Organisational Design & Mirroring in Construction

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Student Statement

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1 Introduction

1. Introduction

Organisational design in construction is concerned with the problem of establishing a temporary governance framework, a project organisation by which to execute a project. Construction project organisations are multi-organisational (Shoesmith, 1991) and formed by means of contractual relationships. Several basic organisational architectures are presently in common use: construct-only, design-and-construct, management contracting and build-own-operate, all with variants and routinely customised. Prior to the Second World War and for an undefined period subsequently, the construct-only system, also frequently referred to in the literature as the 'traditional' method, predominated to a significantly greater degree than presently (Bresnen, 1991; Morris, 1973) and still does in some sectors of the industry.

An organisational architecture can be modelled as a network structure (Sosa et al, 2003). In a multi-organisational network, nodes represent organisations and links between them represent communication channels (see Appendix 1 and 2). However, though a project organisation is implemented by the enactment of contracts, it is not merely a legal problem (Nahapiet and Nahapiet, 1985). Rather than purely legal considerations, the differentiation of project organisational architectures is driven by the inter-relationship between design and construction tasks (Fazio et al., 1988) as well as the pattern of communication links, which does not necessarily follow contractual links (Uher, 1998). For example, in management contracting, each trade contractor has a contractual link with the project client and yet, communication links converge on the head contractor, whose role it is to tender, co-ordinate, instruct and monitor trade contractors. One definition of an organisation's design is "the sum total of the ways in which it divides its labor into distinct tasks and then achieves coordination among them" (Mintzberg, 1979).

The literature on project organisations in construction is initially preoccupied with strategies for overcoming pitfalls associated with the 'traditional' method. This method is widely considered the source of a broader problem of increasing industry ills such as escalation of cost, delays and conflict on projects, observable in the latter part of the twentieth century amidst accelerating technological, economic and social change together with increasingly onerous expectations from the demand sector (Eriksson and Pasemaa, 2007;

Gray and Flanagan, 1984, Pain and Bennett, 1988; Raisbeck et al., 2010).

The construction industry responds to those pressures initially with the professionalisation of project management and restructuring of the traditional system (Bennett, 1983), where 'restructuring' refers to the reordering of the interrelationship between design and construction tasks within the system (Fazio et al., 1988). A 'project manager' here refers to a specialist manager who acts on the proprietor's behalf in delivering a project, commencing as early as project conception and terminating with handover and commissioning, and includes the roles of project organisation establishment, design management, head contract tendering and superintendent (Cooke, 1989). Literature arises concurrently which reports the outcomes of various approaches but with increasing complexity soon shifts focus to the development of 'selection' or 'decision' models with which to design a project organisation (Chan, 2007; Skitmore and Marsden, 1988). Various analysis methods are applied to this problem, such as regression model (Drew et al.,1997) and delphi method (Chan et al., 2001). Subsequently, new theoretical perspectives bring about a shift away from selection models in several directions, particularly collaborative contracting (Mason, 2007; Wood and Robert, 2005), and to a lesser degree, incentive schemes (Ashley and Workman, 1985), transactional analysis (Ive and Chang, 2007) and contract theory (Dagenais, 2007).

Meanwhile in the manufacturing industry, a theoretical perspective emerges known presently as the 'mirroring hypothesis'. It builds on a stream of literature devoted to product architecture, modularity and the simple intuition that "organisations design products and products design organisations" (Sanchez and Mahony, 1996). Also ultimately concerned with the broader imperative of improving industry and product performance in response to contextual pressures (Braha and Bar-Yam, 2007), the mirroring hypothesis posits that an intrinsic connection between product and organisational architectures exists, which can influence operational efficiency (Hirtz et al., 2002; Sosa et al., 2004).

The mirroring hypothesis relies on the modelling of architectures, where the term 'architecture' is defined in this context as "the scheme by which the function of a product is allocated to physical components" (Ulrich, 1995). Another definition is "the scheme by which the decomposed elements are arranged in chunks" (Ulrich and Eppinger, 1994). The mirroring hypothesis movement draws upon a sub-genre of functional dependence modelling as well as network theory (Appendix 1 and 2) to model product architecture (Hirtz et al., 2002) and organisational architecture (Sosa et al., 2004). Although the literature on project organisations in construction occasionally alludes to a hypothesis akin to the mirroring hypothesis (Bennett, 1983) and various network-based studies have been performed (Alsamadani et al. 2012; Hossain, 2009; Loosemore, 1998), the notion of modelling the architecture of project organisations, buildings and structures is yet unaddressed and hence forms the 'research gap' of this thesis.

Several motivations comprise a compelling case for the introduction of concepts and methods from the mirroring hypothesis to the problem of organisational design in construction. This is summarised here and explained further in the Literature Review chapter.

First, a degree of objectivity suffers where there is a lack of consensus amongst experts in relation to multiple variable factors (Skitmore and Marsden, 1988), as is the case in much of the literature on construction project organisations. Increased objectivity can be achieved by shifting the sourcing of primary data away from multiple variable factors towards predominantly binary variables associated with the functional modelling of components (Sarkar et al., 2014). Many types of dependencies exist in the context of manufacturing which in construction do not, or are subsumed within the dependency of physical connection between one component and another. Hence, it enables a simpler regime to be implemented in a construction context, and therefore fewer questions to be agreed upon and, consequently, further reduced uncertainty.

Second, the association between modularity and architecture in construction remains unexplored, in spite of modularity being highly influential in the design of buildings and structures as well as, though perhaps less consciously, in construction management. Meanwhile, the concept of modularity in product design is substantially embroiled with that of architecture in manufacturing (Sarkar et al., 2014) and other industries such as information technology (MacCormack et al., 2012).

Third, network science offers the possibility of modelling architectures with a common language, that of node-link networks, such that a meaningful comparison can be made between disparate and seemingly unrelated systems (Sosa et al., 2004). Previously, this was achieved with mathematical modelling and other techniques. Network modelling, being a relatively new phenomena, has been applied to manufacturing and information technology but not in construction to model the architectures of building, structures, project organisations or design data.

Fourth, there is a common genealogy of literature between construction project organisations and the mirroring hypothesis. Organisational design and network theory stem from the small group studies movement of Bavelas (1950), Leavit (1951), Shaw (1954) and others. From this movement, it can, in turn be traced back to the human relations movement (Mayo, 1949) and scientific management (Taylor, 1911), commencing with the problem of management of the factory floor (Taylor, 1903). It is from this base that the mirroring hypothesis descends directly as part of manufacturing management. Nowadays, organisational design tends to be classified under strategic management (e.g., Malone, 1986; Mintzberg, 1981; see also Appendix 3) or project management (Sidwell and Ireland, 1978) and network science can be considered a separate discipline altogether. However, all these knowledge fields emanate from early modern management theory and ultimately to early Taylorism (Taylor, 1903).

Fifth, similarities and analogous features between construction and manufacturing permit and encourage the transposition of theory. The mirroring hypothesis is particular suitable for transposition between the two domains because a construction project organisation also has the property of architecture, as do buildings and structures in the same vein as manufactured products. The two production industries also depend on design, modelling the final product with an information system. Consequently, the transposition of theory between the two industries is ongoing, albeit with adaption as in the case of the 'lean construction' movement (Bertelsen and Koskela, 2004).

Sixth, just as there is precedence for transposition of the mirroring hypothesis to other industries, as well as precedence for the transposition of other theories from manufacturing to construction such as 'lean construction', there is ample precedence for new perspectives in the literature on construction project organisations. In the question of selection models alone, several analysis approaches have prevailed: multi-attribute analysis (Aniekwu and Okpala, 1998, Eriksson and Pasemaa, 2007), discriminant analysis (Skitmore and Marsden, 1988), deterministic analysis (Russell and Ranasinghe, 1991), systems approach (Nahapiet and Nahapiet, 1985), weighted score model (Griffith and Headley, 1997), multiple regression (Drew and Skitmore, 1997), analysis hierarchy process (Cheung et al., 2001), delphi method (Chan et al., 2001), fuzzy mathematical rank model (Chan, 2007) and custom methods (Ive and Chang, 2007).

Finally, project organisational design is seen as a crucial element in improving the overall state of the industry (Egan, 1998; Latham, 1994), which still suffers from poor performance (Bresnen, 1991; 2010; Doloi, 2008; Raisbeck et al., 2010). It is posited here that if information embedded in the architecture of buildings and structures should inform the formulation and implementation of construction project organisations, then performance enhancement may be achieved.

The mirroring hypothesis is broadly defined rather than precisely, and open to varying interpretation. For example, the notion of organisational architecture has been interpreted as that of the design team rather than the entire organisation associated with a product (Braha and Bar-Yam, 2007; Sosa et al., 2003, 2004) whereas others have focussed on buyer-supplier relationships (Cabigiosu and Camuffo, 2011). In this thesis, a generic view is adopted whereby the architecture of a product is seen to potentially affect the architecture of other systems (Ethiraj and Levinthal, 2004), where in this case, the product is a building and the 'other system', rather than the construction project organisation itself, is design data, given that in a construction project, design data is the direct product of the design team. The final product, a building or structure, is the product of a construction team, not the design team, which does not produce working protocols as a manufacturing design team would.

