced at stage two. For example, actor repositioning (e.g. Tier-one contractor re-allocated resources to other designers to deal with the design delay and uncertainty regarding the buildability of proposed options), encouragement of resource sharing, and arranging for regular breakfast meetings. The management found these to be particularly viable to enable more effective allocation of tasks, both gathering and dissemination of information, and improved decision-making and problem-solving.

- It is also worth highlighting that defined clusters at both stages could be considered as an interpersonal relational capital that adds value to BSCU project and organisations (Pryke *et al.*, 2018; Kilduff and Krackhardt, 2008). This is because they are neither formally/contractually procured by the client (TfL), nor are they owned by the organisations involved;

- The ratio of inter-links:intra-links at both stages remained almost at the same level of 70:30% (see Table 7.2 and Table 7.3). One may argue that the high percentage of inter-links means inadequate clustering since the actors are primarily engaged in an outward/cross-functional communication activity. However, this is not quite true because the algorithm used to produce these clusters is based on a density-based clustering method which defines clusters as regions of higher density than the remainder of the dataset. The density, in turn, is determined by the ratio of the number of links an actor has to the total possible links an actor could have (see Equation 3.1). The higher the ratio, the denser the set of connections. This explains the reason why intra-links are mainly formed by one-to-one relationships (that have fewer number of links but a high ratio of density; hence high clustering), whereas inter-links are mainly formed by one-to-many relationships (that have a large number of links but a low ratio of density; hence low clustering).

- Distribution of decision-making strategies at the overall network level remained almost the same (see Figure 7.3). Repetition is the highest at 40%+, usually representing routines in projects which are necessary to provide consistency and stability and reduce mental effort (Becker, 2004). Deliberation is at 30%, reflecting discussions taking place to exchange ideas and reach common grounds. Imitation and social comparison is around 20% and 10% respectively, used to cope with higher levels of differentiation in the network (e.g. prominence and/or information asymmetry). This is common in highly complex construction projects, such as the BSCU project, as actors are highly specialised.

For the purpose of studying intra-relationships, next sections present the sociograms of each cluster at both stages of BSCU project. In these individual graphs, size of nodes (based on their betweenness centrality degree) and internal ties are kept as presented earlier at the whole network graphs. This means that centrality shown in cluster-by-cluster sociograms is based on the overall network data. For illustration purposes only, the external links of the clusters were removed from these individual graphs (since they depict the cross-functional communication). Additionally, tie strength is illustrated by linkages' thickness, i.e. the thicker the line, the stronger the relationship is and vice versa. The mean value of tie strength data (calculated based on the overall network) will be used as the threshold. That is, any tie has a value that is above the average will be considered strong and vice versa. The threshold is based on frequency values of 0.126 and 0.133 at stage one and stage two respectively.

The following description constitutes the findings from both data mining and SNA carried in this thesis.

7.4.1 Architectural Design and Management Cluster

The primary focus of this cluster was the design and management of architectural works at the detailed design stage of BSCU project. Reflecting on the questionnaire statistics, the main purposes of communication were: Understanding, reviewing or developing the design across functional disciplines to manage design interfaces (≈ 41% and 49% at stage one and stage two respectively)[57] and reporting or preparing progress data (≈ 20% and 28% at stage one and stage two respectively). This indicates no material change in the main purposes of communication.

The sociograms of this cluster at both stages are illustrated side by side below. The key characteristics are described next.
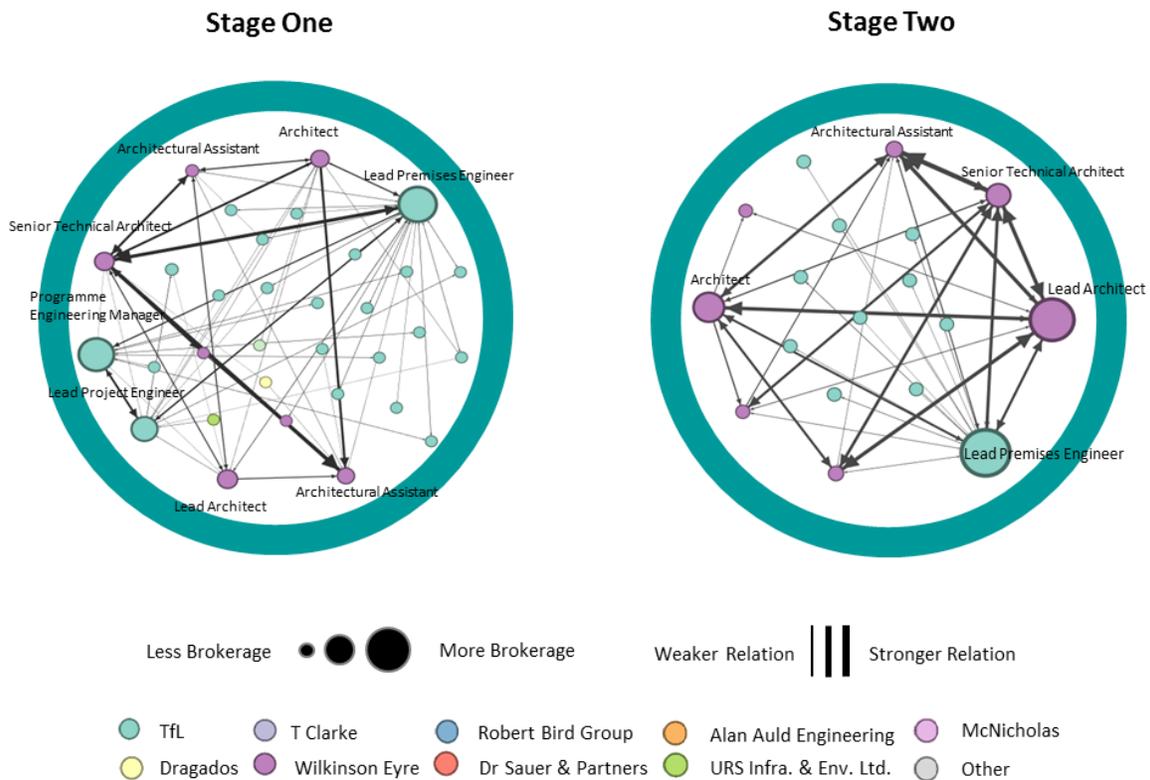
Figure 7.4: The Sociograms of Architectural Design and Management Cluster at Stage One and Stage Two of BSCU Project. Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Original)

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[57] These data for purpose of communication were collected as part of the study questionnaire. The results of each cluster are expressed in relative terms, i.e. "Number of times that a specific purpose of communication in a given cluster was identified" / "Total number of communication activities for the same cluster".

Stage One:

This cluster was the largest by size (based on number of actors) at BSCU network of stage one (see Table 7.2). Referring to Equation 3.3, the denominator (driven by large number of nodes) outpaces the numerator (number of ties); hence this cluster reported the lowest density. The cluster is quite homogeneous in terms of actors' organisational affiliation (see Table 7.4), as it is denominated mainly by two organisations: the client organisation (TfL) with actors from the design management discipline (69% of total actors), and Tier two subcontractor (Wilkinson Eyre) which is responsible for the architectural design (22% of total actors). The cluster exhibited high level of communication activities (see Table 7.2), being the third largest in the whole network (its number of links accounting for 18% of the whole network), with focus on cross-cluster communication (its inter-links:intra-links is at 74:26% respectively).

The heavy involvement of TfL actors in this cluster demonstrates the 'hands-on' approach adopted by TfL to resolve the design issues encountered at this stage. The Lead Premises Engineer followed by the Program Engineering Manager from TfL were the most prominent actors (based on betweenness centrality). Interestingly, this appears to contradict with what would be expected from a traditional project management perspective, in which this formal/contractual function should be dominated by the procured architects and not the client. There is, therefore, a possible need for future intervention. Additionally, it is observed that the Senior Technical Architect is placed in a central position in the communication of the design team (Wilkinson Eyre team), with relationships that are characterised as strong and reciprocal with the architectural assistants. This again mismatches with what would be expected to be seen based on the contractual reporting network, where the Lead Architect should be in a more central position, being the most senior person at design hierarchy. Such observation suggests the emergence of informal prominent actors that differ from the formal structure.

Stage Two:

Similar to stage one, this cluster was dominated by actors from TfL (≈ 61%) and Wilkinson Eyre (≈ 39%). It no longer has actors from other organisations (see Table 7.4). Number of TfL actors reduced by half to 11 whereas Wilkinson Eyre maintained its number of 7 actors. This reflects the shift in TfL focus from design to completion of TWOA process in stage two. The cluster at stage two comprised mainly the earlier actors of stage one (67%) and had 6 new actors, out of which 5 were new hires and additional one was an inter-transfer coming from Project Control and Management cluster. Reduction in number

of nodes involved three actors leaving the project and another 17 actors joining other clusters (majority, 10 actors, moved to Design Management cluster).

Following 44% reduction in number of nodes (from 32 to 18 actors), the cluster lost its leading position (by size) at stage two (see Table 7.3). It ranked the second smallest. Referring to Equation 3.3, as number of nodes reduces in large numbers, the denominator starts underperforming in a way that cannot be counterbalanced by the numerator (number of ties); hence this cluster reported higher density value. Interestingly, communication activity remained almost at the same level as that of stage one, accounting for 16% of the whole network (compared to the ratio of 18% at stage one). Number of links reduced only by three links which is disproportionate to the reduction in number of nodes. This is explained by the fact that this cluster maintained its relationships with its ex-actors (i.e. the inter-transfers who joined other clusters). At stage two, therefore, the cluster was the second largest in terms of external communication activity. Its intra-cluster communication reduced by 46% whereas its inter-cluster communication increased by 17%. Its inter-links:intra-links therefore improved to 86:14% respectively. This is a desirable outcome as higher inter-links usually promote global and meso-brokerage roles that in turn connect a group of actors who are positioned at different clusters. As explained in Section 6.2.3.1, this type of cross-functional connections assists in bridging structural holes (disconnections) and supports coordination activities in dynamic situations.

In terms of prominence, TfL is less powerful at this stage compared to stage one, but its Lead Premises Engineer is still the most prominent actor. A number of prominent actors emerge from Wilkinson Eyre team, namely: Lead Architect, Architect and Senior Technical Architect who all played liaison brokerage roles. This reveals a change in the roles of these actors, occupying more powerful positions in the network. The liaison roles were supported by the large number of inter-transfers, leaving Architectural Design and joining other clusters. These inter-transfers facilitated cross-functional communication, leveraging on their previous relationships established at stage one.

In terms of tie strength, the inspection of sociograms reveals a predominance of weak ties at both stages. However, higher number of strong ties emerged at stage two. These strong ties are reciprocal and mainly connect different actors from Wilkinson Eyre team. Lead Premises Engineer (from TfL), the most prominent actor, established strong ties with the other prominent actors from Wilkinson Eyre. This is explained by the concept of preferential attachment, which helped Lead Premises Engineer to maintain its leading prominence. This finding supports earlier observations showing that even in distributed self-organising networks a certain hierarchy or elite group will still be found.

Decision-Making Strategies:

The distribution of decision-making strategies in this cluster, as illustrated in Figure 7.3, suggests that imitation strategy was the dominated strategy at both stages (increasing from 40% to 67%). This means actors of Architectural Design and Management cluster were socially active which is expected since both stages are concerned with design phase. At stage one, the cluster was concerned with development of alternative design proposals resulting mainly from the pile clashes whereas at stage two it was concerned mainly with completion of relevant TWOA requirements. High use of imitation strategy can be further explained by two factors: 1) the relationships maintained with the inter-transfers and hence more use of social process; 2) relatively a wide variation in power (prominence) between actors, which gives rise to information asymmetry. The latter is particularly relevant in situations with high uncertainty. Removal of large number of actors at stage two (44% reduction in nodes), on the other hand, translated into reduced repetition strategy (from 23% at stage one to 14% at stage two).

The high levels of imitation coupled with low levels of repetition indicate a high level of complexity and uncertainty. e.g. actors encountering unexpected issues. More importantly, it implies that actors of Architectural Design and Management cluster, in the majority of the cases, wrestle with the need to gather and disseminate information as they are frequently under time pressure.

7.4.2 Civils and Structures Cluster

The main purposes of communication in Civils and Structures cluster were: Reporting or preparing progress data (≈ 45% at stage one which reduced to 13% at stage two) and understanding, reviewing or developing the design within Civils and Structures functional disciplines (≈ 21% at stage one which increased to 66% at stage two). This indicates a material change in the main purposes of communication towards more focus on design disciplines.

The sociograms of this cluster at both stages are illustrated side by side below. The key characteristics are described next.
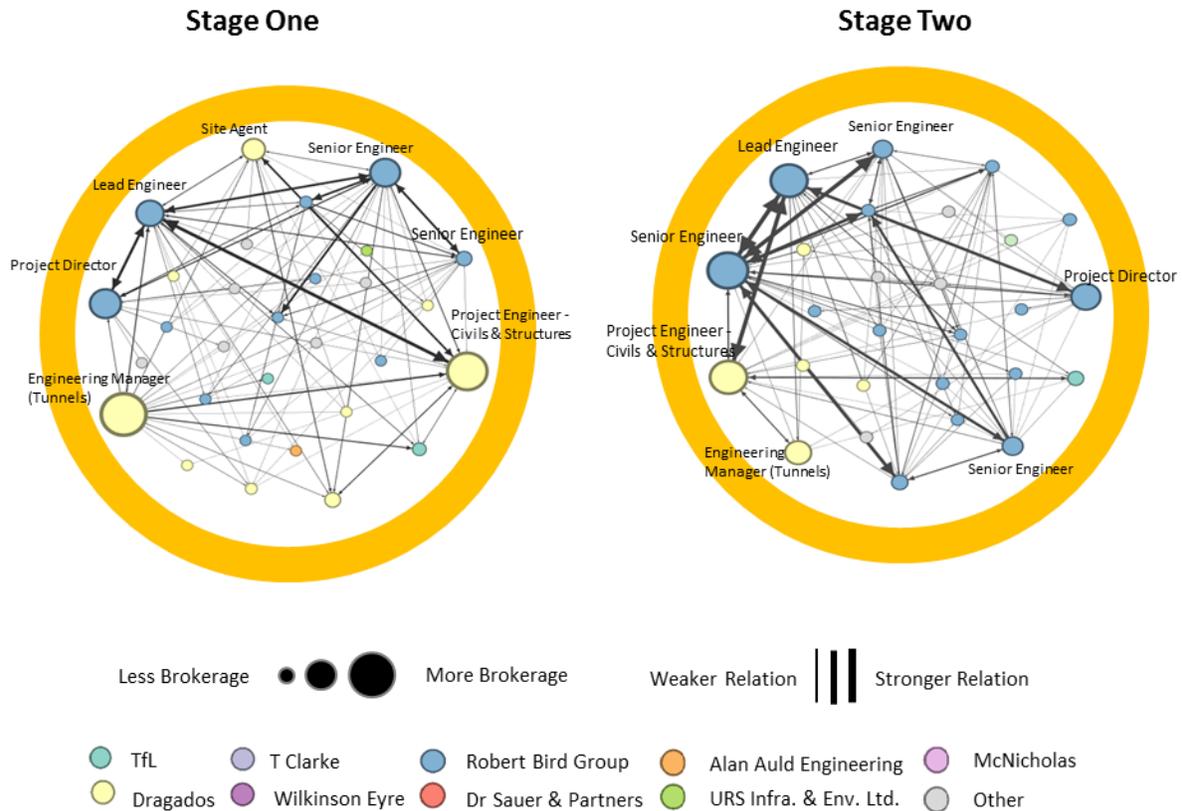
Figure 7.5: The Sociograms of Civils and Structures Cluster at Stage One and Stage Two of BSCU Project. Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Original)

Stage One:

At stage one (see Table 7.2), this cluster was the second largest by size (based on number of actors). It is less homogeneous than the Architectural Design and Management cluster. It is dominated by two organisations: Engineers from Robert Bird Group, a tier-two sub-contractor responsible for Civils and Structures, accounting for ≈ 37% of total actors, followed by actors from Dragados, the main contractor, at ≈ 30% of total actors. The remainder of actors belong to several sub-contract organisations. See Table 7.4 for data on clusters' composition. The cluster reported the highest level of communication activities (22% of the whole network) with inter-links:intra-links ratio of 69:31% respectively. Compared to other clusters, Civils and Structures was the second largest in terms of intra-links ratio (see Table 7.2). The TfL Project Manager explained this by stating:

'The civils designers had joined the project at the detailed design stage, so they probably didn't join until later on, in late 2014, maybe the summer of 2014, so they haven't been there that long, this could be part of the reason why they weren't well connected with the remaining of the network'.

It is observed that the Engineering Manager and Project Engineer from Dragados are the most prominent actors in this cluster followed by three actors from TfL team, namely: The Lead Engineer, Senior Engineer and Project Director. Compared to the rest of the team, the prominent actors exhibited strong ties among themselves, communicating in a reciprocal way. This implies creation of some degree of hierarchy or an elite group within the cluster.

Stage Two:

Compared to stage one, the size of this cluster reduced slightly at stage two (from 30 to 27 actors), i.e. 10% reduction. This was coupled with 20% increase in number of links. Referring to Equation 3.3, the denominator therefore decreased (driven by reduced number of nodes) and the numerator (number of ties) increased; both resulted in having higher density. Civils and Structures cluster is reported to be the second most dense cluster at stage two.

The cluster comprised mainly the earlier actors of stage one (74%) and had 7 new actors, out of which 4 were new hires, two were inter-transfers coming from BIM/CAD and additional one was an inter-transfer coming from Architectural Design and Management. Reduction in number of nodes involved three actors leaving the project and another 7 actors joining other clusters (majority, 5 actors, moved to Project Control and Management, e.g. Site Agent). It is worth highlighting that out of the 7 new actors, 5 were from Robert Bird; and out of the 10 leavers, 4 were from Dragados. The cluster therefore became more homogeneous at stage two with Robert Bird Group comprising ≈ 60% and Dragados comprising ≈ 19% of the cluster. See Table 7.4 for data on clusters' composition.

In terms of communication activity, the cluster maintained its external:internal communication at the same level of 30:70% (see Table 7.3). Robert Bird Group increased its number of actors at stage two. Its power was enhanced, thanks to the prominent positions of Lead Engineer, Senior Engineer and Project Director. Project Engineer (Civils and Structures) and Engineering Manager (Tunnels) from Dragados were still enjoying their prominence but at lower degrees.

The inspection of sociograms reveals that Robert Bird Group established stronger and reciprocal relationships between its team, especially among its prominent actors. This followed the increase in their prominence. The strong relationship between Lead Engineer (Robert Bird Group) and Project Engineer (Dragados) was maintained at both stages.

Decision-Making Strategies:

Distribution of the decision-making strategies between the two stages remained almost the same (see Figure 7.3). The main utilised strategy is repetition at 36% (at both stages), which usually represents routines in projects. This is followed by imitation at 31% (stage one), decreasing to 27% (stage two); and deliberation at 25% (stage one), increasing slightly to 27% (stage two). It can be said that there is reasonably a balanced distribution of these three decision-making strategies at both stages. They range from autonomous actions to social integration strategies. This finding indicates that actors, in response to the unique technical and organisational demands of BSCU project, were under pressure between continuing with the familiar relatively fast and low-cost routines (repetition) and devising and adopting different practices (deliberation and imitation).

7.4.3 Project Control and Management Cluster

The main purposes of communication in Project Control and Management cluster were: Reporting or preparing progress data (≈ 61% at stage one which reduced to ≈ 28% at stage two), reporting, monitoring or controlling cost information (≈ 15% at stage one which increased to ≈ 33% at stage two) and updating, modifying or controlling the schedule (≈ 6% at stage one which increased to ≈ 12% at stage two). The shift in communication purposes at stage two was caused by the process of gathering evidences/information for the TWOA. Although the latter was a client activity, much of the evidences/information to be collected for the public inquiry was to be provided by the contractor.

The sociograms of this cluster at both stages are illustrated side by side below. The key characteristics are described next.
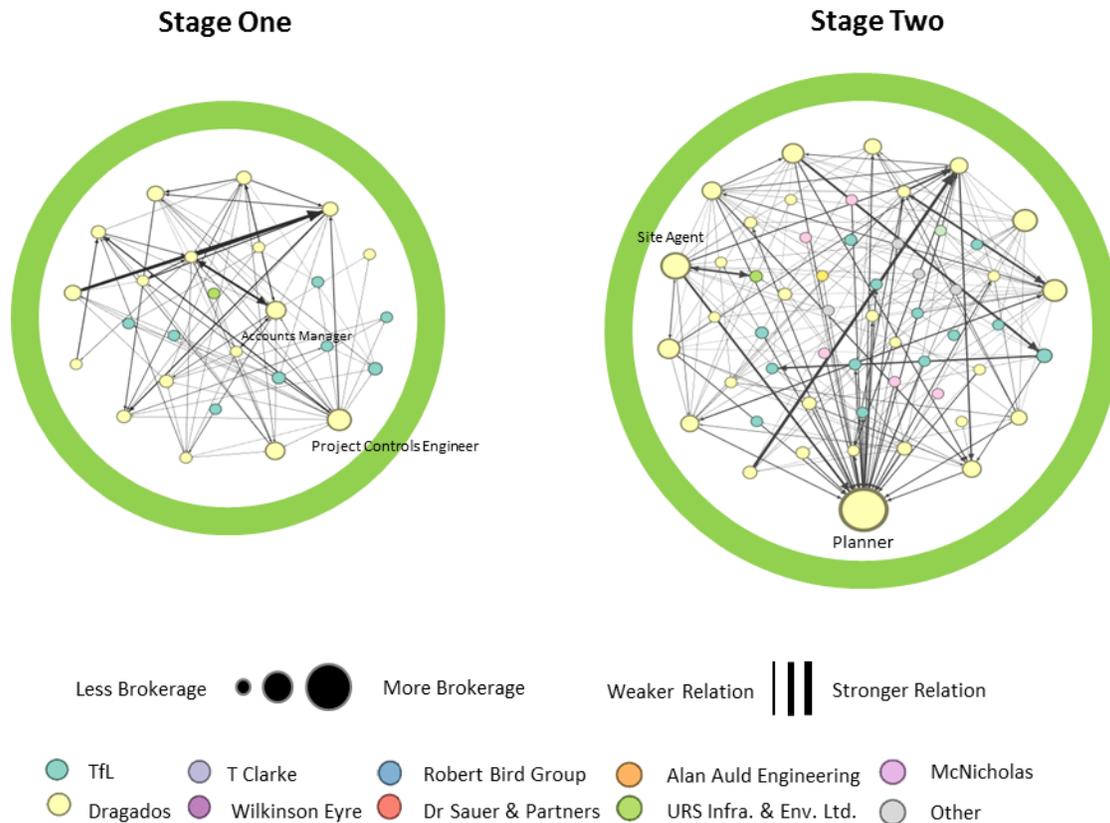

Figure 7.6: The Sociograms of Project Control and Management Cluster at Stage One and Stage Two of BSCU Project. Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Original)

Stage One:

This cluster was the third largest by size (based on number of actors) and had the second highest density value (see Table 7.2). It is quite homogeneous, being dominated by actors from Dragados (65%) followed by actors from TfL (31%). See Table 7.4 for data on clusters' composition. Contractually, it is expected that this cluster will be the primary group for communication activity given their managerial role. However, network analysis reveals that this was not the case; their communication activity represented only 16% of the whole network. Furthermore, their intra-links:inter-links ratio was the highest compared to other clusters at 37%:63%, suggesting highest score for an inward communication.

Communication in this cluster was predominantly conducted using weak ties, apart from couple of strong relationships between few of Dragados members. The Project Controls Engineer (from Dragados) was the most prominent actor. However, power is reasonably balanced across all the actors as evident by the narrow variation in prominence (represented by node size). Additionally, it is observed that three actors from TfL (out of 8 actors) were connected only to actors from Dragados team and not to any other TfL actors. This indicates high integration and that communication was quite targeted.

Stage Two:

Compared to stage one, the size of Project Control and Management cluster more than doubled from 26 to 54 actors (see Table 7.3). It ranked as the largest in terms of size. Referring to Equation 3.3, the denominator (driven by large number of nodes) outpaces the numerator (number of ties); hence this cluster reported the lowest density in stage two.

The cluster is still dominated by Dragados (54% of total actors), followed by TFL (24%). However, it is less homogenous given the inclusion of new actors from sub-contracting companies. Its actors of stage one represented only 41% of total actors at stage two, suggesting a major change in its composition. The cluster had a total of 32 new actors, mainly to help with completion of the public inquiry, out of which 15 were new hires and 17 were inter-transfers (6 were coming from Design Management, 5 from Civils and Structures, 4 from BIM/CAD, and 2 from Architectural Design and Management). See Table 7.4 for data on clusters' composition.

The level of communication of Project Control and Management cluster at stage two increased substantially (see Table 7.3). This is supported by 82% increase in number of links and, as a result, its communication activity was the second largest in the network (19%). Nevertheless, the cluster increased their internalisation of relationships in stage two. It is showing a tendency for an inward communication,

reporting the highest intra-links:inter-links ratio of 39:61%. The BSCU Project Manager explained such behaviour by stating:

> *'Well that's their weakness, it's a weakness for us as a team. There are some controlling going on there, so they are trying to control their entity, they are trying to say that you don't need to come in here, we are in control of this. This hides us from [the rest of the project team]. And afterwards this ends up breaking down because you need to be more open and share information'.*

This reflects that the Project Control and Management cluster was exerting control on the network; hence affecting the evolution of the self-organising network. As explained by the Project Manager, the behaviour of this particular cluster represents an inertia/resistance to change (Borgatti *et al.*, 2014; McMillan, 2006). It limited the system to few eventualities and responses. The Project Manager explained this further:

> *'The focus of the team on the public inquiry and submission of the TWAO had masked over an underlying inertia and lack of communication between the functional teams of the project'*

The structural changes in terms of size and communication activity were coupled with emergence of new prominent actors. This indicates increase in power inequality. The Planner (from Dragados) was noticeably the most prominent actor at this stage and mainly played a locally-focused coordinating brokerage role[58]. The cluster is dominated by weak ties but emergence of new strong ties is observed; for example, the Site Agent (the new inter-transfer actor, coming from Civils and Structures cluster at stage one) occupied a reasonably prominent position and maintained a strong cross-functional communication, leveraging on its previous relationships established at stage one.

Having said that, the behaviour of the Project Control and Management cluster, which was populated by the main contractor followed by the client (TfL), could be attributed to the adoption of ICE as a new project delivery approach. The cluster was significantly influenced by the 'hands-on' client approach justified by "*the need to mitigate risk, maintain the confidence of key stakeholders, and protect project and corporate reputation*" (TfL, 2014, p. 16). Acknowledging this entails accepting the fact that the project actors cultivated on their relationships to get the work done in response to uncertainty and

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[58] This is based on the analysis of Gould and Fernandez (1989) brokerage roles as explained in Chapter Three & Six.

complexity. This is because *"the project team were faced with the delivery of a new process and while the desired outcome was known, the team was embarking on a delivery route which was not only new to it, but had never been tried before by the organisation"*. (TfL, 2014, p. 16)

Decision-Making Strategies:

In terms of decision-making strategies (see Figure 7.3), repetition was the dominated strategy at both stages ($\approx$ 40%). This indicates a high level of 'routinised' behaviour, which is usually used as a tool to bring stability and enhance coordination and control in large construction projects (Becker, 2004). In practice, routines can be achieved, for example, by introducing predefined set of rules and/or checklists to minimise the margin of error (Addyman, 2013). This is particularly relevant to public sector projects (such as BSCU project) which are subject to high levels of audit and scrutiny (Addyman, 2013). The discussion with the TfL Project Manager supported this explanation, i.e. decision-making at BSCU project involved extensive use of predefined set of rules and/or checklists. He provided the below dialogue example between the management and the engineers, to describe the usual process of making decisions:

> *"[Management]: Our issue at a senior management and programme level is that design*
> *doesn't work; Are you sure it doesn't work?*
> *[Engineers]: yes;*
> *[Management]: Go on and do all those checks again".*

Interestingly, at stage two, the high level of routines was coupled with dominance of mainly a single prominent actor (Planner). In a project environment with complex information exchange, this suggests a high key person dependency risk and hence a relatively weaker decision-making structure. Pryke (2017) argues this risk could also cause 'dysfunctional prominence', i.e. the idea that an actor is prominent in a network for negative reasons such as the ability to filter, or control flow of information and hence manage, in some way, the outputs of other individuals.

On the other hand, deliberation was the second highest used strategy ($\approx$ 31% at stage one reducing to $\approx$ 26% at stage two). It reflects the extensive discussions between the client and contractor organisations to carefully determine the "best" perceived decision and act upon it.

The above findings demonstrate a cluster with a relatively high degree of social distance[59], which limits the ability of Project Control and Management to engage with other clusters and hence contribute actively into the co-creation process of the whole network. This is due to inadequate communication or interaction activity which was caused by the following characteristics: 1) a quite high inward communication; 2) excessive use of routines which increases iterations needed to resolve uncertainty; 3) a high level of deliberations which reflects a continuous churn of decisions; 4) majority of the actors at stage two (59%) are considered new, reflecting a high level of discontinuity and organisational changes; and 5) the cluster exhibits a milieu of 'dysfunctional prominence' centred around a single actor. The meeting of the joint management team took place on the 29th June 2015 highlighted the same issue, explaining that management were overwhelmingly focused on completion of the public inquiry and TWAO submission.

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[59] This refers to the level of acceptance or closeness an actor/group feels toward another actor/group. The distance ranges from intimacy to complete separation, i.e. no contact (Matthews and Matlock, 2011).

7.4.4 Design Management Cluster

The purposes of communication in Design Management cluster were dominated by: Reporting or preparing progress data (≈ 33% at stage one reduced to ≈ 11% at stage two); and understanding, reviewing or developing the design across functional disciplines to manage design interfaces (≈ 21% at stage one increased to ≈ 34% at stage two).

The sociograms of this cluster at both stages are illustrated side by side below. The key characteristics are described next.
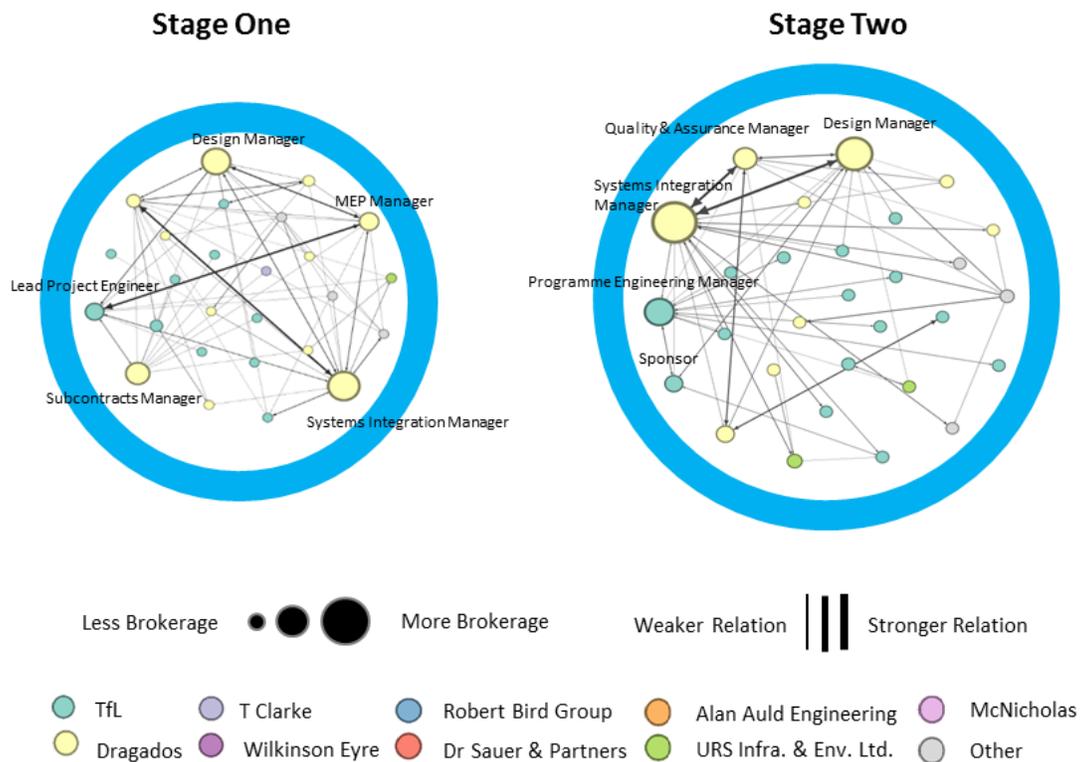

Figure 7.7: The Sociograms of Design Management Cluster at Stage One and Stage Two of BSCU Project. Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Original)

Stage One:

According to Table 7.2, Design Management cluster has the same size as that of Project Control and Management (26 actors) but with a lower density value (which is explained by fewer number of ties - see Equation 3.3). Design Management cluster has a quite fragmented composition with majority of actors belong to Dragados (≈ 42%) and TfL (≈ 38%). See Table 7.4 for data on clusters' composition. Its communication activity was the second largest in the network accounting for 19% of total relationships. Contrary to Project Control and Management cluster, Design Management cluster reported the highest inter-links:intra-links ratio of 75:25% in the network, suggesting a high outward/cross-functional communication activity.

Compared to other actors within the cluster, Dragados (the main contractor) occupied the most powerful positions in the network. All the top four prominent actors belong to Dragados, namely: Systems Integration Manager, Design Manager, Sub-contracts Manager and MEP Manager. The latter held a strong reciprocated tie with the most prominent actor from TfL (Lead Project Engineer for M&E Design). This can be attributed to the fact that both MEP Manager (Dragados) and Lead Project Engineer (TfL) were part of the core design-delivery team that was established at the bidding stage to develop the ICE process.