Also a given is that, to the extent of organisational node identities, the architecture of a construction design team is partially embedded ex ante in a design data package because the various design organisations each produce a sub-package within the overall design data package, each of which corresponds to a node in the model. For example, the electrical engineering organisation produces the electrical engineering design package in its entirety and does not produce any part of any other package. Consequently, a node in a network model of the design data corresponding with the electrical design sub-package would also correspond with the electrical engineering organisational node within a network model of the project organisation. However, it is only the identity of nodes that are embedded in this way. The pattern of connection between them is another matter. The overall design data package must function as an integrated system and is therefore the product of inter-organisational interactions, leaving a legacy of cross-referencing between sub-packages, which together with node identities forms a network model. The architecture of design data on the level of the inter-relationship between design discipline sub-packages forms a major component of this investigation, one which offers the dual opportunity of initiating a previously unexplored proposition in mirroring hypothesis literature as well as initiating the adaption of the mirroring hypothesis for a construction context.

Distilling the above into a hypothesis therefore, this thesis proposes the hypothesis that design data architecture mirrors component architecture in a construction project. The research aim is, firstly, to investigate this hypothesis at face value. Secondarily, an aim of this investigation is innovation generally, bearing out particularly in the question of how to model the architecture of a building, and similarly how to model the architecture of design data, which is addressed in this thesis by adapting the functional dependence modelling regime from manufacturing (Stone et al., 2000; Hirtz et al., 2002; Sosa et al., 2003). Another innovation is the application of centrality measures (see Appendix 1 and 2) to complement prevailing definitions of modularity and product architecture. Lastly, this thesis considers the use of several analysis techniques in interpreting results, such as the spectral algorithm of Sarkar et al. (2014) and the design structure matrix of Sosa et al. (2003), previously not implemented in a construction context.

2 Literature Review

2. Literature Review

2.1. Introduction to the Literature Review

This thesis extends the literature on organisational design in construction with a stream from manufacturing, the mirroring hypothesis, specifically, as encapsulated in Sarkar et al. (2014), thereby introducing a new method and approach to literature testifying to two overall problems: a background problem and a research problem.

The aim of this literature review is to explain the background problem of organisational design in construction as well as the case for introducing the mirroring hypothesis into the research problem, the search for greater objectivity. It is divided into three sections, the first two of which are intended as background for the third.

The first section is an overview of the background problem of how to establish a project-specific organisation within which to manage a construction project. This is considered in the context of a broader industry problem of inefficiency and other ills for which the literature unanimously attributes to the traditional method of organising projects. Strategies for responding to this are classified here as structural strategies – the structural reconfiguration of the traditional method to produce alternative structure; project management – a hybrid structural-management strategy; and non-structural strategies – collaborative regimes and incentive schemes.

The second section is an overview of the two literatures: organisational design in construction and the mirroring hypothesis. The literature on organisational design is divided chronologically into three developmental phases – early literature, a second phase of selection models and new analysis methods, and a third phase of new theoretical perspectives and genres. The mirroring hypothesis literature is discussed in terms of sub-streams relevant to this thesis – definition, architecture, modularity and functional dependency modelling, research methods, design structure matrix and natural module detection.

The third section presents a seven-point case for the introduction of the mirroring hypothesis into the field of organisational design in construction: increased objectivity; modularity as a common sub-stream; the mirroring hypothesis can apply to the study of any man-made product and there is precedence for migration to other fields; significant commonality between the two background problems; either a universalist or contingency view of the literature allows for new methods and theoretical perspectives; and ongoing criticism of the construction industry beckons new research approaches. This section closes with a discussion of the role of design data and topological metrics in this thesis.

2.2. Background Problem

Increasing complexity and demand-side pressures in the late twentieth century economic environment worldwide spawned a notable movement in construction management seeking alternative organisational frameworks by which to procure projects (Fazio et al., 1988), hitherto dominated by a traditional model increasingly considered inadequate in dealing with changing conditions (Bresnen, 1991; Morris, 1973). The 'traditional' model is known as such in the literature because it was the main system used for a long time prior, from at least the late nineteenth century (Aniekwu and Okpala, 1987).

An early example of the use of a 'non-traditional' system is the 'Horizon' factory in Nottingham, UK, 1969, constructed under a 'managing contractor' arrangement (Sidwell, 1983). In the subsequent decade, an increasing diversification and use of 'non-traditional' methods brought the need for 'selection models' or 'decision models' by which to select and adapt 'procurement models' and their variants for a particular project.

The body of literature devoted with this problem, the investigation of theories, models and approaches in relation to construction project organisations is referred to here as 'organisational design in construction' or 'project organisational design'. This terminology, common in the literature, is preferred over other terminology, also common, because the notion of project organisations as a special case of organisations is emphasised: 'project organisation' (Bresnen, 1986), 'temporary multi-organisation' (Shoesmith, 1991), 'organisational forms' (Sidwell, 1982), 'organisation of organisations' (Stocks, 1984), 'organisation systems' (Newcombe et al., 1990), 'organisation and governance' (Reve and Levitt, 1984), 'project governance' (Ive and Chang, 2007), 'governance structures' (Ive and Chang, 2007), 'governance arrangements' (Ive and Chang, 2007). There is also precedence for the term 'design' to be applied to project organisations: 'designing organisational form' (Sidwell and Ireland, 1978), 'designing complex organisations' (Galbraith, 1973). It is also not uncommon for leading figures in general organisational design such as Mintzberg to be transposed to the context of project organisational design (Bennett, 1983; Nahapiet and Nahapiet, 1985; Edkins et al., 2013, Morris, 2013).

Alternative terminology includes 'procurement', 'delivery' and 'contracts': 'procurement routes' (Griffith and Headley, 1995), 'procurement systems' (Ive and Chang, 2007; Garvin, 2009; Skitmore and Marsden, 1988), 'method of procurement' (Brett-Jones, 1983), 'delivery systems' (Chan et al., 2001), 'delivery method' (Chan, 2001), 'contracting methods' (Bresnen, 1991), 'contractual system' (Aniekwu and Okpala, 1987) and 'contractual arrangements' (Nahapiet and Nahapiet, 1985; Aniekwu and Okpala, 1987; Rosenfeld and Geltner, 1991; Latham, 1994). Some alternative terminology is considered too generic. 'Procurement' can refer to purchasing generally, not necessarily the procurement of a project. For example, the purchasing of stationary for an organisation can fall under the rubrik of 'procurement'. Other alternative terms are considered too specific. 'Contracts', for example, although an essential component in assembling a project organisation, the background problem is not concerned with contracts per se or as legal documents (Nahapiet and Nahapiet, 1985). Broader issues such as communication channels and relationship between design and production are also embroiled.

The traditional system of organising construction projects is based on the proposition of designing a building or structure to the last detail, thereby producing a complete package of design data which a contractor should take as a standalone set of instructions from which to construct the building or structure (Gray and Flanagan, 1984; Eriksson and Pasemaa, 2007). This offers the buyer a mechanistic framework, which, in theory, should achieve good value for money because, as the design process moves through progressive iterations, value and cost assessments are possible with increasing certainty. When the design process is complete, there should be sufficient detailed information for tenderers to price the work competitively and with enough certainty to enter into a fixed-price contract with the buyer. The ideal is that the work can thereby be completed from the design data, for a fixed bid price and with minimal further input from designers.

There are several views on the pitfalls of the traditional method. Commonly cited is start to finish time. Construction on site cannot commence until the contract between builder and client is let, which entails completion of design and the tendering process. Thus, parallel design and construction is precluded (Cheung et al., 2001, Eriksson and Pasemaa, 2007). This does not necessarily suit an environment where economic pressures – interest rates, inflation and operational revenue – increasingly demand sooner commencement and more rapid completion (Gray and Flanagan, 1984, Pain and Bennett, 1988). Studies have also investigated historical cost data, empirically concluding that the traditional method is more costly relative to other methods (Raisbeck et al., 2010). The traditional method is seen as inherently adversarial (Bresnen, 1991) and inhibitive of trust development (Rosenfeld and Geltner, 1991); precludes contractor input in the design phase which inhibits innovation and buildability (Korczynski, 1996; Dubois and Gadde, 2002); does not cope well with project complexity (Bresnen, 1991); is susceptible to quality defects if under-budgeted (Bresnen, 1991); is inhibitive of the flow of design data and inflexible with regards to design changes upon clients' wishes or latent conditions (Bresnen, 1991); and generally does not cope well with problems stemming from uncertainty (Morris, 1973). Although contractual mechanisms exist to deal with such issues, they are exploitable by the builder and increase the cost to the client (Boukendour, 2007). Some studies indict the traditional system for many of the above combined, including the denial of "happier working relationships" (Pain and Bennett, 1988).

In spite of continuing predominance of the traditional method in industry practice, there is a unanimous consensus in the literature that alternative or concurrent strategies are necessary to overcome these pitfalls.

The various responses to this problem by industry and in the literature are classified here under three general strategies.

The first strategy is structural reconfiguration of design and construction, classified here as 'structural' because the relationship between design tasks and construction tasks is generally seen as the defining factor between organisational models (Fazio et al., 1988). Restructuring tends either towards a one-tier system ('design-build') or multi-tiered system ('management' systems), and variants prevail (Bennett, 1983; Brett-Jones, 1983; Love et al., 1998; Nahapiet and Nahapiet, 1985; Pain and Bennett, 1988; Skitmore and Marsden, 1988).