Stage Two:

The cluster size increased by three nodes, from 26 to 29 (see Table 7.3). It became more homogeneous at stage two, being dominated by actors from TfL (≈ 52%) and Dragados (≈ 31%). Its actors of stage one represented only 48% of total actors at stage two, suggesting a major change in its composition. The cluster had a total of 15 new actors, out of which 3 were new hires and 12 were inter-transfers (10 were coming from Architectural Design and Management, and 2 from BIM/CAD). See Table 7.4 for data on clusters' composition.

The level of communication activity of Design Management cluster at stage two increased by 27%, representing 15% of the whole network. Compared to stage one, it reported a higher outward communication activity with inter-links:intra-links ratio of 83:17% (see Table 7.3). The cluster was dominated by weak ties, and only few strong ties present among the prominent actors of Dragados.

The number of Dragados actors reduced from 11 to 9 whereas number of TfL actors increased from 10 to 15. While Dragados is still occupying the most powerful positions in the network, a shift in power is noticed. The main two prominent actors were from Dragados, namely: Systems Integration Manager followed by Design Manager; both were heavily involved in liaison brokerage roles, maintaining their earlier relationships with MEP Manager and Sub-contracts Manager who moved to Project Control and Management cluster and M&E cluster respectively. TfL gained some power at stage two thanks to the newly added actor, the Programme Engineering Manager, who was engaged in reciprocated communication with almost all other TfL members.

Interestingly, TfL nodes were centred around a single prominent actor, Programme Engineering Manager, forming a configuration resembling a 'hub-and-spoke' typology. This configuration is frequently seen where contractual relationships are represented and it is commonly used where the client leads in managing the supply chain (Pryke, 2017). It is of a low density because almost every node is connected to only one central actor, i.e. ties among the other nodes are limited. Therefore, when the central actor is removed, TfL network of this cluster is almost dissolved and nodes become isolates or at best they form dyads. However, this gives rise to 'dysfunctional prominence', i.e. routing all information flows through Programme Engineering Manager leads to an excessive control over the outputs of others. This also means unfair distribution of network prominence where other actors have low prominence because they are not connected to other nodes and the central actor has short links to all other nodes.

Decision-Making Strategies:

This cluster is concerned with managing design-related issues. It exhibited high levels of both repetition and imitation at both stages (see Figure 7.3). As highlighted earlier under Project Control and Management cluster, repetition strategy (36% at stage one and 28% at stage two) can be explained by the extensive use of checklists, which are commonly used tools for managing large projects to ensure everything is planned properly. High levels of repetition can also be explained by the fact that this cluster consisted of actors from the core design-delivery team who followed an early engagement approach. In this context, it is expected that large number of issues were pre-addressed, i.e. adopting repetition strategy implies that previous decisions were reinforced again. High level of imitation (33% at both stages), on the other hand, can be explained by the varying degrees of power (prominence) observed in the cluster, which gives rise to information asymmetry. That is, ill-informed actors usually imitate those actors who possessed a greater level of time-sensitive information.

Design Management cluster exhibited moderate levels of both deliberation and social comparison. Deliberation ($\approx$ 20% at both stages) used mainly to optimise decisions and work towards development of mutual agreement. This is an essential strategy to resolve design issues. However, social comparison strategy was 10% at stage one but almost doubled to 19% at stage two. The increase in adopting social comparison strategy was demonstrated mainly by TfL actors. This can be attributed to their 'hub-and-spoke' typology that makes the actors at the end of each spoke having a low degree of prominence but yet centred around a single prominent actor (hub). Such differentiation between the hub and spoke nodes requires exercising a high degree of social process (i.e. the nodes need to route information through the central actor rather than establishing direct and shorter paths between them).

Similar to Project Control and Management cluster, Design Management cluster exhibited 'dysfunctional prominence'. This was observed by having a high level of routines coupled with dominance of a single actor, Programme Engineering Manager, in TfL communication network. In a project environment with complex information exchange, this suggests an increase in iterations with high key person dependency risk and hence a relatively weaker decision-making structure.

7.4.5 M&E Design Cluster

The main purposes of communication in M&E Design cluster were: Reporting or preparing progress data (≈ 33% for both stages of BSCU project); understanding, reviewing or developing the design within M&E Design functional disciplines (≈ 39% at stage one increased to ≈ 42% at stage two).

The sociograms of this cluster at both stages are illustrated side by side below. The key characteristics are described next.
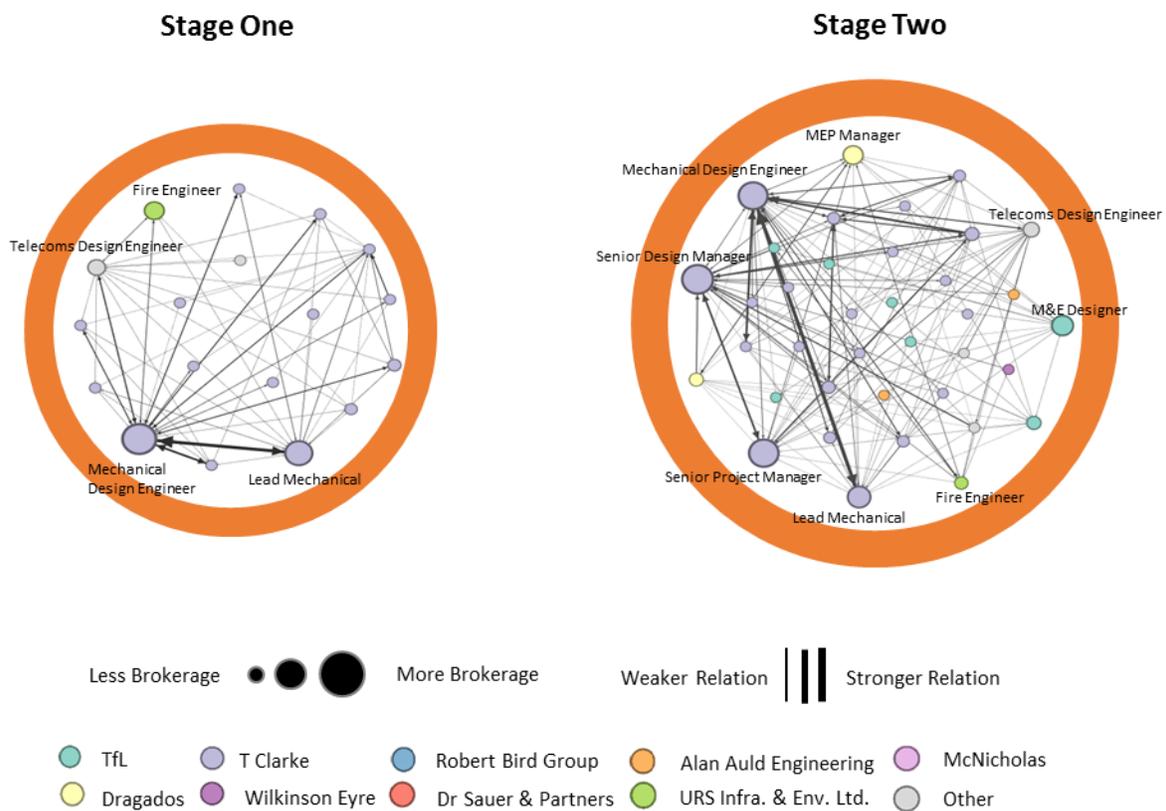
Figure 7.8: The Sociograms of M&E Design Cluster at Stage One and Stage Two of BSCU Project. Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Original)

Stage One:

This cluster was the third smallest by size (based on number of actors - see Table 7.2) and had the most homogenous composition compared to the rest of the clusters. Number of actors was 18, out of which 15 actors (i.e. ≈ 83%) belong to T Clarke, the sub-contractor responsible for the Mechanical, Electrical and Public Health (MEP) works. See Table 7.4 for data on clusters' composition. M&E Design cluster had the highest density value in the network, which can be explained by the small number of nodes and relatively large number of ties (see Equation 3.3).

In terms of communication activity (see Table 7.2), the cluster reported the third highest intra-links:inter-links ratio of 30:70%, suggesting a focus towards inward communication. This could be attributed to the specialised nature of the function and the fact that M&E design team was established towards the end of stage one, i.e. they were still in the process of getting to know each other and integrating into the project (Pryke *et al.*, 2017). TfL Project Manager reflected on the graphs saying:

> '*The M&E people, if I can recollect properly, as individuals they weren't connected very well with the other teams in the project, they struggled'.*

> And he continued to provide an explanation to this:

> '*We asked the M&E to do a design and build, whereas traditionally they just do the build. They do design and build, but normally in commercial building environment not in a public transport environment. So, a lot of their staff were contract staff and haven't necessarily worked together before, that's why they were less connected with other teams'.*

The sociogram of stage one exhibits unfair distribution of network prominence among the actors of M&E Design cluster. The Mechanical Design Engineer followed by the Lead Mechanical were the two most prominent actors and were having the strongest reciprocated intra-cluster relationships.

Stage Two:

In stage two of the project, M&E Design cluster underwent a major change in terms of its size, composition, and communication activity. That is, number of actors more than doubled from 18 to 37 (see Table 7.3). It ranked as the second largest in terms of size. Referring to Equation 3.3, the denominator (driven by large number of nodes) outpaces the numerator (number of ties); hence this cluster reported reduced density value. While the cluster is still dominated by T Clarke, its share diluted to ≈ 57% due to adding 19 new actors, out of which 9 actors were new hires and 10 were inter-transfers (mainly joining from Design Management, contributing 5 actors; and Architectural Design and Management, contributing 3 actors). It is worth highlighting that all the actors of stage one remained at the same cluster, i.e. without moving to another cluster or leaving the project. In terms of organisational affiliation, the new actors joined mainly from TfL, which represented ≈ 19% of the cluster composition. See Table 7.4 for data on clusters' composition.

As the project made more progress, M&E cluster at stage two was more connected. Following the increase in its number of actors, the cluster reported a substantial increase in its communication activity, becoming the leading one in the network with a share of 21% in terms of number of relationships. Nevertheless, it is still showing a tendency for an inward communication, reporting the second highest intra-links:inter-links ratio of 33:67% (see Table 7.3). The structural changes in terms of size and communication activity were coupled with emergence of new prominent actors. The top three prominent actors belong to T Clarke, namely Mechanical Design Engineer, Senior Design Manager and Senior Project Manager. It is also observed that weak ties were dominating the communication, but few strong ones emerged at this stage. The key one, however, was between Lead Mechanical and Mechanical Design Engineer, which was carried over from stage one.

Decision-Making Strategies:

The above Project Manager quotation suggests that members of M&E Design cluster were working on a temporary basis (i.e. contract staff) and lacking relationship history. This usually gives rise to autonomous actions and/or reliance on direct instructions, both of which are considered the simplest way of making decisions, involving low cognitive effort. This explains why actors of this cluster predominantly followed repetition strategy which was 39% at stage one and 33% at stage two (see Figure 7.3).

Deliberation strategy was also used considerably (26% and 29% at stage one and stage two respectively). This is justified in view of the large number of new joiners who usually require higher levels of coaching and supervision. As number of actors increases, the conflicts/politics between them also increase; for example, in terms of their organisation affiliation and/or competition for allocation of resources. Deliberation, therefore, plays a crucial role in order to minimise any conflicts and increase mutual understanding. Such strategy is also helpful in synergising various efforts to resolve a specific problem, e.g. developing the M&E alternative designs in response to the issue of the pile clashes and changes in the shaft structure.

Imitation strategy was at the level of ≈24% at both stages. The high use of this strategy can be attributed to the fact that majority of M&E Design actors were hired for short tenures (i.e. contract staff) with the aim to complete ad-hoc tasks within agreed timeframes. Thus, under high levels of uncertainty, they did not have the sufficient time/courage to challenge the existing arrangements.

Social comparison strategy was moderate at the level of ≈14% at both stages. High level of differentiation between actors breeds social comparison (Jager and Janssen, 2003). This can be caused by different factors, such as variation in prominence/power. High levels of differentiation pose challenges to project managers, especially in situations where high levels of uncertainty prevail. It places pressure on 'self-organising' project function-related clusters to deal with increased demands for information and coordination. Actors, therefore, will often resort to social comparison to put additional cognitive effort in order to optimise their decision-making.

7.4.6 BIM/CAD Cluster

Actors of BIM/CAD cluster classified the following as their main purposes of communication in stage one: Reporting or preparing progress data (≈ 44%), and submitting, retrieving or analysing design and survey data (≈ 41%). Given the shift in focus, the main purposes of BIM/CAD cluster changed in stage two to the following: understanding, reviewing or developing the design within BIM/CAD functional disciplines (≈ 33%) and understanding, updating or developing work process (≈ 33%).

The sociograms of this cluster at both stages are illustrated side by side below. The key characteristics are described next.
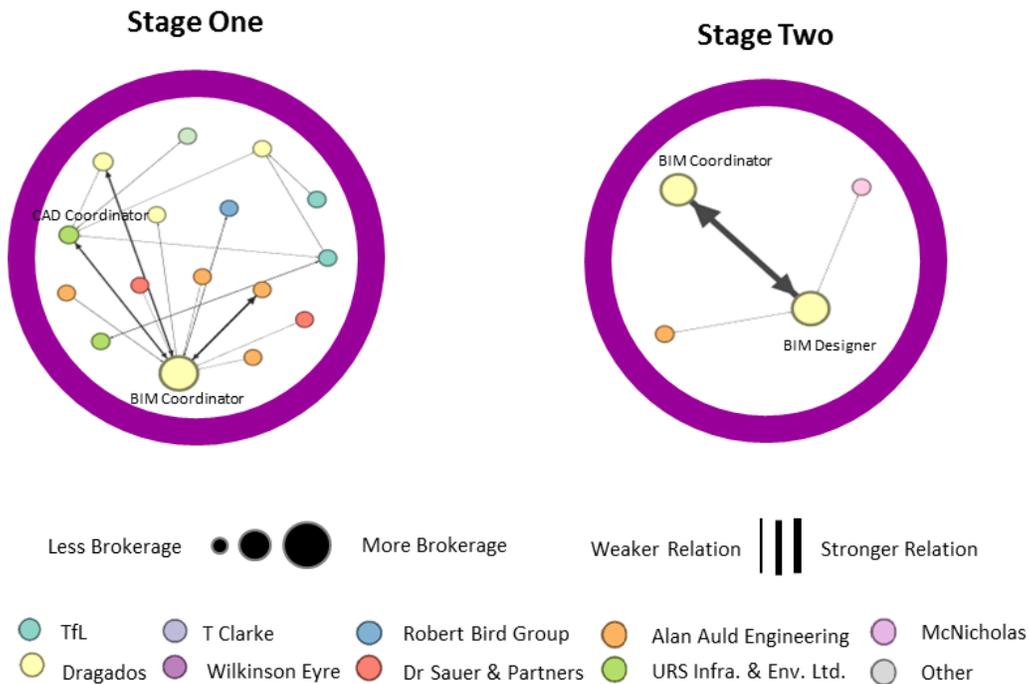

Figure 7.9: The Sociograms of BIM/CAD Cluster at Stage One and Stage Two of BSCU Project. Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Original)

Stage One:

BIM/CAD was the second smallest cluster by size (16 actors - see Table 7.2). It also had the penultimate value in both density and communication activity. It had the most fragmented composition in the network with majority of its actors belong to the main contractor, Dragados (≈ 25%), and Alan Auld Engineering (≈ 25%), the organisation responsible for the detailed design of the tunnels and shafts. See Table 7.4 for data on clusters' composition.

Interestingly, the cluster reported the highest inter-links:intra-links ratio of 79:21% (see Table 7.2). The latter implies an outward focus in communication. This reflects the specialised nature of the cluster that provides on-demand professional services, that are complementary to the work of other clusters.

The BIM Coordinator from the contractor organisation (Dragados) was the most prominent actor and he played the role of Representative/Gatekeeper[60], i.e. managing the communication process of the cluster with the rest of the network. This indicates potential of 'dysfunctional prominence', i.e. by way of information bias, hoarding, filtering and controlling.

Stage Two:

Compared to stage one, the size of BIM/CAD cluster decreased significantly, comprising of four actors only (see Table 7.3). It was the smallest cluster in the whole network. Referring to Equation 3.3, as number of nodes reduces significantly, the denominator starts underperforming in a way that cannot be counterbalanced by the numerator (number of ties); hence this cluster reported the highest density value in the network. In terms of organisational affiliation, two of the actors belong to Dragados, one belongs to Alan Auld Engineering and another one belongs to McNicholas. The latter actor was a new hire whereas the others were already part of BIM/CAD cluster in stage one. See Table 7.4 for data on clusters' composition.

Given its small size, BIM/CAD reported the lowest communication activity (see Equation 3.2). The cluster reported only 3% of the whole network's communication activity. Its inter-links:intra-links ratio, however, was the highest at 95:5% (see Table 7.3), suggesting a focus on outward communication. Reflecting on the results, the TfL Project Manager highlighted that: '*BIM/CAD usually do more in stage two [compared to stage one]. This is in response to the shortage in resources and continued program delays'.*

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[60] This is based on Gould and Fernandez (1989) brokerage analysis as explained in Chapter Three and Six.

In terms of power, BIM Coordinator maintained its prominence. However, BIM Designer emerged as a new prominent actor in the cluster. Both of them belong to Dragados and had a strong and reciprocal relationship between themselves.

The cluster reduced by 13 actors (81%) between stage one and stage two of the project. Only two of them left the project, but 11 joined other clusters (4 actors joined Project Control and Management, 2 actors joined Civils and Structures, 2 actors joined Design Management, 2 actors joined Tunnelling Design, and one actor joined M&E Design). This suggests a substantial change in the composite of BIM/CAD cluster.

Decision-Making Strategies:

The low intra-cluster connectivity of BIM/CAD cluster indicates that most actors rely on other clusters to execute their work, i.e. the decisions made in this cluster was mainly influenced by other actors or decisions made in other clusters. This explains why actors predominantly followed repetition strategy (44% and 33% at stage one and stage two respectively) and imitation (26% and 33% at stage one and stage two respectively). See Figure 7.3 for these data on decision-making strategies.

The increase externalisation of links of the BIM/CAD cluster at stage two can be attributed to the implementation of the 3D Clash Detection Review[61]. It involved arranging fortnightly design coordination meetings with other clusters in order to identify key outstanding interface issues. This co-contribution approach also explains the increase in deliberation strategy between stage one and stage two (19% and 33% respectively).

The use of social comparison strategy at stage one (11%) can be attributed to the high level of differentiation between the actors (e.g. in terms of their fragmented organisational affiliations and the fact that the intra-flow of information is tightly controlled by a single prominent actor). Interestingly, social comparison strategy was not used at stage two. This is because the small number of actors limits the cluster capacity in using costly/sophisticated strategies such as social comparison. Additionally, the high inter-links (95%) coupled with a high-density value indicates a higher level of integration; hence it obviates the need to invest large cognitive efforts for information gathering.

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[61] Clash detection allows effective identification and reporting of interferences (clashes) in a 3D project model. Hence, it aims at reducing errors through the 3D design coordination and enhances the quality of the BIM model before construction begins (Akponeware and Adamu, 2017).

Stage one had a single prominent node in a cluster of 16 actors whereas stage two had two prominent nodes in a cluster of just 4 actors. This structural change towards reduction in number of actors and increase in prominence reduces the disproportional concentration of power and hence it enhances the probability of coordination and dissemination of information being achieved.

7.4.7 Tunnelling Design Cluster

The main purposes of communication in Tunnelling Design cluster were: understanding, reviewing or developing the design within Tunnelling Design functional disciplines (≈ 66% at stage one and ≈ 63% at stage two); and understanding, reviewing or developing the design across functional disciplines to manage design interfaces (≈ 13% at stage one increased to ≈ 19% at stage two).

The sociograms of this cluster at both stages are illustrated side by side below. The key characteristics are described next.
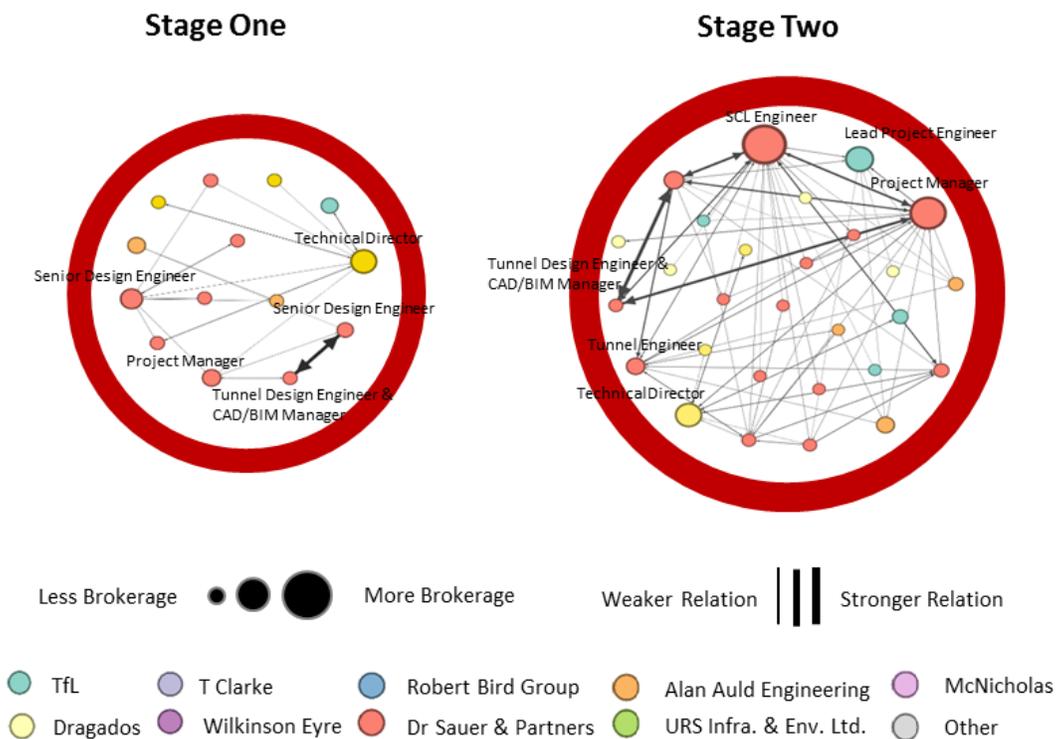
Figure 7.10: The Sociograms of Tunnelling Design Cluster at Stage One and Stage Two of BSCU Project. Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Original)

Stage One:

Tunnelling Design cluster was the smallest in the whole network (14 actors only) and reported the lowest communication activity (see Table 7.2). It was dominated by actors from tier-two tunnelling sub-contractors, Dr Sauer and Partners (≈ 57%). The actors were mostly focused on tunnelling design, geotechnics and utilities design disciplines. See Table 7.4 for data on clusters' composition.

As illustrated in the sociogram, the nodes of stage one have relatively the same size. That is, the nodes of prominent actors, compared to others, were just slightly larger in size. This indicates a reasonably even distribution of power. Nevertheless, the most prominent actors were Technical Director for geotechnics (belongs to tier-three subcontractor) followed by Senior Design Engineer (from Dr Sauer and Partners). It is also noted that a reciprocated strong relationship formed between two tunnelling design engineers (both from Dr Sauer and Partners), which suggests a high level of trust between these two actors.

Stage Two:

The size of Tunnelling Design cluster doubled at stage two, reaching 28 actors (see Table 7.3). All the actors of stage one remained at the same cluster, i.e. without moving to another cluster or leaving the project. They represented 50% of total actors at stage two. The new 14 actors consisted of 7 new hires and 7 inter-transfers (mainly coming from BIM/CAD and Civils and Structures). This cluster continued to be dominated by actors from Dr Sauer and Partners (50%). In terms of organisational affiliation, stage two had additional actors from the client organisation (TfL) and main contractor (Dragados) with each having 4 actors. See Table 7.4 for data on clusters' composition.

Following the increase in its number of actors, the cluster reported a substantial increase in its communication activity. The number of its relationships increased by 2.7 times (from 112 relationships at stage one to 413 relationships at stage two). The structural changes in terms of size and communication activity were coupled with a higher variation in prominence. The Sprayed Concrete Lining (SCL) Engineer followed by the Project Manager for Tunnelling Design were the most prominent actors in this cluster – both were playing a gatekeeping/representative role. The communications were dominated by weak ties, except those between Dr Sauer and Partners prominent actors and the one carried over from stage one (between Tunnel Design Engineer and Senior Design Engineer).

Decision-Making Strategies:

Despite the structural changes introduced at stage two, the cluster maintained almost the same distribution of decision-making strategies (i.e. Repetition ≈ 37%; Imitation ≈ 25%; Deliberation ≈ 25%; Social Comparison ≈ 13%). See Figure 7.3 for these data on decision-making strategies. This is coupled with almost unchanged intra-links:inter-links ratio which reported outward links at 70%+ at both stages, indicating a focus on cross-functional communication. This reflects the fact that Tunnelling Design cluster (mainly sub-contractors) provides outsourced services to other clusters in the network. The TfL Project Manager reflects on this by saying:

> *'The tunnelling contractor was quite mature in doing tunnelling projects on London Underground. They worked on previous London Underground station projects and still working on some of them as part of the development programme'.*

In complex projects, where the product of the project is essentially unique (having never been produced before), the mix use of strategies reflects that actors are under pressure. Actors usually resort to routines in order to comply with contract conditions and project protocols, but at the same time the unique nature of complex projects demands adaptability in these routines. In terms of decision-making strategies, this conflict translates into an interplay between the desire of adopting autonomous actions (repetition) and/or cultivating social relationships.

Similar to BIM/CAD, Tunnelling Design cluster is responsible for provision of specialised services. Custom and practice within certain professional and practice groups, especially which perform unique duties, conspire to marginalise social comparison. This is because delivery of these groups is subject to strict time, cost and specification constraints, which are further exacerbated by involvement of many contract employees. Social comparison strategy is therefore restricted since it requires a high level of resources to be invested.

At the end of the intra-cluster analysis, the following question is posed: *how these different self-organising project clusters fit together?*

Exploring this question is essential to understand how coordination emerges in networks from segregated and transient clusters. This is analysed next.

7.5 Inter-Cluster Relationships: Development of Functional Themes

In previous section, the network nodes were grouped based on their distinctive interaction patterns, classified by project functions. This is a problem-solving-based classification. Pryke (2017), however, highlights that unlike some other areas of social network study, the large infrastructure projects are not just multi-disciplinary but also multi-functional. This extends the concept of community detection in networks beyond the clusters of individuals, which are regarded as 'mono-functional'. This type of multi-functional communities is dubbed "networks within networks" (Pryke, 2017, p. 147) or sometimes 'functional themes' (Pryke *et al.*, 2018). They usually co-exist simultaneously within a network, taking into consideration the interactions between the individual clusters (Pryke, 2017). Putting multi-level terminologies onto this concept, it is usually referred to as the creation of meso-level structure (Tunç and Verma, 2015; Jeub *et al.*, 2015), which forms the core of communication networks and serves as the link between local and global levels. The investigation of this structure in project networks can reveal how coordination emerges, as a function of the underlying processes of distinct clusters and their cross-functional communication (Tunç and Verma, 2015). It helps in the identification of the underlying hidden project-delivery structure of a network. That is, how projects deal with complex tasks, leveraging on various interdependent and sometimes conflicting functions.

Building on the earlier results which detected seven self-organising clusters, the functional themes emerged from BSCU project will be identified by examining the inter-cluster relationships. Different clusters can be grouped under the same functional theme based on how strong the relationships between them are. For this purpose, an adjacency matrix of the inter-cluster relationships is produced for each stage of BSCU project. This is a 7X7 matrix, where the names of columns and rows are identical, arranged by the names of identified self-organising clusters. The intersection of a row and a column represents the number of inter-cluster interactions between the corresponding clusters. The diagonal values are the interactions between a cluster and itself; hence these are set at zero since they represent the intra-cluster interactions, i.e. no inter-cluster interactions/self-loops exist. Table 7.5 presents the adjacency matrix for stage one whereas Table 7.6 presents the adjacency matrix for stage two. Microsoft Excel was used to produce the Heat Maps of these inter-relationship matrices. This functionality applies a colour gradient (Green-Yellow-Red scale) to a range of cells, based on their values. The colour indicates where each cell value falls within the range; hence Heat Maps makes it easy to spot the maximum and minimum values. Clusters are paired if they have high inter-relationship values among them (this will be highlighted in green and circled on the Heat Map).

Cluster Function	Architectural Design and Management	Civils and Structures	Project Control and Management	Design Management	M&E Design	BIM/CAD	Tunnelling Design
Table 7.5: The Heat Map / Pairing Matrix of Stage One (Source: Original)							
Architectural Design and Management	0	**97**	24	78	**77**	16	13
Civils and Structures	**97**	0	77	58	49	28	30
Project Control and Management	24	77	0	**92**	17	10	9
Design Management	78	58	**92**	0	47	19	21
M&E Design	77	49	17	47	0	22	3
BIM/CAD	16	28	10	19	22	0	4
Tunnelling Design	13	30	9	21	3	4	0
Pairing Result	Architectural Design and Management + Civils and Structures	Civils and Structures + Architectural Design and Management	Project Control and Management + Design Management	Design Management + Project Control and Management	M&E Design + Architectural Design and Management	No Pairing	No Pairing

- **Group One:** Architectural Design and Management + Civils and Structures + M&E Design

- **Group Two:** Project Control and Management + Design Management

- **Group Three (No Pairing):** BIM/CAD + Tunnelling Design

Strong Pairing   No Pairing

Cluster Function	Architectural Design and Management	Civils and Structures	Project Control and Management	Design Management	M&E Design	BIM/CAD	Tunnelling Design
Table 7.6: The Heat Map / Pairing Matrix of Stage Two (Source: Original)							
Architectural Design and Management	0	66	41	79	**126**	18	26
Civils and Structures	66	0	**96**	72	87	18	78
Project Control and Management	41	**96**	0	92	86	21	67
Design Management	79	72	92	0	117	18	63
M&E Design	**126**	87	86	**117**	0	25	54
BIM/CAD	18	18	21	18	25	0	12
Tunnelling Design	26	78	67	63	54	12	0
Pairing Result	Architectural Design and Management + M&E Design	Civils and Structures + Project Control and Management	Project Control and Management + Civils and Structures	Design Management + M&E Design	M&E Design + Architectural Design and Management	No Pairing	No Pairing

- **Group One:** Architectural Design and Management + M&E Design + Design Management

- **Group Two:** Civils and Structures + Project Control and Management

- **Group Three (No Pairing):** BIM/CAD + Tunnelling Design

Strong Pairing   No Pairing

The functional themes are the outcome from the process of pairing detection between BSCU self-organising clusters. A cluster is paired with another one in the network if the Heat Map highlights their inter-relationship value in green (i.e. they have a strong inter-relationship) and it was the maximum within its range (i.e. the corresponding column and row). A value with a colour other than green suggests the corresponding clusters have no strong inter-relationship; hence lack of pairing.

The corresponding matrices at both stages reveal an emergence of a 'meso-structure', consisting of three distinct functional themes in which the clusters are nested within them. These themes combine actors from a range of diverse disciplines and found to be organised around the highly prominent nodes within the network. They were validated with the Project Manager and their names came about in consultation with him, as follows:

- **Design Group:**

  This is the largest functional theme at both stages because the design change was identified during this time and the alternative proposals were being finalised. It represents 49% and 43% of total actors and 54% and 48% of total communication activity (at stage one and stage two respectively). It is made up mainly of design engineers who engaged in gathering and dissemination of information to deal with daily tasks.

  At stage one, this theme included the following clusters: Architectural Design and Management, Civils and Structures, and M&E Design. TfL Project Manager reflects on this by saying:

  'Looking to the integration and connectivity between the architects and the civils and the M&E, alright these guys are really speaking one to another, there isn't someone disturbing that communication. They are sitting closer together in the network, the circles are in sensible sizes, the ties between them were odd normally, but generally we sounded like ok'.

  At stage one, this theme was led by three prominent actors (based on their betweenness centrality scores), namely: Engineering Manager (from Tunnels; belongs to Dragados), Project Engineer (from Civils & Structures; belongs to Dragados), and Lead Premises Engineer (TfL). Actors from the Civils and Structures cluster, therefore, were more central in the design theme. This is justified given the structural-related issues encountered at this stage.

At stage two, Civils and Structures moved to another theme and it was replaced by Design Management. The movement of Design Management to this theme at stage two was supported by having 10 inter-transfer actors coming from Architectural Design and Management (at stage one) and joining Design Management (at stage two). This suggests the inter-relationships are path-dependent (i.e. stemming from pre-existing/historical relationships). At stage two, prominent actors were Lead Premises Engineer (TfL), Systems Integration Manager (Dragados), and Lead Architect (Wilkinson Eyre).

Interestingly, the actors of M&E design cluster, at both stages, were classified under Design Group rather than Special-Functions Group. This means they were heavily involved in gathering information resources and disseminating information resources created. The BSCU Project Manager attributes this finding to the fact that:

'the architects and M&E had been involved since tender stage, so they have been working much closely together, they knew each other better. And the client was quite well integrated into those organisations'.

- **Decision-Making Group:**

  This is a smaller group than the 'design' group and with actors of lower prominence. It represents 32% and 41% of total actors and 35% and 36% of total communication activity (at stage one and stage two respectively). It is made up mainly by actors from the client/sponsor organisation (TfL) and the main contractor (Dragados), i.e. senior management. They engaged in strategy formulation and providing necessary direction for problem-solving. The increase in size (i.e. number of actors) can be attributed to putting a larger team together to complete the statutory TWAO process.

  At stage one, this theme included the following clusters: Project Control and Management, and Design Management. At stage two, however, Design Management moved to another theme and it was replaced by Civils and Structures. The pairing of Civils and Structures with Project Control and Management under this theme at stage two was supported by transferring 5 actors from Civils and Structures to Project Control and Management.

At stage one, the Design Management cluster dominated communications in the decision-making theme. This theme was led by the prominent actors Systems Integration Manager (Dragados), Design Manager (Dragados), and Subcontracts Manager (Dragados). At stage one, however, this theme was led by the prominent actor from project controls, Planner (Dragados).

At stage two, the Project Control and Management cluster put itself in a central position in the overall project communication network. This is due to the nature of the issues encountered in stage two, related to the completion of design changes, the implementation of construction sequence changes into the programme. Additionally, this is also attributed to the change in focus to concentrate on getting the statutory planning approvals through a Transport and Works Act Order (TWAO) application that was subject to a public inquiry. The granting of the TWAO itself was a significant turning point in the project as delivery (construction) works could not commence without it. This was mainly a control and management task, and in this case, it was mainly managed by this self-organising cluster.

- **Special-Functions Group:**
  This is the smallest of the themes. It represents 19% and 16% of total actors and 11% and 15% of total communication activity (at stage one and stage two respectively). It is made up mainly by actors from the tier-two and tier-three sub-contractors. They engaged in processing information to provide outsourced specialised services to other clusters in the network.

  At both stages of BSCU project, this theme included the following clusters: BIM/CAD and Tunnelling Design. At stage one, it is led by the prominent actors BIM Coordinator (Dragados) and Technical Director (Hyder Consulting). However, at stage two, SCL Engineer (Dr Sauer & Partners, for Tunnelling Design) led the theme.

It is important to note that this meso-scale structure and its constituents (i.e. the seven self-organised communities nested within the three themes) are a function of the self-organising activities of project actors. This is to say that they are not procured by the client in any contractual sense but emerge in response to complexity and uncertainty, which are exacerbated by operating under financial and time constraints (Pryke, 2017).

While network topologies are unique, context-specific and differ from one project to another, Pryke (2017) suggests that functional themes of design phase are quite ubiquitous and would be particularly relevant where the project extends over a long period. The idea of breaking project settings into distinct themes is therefore rather appealing. This is because it implies that there is a potential to identify, replicate and manage these themes on other projects. This, therefore, can lay the groundwork for introducing specific managerial interventions to deal with the complex interdependent activities, e.g. designing better contracts and addressing issues within the relationships that deliver project outcomes.

This structure for design multi-functional trinity for stage one and stage two of the BSCU project is presented in Figure 7.11 and 7.12 respectively. These figures were produced using the Network Splitter 3D layout in Gephi (Barão, 2014) and involved a re-arrangement of the clusters. The Network Splitter 3D layout adds a third vertical dimension (z-axis) to the graph, making it possible to display a network beyond a simple x, y space (Barão, 2014). It is used to split a network into distinct functional groupings or sub-layers along a vertical axis. In these figures, the size of the nodes corresponds to the degree centrality of an actor and the ties represent communication activity between the nodes. Similar to the earlier graphs, ties were weighted by communication strength. A colour gradient was also applied to distinguish between the three main functional themes.

Tunnelling Design

BIM/CAD

3 Special Functions

Project Control and Management

2 Decision Making

Design Management

M&E Design

I Design

Civils and Structures

Architectural Design and Management

Less Degree ● ● ● More Degree   Weaker Relation ||| Stronger Relation
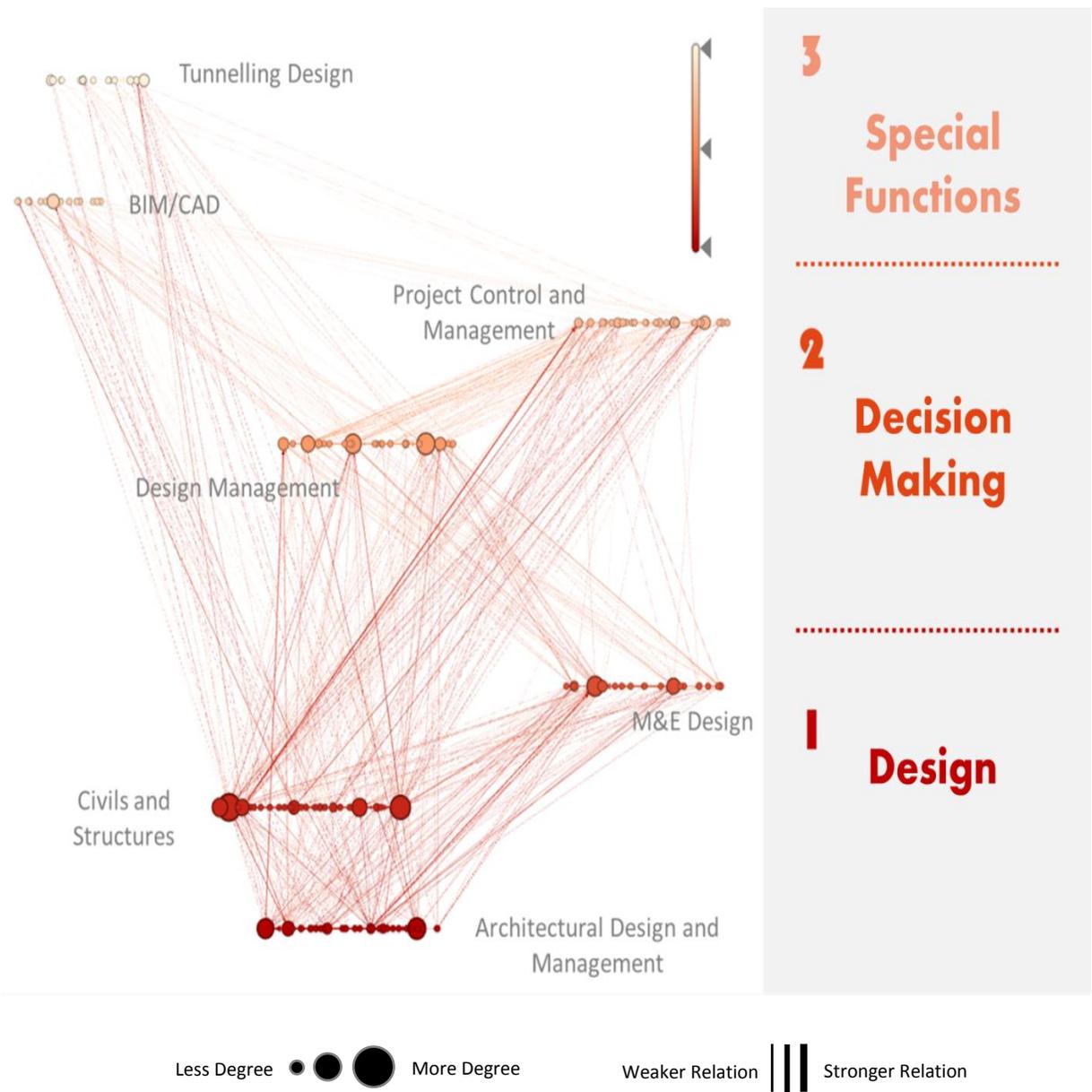
Figure 7.11: Stage One - Community Structure Split on the Z-axis Based on the Three Project Functional Communication Themes. Nodes are Sized by Degree Centrality.
(Source: Original)
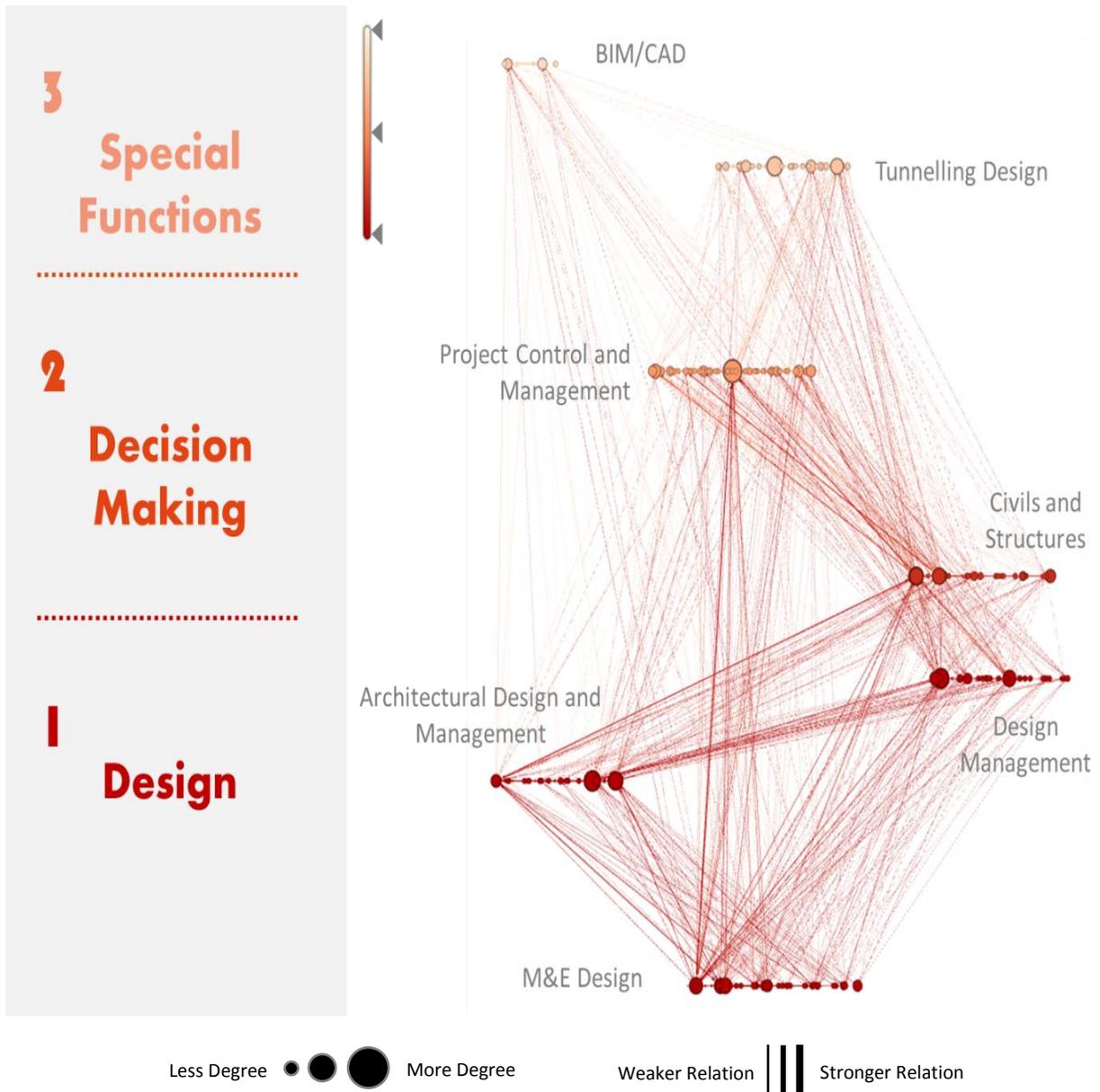
Figure 7.12: Stage Two - Community Structure Split on the Z-axis Based on the Three Project Functional Communication Themes. Nodes are Sized by Degree Centrality.
(Source: Original)

Less Degree ● ● ● More Degree

Weaker Relation ||| Stronger Relation

3 Special Functions

2 Decision Making

1 Design

BIM/CAD

Tunnelling Design

Project Control and Management

Civils and Structures

Architectural Design and Management

Design Management

M&E Design

A simplified depiction of the functional themes is shown in Figure 7.13. This displays the transition between stage one and stage two, highlighting how various clusters are grouped under their respective themes. For the sake of simplicity, clusters in this figure are presented by highlighting number of their nodes only, i.e. without giving reference to centrality measures or illustrating the inter- and intra- ties. The focus is on defining the boundaries of functional themes and how these changed between the two stages.

As the project moves from stage one to stage two, the clusters change their compositions mainly due to new hires or intra-transfers. The latter reflects the evolution and decay of clusters. More importantly, two clusters changed their themes. That is, Design Management moved from Decision-Making theme to Design theme, whereas Civils and Structures moved in the opposite direction, i.e. from Design theme to Decision-Making theme. This change may be due to the completion of the design changes and start of a new activity at stage two (i.e. TWAO submission).

Overall, the analysis reveals that the designers and decision-making actors implicitly differentiate the daily design activities from dissemination and information gathering and the need to make decisions. These three functional themes are usually not procured, facilitated, or managed as they are essentially hidden from view in projects. Furthermore, analysis reveals that clusters are strongly connected within themselves and strongly connected within the themes. The themes are formed around a small number of relatively prominent actors who are strongly connected within those clusters. This suggests that the themes were emerging from actor-based prominence within the network.

Of particular interest, the TfL/BSCU Project Manager stresses on the role played by physical proximity (i.e. co-location) as a factor contributing to the formation of these functional themes:

> *'All the project participants were collocated in a single office and those visiting found it difficult to tell which participant was from which organisation.*

> *If you come in the lifts, on the right-hand side you had the engineering managers and then architects and then M&E people and then the civils people and around the corner here the tunnelling people, so everybody was pretty well connected together, it was an open floor plan arrangement, we all knew each other pretty well. We had social projects every month; we have breakfast meetings'.*

From the above quotation, it can be concluded that functional themes can be encouraged through the use of various interventions affecting the context of networks. Project team, for example, might benefit from co-location, facilitating easier communications, particularly face-to-face. This is especially the case for the BSCU project where actors were co-located in a single office. It can be argued, therefore, proximity contributed to the development of strong relationships and formation of the project groups/clusters within the network. In fact, proximity as a spatial characteristic has long been identified to be a main factor influencing communication patterns, having a strong correlation with the formation of informal relationships and groups (e.g. Sailer, 2010).

This finding highlights the positive impact of sharing spaces/working in open plans. Such arrangement encourages actors to break out of their silos, facilitates regular meetings and interactions, enhances exchange of resources and information, and hence improves collaboration. It is a way to "get a coalition of the willing", through encouraging disruptive behaviours between the interfaces of different groups/clusters that challenge the status quo. Spatial plays a crucial role on how informal relationships are formed, strengthened and sustained over time. It provides project managers with an entry point to unleash informal networks and their invisible powers. It is a way to increase effectiveness as spaces can help to intervene to optimise the functioning of project delivery networks.

The breakfast meetings are another example. At stage two, these meetings were regularised/routinised in the project, to be part of the project's business rhythm. During these meetings, actors were connecting, sharing their views/information and influencing each other; hence leading to an overall higher network cohesion/integration at stage two. On top of everything else, actors were actively reminded in the breakfast meetings about the network study being done (i.e. The KTP project). The network diagrams were projected and expectations were declared clearly. Therefore, it can be inferred that the participants' consciousness affected the evolution of the self-organisation in BSCU project (Sherblom, 2017).
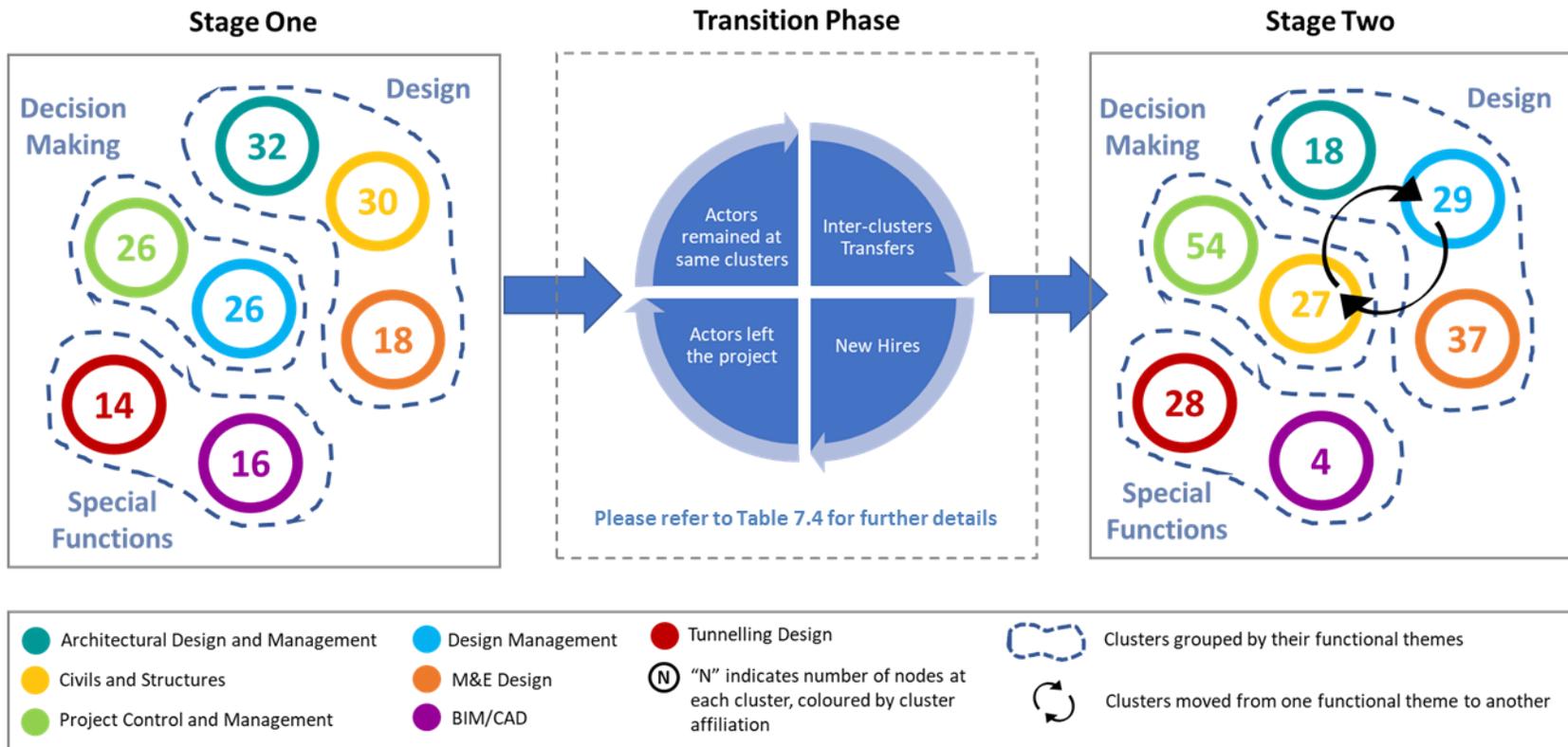
Figure 7.13: A Simplified Depiction of the Functional Themes.
(Source: Original)

7.6   Summary

Similar to any other large infrastructure project, BSCU project is characterised by a high level of uncertainty due to involvement of array of interfaces and interdependencies between its stakeholders who came from diverse disciplines. This chapter makes the point that project delivery relies upon a range of activities that are essentially hidden from view, i.e. neither procured contractually nor codified in protocols and contract documentation. These activities are "*difficult to identify, difficult to quantify and therefore difficult to manage*" (Pryke, 2017, p. 172). They essentially involve collaborative problem-solving, i.e. a high degree of self-organisation - a quality needed to overcome the fast-paced nature of infrastructure projects. It arises "*in response to individual actors' autonomy and motivation to seek and disseminate information, and in this way to discharge their contractually prescribed project roles*" (Pryke *et al.*, 2018, p. 37).

The analysis carried out in this chapter conceptualises BSCU project as networks of relationships, which are mapped and interrogated utilising a number of SNA tools. In particular, it suggests identifying and analysing project function delivery clusters, moving away from relatively abstract conceptualisation of project activities to a much more finely-grained approach. As project actors must deal with uncertainty, they tend to form clusters or communities to ensure that project functions are carried out effectively. Typographically, clusters involve "*higher levels of density or connectivity than exists in the networks that surround these clusters*" (Pryke, 2017, p. 147). This is of significance as such structure tends to indicate development of various groups within the network, each with different focus. The study of these clusters' topography, therefore, is important to understanding of project networks and their management. It ultimately helps raising awareness to commence the setting of an agenda associated with the application of network theory. It enables project networks to be designed, replicated and managed, and perhaps sets project managers and clients thinking about interventions needed to achieve effective project execution.

Investigation of BSCU networks identifies seven self-organising clusters in both stages. It looks very specifically at interpersonal communications associated with design information exchange, classified based on project functions. This classification is in line with Pryke *et al.* (2017), which came about in consultation with the project manager. By examining the topography of clusters and their intra- and inter- relationships, the research brings the crucial role played by meso-level to the fore. This level emerges as the core of communication networks, linking underlying local processes (e.g. individual positions within networks) with global project outcomes (e.g. cost measures). As the project moves from

stage one to stage two, the research highlights the key changes at each cluster in terms of composition, prominence, communication activity, and tie strength. Clusters (and hence the overall network) were found to be transient, i.e. they are not static - they evolve and decay over time. Findings further suggest that an element of path dependency affects the evolution of self-organising networks and the creation and re-creation of interaction patterns in construction projects.

Decision-making strategies employed by individuals in BSCU networks were studied by adopting Jager and Janssen (2003) model. This puts a great emphasis on the extent to which social processes are used, which ranges from autonomous actions to social integration. Actors in projects are generally attracted to repetitive behaviours (routines) as they offer consistency and stability, and of a lower cost (i.e. require a low level of cognitive effort). Deliberation is desirable in situations requiring exchange of ideas to reach common grounds. Imitation and social comparison, on the other hand, arise to cope with high levels of differentiation between actors (e.g. prominence and information asymmetry). The results suggest that excessive iterations or control provide a milieu for 'dysfunctional prominence'.

This chapter takes the analysis of clusters beyond the typical 'mono-functional' approach towards identification of multi-functional themes. These represent the major activities that are being performed in a given network because of self-organising behaviour, i.e. they are usually not procured through formal contractual agreements. Three main themes were identified in BSCU project, representing design function trinity, namely: design, decision-making, and special functions. Each theme comprises a number of highly inter-related clusters which are in turn centred around a small number of relatively prominent actors. In this sense, this approach makes a link between local actor-based prominence and emergence of functional themes. The analysis of BSCU functional themes highlights how these evolved between stage one and stage two, as a function of the changing requirements of the project. Pryke (2017) highlights that these themes can be potentially replicated between projects. It, therefore, concludes with the recommendation that these distinct themes need to be sponsored and nurtured to maintain their effectiveness. This entails introducing different network-based interventions, such as co-location of staff, resource sharing, early engagement (e.g. working together at tendering stage) and regular meetings to facilitate communications.

8

Macro-Level Analysis

Whole Network Advantages

8.1 Introduction

The understanding of project networks as Complex Adaptive Systems (CAS), that are self-organising with emergent outcomes, entails focusing on the dynamics of these networks and how they might balance between the different network characteristics. The previous two chapters have investigated the BSCU networks at the micro- and meso- levels. The analysis conducted in this chapter is concerned with the macro-level. It studies the impact of change in the structural regularity of the whole BSCU self-organising network, as it moves from stage one to stage two. This is determined by calculating the efficiency and cost measures of communication (as evaluative outcomes/consequences).

One of the most interesting findings of research literature on complex systems is the co-existing of a number of conflicting forces or paradoxes (Stacey, 2003; Kauffman, 1996). For example, the goals of adaptability and efficiency (Carroll and Burton, 2000), control versus collaboration/flexibility, and individual versus collective power (Duggal, 2018). This chapter will demonstrate how self-organising networks can help Project Managers in dealing with such dualities instead of focusing on one or the other. Essentially, self-organising networks, in response to higher complexity and uncertainty, can compromise between the desire for higher performance (e.g. efficiency) and the need for less cost, yet defending the value outputs. This way of thinking, in terms of paradoxes to reap the benefits of self-organising, is not usual in organisation and management discussions (Duggal, 2018).

The macro-analysis presented in this chapter builds on the small-world (SW) network[62] topology, presented earlier in the Methodology Chapter. It is based on the premise that by identifying the range of SW networks, which lies between regular (ordered) and random (chaotic) network topologies, we are in fact identifying the range that can be tolerated in the respective stage of the BSCU network before the network disintegrates. In other words, the SW network topology bounds represent the network as it starts to be connected globally through the introduction of hubs[63] (to the maximum tolerated connections) before it falls in chaos (through having extensive random connections). That is, this range is where the paradox of co-existing individually or locally (through the segregated clusters) and collectively (whole network) is reconciled (Shaw, 1998; Jarman *et al.*, 2017).

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[62] The term small-world network used to describe a network with both small average path length and significant local clustering (Watts and Strogatz, 1998). This means most nodes in the network are connected locally but they can be reached in few steps through their local hubs that connect them globally. This model was explained earlier in detail in the methodology chapter.

[63] Hubs are the nodes with high-degree, i.e. a highly connected node.

8.2   What's New?

Although Pryke *et al.* (2017) studied network costing, its scope is limited. It is based on linearity, which does not count for multidimensional nature of prevailing forces in construction projects and lacks the mathematical framework. This thesis, however, proposes studying the interaction between efficiency and cost measures, based on Complexity Theory concepts. A mathematical model will be formulated following Latora and Marchiori (2003) framework and linking it to network perspective. This is an original methodological contribution of this thesis, taking into account self-organising features.

It is believed that the interaction between efficiency and cost measures can provide a quantitative explanation for the consequences of the dynamics in the evolving complex networks (Pryke *et al.*, 2017; Opsahl *et al.*, 2017). This chapter will demonstrate how this can be used as a tool by project managers to optimise project networks and infer problem areas to help identify where the project networks are falling short of achieving optimum outcomes.

The key differences between Pryke *et al.* (2017) and this thesis are summarised in the following Table 8.1:

Table 8.1: Key differences between Pryke *et al.* (2017) and this thesis. (Source: Original)

Aspect(s)	Pryke *et al.* (2017)	This Thesis
Definition of Optimum Cost	The optimum value of cost is an additive function of building and operational costs of project-based networks. This approach is limited as it does not link cost with self-organisation features. In particular, linearity was assumed as operational cost was based on the sum of all the shortest distances from each actor in the network to every other actor.	The optimum value of cost is the point where max. Global and max. Local efficiency can be achieved at the same time. This suggests that optimum cost may not necessarily mean lowest cost value, as it takes into account the interaction between Global and Local levels.
Mathematical Formulation	No specific mathematical framework was used. Underlying assumptions are linear. The total cost is defined as the simple sum of both building and operational costs and assuming a one-unit time period.	Based on Complexity Theory, using Latora and Marchiori (2003) model that extends the small-world concept beyond simple unidimensional networks.
Processing of Information	Defining costs based on path length only. It follows, to some extent, Watts and Strogatz's (1998) model which assumes sequential processing of information – traditional communication model.	Parallel or concurrent processing is counted for.
Level of Analysis	Efficiency is defined as a one measure, being a function of cost, without giving any reference to the level of analysis/interactions (i.e. Local/Global levels).	Efficiency is defined based on level of analysis/interactions, and then values are weighted and normalised to reach to a unified measure.
Study of Self-Organisation Features	Theoretical underpinning for self-organisation is limited.	Key areas of self-organisation are studied based on an informed Complexity Theory framework, linking it with network perspective.

8.3   Efficiency and Cost Analysis

Methodology Chapter discussed formulation of mathematical measures for both efficiency and cost that are based on Complexity Theory concepts. Please refer to Section 4.3.3.2 for the relevant equations. For the reader's ease of reference, the below description is given to highlight the meaning of each metric:

- **Global Efficiency:** this is concerned with global communication in a network, i.e. how fast a message can be passed from one end of the network to another. It is an inverse function of shortest path length (L) and thus its reciprocal value gives the minimum number of degrees (i.e. links) between any two nodes. That is, global efficiency measures the average node-to-node travel distance (for the network as a whole) in terms of number of links. To enable like-for-like comparison, global efficiency results are normalised, i.e. expressed in relative terms as a ratio to the respective ideal case of the network (which is the random typology of the network, constructed on the same number of nodes).

- **Local Efficiency:** this metric is concerned with local communication in a network. It is a function of clustering coefficient (C) and thus evaluates how good the clustering of a network is. To enable like-for-like comparison, local efficiency results are normalised, i.e. expressed in relative terms as a ratio to the respective ideal case of the network.

- **The Network Cost:** This measure represents cost of communicating, i.e. transmitting a unit of information through network's links. The cost calculations are based on the assumption that it takes an average of one day's worth of man-hours to build a link in the network, at an assumed average rate of £500 per day (in line with Pryke *et al.*, 2017). The operational cost of the network for a month is assumed to be based on an average of three communications between any two connected actors in a month, at a rate of £1 per minute, and assuming an eight-hour working day (in line with Pryke *et al.*, 2017). Therefore, the average rate is £160 per day[64].

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[64] The cost calculations were based on an estimation of average rate made with the client's Project Manager (adapted from Pryke, 2017).

Key objectives of efficiency and cost analysis are summarised below:

- **Identify SW range of BSCU network:** The SW range is identified through a network re-wiring process. This is explained in full detail in Section 8.4.1 and 8.4.2, but it is essentially the range in which a network reports both high clustering and short node-to-node travel distance. SW range is particularly relevant to the study of self-organising networks, being a key structural property for such typologies (see Section 3.8).

- **Identify the optimum cost value of BSCU network:** this is the point where the network is characterised by both a high global efficiency and a high local efficiency. This lies within SW range and identifies where the most efficient flow of information can be achieved at both global and local scales.

- **Enable cross-comparison between stage one and stage two of the project:** this is in order to evaluate the network's performance in terms of efficiency and cost as it moves from stage one to stage two; thereafter provides insights into its dynamics.

Using the equations described in Section 4.3.3.2, the following Table 8.2 summarises the efficiency and cost calculations for the BSCU project at stage one and stage two:

Table 8.2: Efficiencies and Cost Measures Comparison.
(Source: Original)

Measure	The Unit of Measurement	Stage One (N= 162)	Stage Two (N=197)
Global Efficiency -BSCU Network	Reciprocal value of degrees (i.e. number of links)	0.383	0.414
Global Efficiency - Random Network		0.4285	0.445
Normalised Global Efficiency	%	89.469 %	93.165 %
Normalised Local Efficiency	%	56.425 %	62.049 %
Weighted Building Cost-BSCU Network	GBP/day (per link)	3.266	2.645
Weighted Building Cost-Random Network	GBP/day (per link)	3.086	2.538
Weighted Operating Cost- BSCU Network	GBP/day (per link)	0.148	0.134
Weighted Operating Cost- Random Network	GBP/day (per link)	0.1667	0.148
Total Weighted Cost - BSCU Network	GBP/day (per link)	3.415	2.779
Total Weighted Cost - Random Network	GBP/day (per link)	3.253	2.686
Normalised Δ Weighted Cost	%	4.973%	3.453%

The results presented in Table 8.2 reveal the following:

- Global efficiency of stage two is higher than that of stage one. In stage one, the minimum travel distance needed for a message to pass from one end of the network to another is at 2.6 links (reciprocal value of 0.383), whereas the minimum travel distance in stage two is at 2.4 links (reciprocal value of 0.414). Higher global efficiency was achieved at stage two given the reduction in the node-to-node travel distance.

- The respective random (ideal) network typologies have minimum travel distances of 2.3 links and 2.2 links at stage one and stage two respectively (these are the reciprocal values of 0.4285 and 0.445 respectively). In relative terms to random network values, BSCU project networks achieved high global efficiency results at both stages; stage one was at 89.5% of the ideal network, whereas stage two was at 93.2% of the ideal network.

- Local efficiency of stage two is higher than that of stage one. Results are at 56.4% and 62% of the ideal network for stage one and stage two respectively. It is noted, however, that local efficiency scores are not as high as the scores of global efficiency; they are just at an acceptable level (around 60%). This means, in BSCU project, more focus was given to global communication (e.g. project targets) than local communication (e.g. day-to-day tasks).

- It is worth noting that local efficiency outpaced global efficiency at stage two. This means the constitutive actors of the self-organising network at stage two have a greater autonomy to choose and manage how best to accomplish their own work, rather than being directed by others from outside the team.

- Cost of communicating at stage two (GBP 2.78 per day per link) is lower than the stage one (GBP 3.42 per day per link). This can be explained by the improved efficiencies at both global and local levels.

- The minimum cost of sending a message from one end of the network to another end is GBP 8.89[65] at stage one, whereas it is GBP 6.67 at stage two. This is a minimum cost savings of GBP 2.22 (per message) between the two stages, i.e. a reduction of 25% which is considered substantial cost savings in relative terms.

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[65] This is calculated by multiplying the minimum travel distance (i.e. number of links) X total cost per link. For stage one, this is 2.6 X 3.42 = GBP 8.89 whereas this is 2.4X 2.78 = GBP 6.67 for stage two

- The building cost of the networks is disproportionately higher than the operating costs. This highlights an opportunity for the project managers to intervene as catalysts to increase the rate of interactions at the early stages of the network. That is, the quicker and effective formation of connections could optimise network performance.

- Compared to the ideal network, BSCU network has a relative cost overrun of 5% (per link) at stage one, whereas at stage two the relative cost overrun is at 3.5% (per link). This means the network reduced the cost overruns in its communication network as it moves between the two stages. Both of these cost overruns, however, are considered acceptable if the commonly used tolerance level of 10% is adopted (Yescombe, 2013).

- Improved cost and efficiency figures were achieved for BSCU network at stage two despite the increase in number of nodes. This is attributed to the differences in structural typologies and in particular improved local communication (the higher tendency towards clustering). This finding, in turn, highlights the importance of managing self-organisation phenomena in complex projects. The mathematical framework adopted in this analysis could be helpful in managing and monitoring costing networks. It expands the project costs view from a management perspective beyond the costs of the production of the physical product on site (e.g. costs of construction materials, equipment and labour) to count for impact of network structural changes and cost of communication.

The above analysis suggests that the dynamics of BSCU complex networks can be seen as a function of the interaction between the global, local, and cost variables. However, it is important to recognise the fact that all of these variables are ultimately a function of the microscopic interactions. Network Dynamics are therefore investigated next to provide insights into the patterns of communication.

8.4   Network Dynamics

Network dynamics were simulated through a network re-wiring process, based on Watts and Strogatz's (1998) re-wiring algorithm. The process involves identifying the range of SW networks and starts with a regular network in which all the nodes are locally connected and have a high clustering coefficient (i.e. the network is characterised by segregation). Increasing the re-wiring probability (p) increases the likelihood that links will connect not only to their local cluster, but to somewhere else in the network. This increases the network complexity through functional integration (Tan and Cheong, 2017) and pushes the network towards instability (disorder) (Stacey, 2003). Consequently, this means two basic steps were followed:

1. First, creating a ring lattice for each respective stage of the BSCU project with nodes of average degree of three (as assumed in the previous section that actors on average will engage in three communications);

2. Second, links are rewired with increasing p from 0 to 1. A ring lattice (i.e. ordered network) is achieved with $p=0$, whereas random/chaotic network is achieved with $p=1$ when all links are rewired.