In the design-build system, a buyer engages a contractor to design as well as construct the work (Arditi and Lee, 2004). From the buyer's perspective, the entire project is embedded in one contract. From the contractor's perspective, it is similar to the traditional method except that designers are added to the list of subcontractors and the contractor must undertake design coordination. The distinction between the traditional model and design-build is a minor one conceptually and some categorise it together with the traditional method (Love et al., 1998). However, the systemic effect is major because responsibility is encapsulated into a single point (Ive and Chang, 2007), the contractor, who is responsible for both design and construction, and cannot blame independent designers for design defects, a major source of disputes, delays and cost overruns associated with the traditional method (Bresnen, 1991; Ndekugri et al., 2007).

A variant on design-build is novation (Turner, 1986; Janssens, 1991; Mosey, 1998), where designers are initially engaged by the buyer for preliminary designs and subsequently 'novated', transferred to the builder, for detailed design (Doloi, 2008). Some see this as a separate system (Chan, 1999; Ng and Skitmore, 2002) but it is classified here as a structural reconfiguration towards single point responsibility.

The notion of single point responsibility can be taken further and into the realm of funding and operating, as in Build Operate Transfer (BOT), Build Own Operate Transfer (BOOT), Public-Private Partnership (PPP) and variants. This approach is usually associated with very large public projects, typically involving a consortium that funds, designs, constructs the project, operates it for a period of time, receiving revenue, and finally hands over a fully functional facility to a government. The advantage to the government is that it does not have to expose public funds to cost premiums and high risk associated with government projects (Raisbeck et al., 2010). A major advantage to investors is the opportunity to undertake a large investment without relying on the long term for commercial viability.

In the antithetical structural direction, towards distributed responsibility are 'management' contracting methods, where the buyer contracts with each supplier, trade contractor, designer and consultant separately, and engages a construction manager as a consultant to perform the role that a head contractor would otherwise perform – pricing, planning, construction management, etc., as well as participating in the design process.

The second overall approach is project management. Traditionally, a chief engineer, in the case of engineering works such as civil works and water infrastructure, or an architect, in the case of buildings, was in charge of the management of the design process and administration of the construction contract. The professional project manager offers these functions as core services rather than, as in the case of architects and engineers, supplementary services not part of their core training. Though project management affects organisational structure because it adds another element in the overall multi-organisational structure, it does not represent another structural system, procurement route or 'organisational model' but an additional component that may be used with any procurement model (Love et al., 1998).

The project management phenomenon gives rise to one of the problems for which this thesis proposes a response, that of design coordination. Together with contract administration, the project manager takes on, by default, the role of design coordination, which is more within the training of architects and engineers than managers. Consequently, a project manager without that background, which many are not, being from a construction management background, can produce a situation where design coordination is performed ineffectively or not at all. The architectural mirroring perspective proposed in this thesis brings a response to this problem (refer Discussion chapter).

The third overall strategy is non-structural approaches. Collaborative systems such as partnering and incentive schemes would fall into this category as they are intended to modify behaviour by overlaying a system of clauses over a contractual structure rather than modifying the structure itself. Collaborative systems are based on the building of trust between contract parties in the context of 'relational contracting' (Ive and Chang, 2007), emphasising the duty to inform and council as an integral part of contracts (Dagenas, 2007). Incentive schemes are also overlay strategies, infusing contracts with profit premiums for early completion (Ibbs, 1991). These strategies are ideological or behavioural rather than based on 'structural determinism', the idea that structure can determine behaviour.

An important point about construction project organisational systems is that, though the role of contracts is crucial (Ive and Chang, 2007) and contract type can be representative of a procurement method (Doloi, 2008), their significance is beyond their legal status (Nahapiet and Nahapiet, 1985). Contracts are the mechanism by which to establish binding relationships, formal communication and coordination channels between constituent organisations within an overall project governance framework. Hence, though some theoretical approaches to the problem of organisational design involve the essential nature of contracts (Dagenais, 2007; Ive and Chang, 2007; Boukendour, 2007), and the legal profession is inevitably embroiled in the actual drafting of clauses, in litigation, etc., the matter of contract typology within organisational design is a management problem (Nahapiet and Nahapiet, 1985), not a legal one.

2.3. Literature Overview

2.3.1. Organisational Design in Construction

From a broad chronological perspective, three phases of evolution are identified in the literature on organisational design in construction management: an early phase beginning in the 1980s, a period characterised by selection models and a period characterised by diversification.

The reconfiguration of project governance structures in the construction industry at some undeterminable time in the latter twentieth century gives rise to literature which expands in the 1980s and which, from a theoretical perspective, is simply the relative evaluation of contemporaneous structural strategies employed by the industry to overcome shortcomings of the traditional system. This early literature can be characterised as having a time and cost orientation (Bennett, 1983; Gray and Flanagan, 1984; Nahapiet and Nahapiet, 1985; Sidwell, 1983), which, seemingly, should offer a high degree of objectivity because time is an accurately measurable physical parameter and cost data, inherently quantitative, can be used directly without measurement.

Nevertheless, in spite of the nascent state of the literature at this stage, already apparent are key threads and problems with this orientation, which persist over time. Firstly, the practical limitations of extracting time and cost data from live projects are recognised (Brett-Jones, 1983; Gray and Flanagan, 1984). Secondly, a strong impetus towards holism and recognition of the need for incorporating qualitative considerations such as 'client satisfaction' and 'better working relationships', though qualified as dependent on cost and time (Sidwell, 1983). Thirdly, the difficulty of quantifying qualitative factors (Sidwell, 1983).

Also important and apparent in these early works is 'structural determinism' versus management, that is, to what extent is organisational design crucial to project success relative to real-time management. The ultimate goal of economic efficiency, often unstated and later similarly questioned on the basis of holism, nevertheless pervades the early literature and arguably remains the ultimate goal.

The proliferation of structural models and advent of project management brings the need to determine which model to use and how to implement it on a given project. Thus, the second phase of the literature development is characterised by 'selection models' or 'decision models' proposed to deal with this problem. From a theoretical perspective, the time-cost orientation of the early phase shifts to a holistic orientation (Nahapiet and Nahapiet, 1985), which remains the dominant mode thereafter (Aniekwu and Okpala, 1987, 1988; Pain and Bennett, 1988; Potts, 1988; Bresnen, 1991; Greenwood, 2001; Griffith and Headley, 1995, 2001; Ibbs, 1991; Shoesmith, 1995). New analysis methods are introduced: correlation and discriminant analysis (Skitmore and Marsden, 1988) and Gantt analysis (Fazio et al., 1998), mathematical modelling (Rosenfeld and Geltner, 1991), regression model (Drew et al.,1997), concordance analysis (Love et al., 1998), Delphi method (Chan et al., 2001), hierarchy process (Cheung et al., 2001) and fuzzy model (Chan, 2007). Nevertheless, the paradigm remains that of 'selection models' with data principally sourced from questionnaires and interviews, whether 'structured', 'semi-structured' or 'open'.

The third phase of literature evolution can be characterised by the introduction of various new theoretical perspectives, in particular, non-structural strategies such as collaborative contracting and variants (Mason, 2007; Wood and Robert, 2005), contractual theory (Dagenais, 2007) and transaction cost theory (Ive and Chang, 2007). New genres also appear – books (Chan et al. 2010) and theoretical articles (Boukendour, 2007).

The collaborative contracting movement lacks static definition. However, for the purposes of this study, it is held synonymous with variant movements – relational contracting, alliancing and partnering. This movement represents a paradigm shift away from structural determinism and towards the management process, but nevertheless part of the field of organisation design, given a substantially ex ante component in its implementation, including implications for structure.

Although enabled by the emergence of non-traditional project structures, it is considered here a non-structural strategy because it is more accurately an ideology overlaid onto a structure. A structural strategy can be implemented without this ideological layer but the ideological layer requires certain structure, being particularly well suited to management contracting because of the potential for unfixed pricing, incentive schemes and open accounting. Collaborative systems, generally held as based on cooperation, trust and mutually understanding of goals is the antithetical proposition to the traditional method, which is seen as inherently adversarial.

The rise of the collaborative contracting movement can be seen as an inevitable relationship-based reaction against a previously mechanistic paradigm, just as the Human Relations movement (Mayo, 1949) followed Scientific Management (Taylor, 1903; 1911) in the early twentieth century and, later, relations centred approaches (Shaw, 1964) followed the initially experiment-based small group studies of Bavelas (1950) and Leavitt (1951).

The impetus for the collaborative contracting movement is the same as the raison d'etre for the literature, widespread demand-side feedback and empirical evidence of industry inefficiency, in spite of previous movements. This is evident in highly influential government sponsored investigations such as Latham (1994) and Egan (1998).

Other notable theoretical perspectives associated with the third phase of literature evolution are contractual theory (Boukendour, 2007; Dagenais, 2007; Donohoe and Brooks, 2007; Ndekugri et al., 2007), transactional cost theory (Ive and Chang, 2007), buyer-seller theory (Bildsten, 2014) and multi-variable cad systems (Rowlinson and Yates, 2003). Meanwhile, research continues on structural strategies such as novation (Doloi, 2008). Also appearing at this stage are new genres such as books (Garvin, 2009; Chan et al., 2010; Smyth and Pryke, 2008) and theoretical articles (Boukendour, 2007; Chapman, 2008; Dagenais, 2007; Donohoe and Brooks, 2007; Ive and Chang, 2007; Ndekugri et al., 2007).