Following this model, the rewired link cannot be a duplicate or self-loop. Therefore, network dynamics reflect changes inherent to the network induced by the dynamic creation and re-creation of relational patterns, i.e. determined by the actors' interactions or individual actions (Scott, 2017). The latter gives the self-organising network its small-world properties (Scott, 2017; Jarman *et al.*, 2017).

The above described re-wiring procedure will be followed to identify the range of SW networks for stage one and two of the BSCU project. This is discussed next.

8.4.1 Network Rewiring: Identifying the Range of Small-World Network for Stage One

To set-up the small-world network, a regular lattice with N= 162 for stage one was carried out and the rewiring procedure to model the BSCU project network's dynamics was performed, based on Latora and Marchiori (2003) method. The re-wiring simulation was carried out using the 'brainGraph' package in the RStudio software, to calculate the local and global efficiency of project networks (Watson, 2017). As a result, the three quantities, global efficiency (Eglob), local efficiency (Eloc), and Cost, as explained in the previous section, are reported as a function of p (i.e. rewiring probability). The rewiring probability ranges between 0 and 1 and thus the p-values are presented at the regular intervals that follow the below equation:

The rewiring probability (p-value) = [an integer number/10] ^4   (Equation 8.1)

This equation is the sequence of fourth powers of the tenth of the integer numbers that lie between zero and ten. In this case, zero is the smallest integer number that produces p-value of zero, whereas 10 is the largest integer number that produces p-value of one. The fourth power was chosen because rounding to four decimal places provides greater precision and accuracy[66] which is necessary to determine SW ranges. It also enables better differentiation between stage one and stage two results.

Figure 8.1 is the outcome of the re-wiring procedure. It defines the range of small-world network of BSCU project at stage one. In order to identify the range of SW-network (i.e. minimum and maximum thresholds of p-values), the average path length (L) was observed as it started dropping very quickly, supported by also observing the range of high clustering coefficient[67] (C). The basic insights generated from Figure 8.1 are as follows:

- Path Length at a given p-value, L(p), decreases at a rate proportional to its initial value at p=0, i.e. L(0). This suggests having shorter path lengths as the network moves from ring lattice to random topology, i.e. communication flows faster. The function of L(p)/L(0) found to be concave upward; it has its highest value at the lowest p-value and vice versa.

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[66] When quoting a number to four decimal places, the absolute error (the magnitude of the difference between the exact value and the approximation) will be minimised to lie between 0.00005 and −0.00005, regardless of the size of the number. This is equal to a relative error < 0.05%. For further details, please refer to Jones (2001, p. 29).
[67] Anything above the average is considered high.

- Similarly, clustering coefficient C(p) decreases at a rate proportional to its initial value at p=0, i.e. C(0). This suggests lower clustering as the network moves from ring lattice to random topology. The function of C(p)/C(0) found to be concave downward; it has its highest value at the lowest p-value and vice versa.

- The range of the small-world network for stage one was found to be at p-values between 0.0081 and 0.1296, i.e. these are the corresponding intervals for the integer numbers between 3 and 6 (as defined under Equation 8.1).

- On the scale of integer numbers (between 0 and 10 per Equation 8.1), the SW range of stage one occupies 40% of the scale[68].

- SW range starts at the beginning of third interval, i.e. a lag phase of 2 intervals (from the lower end of the scale), whereas it terminates at the end of sixth interval, i.e. a lead phase of 4 intervals (from the upper end of the scale).

- At SW range, both functions L(p)/L(0) and C(p)/C(0) have a steep negative slope at the same time; i.e. both decreases at a pace less than -1. However, they have a relatively a gentle slope outside the SW range (a pace of > -1).

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[68] This is calculated as: "number of the intervals between 3 and 6" / "the total number of the intervals on the scale" = 4/10 = 40%
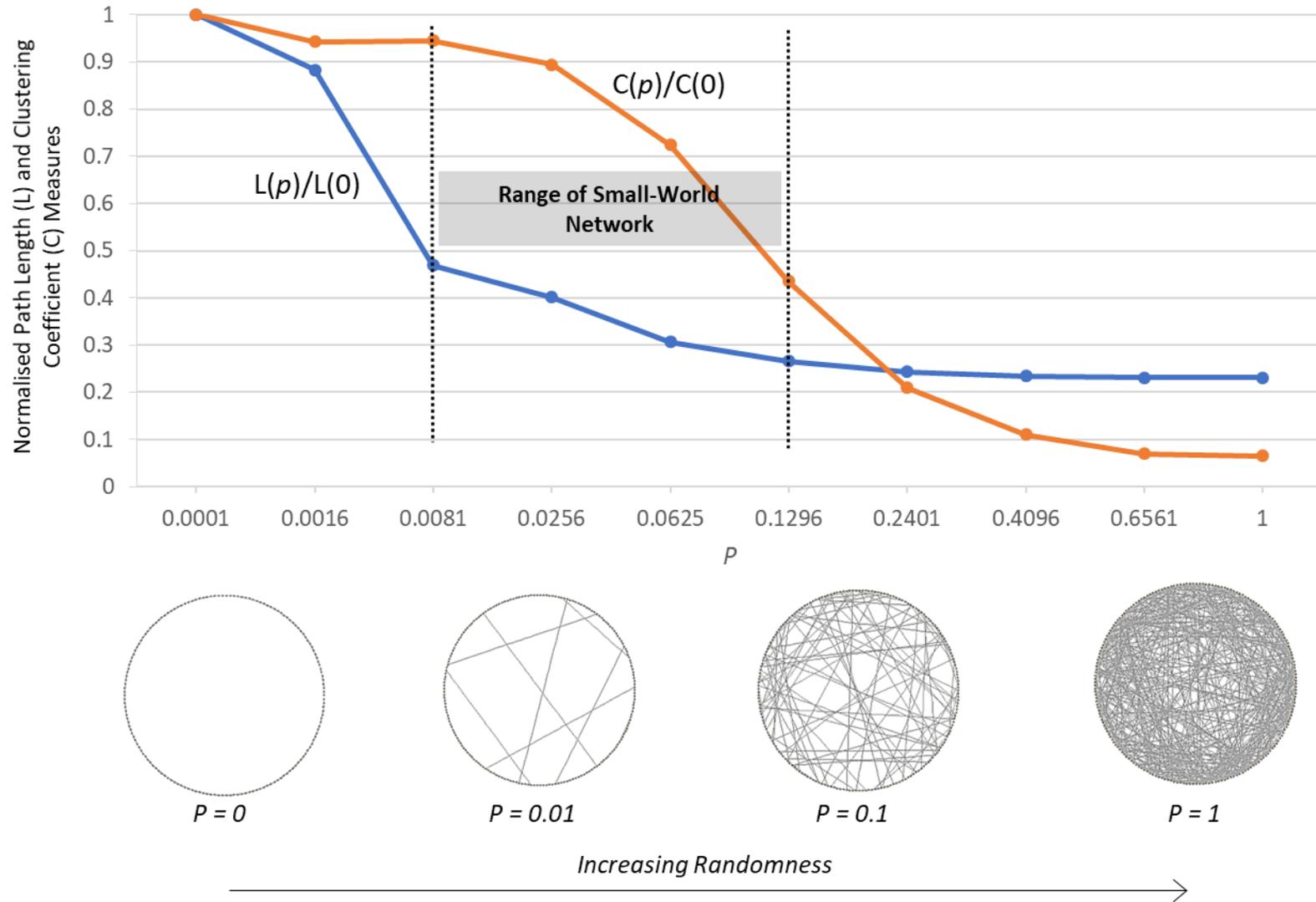
Figure 8.1: The Range of Small-World Network for BSCU Project Network at Stage One. (Source: Original)

Next, the three quantities (Global Efficiency (Eglob), Local Efficiency (ELoc) and Cost) of the simulated network were plotted in Figure 8.2 against each rewiring probability (p). The basic insights generated from Figure 8.2 are as follows:

- Normalised local efficiency decreases as p-value increases. The graph found to be concave downward; it has its highest value at the lowest p-value and vice versa. This suggests the network has lower local efficiency as it moves from ring lattice to random topology.

- Normalised global efficiency increases as p-value increases. The graph found to be concave downward; it has its highest value at the highest p-value and vice versa. This suggests the network has higher global efficiency as it moves from ring lattice to random topology.

- Similarly, normalised cost increases as p-value increases. The graph found to be concave downward; it has its highest value at the highest p-value and vice versa. This suggests the network becomes costly as it moves from ring lattice to random topology.

- At SW range, all functions of global efficiency, Local Efficiency and Cost have a steep slope at the same time; i.e. they decreases or increases at a pace less than -1 or greater than 1 respectively. However, they have a relatively a gentle slope outside the SW range (a pace of > -1 or >1).

The identified small-world network range from Figure 8.1 was overlaid on Figure 8.2 to determine the most efficient and economical network configuration in this range[69]. The optimum cost was identified on the premise that it is the point where the network is characterised by a high efficiency at both global and local scales. This is the intersection of the two lines (Eglob and Eloc), as illustrated in Figure 8.2. It demonstrates a critical transition point where opposing properties of local segregation (i.e. autonomous actions of clusters) and global integration in the network are reconciled (Jarman *et al.*, 2017; Opsahl *et al.*, 2017). The latter is supported by Scott's (2017, p. 38) discussion on the SW network formation/development, as he states:

> *"Networks develop, Watts argues, as a result of gradual, incremental changes that produce sudden, non-linear 'phase transitions' in network structure. Radical macro-level structural changes result from the unintentional accumulation of minor micro-level changes".*

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[69] Again, this range corresponds to the transition phase of the network structure as the network transforms from a regular network to a random network. Hence, when the network remains in this range means the network has a specific dynamic stability as global characteristics are preserved while pattern of interactions is continuously being adjusted to fit the situation.

The results illustrated in Figure 8.2 also suggest that the investigation of the most efficient and economical network configurations in the range of the SW network comes to support Opsahl *et al.*'s (2017) findings. In particular, a noticeable variation in the properties of small-world networks has been observed with cost (as a variable) having very tiny implications. This highlights the limitation of defining Efficiency as a function of cost only (e.g. Pryke *et al.*, 2017), without giving any reference to the level of analysis/interactions (i.e. Local/Global levels). Such cost-based approaches are able to identify the various configurations of small-world networks, but do not necessarily identify their efficient properties. In contrary, the tool proposed in this study is informed by Complexity Theory and it gives precedence to interactions/communication patterns. It explains the dynamics of self-organising networks and how to steer the network towards the desired outcomes by assessing three quantities (Global Efficiency; local Efficiency; Cost) that are all rooted to the microscopic interactions. Linking this line of thought back to the research problem, it can be argued that the microscopic origin of efficiency and cost of communication project-based networks suggests that coordination is relational. This discussion theme will be elaborated on in the Discussion Chapter.
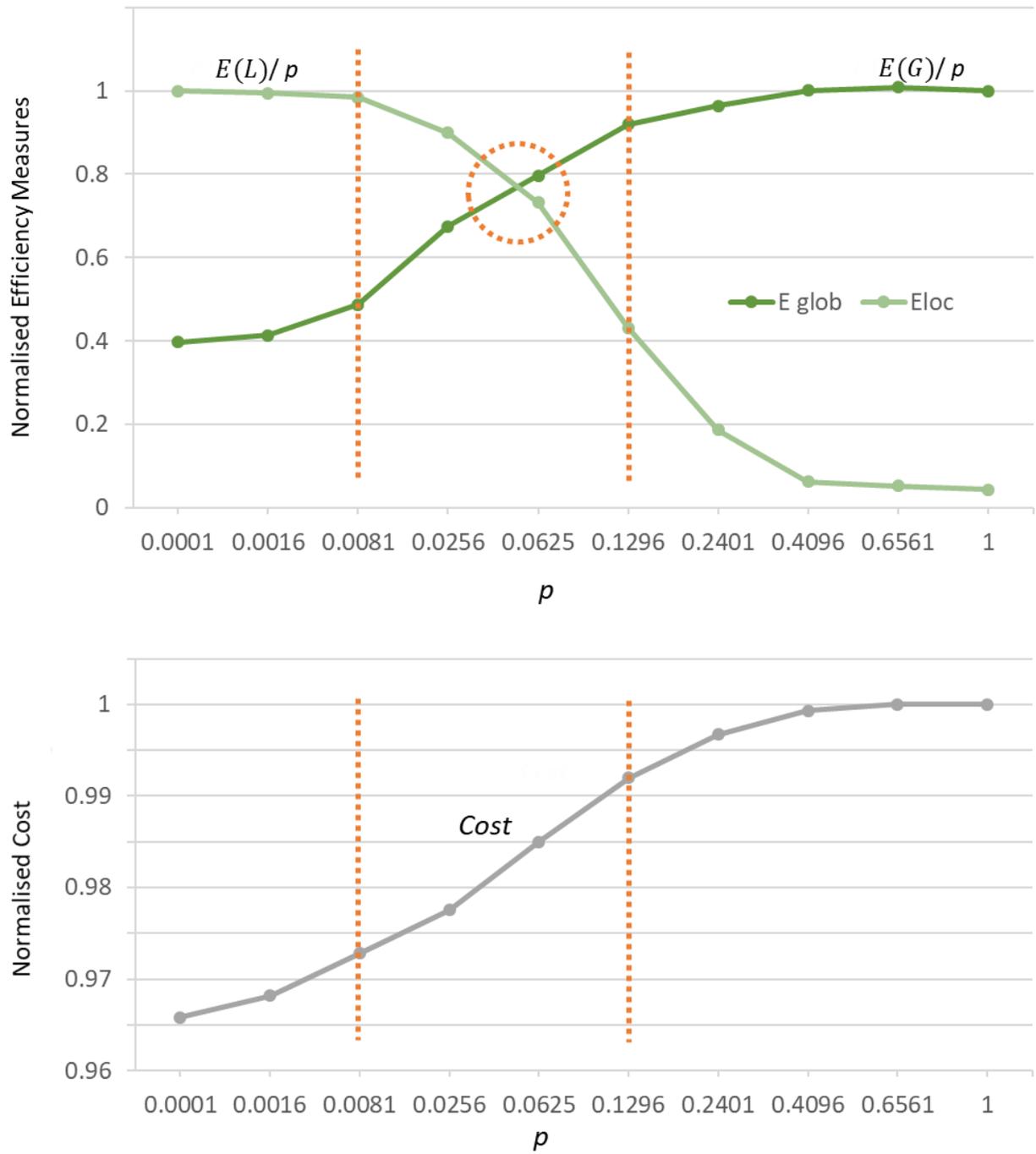
Figure 8.2: Stage One - Eglob, ELoc and Cost are Reported as a Function of *p*. (Source: Original)

In order to display the dynamics of the three variables (Eglob, ELoc and Cost) in the SW networks range identified by the simulation procedure, the changes in these parameters over time are plotted on a radar chart[70]. The shape allows spotting which areas the network performed well or poorly in.

Figure 8.3 is the radar chart for stage one, illustrating Eglob, ELoc and Cost measures at the identified range of SW as per Figure 8.1 (i.e. at p-values between 0.0081 and 0.1296 - see Equation 8.1). The produced graphs represent the outcomes from different network configurations, but all fall within the identified SW networks range that is capable of addressing the paradox of the routine creation and re-creation of relational patterns as necessary to accomplish goals without falling into chaotic status (Kilduff *et al.*, 2006). Such variety indicates the adaptive capacity of the network. It is also worth highlighting that such dynamics could result in less efficient or costly SW networks, confirming Opsahl *et al.*'s (2017) findings regarding the inconsistent evidence on the positive effect of SW networks to measure organisation performance. The local adaptation, for example, can be manifested by responses to events/issues within the functional/technical clusters, based on autonomous actions with minimum connections to the rest of the network. Such strategy is "*an intrinsically stabilizing process*", leading to repetitive patterns/behaviours, and hence reducing the conflicting constraints among clusters (Stacey, 2003, p. 137). Global adaptation, on the other hand, can be based on strategic managerial decisions (or in network terms, decisions made by prominent actors), therefore establishing power differences and affecting the whole network. Such distribution of power at both levels is the main determinant for shaping the network adaptive capacity and can have ramifications beyond the intended outcomes (Scott, 2017), as explained earlier in Chapter Three.

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[70] This chart is a two-dimensional graphical method to plot one or more series of values with each variable having its own axis and all axes are joined in the centre of the figure.
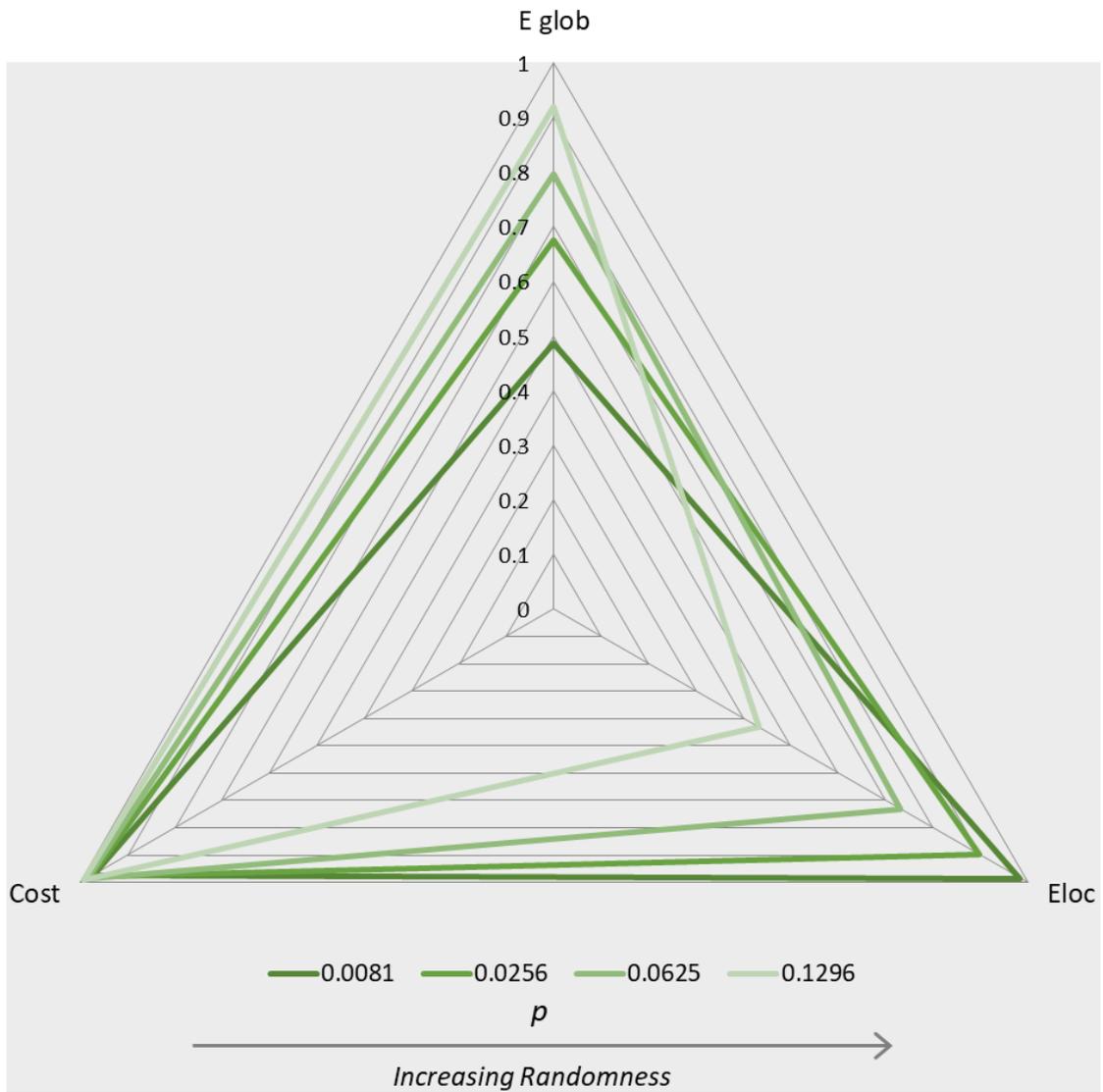
Figure 8.3: Stage One - Dynamics of Eglob, Eloc and Cost Variables in the Range of SW Networks. P-values are chosen at the regular intervals that fall within SW range of stage one network. (Source: Original)

Figure 8.4 below illustrates a comparison between the values of Eglob, ELoc and Cost for the identified most efficient and economical theoretical SW network (i.e. the network configuration at the critical transition point) and the BSCU project network at stage one. This comparison provides the ability to identify where the BSCU project network falls short and highlights potential opportunities for improvement. From the radar chart of stage one, it is noted that the stage one network exceeds the theoretical SW network in terms of global efficiency only, but falls short in terms of local efficiency. The overall cost of communicating is higher than what can be ideally achieved. This can be explained in view of the network structure. The network in stage one set closer to the upper limit of small-world range, which indicates a more centralised structure. This is due to introduction of hubs that increases network global efficiency, but concentrates power in few hands. The high dependence on global adaptation in this case resulted in a skewed distribution of power and hence lower local efficiencies (i.e. cluster efficiencies). Overall cost therefore was higher since global relationships and interactions are expensive in nature. For the project management, this is an indication of redundancy. Given disparity in the local efficiency score, it can be said that there is a delay between processes and consequences/outcomes at this level. Such time lags delay the ability to mobilise resources locally in a timely manner, resulting in information asymmetry[71] and hence potential rise of opportunistic behaviour. This could be because of having unnecessary layers in decision-making processes or due to non-decision-making behaviours (as some actors wish to maintain status quo).

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[71] Information asymmetry deals with the study of decisions where one party has more or better information than the other (Walker, 2015).
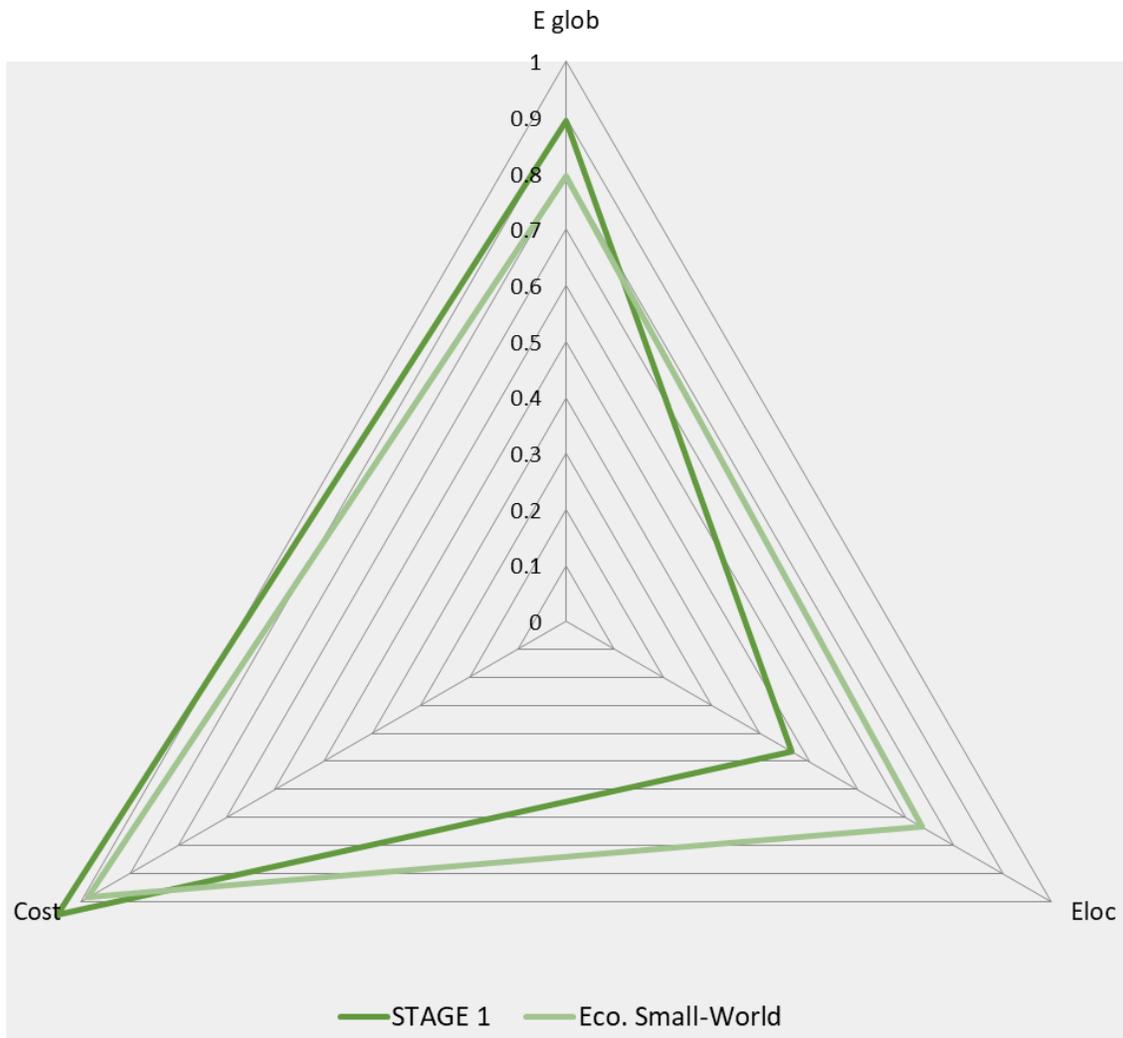
Figure 8.4: BSCU Project Network Dynamics Compared to the Economical SW Network at Stage One. (Source: Original)

8.4.2 Network Rewiring: Identifying the Range of Small-World Network for Stage Two

A similar procedure to the one discussed above has been applied to identify the range of SW networks for stage two of the BSCU project. For this stage, a regular lattice with N= 197 was carried out. The values of average path length (L) and clustering coefficient (C) for the different rewiring probabilities are illustrated in Figure 8.5. The three quantities (Eglob, ELoc and cost) as a function of p for the simulated network are illustrated in Figure 8.6. Then, the small-world network range was overlaid, in order to identify the most efficient and economical configuration of the network.

The basic insights generated from Figure 8.5 and Figure 8.6 are similar to those generated for stage one (see Section 8.4.1), apart from the following:

- The range of the small-world network for stage two was found to be at p-values between 0.0256 and 0.1296, i.e. these are the corresponding intervals for the integer numbers between 4 and 6 (as defined under Equation 8.1).

- On the scale of integer numbers (between 0 and 10 per Equation 8.1), the SW range of stage two occupies 30% of the scale[72]. This is a reduction from 40% at stage one.

- SW range starts at the beginning of fourth interval, i.e. a lag phase of 3 intervals (from the lower end of the scale), whereas it terminates at the end of sixth interval, i.e. a lead phase of 4 intervals (from the upper end of the scale). Compared to stage one, this means SW range of stage two has an additional lag phase of one interval. However, SW ranges of both stages terminate at the same interval (i.e. no phase difference between them).

A comparative analysis of SW ranges between stage one and stage two is illustrated in Figure 8.7. The simulation reveals that the critical transition point remained at the same position at $p \sim 0.0625$. This corresponds to 5 on the scale of integer numbers (per Equation 8.1). This transition point is the domain at which BSCU project networks reconciled both local and global efficiencies; hence achieving optimum cost. However, the SW network range decreased in stage two when compared to stage one. That is, with the increased complexity of the network in terms of size, communication patterns, and the presence of multiple communication layers, as explained in earlier chapters, it becomes harder for the network to be

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[72] This is calculated as: "number of the intervals between 4 and 6" / "the total number of the intervals on the scale" = 3/10 = 30%

locked in the same SW range defined for stage one. For the project managers, the narrower range is an indication of higher uncertainty/challenges being faced and thus the need to change existing strategies to more effective ones. The shift to stage two and the ability to still operate within SW range is an indication that project management were successful in addressing the pile clash issue at BSCU project and the resultant re-designing requirements.

Furthermore, the cross analysis of SW ranges can be used as an indication of network resilience. That is, resilience of self-organising networks can be understood as the ability of the network to operate within the identified range of the SW network, despite facing numerous issues/risks that are pushing the network to fall outside this area. The lower and upper limits defining the area of SW networks can be viewed as two competing forces moving towards each other along the complexity continuum (e.g. order and chaos). As complexity/uncertainty of the network increases, the range of SW will narrow. Figure 8.7 shows that stage two still falls within SW range despite being narrower. It can be concluded therefore that stage two has an improved network resilience when compared to stage one. This can be attributed to the change in communication patterns which can be explained by investigating Eglob, ELoc and cost quantities. This will be discussed next.
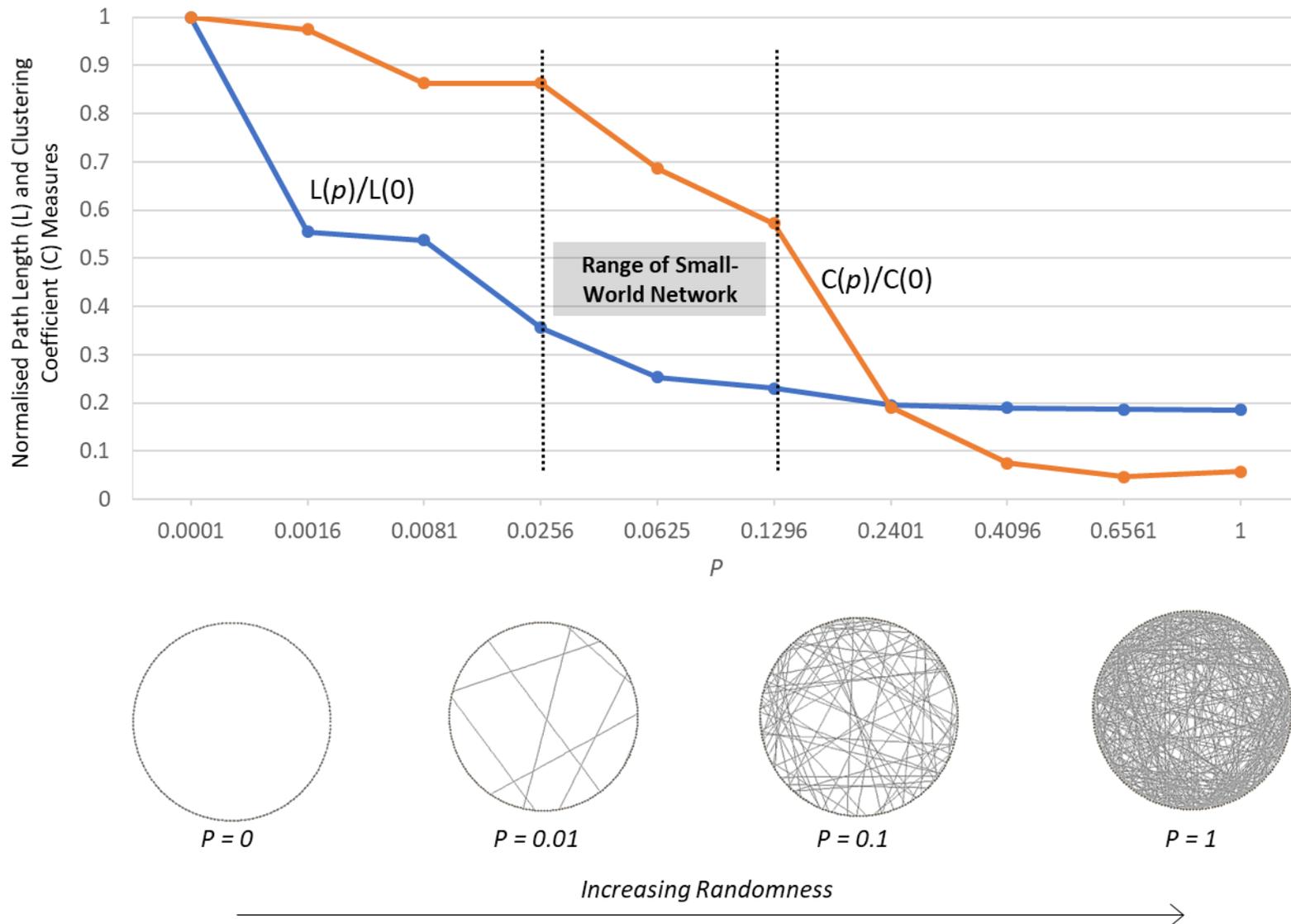
Figure 8.5: The Range of Small-World Network for BSCU Project Network at Stage Two. (Source: Original)
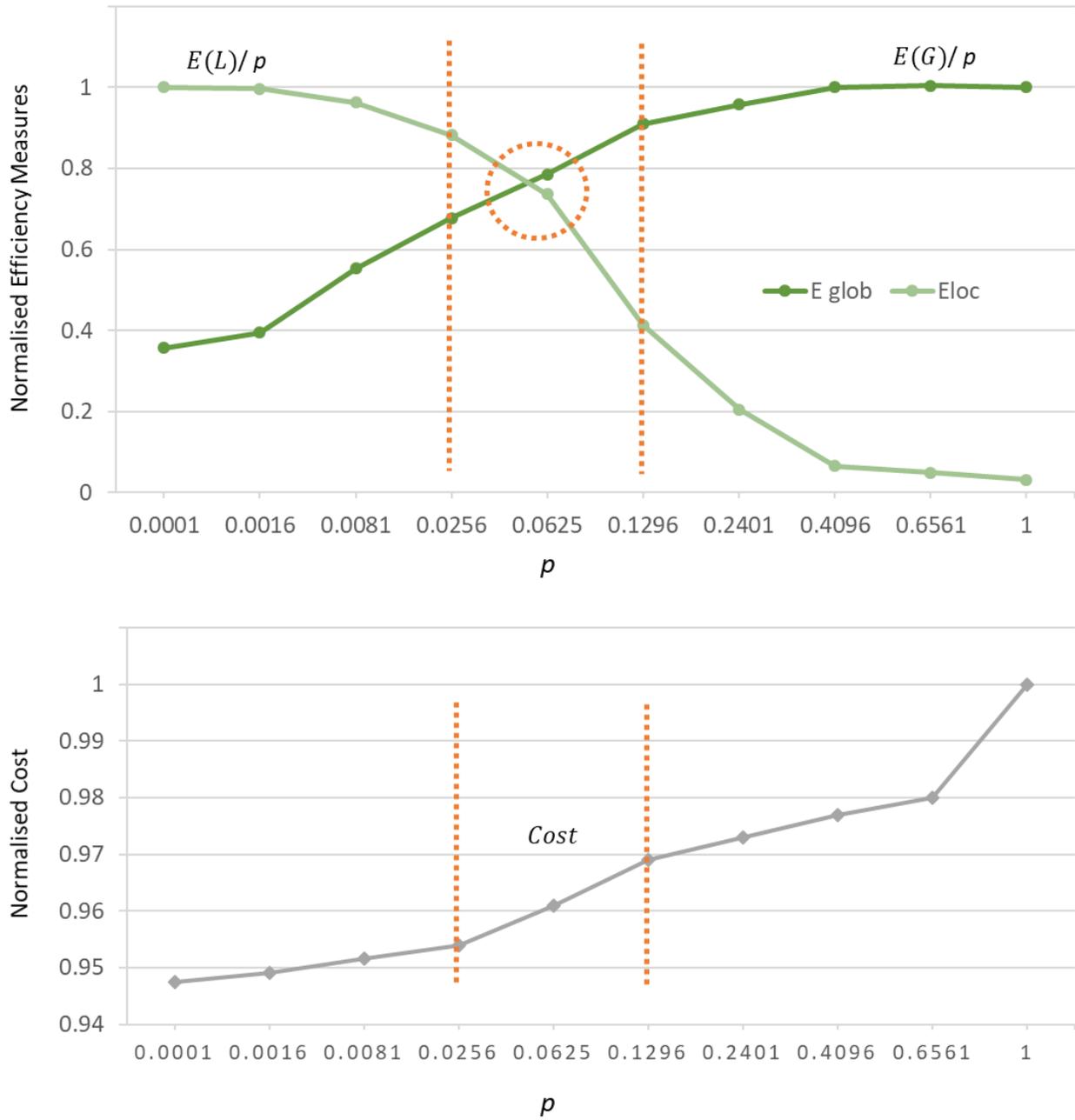
**Figure 8.6: Stage Two - Eglob, ELoc and Cost are Reported as a Function of *p*. (Source: Original)**
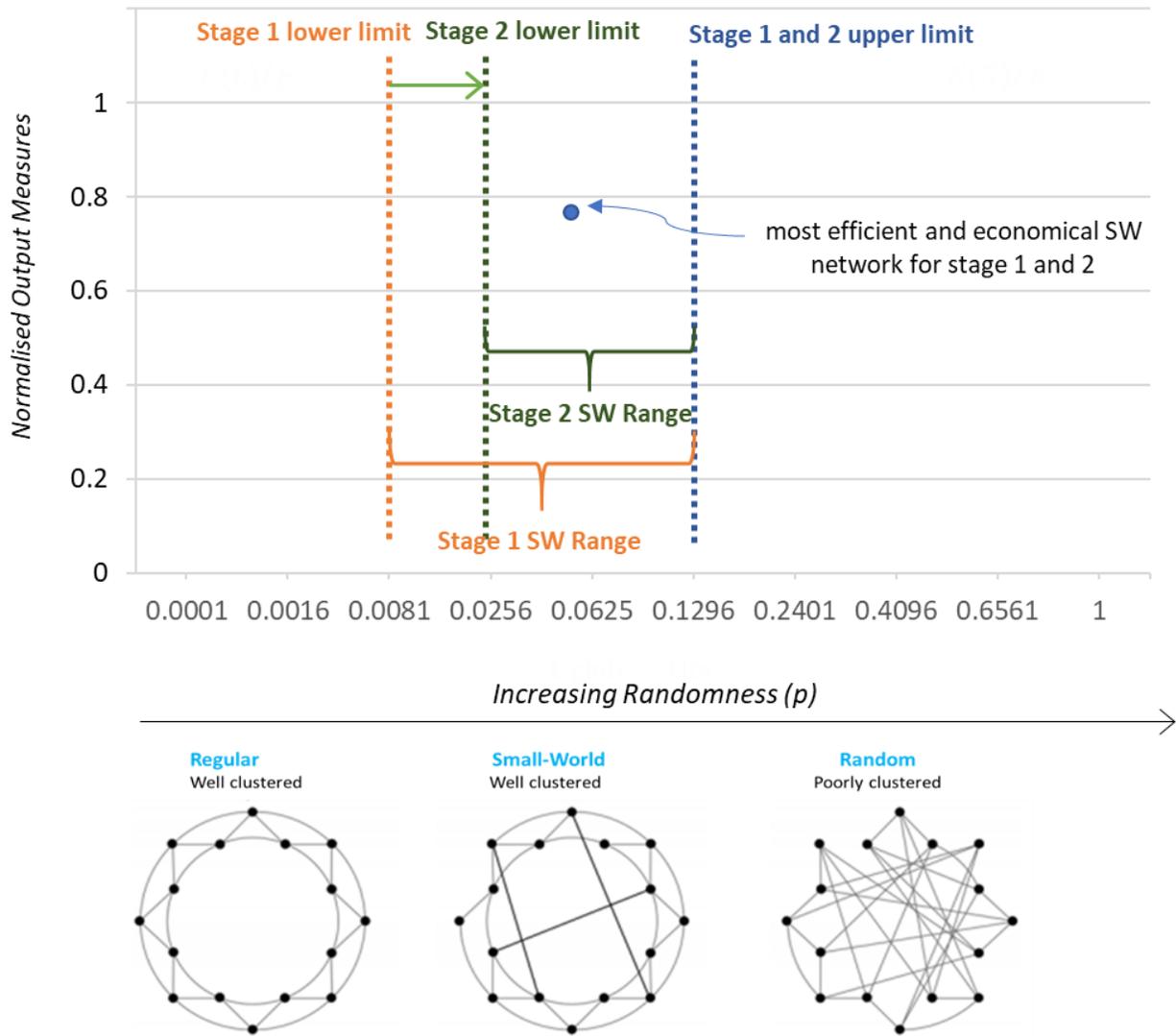
Figure 8.7: A comparative analysis of SW ranges between stage one and stage two. Reported as a Function of *p*. (Source: Original)

Figure 8.5 defines the range of small-world network of BSCU project network at stage two. This was found to be at p-values between 0.0256 and 0.1296, i.e. these are the corresponding intervals for the integer numbers between 4 and 6 as defined under Equation 8.1.

The SW dynamics of the simulated network for stage two are illustrated in the radar chart in Figure 8.8. In this figure, Eglob, ELoc and Cost measures are illustrated for the identified range of SW (i.e. at p-values between 0.0256 and 0.1296 as per Equation 8.1). The produced graphs represent the outcomes from different network configurations, but all fall within the identified SW networks range. Figure 8.9, on the other hand, illustrates a comparison between the values of Eglob, ELoc and Cost for the most efficient and economical theoretical SW network and the BSCU project network at stage two.

The comparative analysis of stage one and stage two radar charts shows improvement in local efficiency from a normalised value of 56% in stage one to 62% in stage two. Similarly, global efficiency improved from a normalised value of 89% to 93%. This was achieved with an overall reduction in cost from a normalised value of 5% to 3.5%. The improvements in efficiencies and cost can be attributed to the changes in network structure. It can therefore be said that the project network in stage two has moved closer to the economical SW configuration.
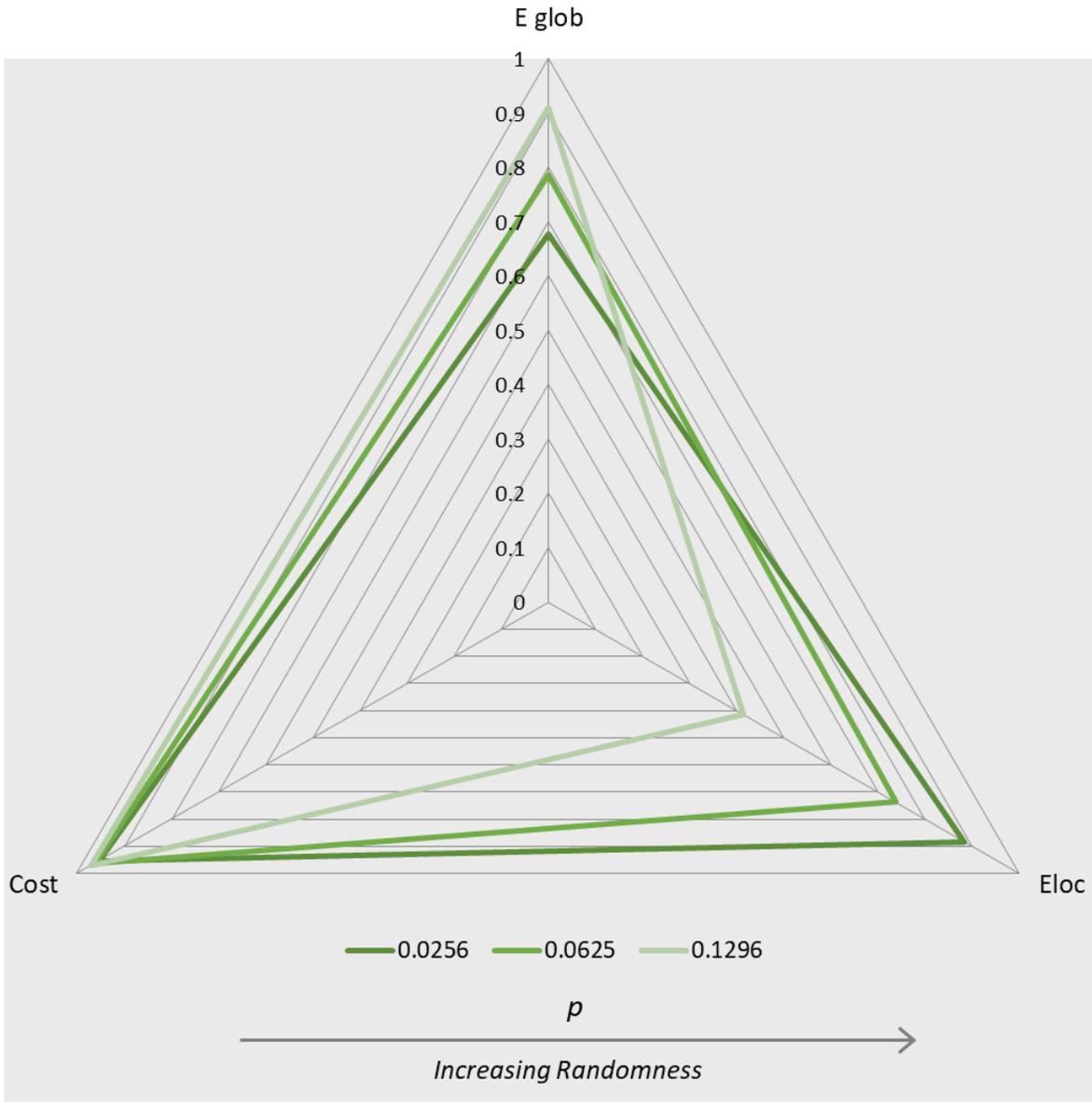
Figure 8.8: Stage Two - Dynamics of Eglob, Eloc and Cost Variables in the Range of SW Networks. P-values are chosen at the regular intervals that fall within SW range of stage two network. (Source: Original)
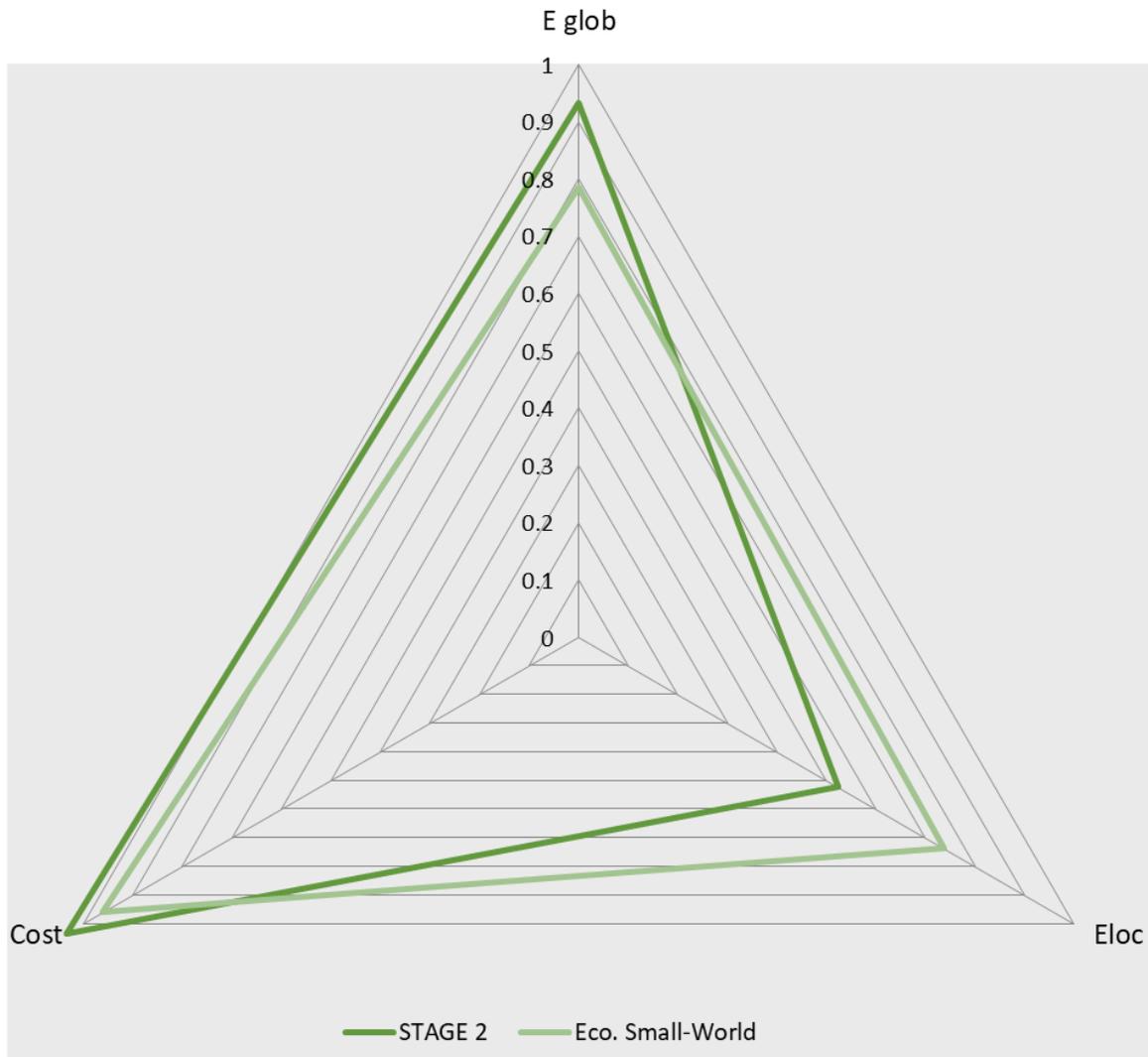
Figure 8.9: BSCU Project Network Dynamics Compared to the Economical SW Network at Stage Two. (Source: Original)

Figure 8.7 illustrates that stage two became closer to the lower limit of the small-world network range (i.e. towards the regular well-clustered configuration). This suggests a more reliance on autonomous actions of the clusters rather than global integration. It reflects a power shift as decision-making processes became more decentralised and focused on the local levels (i.e. clusters). Overall impact resulted in reduced time lags and costs. For project managers, this suggests that adopting a decentralised structure could help in handling increase level of uncertainty. It provides a better ability to mobilise resources (including information) at the local levels without the need to go through the lengthy approval process at the global level.

Given the interaction between local and global levels, the increase in the global efficiency can be attributed to the network characteristics of local levels. Next section, therefore, investigates the cluster efficiencies to explore the interaction between local and global levels.

8.5   Clusters Efficiencies

Investigation of local efficiencies (at the cluster levels) reveals that both stages have more or less the same averages across all clusters, apart from BIM/CAD cluster that exhibits a significant increase. This result is illustrated in Figure 8.10. The local efficiency of the BIM/CAD cluster at stage two is found to be within the ideal cluster efficiency at 72%, as per the optimum SW-network configuration identified earlier. This improvement was due to the decrease in the average path length, resulting from the decrease in cluster size (as some actors were made redundant/re-allocated). Moreover, the increased level of interactions between BIM/CAD cluster and others, through the fortnightly review meetings and the use of 3D clash detection modelling, explains the better scores achieved in stage two. Such intense interactions have increased the level of coordination across the network, as reflected in the improved Efficiency scores.

A comparison of the intra-cluster average path length (Figure 8.11) and cluster densities (Figure 8.12) gives similar results. For the project managers, this highlights the importance of having regular inter-group communications as well as the role of technology in fostering collaboration between project design teams. In BSCU project, this was further facilitated at a global level, by exploiting the use of the co-location (having the teams working in the same place) and implementing the ICE strategy of integrated teams.
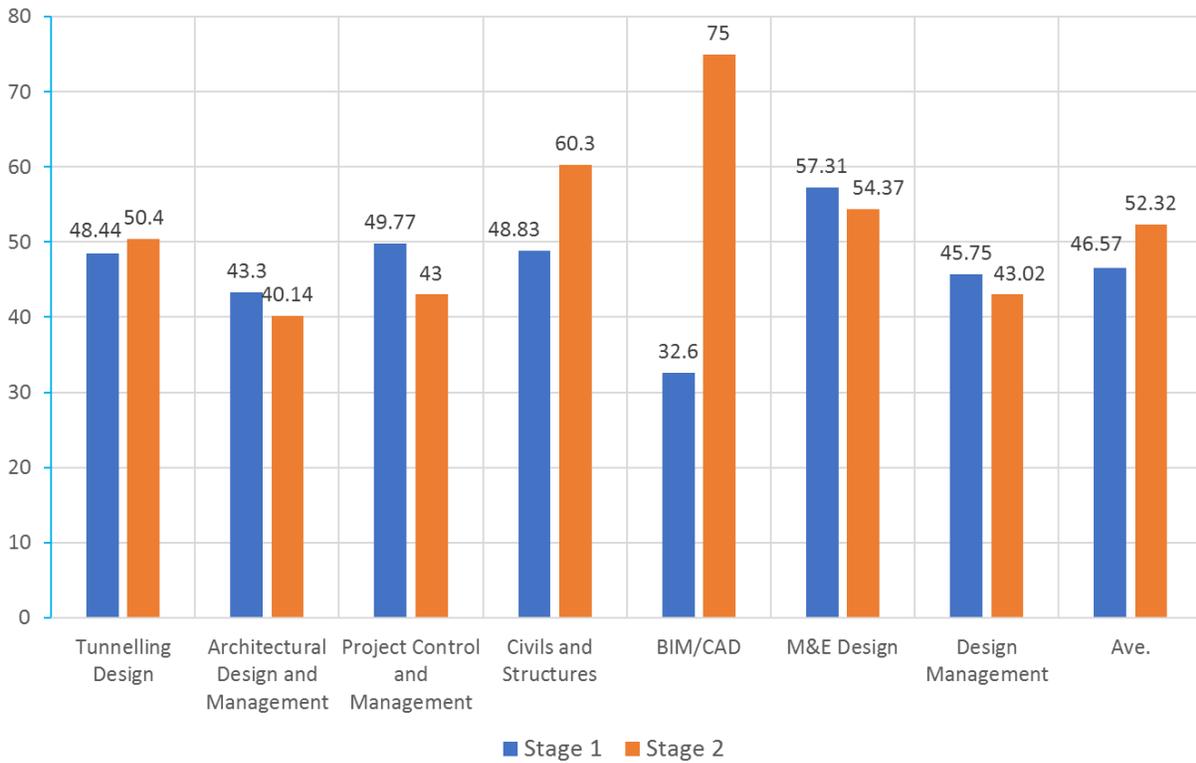
Figure 8.10: Local Efficiencies of Project Functional Communities/Clusters. (Source: Original)
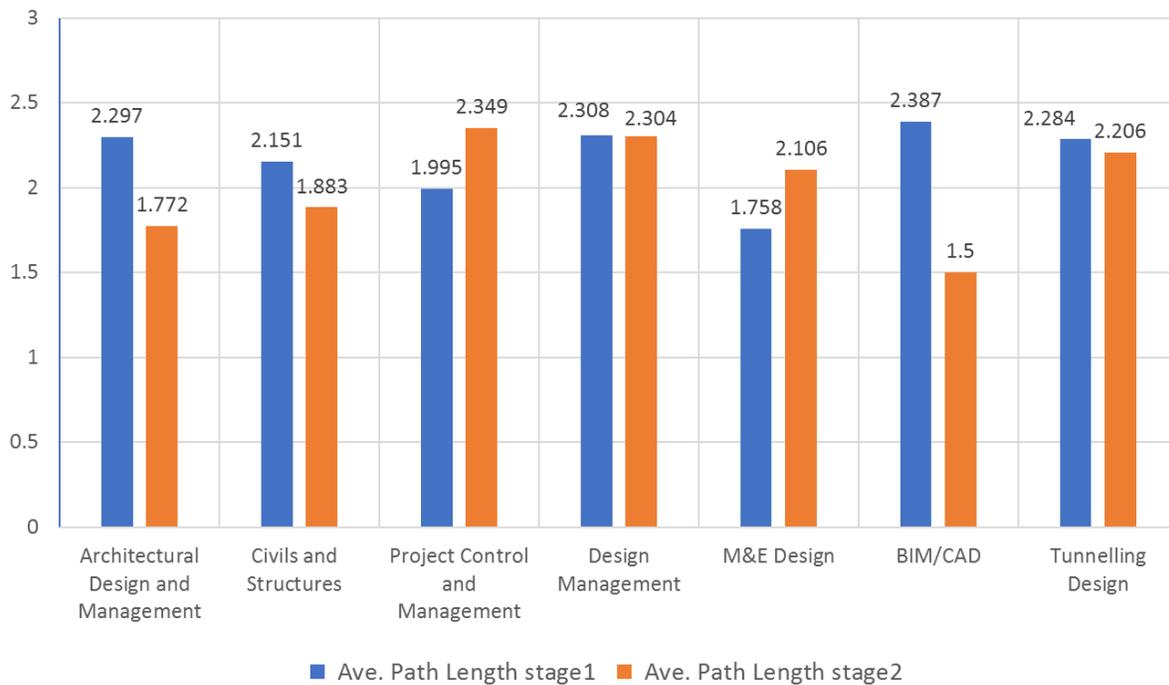
Figure 8.11: Average Path Length Intra-Clusters. (Source: Original)
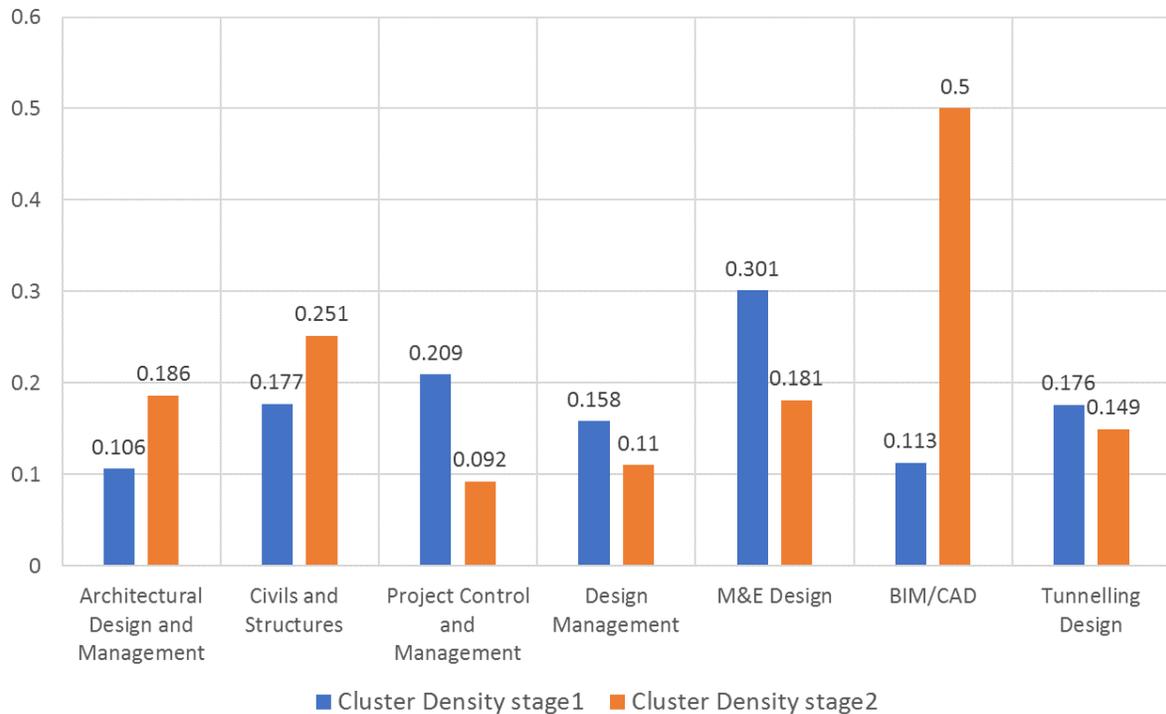
Figure 8.12: Cluster Densities Comparison Between Project Stages. (Source: Original)

Researchers generally argue that group size matters to the efficiency of the network. This subject has been extensively researched by social psychologists and organisational theorists (Gooding and Wagner, 1985). The findings of such research often suggest an insignificant or negative relationship between group size and performance. This is usually attributed to members' free-riding, higher communication and coordination costs, and increased structural complexity (Fleishman, 1980; Gooding and Wagner, 1985). In terms of the BSCU project networks, the BIM/CAD cluster size decreased from sixteen to four actors due to resource changes, resulting in the dramatic change in average path length, cluster density and cluster efficiency. This was due to the intervention of Tier one contractor and the client as a result of Alan Auld Engineering (responsible for the BIM/CAD design) being on programme delay and lacking transparency over buildability and CAD model integration. Consequently, Senior Management re-located some of the BIM/CAD work to their main office and the rest of the team (particularly - Wilkinson Eyre Architects) in order to reduce the delay impact and give greater certainty on delivery. Additionally, BIM clash resolution models were introduced in stage two and used in the coordination meetings to increase designers' involvement in clash resolution process. These induced changes resulted in a positive impact on delivery of the design and the technical decisions, confirming the interplay between

formal and informal structures. The discussion theme that can be developed from the findings here is that emergence of coordination needs formal interventions to continuously facilitate constructive interactions, but this is not to suggest all acts should be formalised (Grove *et al.*, 2018).

8.6 Summary

Over the years, much work has been done on the small-world concept, with the intention of resolving the optimisation problem in networks. From a Complexity Theory perspective, supported by previous studies from network science (e.g. Pryke *et al.*, 2017; Tan and Cheong, 2017; Kanders *et al.*, 2017), it has been shown that some aspects of project-based communication networks can be optimised by exploiting self-organising features. Taking the analysis and theoretical underpinning further, this chapter provided a distinguishing approach both theoretically and methodologically to that presented in Pryke *et al.* (2017). It suggests that network performance (e.g. efficiency) is a complex interplay of global and local measures. This view confronts the traditional project management that is based on linear, logical, and waterfall processes (cf. Pryke *et al.*, 2017). In fact, this new perspective suggests thinking in terms of paradoxes to recognise the potential for tolerating different multi-level perspectives, hence recognising the inherent incompatibility in projects. The results also demonstrate the importance of local properties in determining the emergent global outcome of the network. This is in contrary to Pryke *et al.* (2017) who consider the multi-level measures mutually exclusive where they cannot occur at the same time.

Overall, the results presented in this chapter lead to development of the following discussion themes which will be further elaborated on in the Discussion Chapter:

- Thinking in Terms of Paradoxes;
- Managing projects following a multi-level perspective;
- Coordination is relational but still needs formal interventions;
- Rethinking the role of managers in self-organising networks;
- The crucial role played by the meso-level (brokers).

9

Discussion

Interpreting Findings and Answering the Research Question
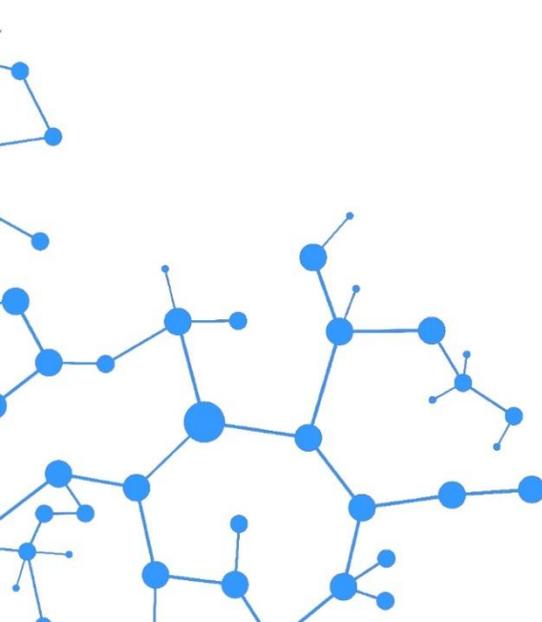
9.1 Introduction

This chapter draws further conclusions from the results presented in the previous chapters. It outlines the main findings regarding the research question and literature by making more of a discussion chapter in style. The chapter concludes by proposing an answer for the research question.

9.2 An Account of the Findings Regarding the Research Question

The *raison d'être* of this thesis is to study construction projects as multi-agent complex systems, employing a raft of social network analysis techniques. It is primarily concerned with the investigation of the communication networks, in an attempt to explore the void that is evident between systems and organisational hierarchies. It comes in response to calls to operationalise and apply the theory developed in *Social Network Analysis in Construction* (Pryke, 2012). By doing so, it challenges some of the traditional thinking on the conceptualisation of projects and their management which essentially involves task-dependency-based approaches, structural analysis (hierarchical) and process mapping, all of which fail to reflect the relationships that actually deliver construction projects (Pryke, 2017).

The research question focuses on two possible outcomes, i.e. whether self-organisation supports or constrains coordination. Table 9.1 below provides a summary of key empirical evidence for different aspects of self-organisation under study. These aspects are informed by the roadmap of the research analysis developed earlier in the Methodology Chapter (see Figure 4.6).

Aspects of Self-organisation	Evidence of Support	Evidence of Constraints
Table 9.1: An Account of Empirical Evidence Where Self-Organisation Either Supported or Constrained Coordination (Source: Original). *Table continued on the next page.*		
Connectivity and Flow of Information	• As the network shifts from stage one to stage two, Table 5.2 suggests that all layers (apart from the Instruction layer) reported growth in connectivity, i.e. higher flow of information. • Section 6.2.1 suggests that connectivity per node is higher at stage two, i.e. the project teams became more connected and integrated. Higher connectivity is an indication of enhanced access to information.	Table 5.2 shows a reduction in number of links at the Instruction layer of stage two. This finding suggests a lower level of coordination at this layer which mainly represents the formal form of communication.
Small-World Property	Table 5.1 highlight that BSCU project networks have "small-world" features, i.e. a quite high average clustering coefficient and short average path length (when compared to the values of the corresponding random network). These features enable quick information flow that is necessary for effective coordination and problem resolution.	Small-World property was observed at a very narrow range of the network topology spectrum (see Figure 8.7). This makes achieving the optimum value for coordination quite difficult.
Multi-layered Networks	• Communication networks are concentrated on Information Exchange and Discussion layers which indicate an environment that relies on collective participation and collaborative decision-making (see Section 5.6). • Instruction layer represents the formal approach to communication. Unlike the other multi-layered networks, the reduced connectivity scores of Instruction layer (Table 5.2) therefore suggest less reliance on contractual communication channels. This means the BSCU network in stage two moves towards establishing more collaborative and informal relationships to facilitate knowledge transfer and exchange in response to project complexity/uncertainty. • Network roles are quite different to contractual project roles and actors can assume multiple positions to support emergence of coordination (see Section 6.2 and Section 5.6).	This imbalance in actor roles suggests that networks suffered from information asymmetry among its actors, and hence leading to a degree of inequality in level of power (see Sections 6.2.1.1, 6.2.3.1, 6.2.3.1).

Aspects of Self-organisation	Evidence of Support	Evidence of Constraints
Table 9.1 *[Continued]*: **An Account of Empirical Evidence Where Self-Organisation Either Supported or Constrained Coordination (Source: Original).** *Table continued on the next page.*		
Path Length	The scores for average path length (see Table 5.1 and Table 5.3) were found to be low across all BSCU networks and layers. In fact, the whole BSCU network remarkably scored just above 2.5 degrees at both stages. This is very close to the score of the respective random networks. This finding means that ICE relational model was successful to bring BSCU actors closer to each other, enhancing access to resources.	Formal forms of communication, represented by Instruction and Advice layers, have a relatively high path lengths compared to other layers (Table 5.3). This highlights that self-organisation favours informal over formal communication, constraining contractual roles of project managers.
Clustering Coefficients	• The increased level of average clustering coefficients in stage two indicates that actors have evolved to operate relying on highly intra-related structures (see Table 5.3). • Investigation of clustering coefficients at the sub-networks level highlights that Information Exchange and Discussion layers have comparatively high scores compared to others (see Table 5.3). It means that adoption of the ICE relational model helped to foster collective participation and collaborative decision-making.	Table 5.3 shows low clustering coefficients for Instruction and Advice layers. This finding suggests a lower level of coordination at these layers which mainly represents the formal form of communication.
Trust	An increased level of trust as the project progresses into stage two (see Section 5.6, Section 6.2.1.1 and Section 7.4).	Analysis chapters did not provide empirical evidence of constraints under this aspect.