2.3.2. The Mirroring Hypothesis

In this section, an overview of the relevant components of the mirroring hypothesis literature is provided as background for the next section, The Research Case, where a rationale is proposed for transposing concepts from the mirroring hypothesis literature into that of organisational design in construction.

The mirroring hypothesis has emerged within the broader field of engineering and as such seeks to improve efficiency, specifically by improving efficiency in product design and management. The topic has been investigated under various contexts and theoretical frameworks such as large-scale networks (Braha and Bar-Yam, 2007), misalignment in complex product development (Sosa et al., 2003), modularity and information sharing in stable architectures (Cabigiosu and Camuffo, 2011) and distributed versus integrative software development (MacCormack et al., 2012).

The mirroring hypothesis, like the partnering movement in construction, can be allusive in its definition. Arising from an intuition that "organisations design products and products design organisations" (Sanchez and Mahony, 1996), the mirroring hypothesis proposes that an intrinsic connection between product and organisational architectures exists, which can influence the net behaviour of a system and hence outcomes. Independent of direction of causality, the mirroring hypothesis is considered to hold if a connection exists at all, irrespective of whether it operates from organisation to product, vice versa or both.

Much of the literature is implicitly or explicitly based on this definition (Sosa et al., 2003; Sosa et al., 2004; Sarkar et al., 2014). However, more generic definitions are identifiable which replace 'product architecture' with "design of the system under development" (Colfer and Baldwin, 2010) or "the nature of the tasks that they [organisations] perform" (Lawrence and Lorsch, 1967; Burns and Stalker, 1961). In this thesis, a generic perspective on the mirroring hypothesis is adopted to include other systems such as design data as well as the conception of mirroring beyond the dimension of modularity and the standard definition of architecture.

Apart from the mirroring hypothesis itself, some common threads and concepts from this literature stream encapsulated in Sarkar et al. (2014) are drawn upon in this thesis, in particular, a new algorithm for detecting a 'natural' modular hierarchy within a graph structure. Sarkar et al. (2014) also introduces functional modelling, design structure matrix and modularity.

Architecture, Modularity & Functional Dependence Modelling

A common definition of 'architecture' cited in mirroring hypothesis literature is "the scheme by which the function of a product is allocated to physical components" (Ulrich, 1995). Another definition is "the scheme by which the decomposed elements are arranged in chunks" (Ulrich and Eppinger, 1994). Architecture is seen as important in terms of a product's performance, change, variability of design, manufacturability as well as a firm's development capability, manufacturing specialities and product strategy (Pimmler and Eppinger, 1994).

Modularity is a related concept, concerned with the extent and distribution of 'modules' within a scheme of components. Modules are, broadly, subsets of components with relatively high interdependence within them and independence between them (Ulrich, 1995). The study of modularity in architecture is important because modular design, that is, architectures with a high degree of modularity are recognised to offer ease of coordination (Salvador, 2007), redesign, redevelopment and adaptability, lower costs of production, and interchangeability of components, which can produce a family of products (Sarkar et al., 2014), by a single manufacturer such as Meccano, Leggo, Arduino and Olive, or distributed such as Intel based computers and open source software. Other work on modular design includes the relationship to product life cycle, supply chain factors and testing of design alternatives (Sosa et al., 2003).

Considering structural strategies for organisational design in construction from the point of view of modularity at the uppermost hierarchical level of client, builder and designers, the traditional method is relatively highly integrative, that is, less modular because the buyer has a minimum of two contracts, one with a lead designer and one with a builder. All other contracts are embedded in those. This contrasts with 'management' models where the client would have separate contracts with individual design firms and trade contractors (Love et al., 1998) and, hence, more modular. A variant on the traditional method is a hybrid between the two where the buyer still has one contract with a builder but separate contracts with design firms, hence, more modular than the traditional method. Design-build models can be more integrative than the traditional system because, potentially, the buyer need only have one contract with a designer-builder (Arditi and Lee, 2004).

The study of architecture and modularity resolves down to the modelling of functional interdependence between components. A subgenre in itself, early literature on functional dependency modelling is approximately contemporaneous with that of organisational design in construction (e.g., Pahl and Beitz, 1988; Altshuller, 1984). It is also closely tied to the mirroring hypothesis. Functional dependency modelling typically entails the development of a network model where components are nodes and their interrelationships are links. Thus, a functional dependency model can be subjected to the analysis techniques of network science.

Functional dependency modelling involves the conceptual separation of a component's function from its physical characteristics (Ulrich, 1995). Hence, a degree of abstraction is necessary, leading to components being synonymous with function and interdependence with flows, as in the 'verb-object pair' approach where functions are verbs and flows are nouns or objects (Stone et al., 2000). An example of a 'verb-object' pair is 'transmit torque'. Other function verbs are 'branch', 'channel', 'connect', 'control magnitude', 'convert', 'provide', 'signal' and 'support'. Flow objects are 'material', 'energy' and 'signal' (Stone et al., 2000), rationalised from a previous definition of interactions – 'spatial', 'energy', 'information' and 'materials' (Pimmler and Eppinger, 1994), and subsequently revisited with the addition of 'structural' (Sosa et al., 2003).

A departure from the verb-object pair paradigm produces longer but more generic definitions derived from a further rationalised set of source concepts. Thus, for example, "transmit torque" becomes "convert rotational mechanical energy" (Hirtz et al., 2002).

More recently, a move toward concretisation in functional dependency modelling posits that the relationship between a verb-object function definition and its implementation is relatively constant in the case of 'architecture stability' – mature architecture where technological improvement takes place incrementally at the component level (Cabigiosu and Camuffo, 2011), thereby reducing the need for abstraction and permitting analysis at the physical level, actual components and their functions rather than verbs and nouns.

Though the functional modelling literature is an important precedence in this thesis, the general idea and some conventions of functional modelling are adopted, not any particular methodology completely. For example, an adopted convention is that nodes of a model are first order components. Minor, ubiquitous parts such as screws and bolts are omitted, as are components beyond the first level of product hierarchy. In aircraft engine models, the gearbox is a node, not components within the gearbox (Sosa et al., 2003; Cabigiosu and Camuffo, 2011).

This expresses itself in various ways in construction. Some items are first order components because they are manufactured separately to the project and incorporated as complete products, for example, an air-handling unit, a light fixture, a pump. These are first-order components in the network model, not the components within them. Other items are purchased in standard units. For example, individual bricks, wall sheets, framing timbers, insulation batts and floor boards. Individual units in these examples are not considered nodes in the architecture. They are assembled within the project to form, for example, a single run of wall, an area of roof or floor. These are considered meaningful first order components, not the individual components comprising them. This is an important principle transposed from the functional modelling literature stream.

This thesis departs from the precedence of functional dependence modelling in one significant way. The static nature of buildings and structures makes redundant, or at least reduces greatly the significance of an extensive range of flow and function definitions such as in the mirroring hypothesis literature, which mainly deals with dynamic systems such as aircraft engines (Sosa et al., 2003; Sarkar et al., 2014) where a diversity of flows and, hence, component functions predominate. In a static system such as a building or static structure, one type of interchange predominates, structural. The notion is introduced that physical connection, the need to fix one component to another in a static system such as a building, embeds other flows even where there is a physical flow of material. For example, pipework components in a building are fixed together to form a system of channels within which fluids flow. Each component depends on the adjacent one for this flow to occur. However, the two components must be fixed in order for this to function. Thus, capturing the physical connection also captures the flow dependency. Pipework components must also be fixed to other components such as walls, thereby capturing structural dependencies. A similar rationale can be applied to electrical networks such as power supply.

Mirroring Hypothesis Methodology & Design Structure Matrix

Various methodologies and graphical representation techniques have been employed in the investigation of modularity and the mirroring hypothesis, from statistical analysis with distribution graphs (Braha and Bar-Yam, 2007) to modularity formulas with no graphical representation (Cabigiosu and Camuffo, 2011) and theoretical articles (Sanchez and Mahony, 1996).

Of particular relevance to this thesis is the three-stage framework comprising: (1) capture product architecture; (2) capture organisational architecture; (3) compare product and organisational architectures (Sosa et al., 2003; 2004). The second stage is redefined to suit this investigation. The adapted framework becomes: (1) capture product architecture; (2) capture design data architecture; (3) compare product and design data architectures.

Associated with this three-stage framework is 'design structure matrix', a matrix representation of a network model, used in modularity and mirroring hypothesis literature to visualise the clustering of components into modular structures within a functional dependency model where modules are identified ex ante, such as in a vehicle climate control system (Pimmler and Eppinger, 1994; Eppinger, 1997), aircraft jet engine (Sosa et al., 2003; 2004) and software architectures (MacCormack et al., 2012). In this thesis, this is utilised to corroborate the results from the ex-post module identification algorithm of Sarkar et al. (2014).

Natural Module Detection

The natural module detection algorithm in Sarkar et al. (2014) is based on the observation that the pattern of eigenvalue differentials of a graph matrix relates to modularity patterns. Identification of the distribution of eigenvalue differentials associated with 'idealized graph models' enables a comparison of a subject graph with that of a random graph of the same size and average node degree in order to reveal a point, **k**, at which the eigenvalues drop sharply in a graph matrix containing modularity structures, indicating an approximate optimal number of nodes beyond which redundancy can be eliminated without significant loss of essential data.