Aspects of Self-organisation	Evidence of Support	Evidence of Constraints
	Table 9.1 *[Continued]*: **An Account of Empirical Evidence Where Self-Organisation Either Supported or Constrained Coordination (Source: Original).** *Table continued on the next page.*	
Network Structure	• Formal reporting networks and emerging communication networks differ (Section 5.5 and Section 5.6). This suggests self-organisation supports development of informal relationships, outside of contractual hierarchies, in order to overcome unequal distribution of power and resources affecting decision-making processes, especially under highly complex and uncertain circumstances. • In Section 6.2.1.1, the reduction of the prominent actors in stage two indicates a move towards a more decentralised structure where more information exchange exists between actors of the lower levels (e.g. sub-groups and disseminators). Power, therefore, is more distributed at stage two, i.e. reduction of prominent actors at stage two shifted the power to the actors residing at the lower levels. • Figure 8.7 illustrates that stage two became closer to the lower limit of the small-world network range (i.e. towards the regular well-clustered configuration). This suggests a more reliance on autonomous actions of the clusters rather than global integration. It reflects a power shift as decision-making processes became more decentralised and focused on the local levels (i.e. clusters). Overall impact resulted in improved efficiencies and reduced costs.	• Self-organisation constrains coordination generated by hierarchical structure (Section 5.6 and Section 7.4.3). • The wider variation between in-degree and out-degree centrality at stage one is an indication of the ill-distribution of power in the network, i.e. some actors are more powerful than others. The network structure of stage one is therefore rather centralised. (See Section 6.2.1.1).

Aspects of Self-organisation	Evidence of Support	Evidence of Constraints
Prominence (Power)	• Self-organisation allows anyone to gain prominence based on their connectivity regardless of their contractual roles (Section 6.2). Table 6.1 and Table 6.2 list the top ten prominent actors of the BSCU communication networks at both stages. These tables suggest that prominent actors came from different tiers and disciplines. • Section 6.2.1.1 highlighted that self-organisation in stage two can help reducing gatekeeper hoarders. This in turn enables better information flows. • BSCU networks were found to be loosely coupled typologies with a relatively non-hierarchical nature. This suggests that low levels of power can be exerted on a macro level, i.e. no single group or actor in full control (see Section 5.6).	• Section 6.2.1 and Section 7.4 suggest that stage two have a wider variation between its actors in terms of degree centrality. Higher variation gives rise to risk of information asymmetry. • Self-organisation can result in dysfunctional prominence leading to bottlenecks that constrain mobilisation of resources (see Section 7.4.3). • Section 6.2.1.1 suggests that some degree of power inequalities (and hence hierarchies) still exists between the different actors in self-organising networks. This cannot be eliminated entirely.
Decision-Making	The investigation of decision-making in Section 7.4 demonstrates interplay between different types of strategies. This explains the extent to which social processes are used, which ranges from autonomous actions to social integration. This diversity in decision-making is necessary to respond to different levels of uncertainty and complexity. For example, deliberation is desirable in situations requiring exchange of ideas to reach common grounds. Imitation and social comparison, on the other hand, arise to cope with high levels of differentiation between actors (e.g. prominence and information asymmetry).	Actors are generally attracted to repetitive behaviours (routines) as they offer consistency and stability, and of a lower cost. The results also suggest that excessive iterations or control provide a milieu for 'dysfunctional prominence'. The high levels of imitation coupled with low levels of repetition indicate that actors wrestle with the need to gather and disseminate information as they are frequently under time pressure (see Section 7.4).

Table 9.1 *[Continued]*: **An Account of Empirical Evidence Where Self-Organisation Either Supported or Constrained Coordination (Source: Original).** *Table continued on the next page.*

Aspects of Self-organisation	Evidence of Support	Evidence of Constraints
Table 9.1 *[Continued]*: **An Account of Empirical Evidence Where Self-Organisation Either Supported or Constrained Coordination (Source: Original).** *Table continued on the next page.*		
Functional Themes	Section 7.5 suggests that self-organisation leads to development of functional themes that combine actors from a range of diverse disciplines and found to be organised around the highly prominent nodes within the network.	Section 7.5 suggests that the inter-relationships are path-dependent (i.e. stemming from pre-existing/historical relationships). The issue of path dependence is, therefore, difficult to avoid even under self-organising structures. This means actors have not benefited from equal opportunity in forming their informal relationships.
Dynamics	• Clusters in stage two have different composition compared to that observed in stage one. Some actors/ties were dissolved, and new/different ones emerged (see Section 7.4). • The top ten prominent actors have changed between stage one and stage two, suggesting a shift in centres of power (see Section 6.2). • Section 6.2.1.1 highlighted that the higher performance in stage two was not achieved because of elimination of hierarchies, but through re-orientation of structures across the three levels of interactions (i.e. local, meso, global).	• The inevitable continuous churn of decisions and change in self-organising process could broaden social distances, hence potentially giving rise to co-destruction processes such as a high level of discontinuity/organisational changes, development of structural holes and loss of power (see Section 7.4). • The need for strategic directions/formal interventions in managing self-organising networks is not limited to risk avoidance but also to steer the self-organising process in order to optimise performance (Section 8.4). • Section 7.4 highlights that relationships develop at different rates; hence the issue of time lags/discontinuity which constrains coordination. Some relationships are just being formed; some have reached maturity stage; others could be residual, carried forward from previous project phases (see also Table 7.2 and Table 7.3 for the imbalance in the ratios of inter-links and intra-links).

Aspects of Self-organisation	Evidence of Support	Evidence of Constraints
Table 9.1 *[Continued]*: **An Account of Empirical Evidence Where Self-Organisation Either Supported or Constrained Coordination (Source: Original).** *Table continued on the next page.*		
Global Efficiency (Global Communication)	• Table 8.2 suggests global efficiency of stage two is higher than that of stage one, given the reduction in the node-to-node travel distance. This means, in stage two, a message can be passed quicker from one end of the network to another. • The stage one and stage two networks exceed the theoretical SW network in terms of global efficiency (Figure 8.4 and Figure 8.9).	Analysis chapters did not provide empirical evidence of constraints under this aspect.
Local Efficiency (Local Communication)	• Local efficiency of stage two is higher than that of stage one. This means an improved level of clustering/intra-interactions was achieved in stage two (Table 8.2). • Local efficiency outpaced global efficiency in growth at stage two. This means the constitutive actors of the self-organising network at stage two have a greater autonomy to choose and manage how best to accomplish their own work, rather than being directed by others from outside the team (Table 8.2).	• Local efficiency scores are not as high as the scores of global efficiency; they are just at an acceptable level (around 60%). This means, in BSCU project, more focus was given to global communication (e.g. project targets) than local communication (e.g. day-to-day tasks). See Table 8.2 for related scores. • The stage one and stage two networks fall short in terms of local efficiency compared to their respective theoretical SW network (Figure 8.4 and Figure 8.9).
The Network Cost	• Cost of communicating at stage two is lower than the stage one. A reduction of 25% in cost was achieved (substantial cost savings). See Section 8.3 for related figures. • The network reduced the cost overruns in its communication network as it moves from stage one (overrun of 5% per link) to stage two (overrun of 3.5% per link). Both of these cost overruns are considered acceptable if the commonly used tolerance level of 10% is adopted. See Table 8.2 for related figures.	• The building cost of the networks is disproportionately higher than the operating costs (See Section 8.3). • At both stages, overall cost of communicating is higher than what can be achieved under theoretical SW network (See Figure 8.4 and Figure 8.9).

Aspects of Self-organisation	Evidence of Support	Evidence of Constraints
Table 9.1 *[Continued]*: **An Account of Empirical Evidence Where Self-Organisation Either Supported or Constrained Coordination (Source: Original).**		
SW Range	• The project network in stage two has moved closer to the most efficient and economical SW configuration (see Figure 8.7). • Stage two remained within SW range despite being narrower. This indicates the adaptive capacity of the network, i.e. its ability to operate within the identified range of the SW network despite facing numerous issues/risks that are pushing the network to fall outside the SW area (see Section 8.4.2 and Figure 8.7).	• Compared to stage one, SW range of stage two has an additional lag phase of one interval. This means network structure of stage two required more time to be built compared to stage one (see Section 8.4.2). • The SW range of stage two occupies 30% of the scale. This is a reduction from 40% at stage one. This reduction in stage two means network structure is at higher risk of operating outside the SW range under increased levels of complexity and uncertainty. This could lead to the risk of losing the associated benefits derived from SW property (see Section 8.4.2).
Clusters Efficiencies	Investigation of local efficiencies reveals that both stages have more or less the same averages across all clusters (Section 8.5).	Section 8.5 highlighted that BIM/CAD cluster was an exception to the rule. It exhibited a significant increase in local efficiencies at stage two. The finding highlighted that coordination in self-organising networks still needs formal interventions to continuously facilitate constructive interactions.

9.3 Discussion of the Findings

This section evaluates what the empirical results mean and how they fit with the literature reviewed earlier in relation to project management. It is then followed by offering an answer to the research question posed at the outset.

9.3.1 Thinking in Terms of Paradoxes

This thesis applies concepts of Complex Adaptive Systems (CAS) to the study of large projects. The consequence of thinking in this complex interactive kind of way is the need to think in terms of paradoxes (i.e. the existence at the same time of two opposed ideas or forces) which is not usual in organisation and management discussions. The paradoxes in this study are manifested by the duality nature of self-organisation, i.e. it is ability to simultaneously support and constrain coordination (see Table 9.1 for the full account of evidence for each possible outcome).

Empirical analysis shows that projects exhibit a number of paradoxes; these are discussed as follows:

- ## Dynamic Stability

Project management approaches to large infrastructure projects have been dominated by assumptions favouring stability and order (Duggal, 2018; Stacey, 2010). This view unfortunately has long been codified in the professional bodies of knowledge which emphasise the importance of managing pre-determined 'life-cycle model' (Lundin and Söderholm, 1995; Addyman, 2019). By adopting the lens of self-organising networks, the discussion presented in this study challenges the predetermined and prescribed forms of organisation and rational-based approaches and gives precedence to ongoing change over stability. This is in line with the work of Tsoukas and Chia (2002), viewing ongoing change as a constitutive of reality rather than exception. The thesis comes in response to the calls to investigate the "*pursuit of consistency and change in contexts where variability and change appear to dominate*" (Turner and Rindova, 2012, p. 44). The aspects of network structure and dynamics summarised in Table 9.1 are examples for the empirical evidence supporting this conclusion. Between stage one and stage two, the network underwent a major change in terms of its size, composition, and communication activity (see Section 7.4 for full details). Section 5.5 and Section 5.6 also highlight that the formal reporting networks and emerging communication networks differ. Consequently, in Section 6.2, network roles were found to be quite different to contractual project roles.

These changes in network structure and its dynamics emerged in response to the additional project requirements and higher levels of complexity/uncertainty created by the pile clash (see Section 5.4.1 and 5.4.2 explaining context surrounding BSCU Project at both stages). Taking this further, this study highlights the need to think about complex projects and organisations as social processes of relating between people, giving attention to relational process. Section 2.10.4 and Section 4.3.2, therefore, outline a multi-level decision-making framework that is based on the extent to which social processes are used. Results presented in Section 7.4 on decision-making suggest that strategies used by actors in self-organising networks range from autonomous actions to social integration, as a function of uncertainty and the resources that are associated with making a decision (e.g. the amount of cognitive effort involved). That is, the focus of self-organising is on what actors are actually doing at their daily tasks in relation to each other (a social-based process). This profoundly focuses on different ontological and epistemological perspectives to "*enrich our understanding of the actual reality of projects and project management*" (Winter *et al.*, 2006, p. 643).

Thinking in terms of paradoxes conceptualises networks as "*Complex Adaptive Systems [CAS] that exhibit both persistence and change*" (Kilduff *et al.*, 2006, p. 1032). As Shaw (1998, p. 29) postulates the potential paradox inherent in the phrase "dynamic stability" or "*stability in flux is fully exposed, putting our dualistic minds in a spin*". In this view, the stability of self-organising networks is manifested in the persistence of core structural properties (e.g. average path length and small-world properties, as presented in Section 5.6 under basic measures, and the functional themes as identified in Section 7.5), whereas dynamic is manifested by the interplay between the actors and the system (Section 7.4 and Section 8.4), and the changes that emerge from such interaction (Kilduff *et al.*, 2006). In Chapter Seven, 'dynamic stability' of self-organising networks is found to emerge by having a large number of relationships at the local level (intra-cluster links) but a fewer number of relationships at the meso-level (inter-cluster links). (See Table 7.2 and Table 7.3 for local level data and Table 7.5 and Table 7.6 for meso-level data). This finding suggests that relationships are constantly evolving over time but at different rates. They are more dynamic at the local (intra-cluster) levels than meso- (inter-cluster) levels. Dynamic stability, therefore, can be defined as a matter of relativities, i.e. one state of interaction is considered in comparison with another state at different level of interaction. This differential between levels of interactions is necessary to reduce number of conflicting constraints and provide the system with the capacity to absorb destructiveness of highly unstable dynamics (Kilduff *et al.*, 2006). It can be argued, therefore, that the "dynamic stability" concept links back to the importance of the duality of

micro-macro analysis and postulates that "*at certain levels of analysis, stability can be seen, and yet at other levels, high degrees of dynamism are apparent*" (Grove *et al.*, 2018, p. 9).

- ## Predictability and Unpredictability

It is believed that there is a misunderstanding of self-organising concept and its features (Stacey, 2010). In the context of social systems, for example, self-organisation is wrongly associated with a free-for-all, where anyone can do anything, leading to chaos (Stacey, 2010). While CAS suggests that it is impossible to precisely predict the outcomes of actions undertaken in projects, it recognises individuals as interdependent individuals rather than being autonomous. This co-dependency implies that actors need to stay in a relationship and therefore they have to take into account the needs of others; otherwise they will be excluded. Individuals, therefore, are confined to a number of possibilities and their actions are the consequence of the interplay of other actors' actions (Stacey, 2012; Fuchs, 2003).

Empirical analysis of decision-making in Chapter Seven (Section 7.4) demonstrates an interplay between various decision-making strategies, especially between repetition and deliberation strategies. This interplay suggests a paradox of predictability and unpredictability, i.e. the interactions are not entirely unpredictable (deliberated patterns) nor is it entirely predictable (repetitive patterns) and in fact these two cannot be separated from each other in view of their co-dependence. This also sheds some light on the paradox between the working behaviour of repetition (working autonomy) and deliberation (working with others).

Extending this further to the question of power, which is central to understand what actually goes on in a system, power is found to be an aspect of every relation that constrains and enables organisational functions at the same time. Empirical evidence found in Section 6.2 suggests that self-organisation allows anyone to gain prominence (power) based on their connectivity regardless of their contractual roles. By doing so, self-organisation enables better information flows (Section 6.2.1.1), and achieving improved efficiencies and cost savings (see Table 8.2). However, unfair distribution of network prominence, could give rise to 'dysfunctional prominence', i.e. routing all information flows through certain actors leading to an excessive control over the outputs of others and creating bottlenecks that constrain mobilisation of resources (see Section 7.4.3). These contradictory findings provide an evidence of the opposite impact of self-organisation. In fact, these conflicting features are inherent characteristics of self-organisation process and their existence is necessary to fuel the ongoing process of creation and

recreation process in self-organising networks. Emergence of these processes can be seen as a form of resistance to the status quo, to rebalance distribution of power affecting decision-making.

- ## Formal and Informal Organisations

Projects are usually viewed as 'transitory units' of the formal organisations (Bakker and Leiter, 2010), involving a number of 'transitions' in order to deliver the functions essential for design and delivery (Winch, 2014). By adopting a network perspective, this study suggests that there is no boundary between the formal and informal organisations because all that matters are relationships. Empirical evidence in this context is the ongoing change in the network structure and the mismatch between formal and communication networks (Section 5.5 and Section 5.6). The top ten prominent actors (i.e. power centres) were also found to be different between the two stages of the network (see Table 6.1 and Table 6.2). The emphasis, therefore, moves towards a practice-based approach looking at 'what is actually being done'. The proposed conceptualisation of project activities as self-organising networks goes beyond defining 'transitions' as deterministic moves from one life cycle stage to another (cf. Winch, 2014). It suggests a continual evolution of relationships supporting information exchange and that network roles are quite different to project roles (as presented in Chapter Six). For example, Section 6.2.3.2 found that Project Control and Management were bypassable by other actors in terms of brokerage flow, whereas Section 7.5 suggests that Planner was the most prominent actor in the functional theme of decision-making group. Most importantly, self-organisation does not suggest that formal hierarchies can be eliminated entirely or power has to be transferred fully to local levels (Section 6.2.1.1). Alternatively, self-organisation suggests there is an interplay between formal and informal structures and that emergence of coordination in networks needs formal interventions to promote constructive interactions or induce certain outcomes (see Section 8.5 and Section 8.3).

Applying self-organising perspective, which focuses upon relational and social aspects of project organisations, to the concept of uncertainty suggests that uncertainty emerges as a state of the social process (see Section 2.10.4 and Section 4.3.2). This means that project actors play a critical role in shaping the conditions to either reduce or increase the uncertainty on an ongoing basis. This explanation challenges the view of Winch (2014) who considers uncertainty as an intrinsic property of the reality of complex projects that can be progressively reduced through the project lifecycle as project information become available. Winch (2014) conceives information gathering as a time-based process, i.e. uncertainty is relative to earlier and later points of a pre-determined path that is there to be

discovered for managing projects effectively. Projects, therefore, are concerned with managing the variation around the baseline. Alternatively, this study takes a subjectivist position, highlighting the importance of contextual circumstances/actors' actions for treatment of uncertainty (see Section 7.4 on decision-making strategies).

9.3.2 Influence of Connectivity on Performance

Literature claims that higher levels of performance tend to be associated with higher levels of connectivity that are necessary to support the formation of decentralised structures (e.g. Kauffman, 1996; Losada, 1999; Fredrickson, 2004). However, this study demonstrated a degree of fluidity, i.e. connectivity can have positive and negative effects, depending on the prevailing conditions. Interestingly, multi-level connectivity analysis (Section 6.2.1.1) highlighted that the higher performance in stage two was not achieved because of elimination of hierarchies, but through re-orientation of structures across the three levels of interactions (i.e. local, meso, global). In stage two, less hierarchies (i.e. decentralised structures) were observed at both local and global levels, but the meso-level remained having a centralised structure. From a social network analysis perspective, this finding implies that even in self-organising networks, which are considered distributed systems, a certain hierarchy will always be found that is centred around prominent actors. In extremis, the higher connectivity of these actors allows them to be dysfunctionally prominent, i.e. the ability to control, hoard or filter the information. It can result in forming information bottlenecks; thus, negatively affecting the speed and quality of information flow (Section 7.4.3). This finding affirms Pryke (2017) and Stacey (2010) findings that prominent actors could constrain the operations of project networks. The design of networks that foster the establishment and maintenance of high levels of performance, therefore, should entail an absence of extreme levels of prominence (dysfunctional behaviours). This can be identified, for example, by monitoring centrality measures to enable early interventions.

Table 8.2 showed improved efficiencies and cost figures at stage two. Figure 8.7 further suggests that stage two was closer to the SW economical network but optimal value was not achieved. The failure for achieving the optimal value can be explained by the cases of dysfunctional prominence and non-decision-making behaviours found in stage two to defend their status quo (Section 7.4.3).

This study argues that centralisation and decentralisation are not mutually exclusive options (see Table 9.1 – aspect of network structure); they exist simultaneously and cannot be separated. Presence of hierarchy within self-organising project networks helps in unpacking the centralisation-decentralisation dichotomy, providing further insights into its definition and causes. Network structures are not about full elimination of hierarchies but rather the ability to facilitate the 'way things are done'. The power differentials (hence hierarchies) are necessary in order to activate dynamics in the complex systems in response to higher levels of uncertainty/risks. In the context of project management, the emphasis will, therefore, move towards accounting for human frailties rather than assuming that 'human resources' will behave consistently and with rationality, under instruction from their line managers. This finding profoundly asserts the importance of adopting collaborative procurement approaches (e.g. the ICE approach in the case of BSCU project) in promoting a re-orientation of interactions towards a more relational position. These approaches can open up opportunities as evident, for example, by re-orientation of power at the meso-level, as the project moves from stage one to stage two.

Empirical findings of Chapter Seven suggested a varying degree in terms of presence of hierarchies within the self-organising clusters. This is because higher levels of decentralisation are not always a panacea as they can lead to some negative outcomes. For example, the hoarding of power and not allowing it to be transferred to local levels. This was particularly found in the Project Control and Management cluster which exhibited resistance to distribution of power outside of contractual hierarchy. This means that organisational structures that are based on collaborative approaches, can shape power relations significantly yet do not determine them entirely. Contextual circumstances and individual behaviours are therefore crucial elements that should always be considered.

9.3.3 The Crucial Role Played by Meso-Level

Chapter Seven investigated inter-cluster relationships and revealed that the pairing between network clusters divulges a meso-scale structure (Section 7.5). This finding brings the concept of connectivity to the fore and highlights the importance of meso-levels' role in managing networks. Thus, discussions about the hierarchy of authority relations represented in the typical organogram (i.e. who reports to whom) has little relevance in the management and leadership of project networks. A network perspective substitutes the concept of enabling and facilitation.

Meso-level is usually occupied by go-to personnel (i.e. brokers, in network terms). Investigation of the brokerage roles in more detail (by adopting a multi-level perspective as presented in Section 6.2.3) revealed that this concept is a double-edged sword. That is, these actors play a dual role (as enablers or inhibitors) in affecting the flows of information through a network. It was found that brokers can help holding the network together and reducing transaction costs. This was explained by having power differentials among actors which induce diversity and in turn can induce positive opportunities to facilitate effectiveness and efficiency. For example, meso-level can facilitate communication between diverse and hard-to-reach parts of the network. However, at the same time, it is important to recognise that brokers can control the flow of information and communication, hence uncertainty level (Freeman, 1979; Borgatti, 2006; Prell, 2012) by retaining or biasing the information (Freeman, 1979; Hossain and Wu, 2009) and creating unnecessary iterative interactions (Pryke, 2017). That is, high levels of power inequality can induce constraints that in turn may add to the possibility of chaotic fall out /network destruction/disintegration – e.g. gatekeepers/hoarders withholding or delaying information dissemination by non-decision-making behaviours to defend their status quo.

This study highlights that meso-level plays a crucial role in keeping the complex system vital. This contrasts with much of the literature that emphasises on macro-level importance (cf. Chawla and Renesch, 1995; Wenger and Snyder, 2000). This study also suggests that approach of systems thinking, i.e. whole system approach where every actor needs to consider the impact of their own actions on the entire network, could be dangerous (cf. Belanson, 2000; Dhanaraj *et al.*, 2004). This is because highly interconnected arrangements exhibited in large projects could exhaust resources, leading to instability and hence destruction/failure. Alternatively, this study suggests that actors/teams need to pursue their own activities and not to be overly concerned with details and how the spillover affects neighbouring individuals/teams or whole organisation. Only some attention needed to be paid but not too much. This is because differentiation in power can naturally produce reasonably counter-balancing forces that

support emergence of new patterns/structures, i.e. self-organising systems. From this perspective, project systems are iterative, i.e. actors do not just create something and end their role therein, but they also have to deal with any issues/problems that may emerge subsequently.

Findings of analysis reveal that meso-level in a network is the nexus of dynamic relationships between the micro practices and the formulation of strategies at the global level (Section 7.5 and Section 6.2.3.1). Changes in networks usually occurs locally given the human intrinsic ability to be reflexive and hence prone to changing the status quo. For these changes at the local level to be institutionalised at the global level, they are highly dependent on the meso-level to amplify the effects. This study, therefore, conceptualises connectivity at meso-level as the conduits in which information and other resources flow; thereby affecting the numerous processes/interactions that lead to emergence of system's properties at the global level. Building on this line of thought, it can be argued that coordination (as a system property) is relational rather than transactional (i.e. not associated with pre-determined structures). Thus, the need to look beyond the governance arising out of standard forms of contract.

9.3.4 The Role of Front-End in Project Development

Chapter Five (Section 5.3) highlighted that BSCU project pioneered a novel procurement approach - Innovative Contractor Engagement (ICE). This is a relational contract with the aim to focus upon the collaborative behaviour of project actors. The collaboration was seen, for example, when Tier-one contractor at stage two re-allocated its own resources to other designers, as both Civils and Structures and BIM/CAD contractors could not handle the design delay and uncertainty stemmed from the new proposals. This decision clearly contributed towards achieving a strategic goal of 'moving the project forward', breeding culture of 'our project' rather than 'my project'.

Section 5.5 further underlines that, as part of ICE, a core design-delivery team was formed at the front-end and this team continued to be part of the project as the design was being developed. This contributed to having a shorter social distance. Investigation of both contractual and informal networks also reveals that members of this team occupied prominent positions at both networks and at both stages of the project (see Section 5.5, Section 5.6 and Section 7.4). This finding stresses the instrumental role played by this team in shaping not just the front-end but also the subsequent project phases.

It can, therefore, be concluded that the management of front-end phase of large infrastructure projects plays a critical role in responding to issues/uncertainties in the VUCA project environment. This is because "*value outcomes tend to start emerging in the latter stages of a project, yet these have a direct link to the conception of a project (front-end stage), where most of the value can be created, designed and configured*" (Fuentes *et al.*, 2019, p. 1). The thrust of the project management, however, has been conceiving front-end as a discrete, pre-determined rational plan/process. By adopting self-organising approach, this study challenges this perspective highlighting that projects are susceptible to social interactions and thus cannot be specified in advance with accuracy. Alternatively, it suggests that front-end of large complex projects is an iterative and evolutionary process, and, to a large extent, unpredictable and ill-structured given the project definition is not complete at contract bid stage, simply because it is based upon incomplete information (Pryke, 2017). This is in line with Morris' (2013) discussions about the maturity of project definition, but it contrasts with Løwendahl (1995, p. 361) who describes management of front-end as "*rationally designed tools for achieving a predefined goal with maximum efficiency*". Taking things further, the analytical framework employed in this study suggests that front-end is often conducted through power and influence rather than through a pre-engineered/rationale approach. As suggested by Pryke (2017, p. 177) *"the existence and location of*

power are important in the way in which the networks evolve and sustain themselves over the life of the project".

From the above discussion, the argument here is that front-end should be managed from "shaping" perspective rather than "planning" perspective. The latter assumes the project unfolds in an orderly fashion and thus an ability for the Project Managers to have a high level of control to reduce levels of uncertainty. However, the "shaping" perspective suggests that a great deal of risks is not yet under control. This is because the front-end is a context of ambiguity where its trajectories emerge/evolve as the project progresses (Fabianski, 2017). It will, therefore, not be possible for Project Managers to predict the journey ahead or set clear objectives with full confidence, but rather will be open to debate. This perspective supports Kreiner's (1995) argument that projects develop in a "drifting environment". From CAS perspective, the project network environment is not static as envisaged in the contracts and protocols, but it is continually transforming and adapting in response to the demands of the project and the actors within the network. Actors *"help define the systems through which the project is delivered; they influence the behaviour of other actors and are influenced themselves by the actions of other actors"* (Pryke, 2017, p. 180).

All in all, it is drawn from the empirical evidence (see Table 9.1 for the summary) that self- organisation is not always unproblematic (e.g. dysfunctional prominence). This challenges the existing literature about self-organising networks which largely assumes positive outcomes (e.g. Pryke 2017). At the same time, the results also provide a balanced view suggesting that some aspects of project-based communication networks can be optimised (e.g. efficiency and cost) by exploiting their self-organising features. This study, therefore, calls to rethink the way in which large construction projects are conceptualised, analysed and managed. By adopting CAS perspective, it argues that hierarchical perspective is actually quite limiting and restricts how relationship structures are understood. It claims that there is value in understanding projects through the study of the networks. It further suggests that SNA has certainly potential for application within the field of construction research and industry. SNA can provide a novel understanding of the invisible, self-organising aspects of project organisations. In particular, the study of the information exchange networks offers a more fine-grained approach that is more closely to the practice-centred project management.

Following the discussion of the findings, next section articulates the response to the research question: ***How do self-organising networks either support or constrain coordination in large construction projects?***

9.4 Answering the Research Question

In response to continuous pressures of finding and dissemination of information in a highly uncertain environment, the study suggests that self-organising process is not a special event that is externally induced but it emerges as an ongoing socially constructed phenomenon from within organisations by the actors involved. Relational dynamics, therefore, are neither rational nor linear, but rather influenced by the subjective understanding of the people involved, and how they make sense of the context, events, and issues/risks as they unfold over time. This line of thought emphasises the importance of individuals and micro interactions within systems, rather than organisations as some larger entity. It places the focus of coordination development in the hands of individuals, as the focus of complexity. The study, therefore, contrasts with much of the literature that stresses on macro-level patterns (cf. Chawla and Renesch, 1995; Belanson, 2000; Wenger and Snyder, 2000; Dhanaraj *et al.*, 2004). It supports the work of Stacey *et al.* (2000) and Stacey (2012) on Complexity Theory and Pryke (2012, 2017) on project networks. Yet, the study goes far beyond that towards exploring how multiple factors (e.g. decision-making, functional themes, multi-level interactions) interrelate in a dynamic way affecting the emergence of coordination in large construction projects.

The dominant discourse in the study of project organisations is based on the sciences of certainty that in turn use linear models, assuming rationalist causality (Stacey, 2012; Cooke-Davies *et al.*, 2008). This approach fails in explaining the temporal and contingent nature of project environments, and in particular self-organising networks (Stacey, 2010; Grove *et al.*, 2018; Pryke, 2017). This thesis, therefore, adopts a CAS perspective by linking the interdependencies between the micro-relations/events and macro-structures at the network level. This is profoundly inconsistent with previous accounts of causality and outside many linear forms of mathematical modelling (Kauffmann, 1993 & 1996). Accepting CAS understanding opens-up new ways to comprehend the ongoing change in organisations. Particularly, conceptualising projects as networks and that network roles are quite different to project roles. Furthermore, networks work within the constraints of very high levels of interdependency and thus they are evolving systems and multi-functional. This is driven by the need to coordinate and integrate and to solve complex problems; hence the rise of self-organisation. This means networks will have several structures or eventualities rather than fixed hierarchies as they respond to client requirements and higher levels of uncertainty. The findings highlighted that these adjustments/responses can range between local to global adaptations with consequences (positive and/or negative), affecting the network efficiency and costs. This understanding puts emphasis on the

open-endedness and the transformational character of the ongoing process of organising (Tsoukas and Chia, 2002).

The analysis in Chapter Five showed that there is a mismatch between informal communication networks and contractual networks of BSCU project. It can be inferred from this finding that coordination in complex projects is not designed *ex-ante* but rather emerges *ex-post* as a result of various interactions. The main argument presented throughout the thesis stresses the dynamic and ever-changing nature of organisational reality in view of the inevitability of human interactions (Grove *et al.*, 2018) and their inter-subjectivity (Stacey *et al.*, 2000) as risks/uncertainties unfold to deal with the demands of the project and the systems in use. This approach enables viewing coordination as an evaluative outcome arising from the nested interactions, and hence proposing a new perspective to study coordination as an ongoing process that is naturally-driven and 'always in the making' (Tsoukas and Chia's, 2002). In this sense, coordination is viewed as an emergent property that is generated 'from within' and can be understood from a multi-level perspective, i.e. how micro-level interactions constitute meso- and macro-level contexts. If this argument is accepted, then it implies that coordination is not a deliberate managerial action, highlighting a need to rethink about the role of project managers. From this proposed view, organisation theorists need to give theoretical priority to microscopic interactions. This profoundly asserts that projects and organisations are not "found"/ "imposed" from top-down but "invented" and "co-created" from bottom-up as a result of human interactions (Smyth and Morris, 2007; Blomquist *et al.*, 2010). Consequently, decision-making power is always negotiated and re-negotiated as a result of network dynamics.

The study showed that BSCU project was delivered by temporary systems that are continually transforming and adapting to deal with higher levels of complexity and uncertainty. Nevertheless, there is no reason to suggest from the findings that formal structure should be rejected in managing projects. In fact, both Chapter Six and Seven suggest that some formal interventions in managing self-organising networks are still needed in order to facilitate constructive interactions. This is because while local interactions are found to be a source for forming new information/structures, findings stress that some interactions, for example, could result in dysfunctional prominence; hence impairing operation of project networks. Interestingly, this highlights that self-organising process could be dangerous, counterproductive or destructive at times. This is due to involvement of numerous interactions and actors in forming value, adding further complexity and leading to inefficient use of resources and scope creep. To overcome these shortcomings, this study concludes by recommending that it is absolutely vital

for Project Managers to take preventive measures when necessary in order to protect the outcomes by containing any negative interactions and stopping them from propagating further. It is worth highlighting that the need for strategic directions/formal interventions in managing self-organising networks is not limited to risk avoidance but may also be required to steer the self-organising process in order to optimise performance, e.g. to speed-up the establishment of networks. This entails regular gathering of network data and monitoring costing networks and actor roles in projects.

9.5 Summary

This chapter starts by providing an account of all empirical evidence in relation to the reserch question. It then discusses the findings of the study, and ends by proposing a response to the research question. Overall, the study offers an original perspective in demonstrating how self-organising networks can be beneficial or detrimental to the development of coordination that is necessary for project design and delivery. By conceptualising networks as Complex Adaptive Systems (CAS) that have a tendency to self-organise, this study gives precedence to ongoing change and highlights the importance of micro-interactions. In this context, dynamic stability perspective is presented as a new way of conceptualising construction organisations and describing the roles and relationships between the actors. By doing so, it challenges the predetermined and prescribed forms of organisation. That is, it provides an alternative perspective to the hierarchical management approach that views projects as rigid systems that have the tendency to "freeze" themselves into a fixed stable state (Ive, 1996) or/and managed through time delimited stages (Addyman, 2019).

Next chapter summarises the key points of this thesis and reflects on its limitations, opportunities for future research, and outlines the key contributions.

10

Conclusions, Limitations, Future Work and Contributions

10.1 Introduction

This is the final chapter of the study. It summarises the context of the study and the work carried out during this research project. It presents what findings mean and considers how they might be useful. The first two sections of the chapter provide a brief synopsis of the contents and key conclusions/takeaways. The following section presents the research limitations and explains how some aspects can be improved or tackled differently. It also outlines how limitations affected the conclusions drawn from the research. The chapter then seeks to reflect on next steps and identify an agenda for future research. The last section ends on a positive note by highlighting research key contributions.

10.2 Chapter Summaries and Conclusions

This is an exploratory study with the aim of developing an understanding of the self-organising aspects in large construction projects. More importantly, it aims to highlight how such understanding might improve management and analysis of complex projects. This is the original contribution of this study.

- **The Introduction Chapter:** clarifies that the origin of the research problem relates to the issue of coordination, focusing on self-organising project communication networks. This is because the delivery and design of a complex project is a very large coordination issue that involves an intensive human/social activity (Pryke, 2017). Thereafter, the following research question was developed: *"How do self-organising networks either support or constrain coordination in large construction projects?"*

- **The Theoretical Chapter of the study**: deals with a brief history of the key theories relating to the study of projects (e.g. Taylor's Principles, systems theory). It then provides an extensive review of existing literature in the areas of Complexity Theory, and project and organisation management. In this way, the knowledge gap of the research was identified. It reveals that existing literature paid scant attention to the application of network approach and SNA to construction projects. A hierarchical, rational and deterministic premise has clouded the study of project management and thus little has been written about how systems evolve and decay in complex settings. The reality of delivering and designing a project operates within a context with a great deal of uncertainty and complexity. Projects are, therefore, increasingly perceived to be more unpredictable, nonlinear, and multidimensional. They comprise a number of interrelated and interdependent communication systems that are in turn associated with the 'social

processes' inherent in human activities. This turns the discussion to self-organising networks, which are defined as the non-contractual information exchange relationships that form in response to the needs of information gathering, processing and dissemination. They enable project actors to facilitate the discharge of their own roles under highly complex and uncertain circumstances. The early chapters of the study conclude by suggesting adopting Complex Adaptive Systems (CAS) perspective, highlighting its potential to provide a very rich framework within which a novel understanding of projects can be developed.

- **Methodology Chapter:** explores the context to provide justification for the conceptualisation of project organisations as networks. Methodologically, project informal communication networks and the analysis of their interdependence will be studied using SNA tools. The key benefits that SNA might bring to the study of construction projects are, therefore, outlined. The research process starts by reviewing a general theory and then applies its principles to a specific case. This sequence represents a path of deductive reasoning to social network study and it is usually associated with quantitative methods (Bryman, 2016). However, using existing data from a two-year large infrastructure project, Bank Station Capacity Upgrade (BSCU), gathered through a KTP project between UCL and TfL, indicates that the element of induction undoubtedly exists (Williams and Shepherd, 2015). This is where implications of the findings have to be inferred to the theory that prompted the whole exercise, i.e. feeding back into the area of enquiry in the opposite direction and using qualitative methods in support of SNA results (Bryman, 2016). The claim here is that the investigation of self-organising networks in infrastructure projects using SNA extends the application of Complexity Theory by taking into the account the informal relationships that are not always recognised, especially in project management. The study, therefore, calls to recognise the importance of social aspects as a factor affecting the establishment of effective project delivery networks and their evolution and maintenance over time.

- **Analysis Chapters**: commence by introducing the case study and its key features. The complexity of BSCU project, its large scale, strategic importance to the UK, and the ICE novel procurement approach are all factors to provide justification for choosing it as the thesis' case study. Context of the project and key events were provided so that the findings can be more fully understood. Detailed analysis chapters are then organised based on the level of analysis, namely: micro-level (the role of individuals), meso-level (clusters), and macro-level (the whole

self-organising networks). These chapters employ a raft of social network analysis techniques supported by insights drawn out from qualitative data. They principally examine the topography of BSCU networks at two different project stages, the connections that form between a given group of actors, project actors' roles and decision-making processes, and how these are translated in terms of efficiency and cost. Key findings from analysis chapters are listed as follows:

Chapter Five:

➢ Formal reporting networks and emerging communication networks differ. In fact, the multi-layered networks are more representative of actual relationships in project settings. They are formed in response to the need to gather and exchange information.

➢ Actors were found to restore to their informal relationships to tackle higher levels of complexity and uncertainty. In these circumstances, the reliance on contractual communication channels reduces substantially. It was also found that the degree to which the networks grow in connectivity is directly proportional with the increase in uncertainty and complexity.

➢ Networks of complex projects exhibit small-world characteristics of high average clustering coefficient and short average path length. These features are helpful in achieving effective problem resolution and coordination.

➢ Trust increases between actors as the project progresses. This translates into a more reliance on intra-related actors (clustering).

➢ Relational procurement models rolled out at the front-end (such as ICE) are helpful in fostering collective participation, enhancing access to resources, and collaborative decision-making.

Chapter Six:

➢ Self-organisation allows anyone to gain prominence based on their connectivity regardless of their contractual roles.

➢ Network roles are quite different to contractual project roles and actors can assume multiple positions to support emergence of coordination.

➢ The imbalance in actor roles is an indication of information asymmetry/power differentials. While self-organisation assists in easing of bottlenecks by way of shaping prominence (shifting centres of power), hierarchies cannot be eliminated entirely in networks.

- Higher performance in networks can be achieved through re-orientation of roles across the three levels of interactions (i.e. local, meso, global).

Chapter Seven:

- Structures of project networks are dynamic; they change in response to the different levels of uncertainty and complexity.

- Self-organising process is not without shortcomings. It can, for example, give rise to co-destruction processes (discontinuity/organisational changes) or provide a milieu for 'dysfunctional prominence'.

- Decision-making is a function of social processes. Actors use different strategies in a way that is commensurate with level of uncertainty.

- Development of functional themes is predicated on the highly prominent actors within a network. These themes are important to understand and manage in complex projects.

- The issue of path dependence is difficult to avoid even under self-organising structures. In project settings, this is pertinent to human social behaviour.

Chapter Eight:

- Achieving the optimum value of a network is quite difficult in view of the narrow SW range. Depending on where you are located on this range, self-organisation can either exceed global or local theoretical efficiency values but in most of the cases will end-up incurring an overrun cost.

- A network can achieve better performance by way of shaping its connectivity and exploiting small-world features.

- The adaptive capacity of a network is its ability to operate within the identified range of the SW.

- Coordination in self-organising networks still needs formal interventions to continuously facilitate constructive interactions. Thus, the need for strategic directions/formal interventions in managing self-organising networks is not limited to risk avoidance but also to steer the self-organising process in order to optimise performance.

- Different network typologies take different time to build and operate. However, it was found that the building cost of a network is disproportionately higher than its operating costs.

- Effective management of communication networks can lead to substantial cost savings.

- The differential between global efficiency and local efficiency is a reflection of whether more focus was given to global communication (e.g. project targets) or local communication (e.g. day-

to-day tasks). This in turn determines the degree to which actors rely on autonomous actions or are being directed by others from outside the team.

10.3 Key Learning Points

- The study stresses the need to rethink the way in which construction projects are conceptualised, analysed and managed. It, therefore, adopts CAS theoretical perspective to better explain the lingering dilemmas of complex projects, such as nonlinearity and unpredictability. In this way, complex and inherently uncertain characteristics of large construction projects are recognised as the norm rather than the exception. Furthermore, the study suggests using a network approach to study project management systems. This is because evaluation of the self-organising networks offers a way to relate to the functional systems and provides evidence to support the nature of effective and ineffective project delivery networks.

- This study demonstrates that conceptualising projects as multi-layered networks along with analysis of network data has the potential to provide a richness of analysis for project organisations. This in turn can make an important and valuable difference to understanding of the management of projects. It emphasises the non-hierarchical nature of information exchanges in large projects, arguing that underlying systems are largely interrelated. The study further postulates that communication process is key to the formation of self-organising networks and thus coordination, generated through self-organisation, can be understood as an ongoing and provisional emergent accomplishment which is 'always in the making'. This conclusion profoundly asserts that projects and organisations are not "found"/ "imposed" but "invented" and "co-created" (Smyth and Morris, 2007; Blomquist *et al.*, 2010).

- The CAS perspective provides a basis for recognising that self-organising networks yield a set of dynamic stability conditions. This property is evident, for example, by the recursiveness of networks, i.e. the creation and re-creation of relational patterns in order to accomplish goals and address uncertainty (Kilduff *et al.*, 2006; Stacey, 2010). This property also alleviates the contrasting role of self-organising that is usually confined to generating change, neglecting the need for contingent and balanced responses. 'Dynamic stability' is, therefore, a valuable perspective to provide fine-grained understanding on how actors/firms develop different types of processes in order to manage varying degrees of uncertainty in large and complex projects. This perspective is an attempt to address the need for *"flexible performance in which an*

organization does different things at different times" and responds *"with a wide variety of performances to variation in the environment"* (Nelson and Winter, 1982, p. 106).

- Accepting the proposal of understanding projects through the study of the networks entails designing project team structures and roles as networks and managing them as networks rather than hierarchies. This is because actors can have some prominence within a network by virtue of their ties. The study, therefore, encourages project managers to pay careful attention to patterns of communication and interactions, i.e. how actors are present in each situation. It further suggests that "reality" is actually a reified social process that is created anew in each moment. It recognises the possibility of change that is hidden within every moment, and that small changes can propagate to become major changes, including emergence of destructive patterns. Studying project systems through the lens of interpersonal relationship networks is important in understanding how self-organisation emerges from bottom-up informal processes/interactions. This is largely overlooked in the literature, suggesting a contribution in this realm.

- The study provides a business case for studying the topography of project networks by proposing measures to estimate costing and financial viability of networks. These measures can be quantifiable through the use of SNA. Confronted by the perception of the construction industry as wasteful, fragmented, and adversarial, this study suggests that significant savings and enhanced efficiency can be achieved through monitoring self-organising networks and counterbalancing any dysfunctional behaviours. For example, disseminating capacity to be closely monitored to ensure backups/other alternatives are available in case of need and avoid forming bottlenecks.

- It is found that the alternative philosophy of developing a relational project management based on self-organising concept is an appealing one as it offers a new perspective to deal with the complexity of large infrastructure projects. However, the study also highlights the key shortcomings and constraints of self-organising process, given its ongoing change and thus its potential tendency to creep, slippage, and drift (Tsoukas and Chia, 2002; Grove *et al.*, 2018). For example, it can lead to emergence of dysfunctional behaviours of gate keeping and hoarding which could impair the functional systems that design and deliver projects. The inevitable continuous churn and change in self-organising process could also broaden social distances, hence potentially giving rise to co-destruction processes such as discontinuity (especially when coupled with poor handover), development of structural holes and loss of power. The point

made by the study is that careful management of network roles and interactions as well as the interplay between different decision-making processes and prominence is crucial to deliver successful project outcomes. This highlights the importance of having project managers with high level interaction competencies and awareness of the dynamic process in complex project environments. This can be achieved through using monitoring measures to detect any early warnings of potential problems. It also highlights the need for interventions to suppress disenabling or dysfunctional behaviours and any other negative consequences of self-organisation.

- For a long period of time, organisation theorists and practitioners have chosen to focus on the formal (visible) forms of organisations, but it's important to not overlook the organisational informal (invisible) aspects. The thesis, therefore, studies projects as social processes that are temporary and contextual. It emphasises that project reality, including perceptions of uncertainty, is socially constructed by actors' actions (Fabianski, 2017). This view challenges Winch (2002) dynamic uncertainty logic that is based on time. Alternatively, the study puts more emphasis on the context, recognising the limited resources for decision-making process and actors' subjectivity, as actors cultivate their relationships and work in collaborative networks to respond to project risks and uncertainties.

- Adopting network perspective suggests the need to provide a more refined understanding of roles in project networks. Roles in networks are transient, i.e. they evolve and change over time. They are subject to continuous negotiation and re-negotiation of power. Project managers, therefore, need to recognise that there are no simple hard-coded techniques or shortcuts, but they play catalyst roles to develop the art of self-management in projects. This profoundly moves away from bureaucratic hierarchies and the "command and control" structures that dominate leadership theory and practice, towards promoting actors' self-awareness to improve understanding of one's own decisions and their effects on others, enabling connections and collaboration (Uhl-Bien and Marion, 2007; Holley, 2012). As a result, this study takes things forward by suggesting that project managers can act *"as much an agent of change as everybody else is"*; the only difference being that mangers are provided with *"declarative"* and visible powers (Tsoukas and Chia, 2002, p. 579). This study, therefore, opens-up new ways to encompass formal interventions as internal acts with the aim of fostering desirable patterns.

- In response to the research question, the study acknowledges that project managers play a critical role in bringing diverse actors together in order to achieve project goals. However, it argues that coordination is not a result of rational planning/a deliberate managerial action, but it comes as a result of individuals trying to accommodate new experiences and realise new possibilities. This is to say that while coordination can be induced in complex environments, it is likely to encounter veto due to existence of diverse and opposing views, practices and preoccupations. Therefore, as suggested by Tsoukas and Chia (2002, p. 579) *"managers need to clear their vision to see what is going on and, at the same time, help fashion a coherent and desirable pattern out of what is going on".* This means that coordination can be achieved through the promotion of social interactions, rather than the use of some form of contractual or formal arrangements. This is because "*an excessive preoccupation with planned change risks failing to recognize the always already-changing texture of organizations*" (Tsoukas and Chia, 2002, p. 579). The process to generate coordination, however, needs formal interventions to continuously facilitate constructive interactions. This strategy was followed in BSCU project where project managers enforced certain narratives of what should be done about certain issues and thus allow local autonomy to flourish whilst exerting lower control levels. Chapter Seven, for example, highlights that actors from the client organisation (TfL) were found to be heavily embedded in different clusters. This is a basic technique but yet it can be argued that coordination emerged from actors' own participation and, to a large extent, was influenced by management and their ability to help raise the skills and awareness of others (Suchman, 1998). In this way, "*complexity does not vanish through the skylight but becomes an integral part*" of the mind-set of those involved (Akaka *et al.*, 2013, p. 17).
- Overall, the concept of self-organising networks in project management offers an alternative approach to project delivery in dynamic and turbulent environments. It provides a more practice focus, moving away from bureaucratic planning and tight management control towards an approach allowing more emphasis on monitoring, integrating and analysing information using contiguous 'bottom-up' adaptation of systems as the project environment evolves.

The first two sections have summarised this study, from the research problem and knowledge gap, through the theoretical framework and methodology into the findings and the response to the research question. In the following sections, research limitations, opportunities for future research, and key contributions are presented.

10.4 Research Limitations

Although this research yielded interesting findings, it is not without limitations. These are outlined as follows:

- **First, limited focus of the study:** This was a study of a single case study and a single life cycle stage. That is, the focus of this study was on communication networks of the detailed design stage of BSCU project. Furthermore, KTP data extends over two time periods only, covering in total almost half of the phase time (as explained in the Section 4.6.4). This limitation was driven mainly by KTP initiative and time constraints to study long-term projects such as BSCU. Nevertheless, the study produced an extensive account of analysis contributing towards an enhanced understanding of project self-organising networks from a complexity-informed perspective. Further research can study self-organising networks across several projects/stages, which can provide further insights into how firms can learn and improve their performance from one project/stage to another.

- **Second, use of secondary data and no access to real project staff:** This study uses an existing KTP dataset. The data was not collected by the researcher from first-hand sources and there was no access to involved participants. This means researcher may have missed some valuable information that can only be understood through observing how events unfold from within. Some subtle details can only be understood and gathered by primary data (e.g. hidden actions and incentives). This issue was partially addressed by using qualitative data, namely discussions with key project informants and access to a number of project-related documents (Chapter Four describes in detail the challenges faced and how they were dealt with). It is also worth noting that there has been precedence in prior research (Ruuska *et al.*, 2009), and thus reliability is pursued, for example, by benefiting from access to TfL published reports, periodic project progress reports, and reflections after the event.

- **Third, the generalisability of research findings:** The unique and temporary nature of construction projects (i.e. in terms of their context, scope, location, etc.) means that limitations have to be accepted in relation to the generalisability of research findings. This is a common issue in the study of projects and was partially mitigated in this thesis by focusing on the way in which organisations are conceptualised rather than looking into specific configurations of project organisations. In this way, the study sought to deepen the understanding of self-organising networks in the field of project management. It suggests that self-organising networks are ubiquitous in large projects and thus identified a number of themes that can be applied and

tested in other cases (e.g. Section 7.5). These can potentially identify repeated interactions and recognisable patterns across different projects.

- **Fourth, definition of boundaries and ties in a specific network:** In this thesis, network boundaries were defined by the researcher adopting Pryke *et al.* (2017) approach, but this approach involved some degree of subjectivity in studying different relationships. This is a common limitation in social network analysis. While it is essential to define the network boundary or separating what is part of the network from what is not, this process is a difficult task, given that social networks are potentially infinite and transitory (Pryke, 2012). Additionally, the special characteristics of construction industry and its multiplexity of networks make it hard to clearly identify the boundaries between different networks, such as contractual relationships, information exchange and instruction.

- **Fifth, definition of power:** Given the limited data available as part of the KTP project, definition of power was based on SNA centrality measures, which are broadly based on actors' positions/roles within the network and their associated relationships. This is in line with Pfeffer's (1981) view that power is relative and not absolute, i.e. it depends upon the context and the relationships, which is an abstract concept from the underlying essence of actors. This definition of power is limited as it does not consider individual qualities. Future research, therefore, should extend this definition to include personality traits as means to acquire influence / gain or lose power.

- **Sixth, small-world (SW) networks:** By adopting a multi-level framework (i.e. local/global) informed by Complexity Theory, this study advanced the measures of network efficiency proposed by Pryke *et al.* (2017). While these measures provided insights into the mechanisms hidden behind the small-world network effect, the used framework is based on Watts and Strogatz's (1998) model which has its own specific boundary conditions. This means that some important information about the network can be lost when such model is applied (Opsahl *et al.*, 2017). This limitation is immaterial to this thesis given that a large proportion of networks studied meets the model criteria, but it is mentioned as a word of caution for future work. It can be a fruitful avenue to further refine SW predictions associated with self-organising networks.

- **Seventh, investigation of multi-layered networks:** The study touches upon multi-layered networks. However, the scope was limited and does not involve using multi-layer analytical tools (e.g. correlation matrices). Therefore, conceptualising projects as multi-layered networks with roles of co-existence nature warrants further research.

- **Eighth, the dynamic nature of complex systems:** This study only investigates two discrete points of time and therefore misses the true dynamic ongoing changes, happening in between the two datasets. To mitigate this issue, reflections on data supported by project documentations and follow-up discussions were used in this study. However, it is acknowledged that this could only approximate the continuously changing process. That is, networks are not static, but they evolve as actors intentionally and unintentionally change their relational patterns by activating or terminating their ties to other actors (Schipper and Spekkink, 2015).

- **Ninth, issues in the translation and application of Complexity Theory:** Application of complex mathematical abstractions was limited in this study due to lack of a validated framework to study project organisations. Despite the growing interest in CAS perspective, there is still no fully-developed theory and methodology to specifically study and manage complexity in project organisations. It is, therefore, worth highlighting that researchers should be careful about how such transdisciplinary theory is applied and translated. This is because Complexity Theory was developed in other realms, for example, in natural and physical systems, without taking into account the fundamental differences between various disciplines. This study, to some extent, addressed this issue by using concepts that were already applied in other social studies (e.g. systems, co-evolution and self-organisation); hence accounting for the conciseness of actors and their decision-making strategies.

10.5 Further Future Work

The novel contribution of this thesis lies in its analysis of project networks from a new theoretical perspective that is based on complexity science. It highlights the need to understand and analyse project self-organising networks as Complex Adaptive Systems (CAS) that can effectively design and deliver large construction projects. Several research themes/directions are seen as particularly fruitful and relevant that can lay the foundations for future enquiry, as follows:

- **First,** the analogy between CAS and SNA can be extended to study supply chain networks in projects. This will add to the growing interest in understanding and managing supply chains and their behaviours from such a new perspective (e.g. Marchi *et al.*, 2014).

- **Second,** applying a multi-layered network perspective reveals that project networks comprise different layers that co-exist simultaneously to support the design and delivery of projects under varying circumstances. Further investigation and categorisation of these layers would be the next step towards a better comprehension of multi-layered project networks. An investigation of the inter-layer links would be particularly interesting since such interactions can shed new light on understanding the adaptability and resilience of multi-layered project networks.

- **Third,** the rich BSCU project data, as well as the wider KTP data, could be further analysed adding more detail and discovering new outcomes/consequences. For example, the analysis carried out in this thesis could move forward by investigating the third level of the multi-layered networks (i.e. by considering the purpose of communication as illustrated in Figure 4.5 in Chapter Four). Moreover, the work presented could have been broadened by considering factors affecting the pattern of communications. For example, it would be an interesting endeavour to investigate the physical space and its influence on communication patterns (i.e. physical proximity between actors, office design in terms of openness or segregated and enclosed spaces) and to explore their interplay with the demographic variables (e.g. personalities, culture, gender, age).

- **Fourth,** this thesis uses a single case study and a single life cycle stage. For future research, it is recommended to conduct a cross-case analysis using multiple case studies and perhaps from more than one life cycle stage. Although project networks and SNA data are often complex in nature, more comparable case studies, both in the UK and internationally, are needed to enrich the field of project management. This approach to studying multiple cases will allow research to

go beyond contextualising factors and draw new conclusions based on recurring observable patterns across cases/projects; hence addressing the issue of the generalisability of findings.

- **Fifth,** discussion of the costing and financial monitoring of networks is still in its infancy. This topic can be established further to provide better refined measures of network efficiency and cost. Particularly it would be interesting to understand how they will be used by the industry and their impact in decision-making.

- **Sixth,** data collection can benefit from the advent of new technology-mediated communication. These new tools could revolutionise the research in social science as they are able to facilitate faster and reliable collection of fine-grained social communication. Tools such as high-resolution sensors demonstrate great capabilities in collecting, storing and analysing enormous amounts of social interactions (Aggarwal and Abdelzaher, 2011). Another suggestion is to develop a smartphone application to help SNA researchers to have access to ready-made analytics templates or code constructs. This will reduce the time spent in solving coding problems or learning programming languages. Development of new software tools and building information systems still have a lot of work to do in project management field.

- **Seventh,** the evolving nature of self-organising networks in large construction projects highlights the need to rethink about project governance. Networks are essentially non-hierarchical and thus there should be a degree of flexibility in the working frameworks to allow creating a dynamic, collaborative and enabling environment. This might usefully be fostered through interpersonal interactions. Actors' roles are also not fixed or singular, but they are subject to a continuous change and feature co-existence phenomena. The latter highlights the need for having a multi-dimensional governance framework that encourages emergence of bottom-up decision-making processes. This can be an agenda for future research.

- **Eighth,** while the primary objective of this study is to sponsor a social network research agenda in construction industry, it should also spur new interest in developing new theoretical constructs, beyond just refining measurement apparatus. New research areas, for example, can include: studying speed of information diffusion, contagion effect, and time-based network evolution.

- **Ninth,** a longitudinal investigation across multiple resource-specific networks is recommended in order to reveal further subtle changes in the interaction patterns over time. The key advantage of such studies is that their breadth can cover a wide range of research areas, such as the impact of external factors (political factors and public support) and relational aspects (trust and other psychological attributes).

Next section highlights what industry might learn from this study.

10.6 Key Contributions of the Study

This research has confirmed the importance of networks in managing project complexity. Specifically, it has demonstrated the significance of self-organising. The original contribution of this thesis lies in applying self-organising concept to the study of large construction projects. In this way, projects can be conceptualised as evolving networks and that roles of network actors are quite different to their contractual roles. The project environment is, therefore, not static as envisaged in the contracts but continually transforming and adapting to deal with complexity and uncertainty.

Key contributions of the study will be presented in further detail, as follows:

10.6.1 Is the Role of Managers Obsolete in Self-organising Systems?

This study contradicts with the common understanding of self-organisation concept that there is no role for managers or leaders to self-organise networks/teams (e.g. Foerster, 1984; Mahmud, 2009). This belief stems from the traditional Newtonian paradigm which proposes that leaders'/management's role in organisations is limited to maintaining equilibrium/stability (Foerster, 1984; Mahmud, 2009; van Eijnatten, 2004). This is because projects are viewed as hierarchical, rational, static and formally (contractually) governed systems. On the contrary, self-organising perspective argues that projects are delivered by people operating with all the usual human imperfections. This study, therefore, stresses that the interplay between formal and informal aspects of organisational structures is important to be viewed as complementary rather than mutually exclusive options. For instance, the Innovative Contractor Engagement (ICE) approach (adopted at BSCU project as a formal structure) has been mainly complementary, working to promote collaborative behaviour within the informal project network, i.e. not contrasting as commonly advocated by the formal-informal dichotomy in the literature (cf. Emmitt and Gorse, 2009). This integrated view, therefore, offers the disciplined flexibility needed whilst

ensuring that original objectives are met within a changing and uncertain environment. Project managers, for example, can develop such arrangements through empowerment, honouring individuals' ideas, and hence releasing them from the gravity of status quo thinking. Rather than using their positions to bend subordinates to their will, managers can implement their way of management through influence. For example, enforcing certain narratives by way of coaching and training, and conducting sample checks on post fact basis to monitor performance and introduce any necessary corrective measures.

10.6.2 Rethinking the Role of Managers in Large Projects

Accepting the conceptualisation of large projects as self-organising networks implies that no central control or authority can be exerted on a global level. However, this does not mean that networks have no direction or control, but rather managers are identified in terms of their network positions. This entails redefinition of managerial roles to shift the focus from control to influence/facilitation. In this respect, the literature suggests that the main role of network managers is to establish a framework upon which network actors can function, while maintaining the resiliency and flexibility they need to accomplish network goals (Keast *et al.*, 2004; Popp *et al.*, 2013). Network managers should be aware of their network dynamics and appropriately balance how much they control and how much they allow to emerge (Choi *et al.*, 2001). The role of project managers, therefore, can be principally seen as "agents of change" to catalyse conditions, structures and interactions, with the purpose of building and re-adjusting the power in network. By embracing such perspective, project managers can remove stigma of shame from their lack of control (Streatfield, 2001). Instead, they should attend to improving relational process (Suchman, 1998). This enhances flexibility and adaptability, increase awareness of context and relationships and fostering a greater receptivity and openness to being changed. These values play a critical role in systems' survival and evolution – the very characteristics that have enhanced survival and success of organisms and species throughout the ages (Darwin, 1859).

10.6.3 Project Managers to Monitor Dysfunctional Prominence

By studying the different types of brokerage roles in BSCU and their possible level of influence (i.e. whether local, meso and/or global level), empirical findings of Chapter Six (Section 6.2.3) suggest that an excessively high level of betweenness centrality score is an indication of dysfunctional prominence. In such cases, actors are identified as a risk, i.e. considered disruptive to information exchange project networks. Typical example is when project teams are over-reliant on certain specialised, knowledgeable

individuals, resulting in these go-to actors becoming overloaded, and eventually leading to poor project performance (cf. Section 7.4.3). Another example from Chapter Seven is investigation of decision-making processes which suggests a tendency for project actors to be path-dependant. This is particularly evident by the dominance of routinised behaviour/repetition strategies (cf. Section 7.4). In high-risk construction projects, this could be perceived by project managers as a positive indicator of stability; however, analysis of Section 7.4 suggests that this could also cause excessive iterations; hence 'dysfunctional prominence'. It might be argued, therefore, that project managers should regularly monitor this form of prominence in project networks which will provide early warning of its development and enable early interventions.

Empirical analysis of decision-making strategies revealed that actors at global levels will maintain greater social distances when faced with higher levels of uncertainty. This is another type of destructive behaviour. For example, it was evident in Chapter Seven that Project Control and Management cluster tried to stabilise the process by resisting to open up and share information with the rest of the team. From a CAS perspective, such inertia/resistance implies accepting only small subset of inputs that is conducive to the system in order to limit the system to few eventualities and responses. While this may increase the efficiency in the short term, it entails controlling the system by exerting some forces to linearise the process and reduce diversity (Comfort, 1994; Kauffman, 1993). Under this scenario, the system becomes more dependent upon a narrower band of input values/people, but over time, it will have to expend a larger amount of its resources in order to maintain the whole mechanism for regulation. Any small change in input values, thereafter, could create a systemic shock since the process was not absorbed gradually over time (Kauffman 1993; Kilduff *et al.*, 2006). This highlights that project managers, who assume sole responsibility for coordinating activities and managing performance, run the risk of over-controlling. This is especially true when the relationships are underpinned by adversarial contractual arrangements (Pryke, 2017). In such cases, project actors are usually less willing to involve in collaborative relationships in an attempt to defend their status quo. The relational basis of collaborative relationships and non-hierarchical nature of information exchanges associated with self-organising networks, on the other hand, suggests involvement of smaller, more focused, groups of actors in making decisions, as exhibited through the process of forming clusters (Chapter Seven). This enables project actors to be more context-specific to their functions since the extent to which complex projects rely on deploying rigid (routine/repetitive) patterns or flexible (deliberated) patterns is contingent on the degree of uncertainty present (Shenhar, 2001; Shenhar and Dvir, 2007).

10.6.4   Costing Networks

Attending to processes of communication and micro-interactions as the central activity for improving projects' macro-performance, Chapter Eight presented the idea that networks could be costed in terms of both its building costs and operating costs. The results of BSCU case study (Table 8.2) showed that building costs are disproportionately expensive compared to operating costs. This highlights the need for interventions to reduce costs of network establishment, e.g. by having a team of brokers to facilitate networking opportunities through introduction of contacts, workshops and social events. Furthermore, this study suggests that the costing and financial monitoring of networks can be used to understand and manage self-organising networks. It highlights the potential of SNA tools, as a way to quantify and analyse networks; thereby enabling the industry to identify its most expensive resources, how these are being utilised, and where to undertake any cost-cutting measures.

10.6.5   The Need for a Nested Governance Structure

Based on the discussion under Section 9.2.4 above, this study calls for adopting a nested governance structure that is based on shaping concept rather than planning concept. It is about Project Managers developing a context for projects to allow them to flourish and succeed, starting from the front-end. This can be achieved by focusing on power and setting up the relational landscape, to ensure emergence of the necessary conditions across different levels and subsequently allow carrying them over to the later stages. From this perspective, project development process to be recognised as a function of human interactions that is not linear but subject to continuous shaping, characterised by a series of episodes or rounds of power negotiation. A nested structure can be created through employing a range of governance devices that vary according to the context within which the project is developed. For example, projects not to be supported by business models or bilateral agreements only but also to be supported by legal and policy structures alongside with any non-contractual protocols. This is evident in BSCU case study were ICE model generated two key documents, namely: relational-based contract and management protocol (discussed in Section 5.5). These elements represent different levels of support to help in governing the behavioural relationship between the client and the contractor in order to manage the uncertainties and the interdependencies (Addyman, 2019). They provide project networks with a framework that supports an ongoing relational investment to achieve continuity of social distance and bridging any gaps. The latter can be achieved, for example, by promoting hands-on involvement of decision-makers at the front-end, rather than introducing new personnel that will be at a greater social

distance from prior decisions. An example from BSCU study is the engagement of the core design-delivery team in design management cluster.

The findings of this research, as highlighted by the study of ICE approach from self-organising perspective, confirm that while the strategic front-end is critical to configure value outcomes (Morris, 2013), projects need to expand their scope beyond the transactional and short-term perspectives in order to connect effectively the front- with the back-end of a project (Artto *et al.*, 2016). Creating a nested project governance structure, therefore, can be seen as a process to continuously reweave different forms of power, leveraging on how micro-level interactions constitute meso- and macro-level contexts on an ongoing basis. This provides systems with a higher degree of resilience (cf. Chapter Six on betweenness centrality and Chapter Eight on SW ranges). Traditional management approaches (e.g. PMBOK Guide) view projects as a set of predictable decisions that follow a specific path that is there to be discovered. Therefore, major changes to the prescribed plan are considered as signs of failure in project management. A nested project governance, on the other hand, postulates there are multiple paths to actualise a project. This perspective increases probability of success because if one of the governance layers/power levels failed, then the project would stay resilient to bounce back from setbacks, supported by existence of other types of governance/power.

10.6.6   Network Roles are Quite Different to Project Roles and are Not Static

This study suggests that actors acquire roles that are related to their network positions. These social positions can be loosely and dynamically structured, and interestingly actors can hold multiple concurrent roles in project networks. Actors roles and ties are not static as envisaged in the contracts, but they evolve and decay over time to adapt to the changing project requirements and conditions. Key examples from analysis chapters supporting this conclusion are:

- Chapter Five reveals that BSCU contractual and communication networks are not identical;
- Chapter Six found that Project Control and Management were bypassable by other actors in terms of brokerage flow; thus, reducing their power in issue resolution. Alternatively, Chapter Seven suggests that Planner was the most prominent actor in the functional theme of decision-making group;
- Chapter Seven suggests that clusters in stage two have different composition compared to that observed in stage one. Some actors/ties were dissolved, and new/different ones emerged; and

- Chapter Seven further reveals that clusters are inter-organisational/cross-functional, i.e. not related to the organisational/hierarchal formal chart.

These findings suggest that network actor roles are not procured through formal contractual agreements. This defies expectations of the hierarchical approach, which conceives the governance of large infrastructure projects as a composite of successive, discrete, and independent phases that are controlled/influenced by specific procured roles (Fabianski, 2017). By adopting the concept of social relationships in project management, this study, therefore, suggests that project managers should re-define actor roles using social network terms rather than focusing only on professional disciplinary specialisations.

Furthermore, findings suggest that project phases are not discrete and independent packages of work as envisaged in the technical aspects of planning and scheduling. This is evident from having the Planner as the key actor in stage two of BSCU detailed design phase, whereas his role is limited to project planning stage only under the hierarchical approach. This is because, in practice, the project phases are *"not only interlocking and overlapping in time but also impacting on each other"* Fabianski (2017, p. 79). This supports the findings of Addyman (2019) who argues against the viability of linear delimited project stages. It highlights that Project Managers need to recognise the iterative and co-creation nature of the processes. The notion of linearity should be challenged as part of the project governance and more focus is needed on understanding the interrelationships leading to self-organising and aiding in project problem-solving.