The algorithm begins with a single value decomposition of the adjacency matrix, **M**, associated with the network data, thereby producing three factors (**USV**). **S** contains the square roots of the eigenvalues of **M** x **M**. These are referred to as 'spectra'. A chart showing eigenvalues as a function of nodes can be utilised to identify a point along the x-axis where the function begins to exhibit random behaviour and effectively removing much of the 'noise' factor in the data.

For example, the following spectra charts show eigenvalue to node functions for the components network and design data network:

Figure 1: Spectral graph of components model

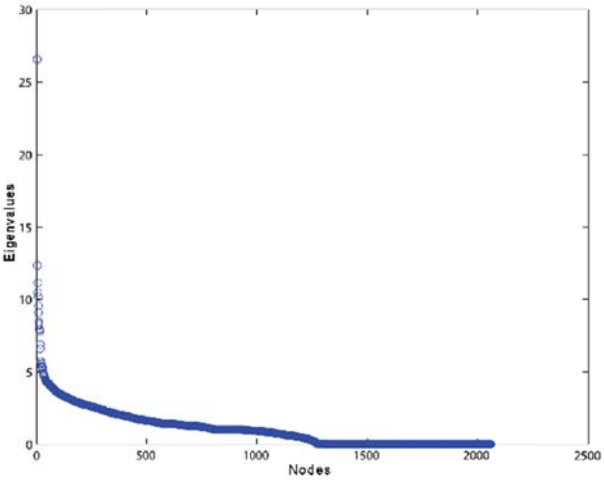
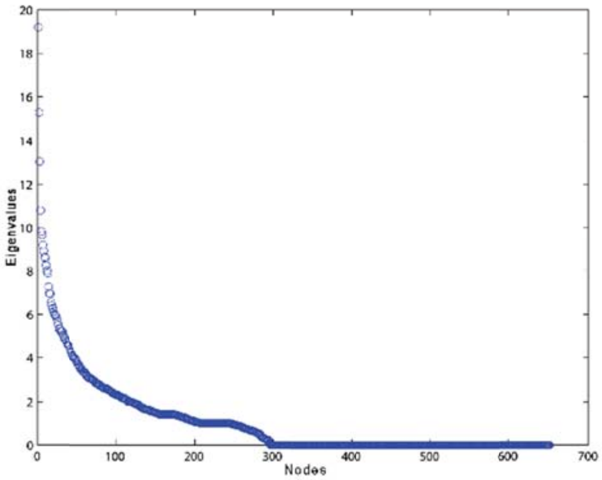


Figure 2: Spectral graph of design data model



Spectral analysis charts. Refer Sarkar et al. (2014) for algorithm.
Charts produced by Andy Dong using Matlab.

A truncation value is determined, either by calculation or by inspection of the spectra chart, prior to proceeding. In Figure 1 above, this value is approximately 1250 and in Figure 2 it is approximately 300.

Having established a truncation point, **k**, in the Matlab script, the two matrices **U** and **S** are truncated to this value, generating the dot product, **US**. In the next step, the cosine angles between each node in **US** are calculated utilising the following formula and assigned to the corresponding cell in the matrix to produce a cosine angle matrix, **Z1**:

Equation 1: Cosine angle formula version 1

$$\frac{a.b}{\sqrt{\sum_{i=0}^{n}(a_i)^2}\sqrt{\sum_{i=0}^{n}(b_i)^2}}$$

Or,

Equation 2: Cosine angle formula version 2

$$\frac{\sum_{i=0}^{n} a_i b_i}{\sqrt{\sum_{i=0}^{n}(a_i)^2}\sqrt{\sum_{i=0}^{n}(b_i)^2}}$$

Z1 is subsequently reordered according to the following procedure:

1. An index column containing row index values, commencing with 0 at the top, is prepended to a copy of **Z1**, **A**.
2. The index column, together with the first column of the original **A** (second column in new matrix) are sorted together in reverse numerical order, that is, greatest to least values from top to bottom, according to the values in the second column.
3. The rows of **A** are sorted utilising the values in the index column.
4. The columns of **A** are sorted according to the values in the index column.
5. The values in the index column are transferred to a master index vector, **I**.
6. The first row and second row of the matrix are deleted and the process is repeated with the resultant matrix. This is repeated to the end of **I.**
7. The rows and columns of the original matrix **Z1** is reordered according to the index values in **I,** which produces the matrix, **Z2**, consisting of cosine angles between nodes, with columns maximised along the diagonal. This is the final, reordered module matrix.

Finally, the Matlab function, 'imagesc' produces the colourised chart where darker colours correspond to greater cosine angles, which in turn correspond to stronger edge relations (Dong and Pourmohamadi, 2006).

2.4. The Research Case

In this section, a case is presented for the introduction of mirroring hypothesis concepts into the background problem of organisational design in construction and associated literature. The sections above – Background Problem and Literature Overview, provide background details for this discussion.

The first point is that the techniques introduced from mirroring hypothesis research are proposed to offer a higher degree of objectivity to the subject literature where a sense of objectivity deficit ostensibly persists throughout its evolution. This is identifiable in the early literature (Bennett, 1983; Sidwell, 1983), through the movement towards holism and new analysis techniques in the second phase of evolution (Chan et al., 2001; Cheung et al., 2001; Griffith and Headley, 1995; Ibbs, 1991; Love et al., 1998; Pain and Bennett, 1988) and with the emergence of new theoretical perspectives in the third phase (Eriksson and Pesamaa, 2007; Gruneberg et al., 2007; Ng et al., 2004; Nystrom, 2008; Waara, 2008).

Most of this research is carried out as various types of multi-variable analysis. However, the problem of objectivity is not in the research method, theoretical perspective or even the source of data, usually experts or practitioners, but in the type of variables. These diversify qualitatively and in number over time. In one early study, experts are asked to rate the importance of various factors affecting delay such as 'shortage of materials', 'design changes' and 'labour supply', and factors affecting cost such as 'inflation', 'additional work' and 'fraud', a total of 27 factors (Aniekwu and Okpala, 1987). Subsequently, this is expanded with a 'quality' category (Pain and Bennett, 1988); then 'speed', 'certainty', 'flexibility', 'quality', 'complexity', 'single point risk responsibility' and 'price' (Skitmore and Marsden, 1988); then expanded again to 56 items categorised under 'cost effectiveness', 'schedule', 'quality', 'safety' and 'other' (Ibbs, 1991). Later, there is emphasis on client factors such as technical and market knowledge relative to building types such as commercial, residential, industrial, etc. (Love et al., 1998); subsequently distilled back to 23 factors including 'familiarity', 'distrust of new system', 'nature of the project', 'complexity', 'flexibility', 'value for money', 'peer relationships', 'state of the market', etc. (Chan et al., 2001).

The problem with these variables is twofold: they are multi-value, that is, not binary, and they are subjective in nature. Values are usually in discrete categories numbering between five and ten, for example, 'much better', 'somewhat better', 'about the same', 'somewhat inferior' and 'much inferior' (Pain and Bennett, 1988). The variability of mean values derived from these ratings can vary significantly because experts and practitioners, though skilled, can have varying biases based on experience, training and outlook. The lack of consensus among experts is recognised as an intractable problem (Love et al., 1998; Skitmore and Marsden, 1988).

For example, asking ten experts on whether the 'distrust of a new system' is 'critical', 'very important', 'important', 'mildly important' or 'not important' can generate $5^{10} = 9765625$ permutations for the variable. Deriving a mean score from this as a percentage effectively converts it to a continuous one. Combining such variables into a net result for procurement system selection compounds the effects of the initial bias embedded in each variable.

In mirroring hypothesis research, the capturing of product architecture is achieved by functional dependency modelling (Sarkar et al., 2014; Sosa et al., 2003; 2004), the sourcing of data for which is also dependent on the advice of experts and practitioners obtained by survey or interview methods (Hirtz et al., 2002; Stone et al., 2000). However, the degree of objectivity is markedly different because of the nature of the variables. Instead of being multi-value, they are mostly binary. For example, whether there is a transfer of fluid between two components. The expert is still the source of knowledge but their opinion is involved to a lesser degree than a technical determination for which the potential for consensus is significantly greater. The net result is a higher degree of objectivity.

The second point of the research case is a conceptual connection of modular design, important in construction as it is in manufacturing. In the industrial age, modular design in construction, in the physical product as opposed to organisational, can be traced back to early nineteenth century iron bridges and industrial structures and first applied to buildings in early railway stations and glasshouses such as the Chatsworth Conservatory, UK, in 1836. This is epitomised by the Crystal Palace, London, completed in 1951, where a high degree of efficiency was attained. Design, calculations and cost estimates were completed in two weeks and construction of the 92,000 m2 facility was completed in five months. Product modularity, being embroiled with prefabrication and mass production, was a key founding concept in the development of the modern movement in twentieth century design and implemented by leading exponents such as Le Corbusier, who devised a modular geometry for design based on the human body (Le Corbusier, 2004). Later, Harry Sielder in Australia employed a significant degree of modular design in several projects such as the Australia Square and MLC towers in Sydney, where floors and façades are constructed from precast concrete components.

Along with modular design there is a sense in the literature that organisational mirroring can be advantageous. Generic notions of mirroring are identifiable in calls for "design and construction strategies which match the essential nature of the project" (Bennett, 1983, p183) and that "Management, design and construction must match" (Bennett, 1983, p183).

Organisational modularity is associated with management contracting methods because instead of the work being embedded in a design-build contract or design contract(s) with construction contract as in the traditional method, the buyer enters into separate contracts with each trade contractor and supplier, which can be numerous. This has been extended in the US industry in particular, by delegating detailed design to trade contractors (Gray and Flanagan, 1984), a model resembling complex product development in manufacturing where design teams are designated ex ante to the design of product modules (Sosa et al., 2003).

The third point in the research case is precedence in the migration of mirroring hypothesis between industries. All man-made products are the result of interactions between organisations of people. Hence, it is argued that, if an important connection exists between the architecture of products and that of their associated organisations then it should hold significance for any man-made product. Buildings and engineering structures are man-made products. Therefore, if the mirroring hypothesis is significant for man-made products then it is also significant for construction.

For example, in a recent study, the mirroring hypothesis was investigated in the context of software development to test the relationship between the degree of coupling in software architecture and degree of information flow between development teams (MacCormack et al., 2012). In software development, movements towards increased modularity of architecture such as object oriented programming can be seen in the literature from at least 1972 (Sanchez and Mahony, 1996).

The fourth point in the research case is common genealogy of the two subject literatures within the broader field of management. The mirroring hypothesis can be seen as a management problem (Sanchez and Mahony, 1996; Sosa et al., 2003; 2004), which overlaps the product design problem in manufacturing (Braha and Bar-Yam, 2007; Cabigiosu and Camuffo, 2011). Organisational design in construction can similarly be viewed (Bennett, 1983; Gray and Flanagan, 1984; Cheung et al., 2001). Both literatures are concerned with organisational design, as in management (e.g. Malone, 1986; Mintzberg, 1981, see also Appendix 3), which traces back to early small group studies (e.g. Bavelas, 1950), in turn, to the Scientific Management movement of Taylor and Ford, and the fundamental problem in manufacturing of increasing efficiency (Taylor, 1903; 1911). Furthermore, cross-citation continues into recent times. For example, Nahapiet and Nahapiet (1985) and MacCormack (2012) both cite Lawrence and Lorsch (1967); and Sosa et al. (2007) cites Bavelas (1948) and Freeman (1977; 1979), both are key works in organisational design in management as well as network science (see Appendix 1 and 2).

Consequently, it is reasonable to expect transposition of methods and approaches between the two genres merely because of shared origins and principles.

The fifth point in the research case is significant commonality between the context of the two subject literatures – design and production managed within an organisational framework. Design data is produced which models the final product. The design of products and organisations are background problems in both industries, as is the broader problem of improving efficiency.

The sixth point in the research case is the continual diversification of new methods and theoretical frameworks. Being expressly stated in the literature (Bresnen, 2010; Chan et al., 2001; Gray and Flanagan, 1984; Love et al., 1998; Nystrom, 2008), this phenomenon itself may be taken as an expression of a sense of inadequacy of current solutions if a universal decision framework is the ultimate goal of the research, as is sometimes apparent (Chan et al., 2001; Nahapiet and Nahapiet, 1985). Otherwise, from a contingency perspective, also prevalent in the literature (Bennett, 1983; Chapman and Ward, 2008; Shoesmith, 1995), it is simply consistent with the notion that there should be multiple methods and approaches to draw upon according to varying conditions. Either way compels the introduction of new approaches. From a universalist perspective, if a universal approach has not been found then new methods and approaches should be introduced to the problem. From a contingency perspective, if there is no one way then new methods and approaches will add to the repertoire from which to draw upon.

The seventh point in the research case is persistent criticism by government and business sectors of construction industry inefficiency and other ills, an ongoing impetus for new ideas and practices to be implemented in the industry, hence for new methods and theoretical perspectives to be introduced into the research.

As outlined in the previous section, overcoming endemic pitfalls in the traditional method of organising projects is an underlying problem in organisational design and the literature focuses on various means of addressing this – selection models, contracts, partnering, etc. The state of the industry is a broader problem of construction management, hence the appearance of industry reports in the US and UK sponsored by government or professional institutes such as the Construction Industry Institute in the US, highlighting industry ills such as inefficiency, cost and time escalations, rework, conflict and opportunism. Organisational design is recognised within such reports as a major component of responding to these ills vis-à-vis overcoming the traditional method (Ashley and Workman, 1985, Business Roundtable, 1982; Egan, 1998; Ibbs and Ashley, 1986; Latham, 1994).

Within the literature, in addition to commonplace referral to these reports, criticism of the construction industry persists throughout its evolution (Aniekwu and Okpala, 1987; 1988; Bennett, 1983; Boukendour, 2007; Bresnen, 1991; 2010; Cheung et al., 2001; Dagenais, 2007; Doloi, 2008; Donohoe and Brooks, 2007; Drew and Skitmore, 1997; Eriksson and Pesamaa, 2007; Fazio et al., 1988; Gray and Flannagan, 1984; Greenwood, 2001; Griffith and Phillips, 2001; Mason, 2007; Nahapiet and Nahapiet, 1985; Ndekugri et al., 2007; Nystrom, 2005; 2008; Raisbeck et al., 2010; Rosenfeld and Geltner, 1991; Rowlinson and Yates, 2003; Sidwell, 1983; Wood and Ellis, 2005).

Furthermore, the literature testifies to a lack of evidence for industry implementation of models and strategies proposed in the bulk of the literature, particularly the early selection or decision models. Non-structural strategies such as incentive schemes, partnering and other collaborative approaches have influenced industry practice to a limited degree (Bresnen, 2010; Dagenais, 2007; Greenwood, 2001), mainly on very large projects (Rowlinson and Yates, 2003), structural strategies having already been implemented prior and concurrent with the early literature. In spite of this feedback, the traditional method still dominates most of the industry (Greenwood, 2001).

Industry improvement such as fast-tracking practice in the US relative to the UK is observable, though not necessarily as a result of research implementation but of industry innovation (Gray and Flannagan, 1984). However, continual testimony in the literature that the problem remains, suggests that organisational design in practice has not made an effective response, hence the case for new approaches.

The Incorporation of Design Data

This research project was undertaken based on data from completed projects. Several difficulties in doing so are recognised in the organisational design literature such as the unreliability of retrospective reconstruction by participants, the commercial-in-confidence nature of important data and the non-existence of life cycle cost data as this is rarely produced (Badenfelt, 2010; Chan et al., 2010). The difficulty of obtaining data is also recognised in the mirroring hypothesis literature (MacCormack et al., 2012) and management literature (Yates, 1989).

Although the notion of design data architecture serving as a proxy for organisational architecture is not investigated in this thesis, it is a possible future approach suggested by certain clues in the literature. Firstly, the notion of one system as a proxy for another is intimated in the mirroring hypothesis literature, where the degree of information sharing serves as a proxy for degree of coupling between organisations (Cabigiosu and Camuffo, 2011). This raises the possibility of using one architecture as a proxy for another. Secondly, a study within the organisational design literature undertakes a 'quasi-experimental' approach, where 'project documentation' serves as a proxy for the inter-organisational relationships (Nystrom, 2008). The term 'project documentation' in this study refers to project management documents such as site meeting minutes and various procedural forms and reports. In the context of design, the same term refers to design data – drawings, specifications, schedules, etc. Hence, taking this not as a literal precedence but as an analogous one led to the question of whether design data might serve as a proxy for design team architecture.

Given that, at the organisational level, the design process is structured ex ante by discipline – architect, structural engineer, electrical engineering, mechanical engineer, hydraulics engineers, etc., that these disciplines are not interchangeable, that is, none of them can do the work of the others and that all of these disciplines are required for the design of any sizeable building, there is no need to discover the decomposition at the organisation level. It is determined ex ante. A similar situation can be seen in some mirroring hypothesis studies where design teams are divided ex ante (Sosa et al., 2003; 2004). Some qualification is required to put this into perspective.

First, though studies have been carried out at the individual level, that is, where nodes are individual people (Alsamadani et al. 2012; Hossain, 2009; Loosemore, 1998; 1999; Ruan et al., 2013; Pryke, 2004; 2005), this investigation is concerned with the organisational level, where nodes are organisations, where it is possible to define ex ante the first order decomposition of the overall design organisation into constituent design organisations.

Secondly, engineering construction projects such as civil and water infrastructure would have a different break up mainly consisting of structural/civil engineers, hydraulics engineers and other specialists, also established ex ante.

Thirdly, this standard suite of design organisations is ubiquitous although distributed differently in different organisational design models. In this investigation, the subject project was constructed under the traditional method. Consequently, there is a complete package of design data, divided into consultant packages. This would also be the case in a design-build scenario. Under a management system there would be another level of decomposition into trade packages. For example, the architect's package would be broken down into windows, roofing, etc. The degree to which design is delegated to trade contractors in management contracting is also the degree to which the standard suite of design disciplines in an organisational arrangement can be broken down (Gray and Flanagan, 1984). However, in that scenario the standard suite of design disciplines are still required for preliminary designs and integration.

Fourthly, in spite of the 'ex ante' component, the relationship to product architecture is unknown. The findings of this investigation are that they do not mirror in terms of modularity. Also, the ex ante component relates to modularity and says nothing about topology. For example, whether one organisation has a disproportionately central position. Traditionally, this is also decided ex ante because of the need for design coordination responsibility. This leads to the notion of the mirroring of topological properties.