10.6.7 Importance of Bottom-up Actions

The investigation of decision-making strategies (Chapter Seven) suggests dominance of routinised behaviour (repetition strategies). This is explained in the view of the intense activity at the local level which is usually bounded by tight deadlines for delivery. That is, local actors tend to adopt resolutions that usually require less cognitive efforts, i.e. transactional-based and short-term resolutions in facing challenges arising in complex projects. From self-organising perspective, however, bottom-up actions in complex dynamics are largely responsible for emergence of the outcomes. Thus, intense local actions can reshape distribution of power and eventually result in system transformation (evolution). In this sense, project organisations are defined as an intrinsic property that "emerges" from the interactions between the project network actors.

In view of the above explanation, project managers should be aware about the inevitable relationship between local interactions and global outcomes. This is because the absence of such awareness makes organisational changes at the micro levels seem less important or dangerous than they really are. The issue is further exacerbated in large projects given the existence of numerous and disparate actors with different perceptions of reality. Project managers, therefore, should think about how local interactions would play out in real life. It is crucial to reflect upon what actors might begin to develop together. This is where emphasis on "taking experience seriously" (Mowles, 2017) comes in. The latter means the need for actors to discuss with each other what they are actually doing and feeling and to think about what kind of consequences this may have. Satisfactory upward and downward communication is, therefore, vital for achieving successful projects because it closes the gap between top-level and middle/lower-levels by increasing the levels of support and interactions. It also means paying attention to power, to the way actors converse with each other, and to the forces governing behaviours. This is important because if actors do not think about what they are doing, they are likely to end-up trapped in the way that they have always thought and therefore done. And even if it is not working, actors will just find it difficult to identify proper alternatives. The likely option they will then have is to work more and harder which could make things even worse. This further highlights that project managers should consider network interventions in order to foster desirable patterns. Chapter Eight, for example, demonstrated that re-orientation of actor positions can enhance network resilience and improve the flow of information. This opens-up new ways to encompass formal interventions as internal acts, i.e. as counterbalancing forces to the self-organising processes which are usually subject to creep, slippage and drift if left at the mercy of inevitable human interactions (Tsoukas and Chia, 2002; Grove *et al.*, 2018). The key implication here is that management of self-organising networks requires formal interventions to continuously facilitate constructive interactions, but this is not to suggest all acts should be formalised (Grove *et al.*, 2018).

As a final remark, it is hoped that this study was successful in presenting self-organising networks as a fascinating area of research that others might be interested in pursuing. It also will be highly desirable to see a larger number of academics and practitioners using SNA as a means of understanding how projects are actually delivered and how they can be analysed and managed.

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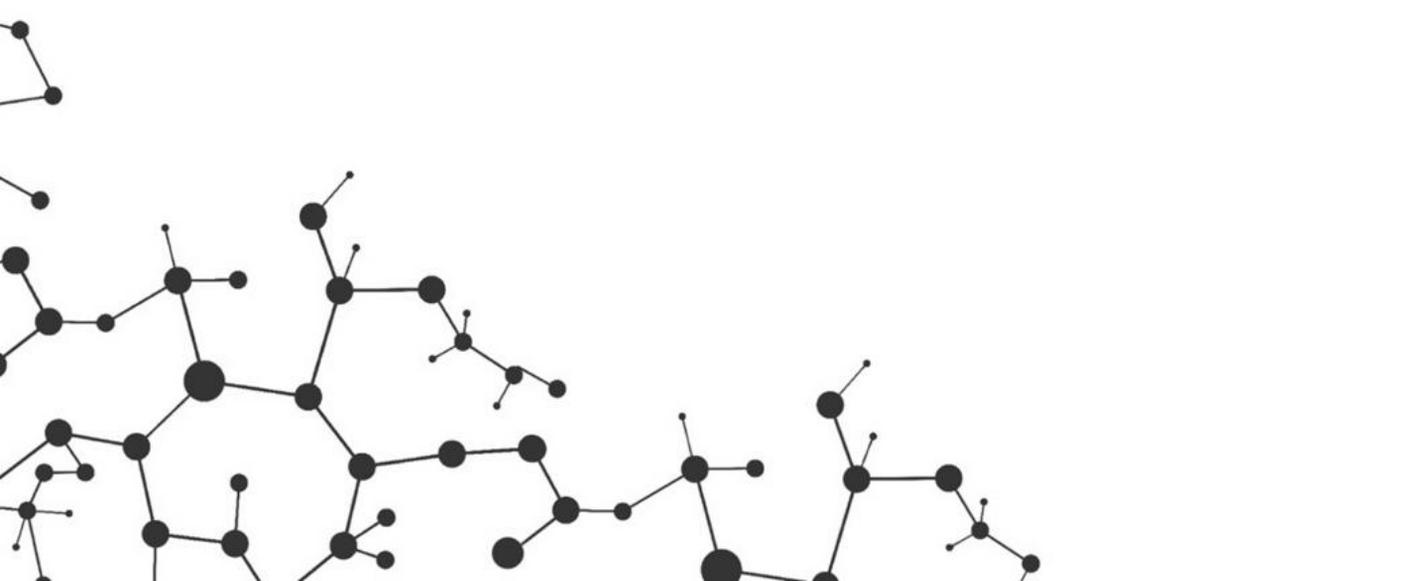
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Appendix One: Existing LU Infrastructure (Source: TfL, 2014, Figure A1, p. 62)

Central line platforms

Bullring ticket hall

Lombard Street ticket hall

Cruciform

Lombard Street lifts to triplication area

Waterloo and city line platforms

Triplication

Northern Line platforms

DLR Platforms

District and Circle line platforms

Monument ticket hall
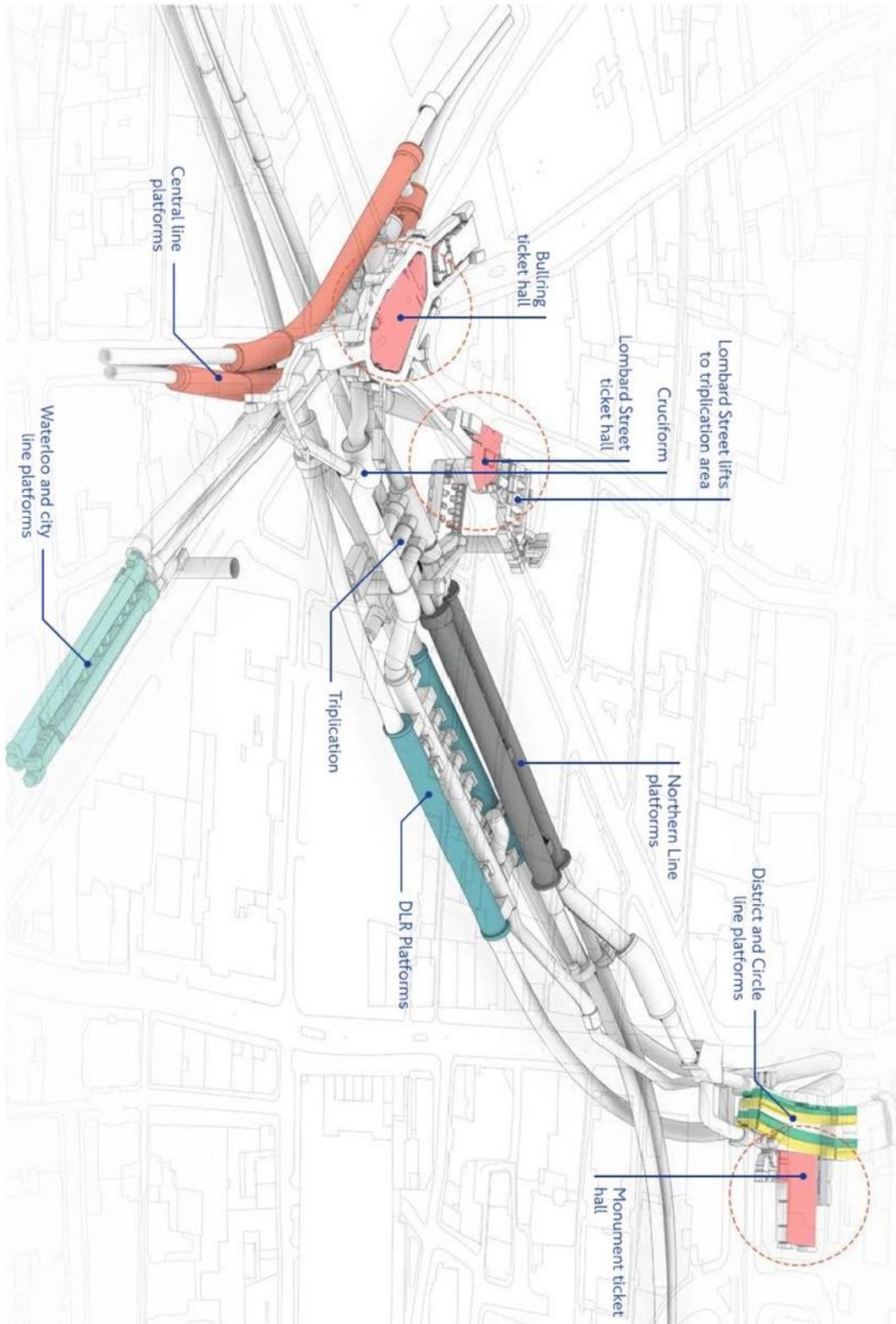
Appendix Two: BIM/CAD Model Showing the Station Box/Ticket Hall (Source: Unpublished KTP questionnaire Data, 2015)
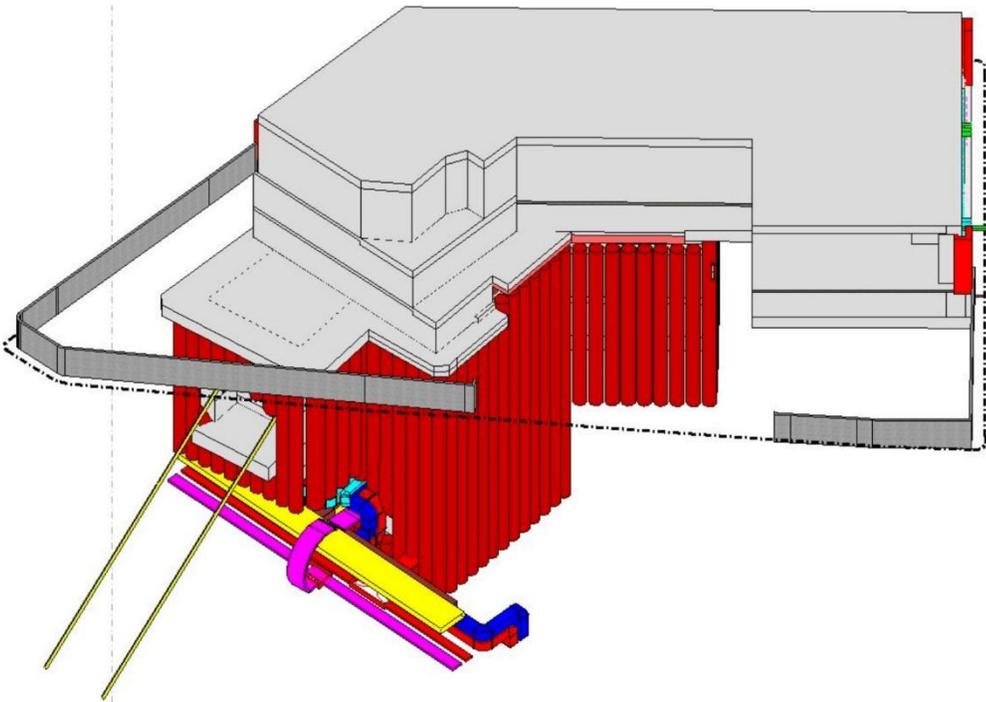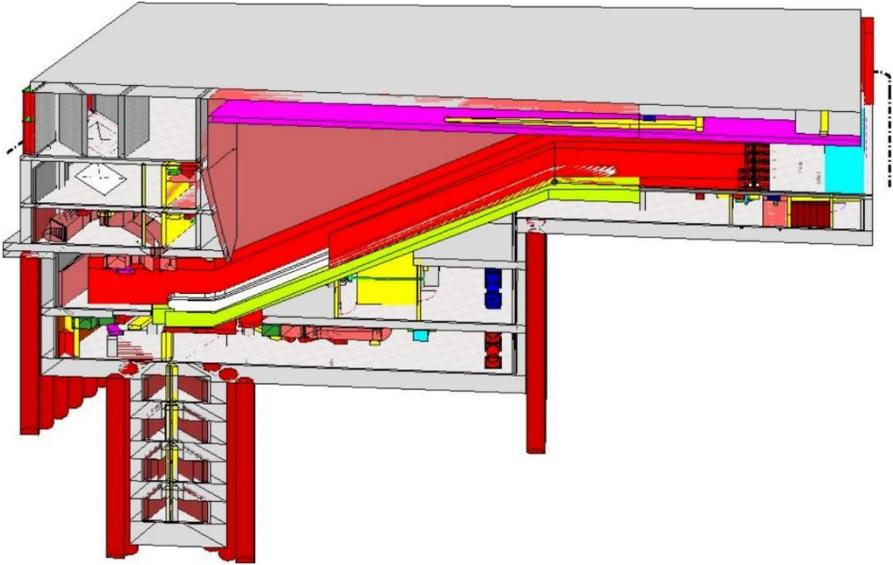
Appendix Three: KTP Questionnaire Screenshots[73]

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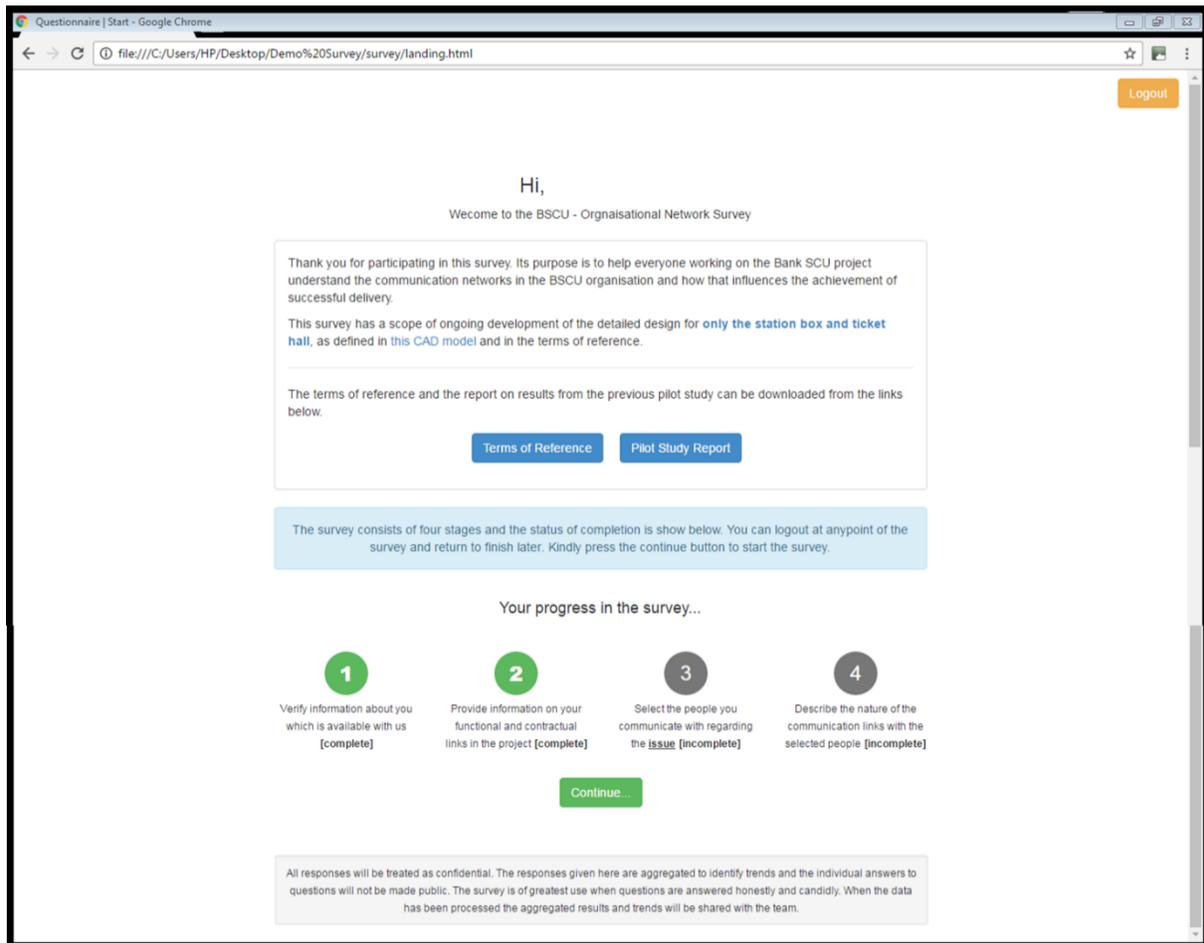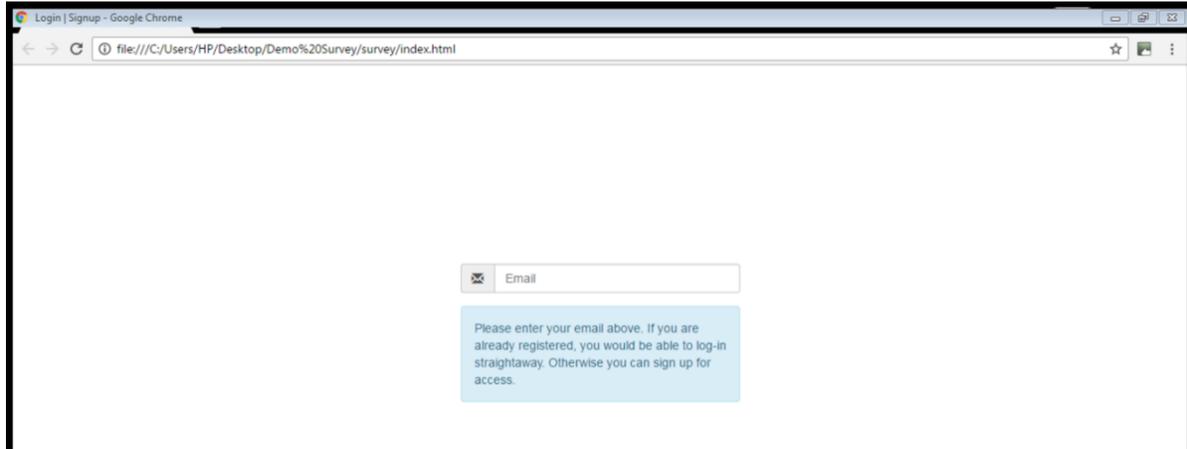
[73] It is worth highlighting that names, pictures, phone numbers and other personal information were masked from the figures in order to maintain confidentiality.

judgement and select the one that has been the most dominant and directly associated with the design and planning of the 'station box/new ticket hall'.

| Frequency ⟳ | Importance ❶ | Accuracy ✦ | Timliness ⟳ | Clarity ⊘ | Trust 𝒮 |

Frequency: Please select the appropriate number based on how often do you communicate with the person as follows, ⑥ More than once a day | ⑤ Daily | ④ Several times a week | ③ A few times a week | ② Once a week | ① Less than once a week | ⑩ Once or twice in total

| Reporting or preparing progress data |
| Understanding, updating or developing workprocess |
| Undertaking or participating in quality audit or assurance |
| Structuring, retrieving or archiving documents |
| Submitting, retrieving or analysing design and survey data |
| Reporting, monitoring or controlling cost information |
| Updating, modifying or controlling the schedule |
| Reportingon, updating or identifying risks |
| Preparing, identifying or instructing client change |
| Preparing, identifying or instructing third party change |
| Understanding, reviewing or developing the design within your functional disciplines |
| Understanding, reviewing or developing the design across functional disciplines to manage design interfaces |
| The escalation of critical issues or problems for discussion or resolution |
| Identifying, reporting or discussing issues of health, safety and environment in relation to design development |

y clicking the help buttons) ⑥ Strongly

send ☑   recieve ☑

Reporting or preparing pr ▾	4	Reporting or preparing progre ▾	3		2				
Nature ❶		Nature ❶							
Instruction ▾	⟳	Instruction ▾	⟳	❶	✦	⟳	⊘	𝒮

Appendix Four: Purpose of Communication Classifications

| Appendix Four: Purpose of Communication Classifications and their Share in the Project Networks. (Source: Original)				
Purpose	**Stage 1**	**Stage 2**	**Stage 1 (%)**	**Stage 2 (%)**
Reporting or preparing progress data	592	407	41.111	18.441
Understanding, updating or developing workprocess	87	164	6.042	7.431
Undertaking or participating in quality audit or assurance	39	55	2.708	2.492
Structuring, retrieving or archiving documents	34	62	2.361	2.809
Submitting, retrieving or analysing design and survey data	41	42	2.847	1.903
Reporting, monitoring or controlling cost information	50	147	3.472	6.661
Updating, modifying or controlling the schedule	21	93	1.458	4.214
Reporting on, updating or identifying risks	32	55	2.222	2.492
Preparing, identifying or instructing client change	9	38	0.625	1.722
Preparing, identifying or instructing third party change	0	11	0	0.498
Understanding, reviewing or developing the design within your functional disciplines	187	436	12.986	19.755
Understanding, reviewing or developing the design across functional disciplines to manage design interfaces	286	575	19.861	26.053
The escalation of critical issues or problems for discussion or resolution	55	98	3.819	4.440
Identifying, reporting or discussing issues of health, safety and environment in relation to design development	7	24	0.486	1.087

Appendix Five: The Full-Size Versions of BSCU Multi-Layered Networks at Stage One and Stage Two.

- **Information Exchange Layer at Stage One:** *Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Original)*

- **Information Exchange Layer at Stage Two:** *Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Original)*

- **Discussion Layer at Stage One:** *Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Original)*

Less Brokerage ● ● ● More Brokerage   Weaker Relation | | | Stronger Relation

- TfL
- Dragados
- T Clarke
- Wilkinson Eyre
- Robert Bird Group
- Dr Sauer & Partners
- Alan Auld Engineering
- URS Infra. & Env. Ltd.
- McNicholas
- Other

- **Discussion Layer at Stage Two:** *Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Original)*

Less Brokerage ● ● ● More Brokerage   Weaker Relation ||| Stronger Relation

- TfL
- Dragados
- T Clarke
- Wilkinson Eyre
- Robert Bird Group
- Dr Sauer & Partners
- Alan Auld Engineering
- URS Infra. & Env. Ltd.
- McNicholas
- Other

- **Instructions Layer at Stage One:** *Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Original)*
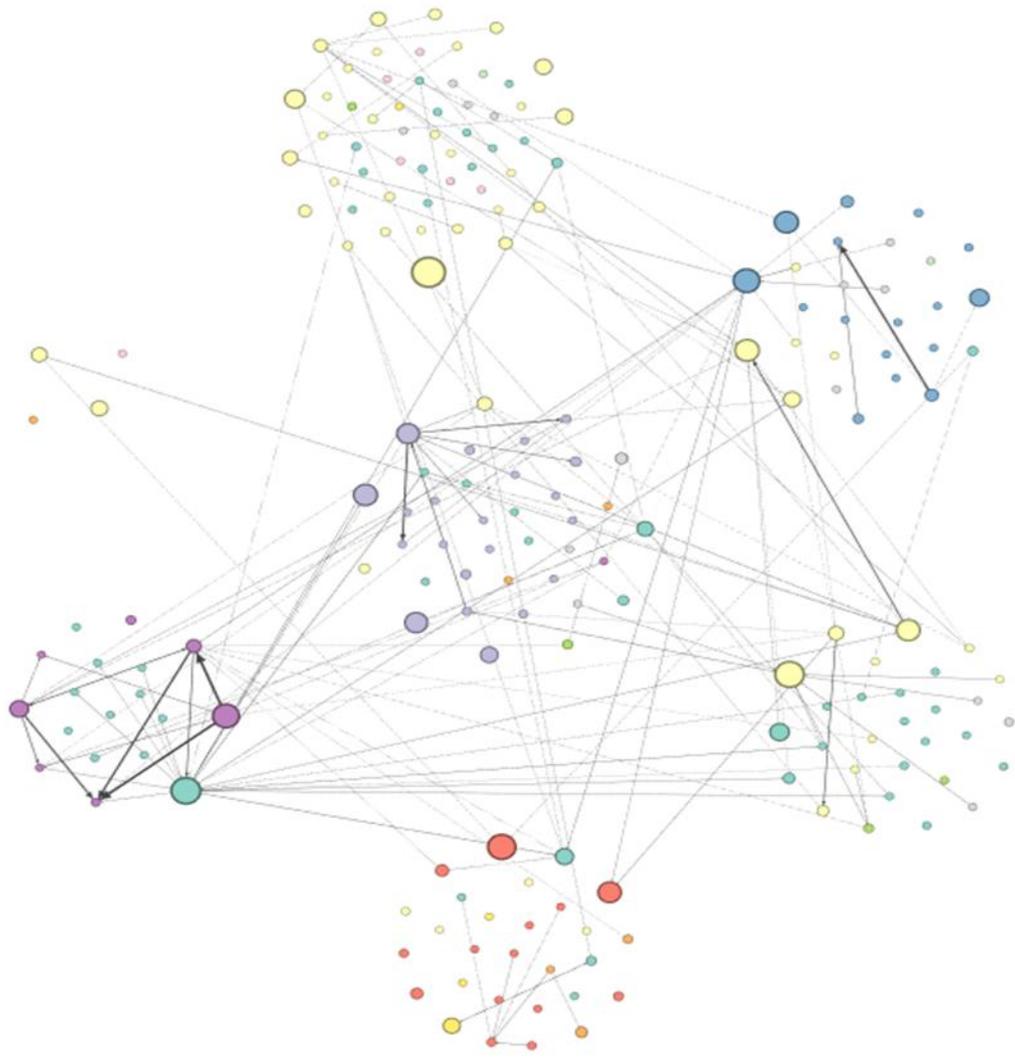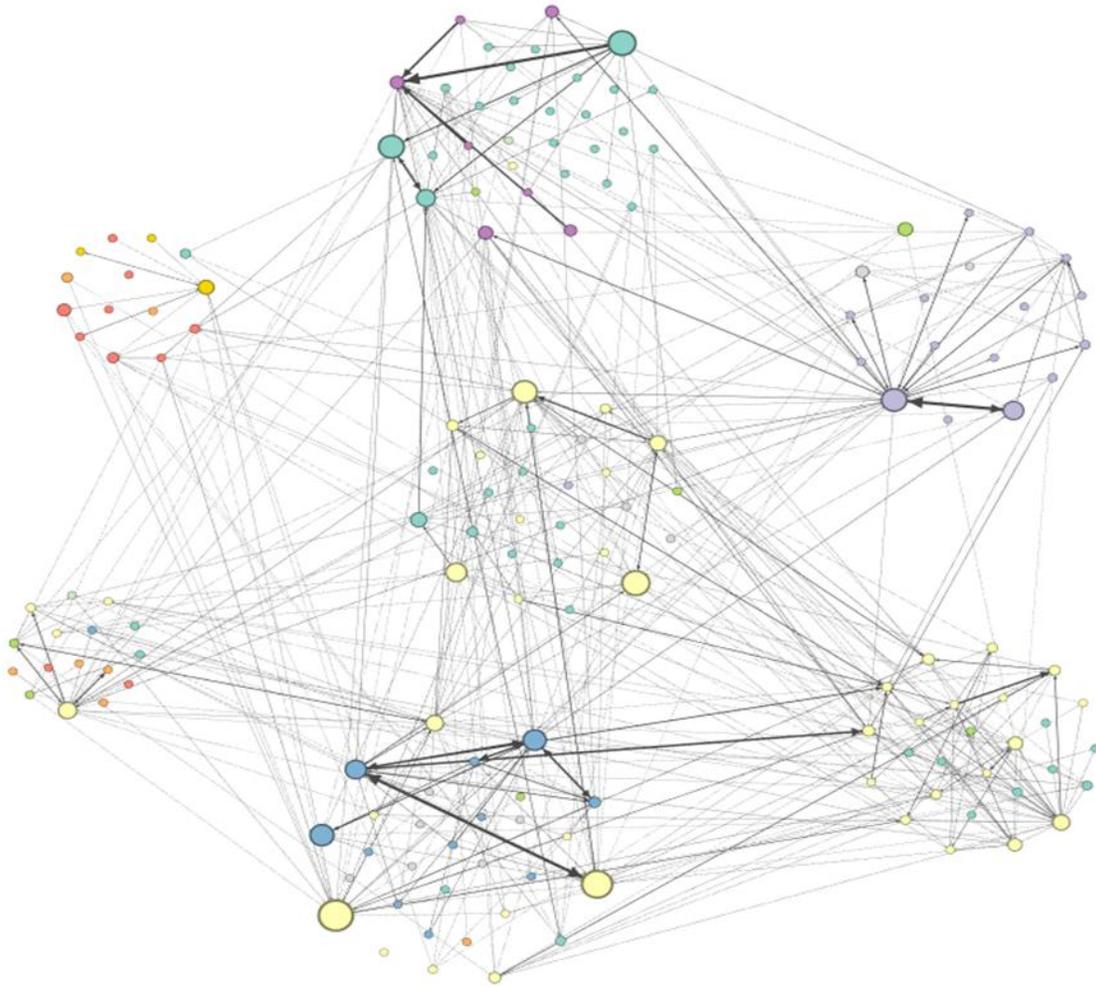

Less Brokerage ● ● ⬤ More Brokerage   Weaker Relation | || Stronger Relation

◯ TfL   ◯ T Clarke   ◯ Robert Bird Group   ◯ Alan Auld Engineering   ◯ McNicholas
◯ Dragados   ◯ Wilkinson Eyre   ◯ Dr Sauer & Partners   ◯ URS Infra. & Env. Ltd.   ◯ Other

- **Instructions Layer at Stage Two:** *Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Original)*
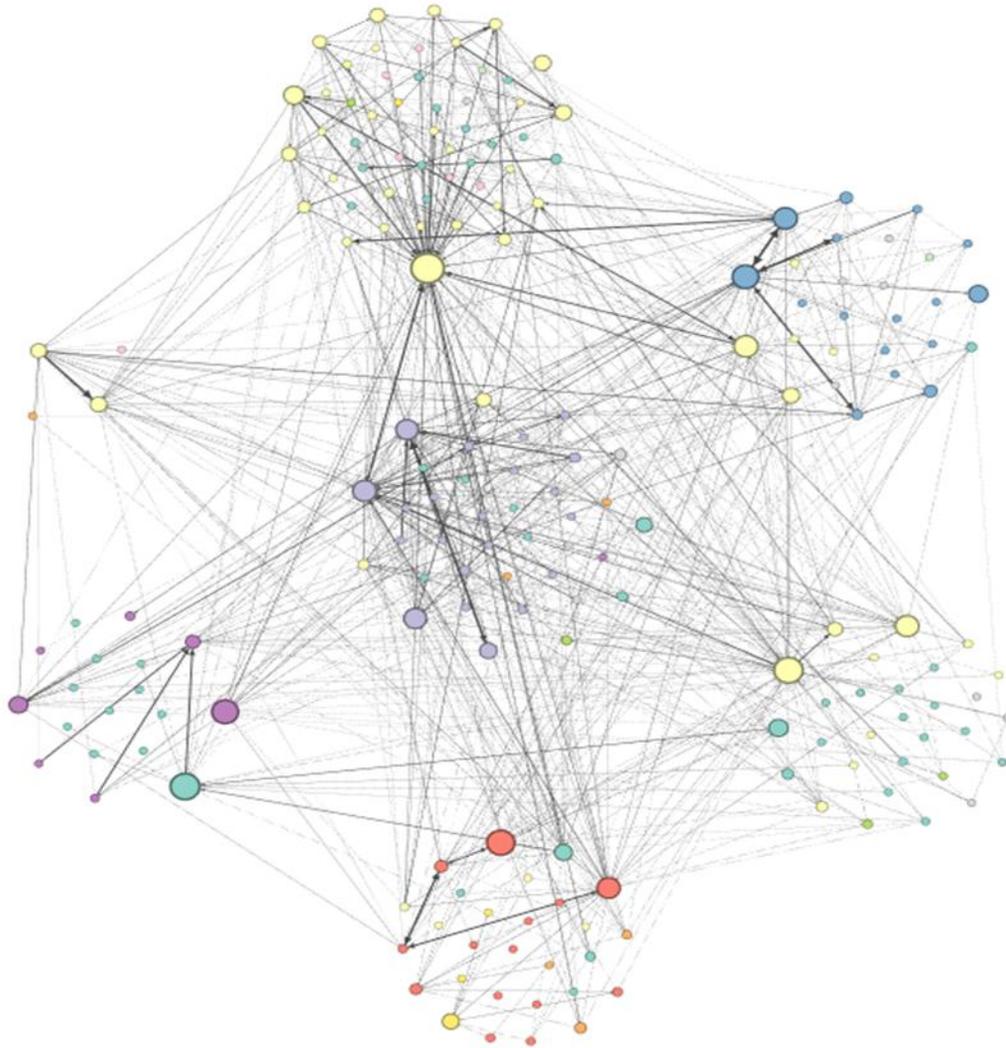

Less Brokerage ●●● More Brokerage   Weaker Relation ||| Stronger Relation

TfL   T Clarke   Robert Bird Group   Alan Auld Engineering   McNicholas
Dragados   Wilkinson Eyre   Dr Sauer & Partners   URS Infra. & Env. Ltd.   Other

- **Advice Layer at Stage One:** *Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Original)*

- **Advice Layer at Stage Two:** *Nodes are Sized by Betweenness Centrality and Coloured by Organisation. Ties are Weighted by Communication Strength (Source: Original)*