The Incorporation of Centrality Measures

The potential role of topological measures in a generic notion of the mirroring hypothesis, or a variant one, has also influenced this investigation.

Like organisational design in management, topological measures within network theory trace back to the small group studies of Bavelas and Leavitt (Freeman, 1979), which were concerned with the relationship between node centrality and team efficiency (Bavelas, 1950). This does not cease over time but diversifies into different measures of centrality (Freeman, 1979) and other topological measures of nodes and networks such as density and transitivity.

Centrality measures have also been applied to the problem of construction coordination (Hossain, 2009), finding as Bavelas (1950), that a high degree of centrality is associated with potential for coordination efficiency. This revisiting of one of the founding principles of organisational design in management raises the argument that if centrality is a major consideration in construction coordination then it has major implications for organisational design in construction management.

Based on this precedence in the literature, this thesis proposes that two networks can be similar or dissimilar topologically, in terms of centrality for example, and hence that the mirroring hypothesis need not be restricted to a mirroring of modularity.

There is also precedence in the mirroring hypothesis literature for utilising topological measures to study complex product networks (Braha and Bar-Yam, 2007), where characteristic patterns of product development networks are explained with the mirroring hypothesis, thereby associating topological properties of networks with isomorphism.

3 Methodology

3. Methodology

Sosa et al. (2003) proposes a general approach for investigating mirroring hypothesis problems:

1. Capture product architecture.
2. Capture team interactions.
3. Compare product architecture and team interactions.

This research project undertakes a similar but modified approach. Points of departure are, firstly, that 'integration teams' are not omitted. As explained in the Literature Review, these are either architects or chief engineers; secondly, product architecture is modelled according to construction specific functional dependency; and, thirdly, multi-organisational architecture is derived from design data, hence the model for this thesis:

1. Capture product architecture.
2. Capture design data architecture.
3. Compare product architecture and design data architecture.

Product architecture is modelled in terms of functional dependency between components, partially based on Sosa et al. (2003), Stone et al. (2000) and Hirtz et al. (2002), as explained in the Literature Review. Design data is similarly modelled and influenced but components are drawings, symbols and notes.

3.1. Node Labelling

In the labelling of nodes, a code representing design discipline is prepended. 'A' represents 'Architectural, 'S' represents 'Structural', 'M' represents 'Mechanical', 'H' represents 'Hydraulics', 'E' represents 'Electrical'. Thus, node labels such as 'A.WIN-01' representing 'Architectural – Window # 01', 'S.SEB-01' representing 'Structural – Edge Beam # 01', 'H.CWPW-01' representing 'Hydraulics – Cold Water Pipework # 01'.

This is subsequently used as an analysis mechanism in various ways. Firstly, it enables the identification of nodes within regions of reordered output matrices. This is used in the interpretation of results (refer Section 5.2.1 and Table 7). Secondly, it enables the implementation of a design structure matrix based on pre-ordered data as in Sosa et al. (2003). This is used for corroboration of natural module detection of design data (Refer Section 5.2.2 and Figure 36). Thirdly, it enables the calculation of package level centralities (Refer Section 4.4.2 and Table 5).

Node labels in examples within this chapter do not conform to this labelling policy. They are formulated for the purposes of their immediate context within the text.

3.2. Source of Data

The source project is a residential development in Sydney comprising four levels of apartments and basement car park. As the subject project is a recent private enterprise, no primary material is reproduced in this thesis. Diagrams associated with the examples in this section are hypothetical or from unrelated projects with identification details omitted.

3.3. Component Architecture Model

In Sosa et al. (2003), five types of component dependency modes (spatial, structural, material, energy, information) form the basis for the modelling of "design interfaces between the components required for their functionality" (Sosa et al., 2003, p 241). A flow definition scheme akin to Hirtz et al. (2002) and Stone et al. (2000) is applied to an aircraft engine, hence an abstracted functional scheme applied to real-world components.

Cabigiosu and Camuffo (2011) conduct a Pareto analysis of components of high-precision air-conditioning products. Minor, ubiquitous parts such as screws and bolts are omitted, as are components beyond the first level of product hierarchy. Component modularity is defined as the inverse of the sum of the number of functions and the number of interfaces implemented by a component. The definitions of interfaces are akin to flows in previous research such as Hirtz et al. (2002) and Sosa et al. (2003).

Cabigiosu and Camuffo (2011) describe commercial air-conditioning systems in terms of being a relatively stable product architecture, having evolved to a point where it does not continue to change very much. The commercial air-conditioning industry is seen as "mature, and technological improvements take place "incrementally at the component level". Within a stable architecture, the relationship between a verb-object function definition and its implementation is relatively constant. This permits analysis at a physical level, specific components and functions. Hence, Cabigiosu and Camuffo (2011) depart from the verb and noun tradition and designate nodes as components with functions as attributes. Also observed is that "diverse organizational patterns have been observed across industries so that conventional views are now considered too simplistic, and many studies indicate the need for a more nuanced theory of mirroring" and that studies to date "tend to focus on *whether* the 'mirroring' hypothesis holds, not on *under which conditions* it may hold" (Cabigiosu and Camuffo, 2011, p2).

The notion that mirroring theory needs to be diversified and applied to different industries and product in such a way that incorporates the unique aspects of an industry or product is the impetus for this study, in which product architecture is conceived in terms of a network model where nodes are individual building components and links are functional dependencies. This may be viewed as a variation on Cabigiosu and Camuffo (2011) with elements of Sosa et al. (2003).

Architecture Stability

The architecture of building construction, hence the 'architecture of architecture' can be considered a 'stable architecture'. A major shift occurred during the nineteenth and early twentieth century whereby architectural paradigms such as post-and-beam, composite materials (reinforced concrete) and increased modularity became pre-eminent in communal and public typologies in western architecture. On a certain level, the same architecture predominates in construction to the present time. From a more generic perspective, the architecture of buildings is constant through time. Floor, walls, roof, windows, doors, stairs, etc., as well as the ways in which they must interrelate remain unchangeable.

The twentieth century shift in building construction architecture has produced an architecture based on engineering practice and systems, hence the design and construction of modern buildings follows a framework of custom engineered structural, mechanical, electrical and hydraulic systems. The architecture within each of these main systems may vary but on the macro level they are all invariably present in modern buildings in some form, even in small-scale domestic construction. The type of structural system a building employs may be concrete, steel, timber or hybrids, which differ architecturally, but a building must have a structural system that carries loads to the ground and by statutory regulation, a building's structural system must be certified by a structural engineer. Hydraulic systems provide water supply, drainage, sanitation and fire protection. Internally, these structures may vary but water supply and drainage are minimum standards in modern buildings. Mechanical systems provide ventilation, air-conditioning and vertical transportation systems, without which modern floor space and footprint to lot area ratios would be impossible. Electrical systems supply power, communications and security services to the end user. These systems are not isolated but interact with each other. Electrical services supply power to mechanical and hydraulic systems. Hydraulics services provide water, drainage and fire protection to mechanical systems. All systems are ultimately physically supported by the structural system.

Engineering versus Non-Engineering

The term "engineered systems" refers to systems within a building custom engineered for that building by statutory regulation and by a certified specialist engineering organisation. They are primary building structure, electrical services, hydraulics services and mechanical services. Non-engineering components are not un-engineered in the sense that their manufacture does not involve engineering but they are not engineered specifically for the project and are the designed by the architect. They are purchased from a manufacturer or supplier, transported to the site and fixed onto the building – for example, light fittings, doors, windows, ceilings, etc. Their installation may require detailed design in the form of shop drawings, scheduling or other design instrument but not as part of a system by a certified specialist engineer by statutory regulation - for example, cladding systems, joinery cabinets and metal fixtures.

Manufactured Products Versus Building Construction

In a building, the number of components that are hidden from view, relative to the total number of components, must be far fewer than in complex manufactured products. Similarly, the relative number of components that users interact with must be far greater. For example, in the normal use of an aircraft, most components are hidden and do not interface directly with end-users, many more presumably than within a building. This has an effect on the definition of function. A light, for example, can function as a light without a light switch. However, it cannot function if end-user operability is included in the definition of function.

A building component is a product or material purchased from a manufacturer or supplier, transported to a building site and fixed onto the building. This follows the approach of Cabigiosu and Camuffo (2011) where components are "product components purchased from suppliers", ignoring "components with negligible value or simple parts" and considering "only components at the first level of the product hierarchy" (Cabigiosu and Camuffo, 2011, p 5). Here there is some departure from that but this was the starting point for the implemented approach.

Thus a component is not necessarily an indivisible single component such as a piece of timber or a nail. It may be a tap, a bracket, a truss, all of which can be broken down further into sub-component and/or sub-systems. Although those types of items may themselves be complex product architectures, in the overall scheme of a construction project, in terms of architecture and management they are considered single nodes.

In some cases, such as concrete, the material is delivered to site in liquid form and not so much fixed but poured into place, forming various types of elements – slabs, columns, etc. These elements have unique structural behaviour and form, and are recognised as such in their design. That is, project structural engineers do not design something in a liquid state. Ultimately, they design floor slabs, beams, columns, etc., which are consequently recognised here as node components.

A link in the component dependency model represents functional dependency. For example, a light must be connected to a cable leading to a switchboard. Without the cable, the light cannot function. The cable itself does not depend on the switchboard in order to function properly as a cable but may depend on a conduit. A light depends on both the cable and switchboard in order to function as a light.

A light also depends on the ceiling component to which it is connected in order to remain in position. This is a structural dependency that all components have, that is, every component in a building must be fixed to another component and eventually to a structural component within the structural system designed by the structural engineer, which is in turn secured into the ground. This does not imply that every component is part of the structural system of a building. The structural system is the system of components designed by the structural engineer. In many cases, for example, the structural engineer would not design stud wall framing, ceiling framings, cladding support framings, non-load bearing walls, etc. These are considered secondary structures, part of the architectural system of components, which are fixed to the primary structure and to which other components are fixed but do not form part of the structural system of a building and are not modelled as such in the component dependency model.

Relationship to Other Building Component Models

The component dependency model in this project must also be differentiated from other types of building component models commonly utilised in the industry, such as cost and workflow models. In a typical building cost model such as the NPWC elemental system or SMM5 trade based bill of quantities system, labour and temporary items must also be modelled. In this thesis, component dependency model is not a model of a construction process but of a final product. Consequently, labour items or other items included in other types of models are not included, for example, formwork, cutting, etc.

Another network model in common use in building construction are time scheduling models such as PERT and Gantt charts which incorporate the concept of critical path. In this type of modelling, commonly known in the industry as "construction scheduling" or "construction programming", nodes are tasks and links are prerequisite completion. Again, node definition encompasses a much broader scope than the one proposed in this project. It is also process oriented whereas component definitions for functional interdependency are conceptually static and functional dependency is only important insofar as it hinders or permits commencement of another task. In a construction program, tasks are time components which depend on other time components to the extent that one must be completed or partially completed prior to another one commencing.

Work breakdown structure is another type of building construction modelling utilised in building construction, particularly in the field of project management. Similar to cost and time management models mentioned above, the definition of nodes is generic and incorporates factors beyond the needs of the analysis of architecture – time factors, labour, temporary works, etc.

Consequently, as no currently available or implemented modelling system is considered suitable for the purposes of this project, the modelling methodology adopted is developed specifically for the needs of this study.

General Conventions Adopted

Eight general conventions are adopted in the modelling of functional dependency.

The first one is a binary notion of functional dependency, not a multi-variant one as in the literature, based on the premise that physical connection subsumes structural, hydraulic and electrical flows. The main reason for this is that, though people move within buildings, as do fluids, currents and forces, as far as product architecture is concerned, they are static systems where the predominant component interdependency is physical connection.

The second convention is that only components and relationships present in the final product are considered part of the architecture and hence included in the components model. This excludes all temporary items such as formwork, scaffolds, site shed, temporary fencing, etc.

The third convention is that dependency is inherited. Hence, if A depends on B and B depends on C, there is an indirect dependency of A on C. However, only first degree dependencies are modelled.

The fourth convention is that the sub-components of items manufactured off site are not components of the component model. The entire unit is a component, for example, an oven, a light fixture, an air-handling unit, etc.

The fifth convention is that functional component nodes are not necessarily singular physical units as they are purchased but the basic units comprising the architecture. A brick wall is a component, not each individual brick regardless of the form in which they are purchased. In terms of the architecture, a brick wall is a node but individual bricks are not. Similarly, reinforcement steel in concrete for example.

The sixth convention is that features of physical components may be considered functional component nodes. For example, penetrations and depressions in a concrete slab are modelled as nodes.

The seventh convention is that functional dependency within a building context includes factors beyond physical or chemical exchange and properties. These factors may include dependency for maintenance, protection or operation. For example, a bollard protecting an external air-conditioning invertor adjacent to a carpark is a dependency based on the need for protection. There is no physical connection or flow involved.

The eighth convention is that sundry items such as nails, adhesive, screws, bolts, etc. are not considered nodes in the architecture.

3.3.1. Examples of Component Architecture Modelling

Services Mains Connections

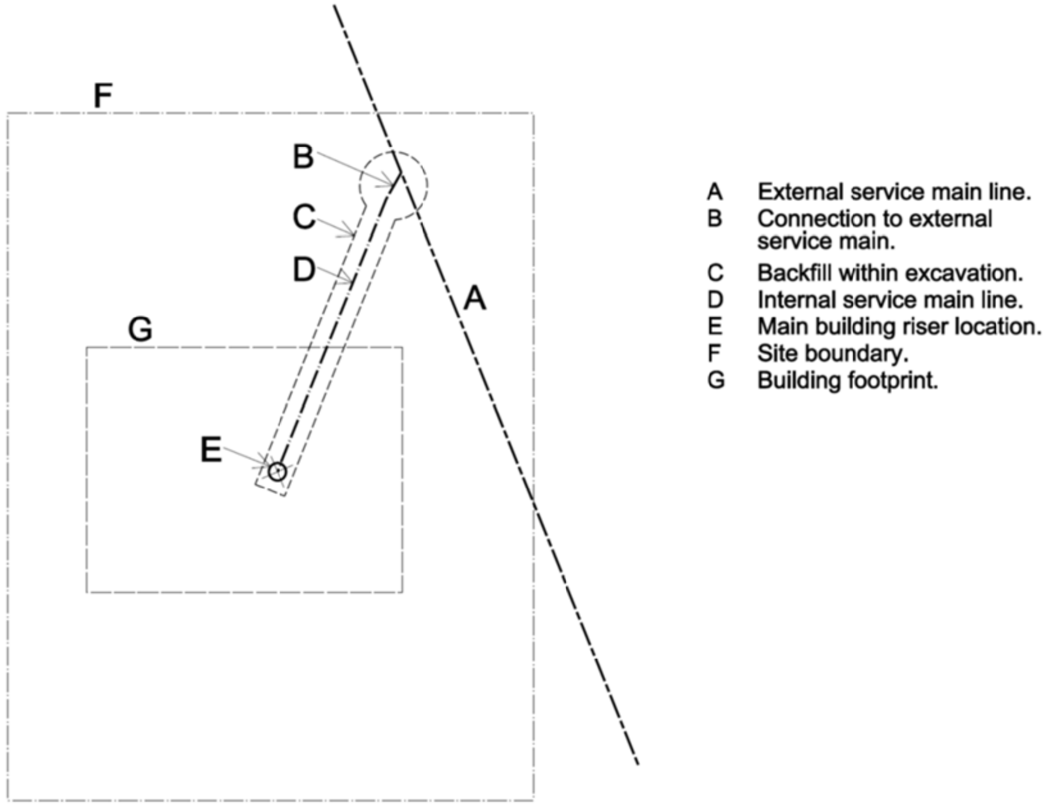
One of the first components to be fixed in a construction project is the laying of internal mains and connection to external service mains. Usually, every property lot is designated an interface component installed in the external service line, running through or near the property and enabling the connection of an internal line to run within the lot boundary.

Once services connections are located, the building footprint is set out, trenches are dug from riser points towards the services connections. For example, the water supply connection is located, then a trench is dug between that location and the point at which the horizontal pipe will turn upward into a supply riser. The connection is then exposed by further careful digging, the main pipe is laid and the connection is made. The trench is typically backfilled with granulated fill prior to and subsequent to laying the pipe. In simple terms, the functioning of the main internal water supply pipe in this example depends on two components:

1. Interface component to the service main, permitting water to flow from the service main into the site main.
2. Trench backfill. This levels the ground and prevents water pressure to accumulate around the pipe or move the pipe.

The following site plan drawing shows a generic outline of the components involved in this example.

Figure 3: Overview of Utilities Connection



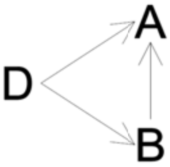
Note, this is a generic outline, which omits silt pits, boundary traps, meters, valves, etc. The aim of this diagram is to introduce the notion of functional dependence between components.

For the proper functioning of the internal service line D, that is, for water to flow as required through the internal service line, it must flow as required through the connection B from the external service main A. In turn, for connection B to function properly the external service main A, which is part of the city's water supply network must also function properly, that is, water must successfully flow through A. This may be stated in terms of functional dependency that there is functional dependency from the internal service line D to the connection B and in turn from B to the external service line A. The node-link relationship this could be modelled thus.

Figure 4: Graph of external main (A), connection (B) and internal main (D)

D depends on B which depends on A. Consequently, D also depends on A. To illustrate the third modelling convention that dependency is inherited, if secondary functional dependencies are also treated as direct links, the node-link diagram would look like this:

Figure 5: Alternative graph of external main (A), connection (B) and internal main (D)



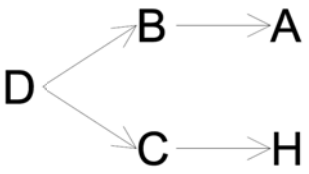
This generates exponential redundancy as nodes are added to a network. For example, a component H that depends on D would also depend on A and B and links would be required from H to A, B and D. Another component J that depends on H would need links to H, A, B and D, and so on.

Figure 6: Redundancy of indirect links

If the proper functioning of node A depends on the proper functioning of node B, then if A is functioning properly it means B is also functioning properly. Similarly if B is functioning properly then all nodes on which B depends must also be functioning properly and so on.

In the water supply site connection example, the proper functioning of internal service main D is also dependent on the granular backfill in the trench. If the trench is considered a feature of the shape of the ground on which the shape of backfill depends then dependency of backfill material on the ground may be construed. The overall node-link graph is as follows (ground is H):

Figure 7: Interdependency between water mains nodes and those of adjacent systems



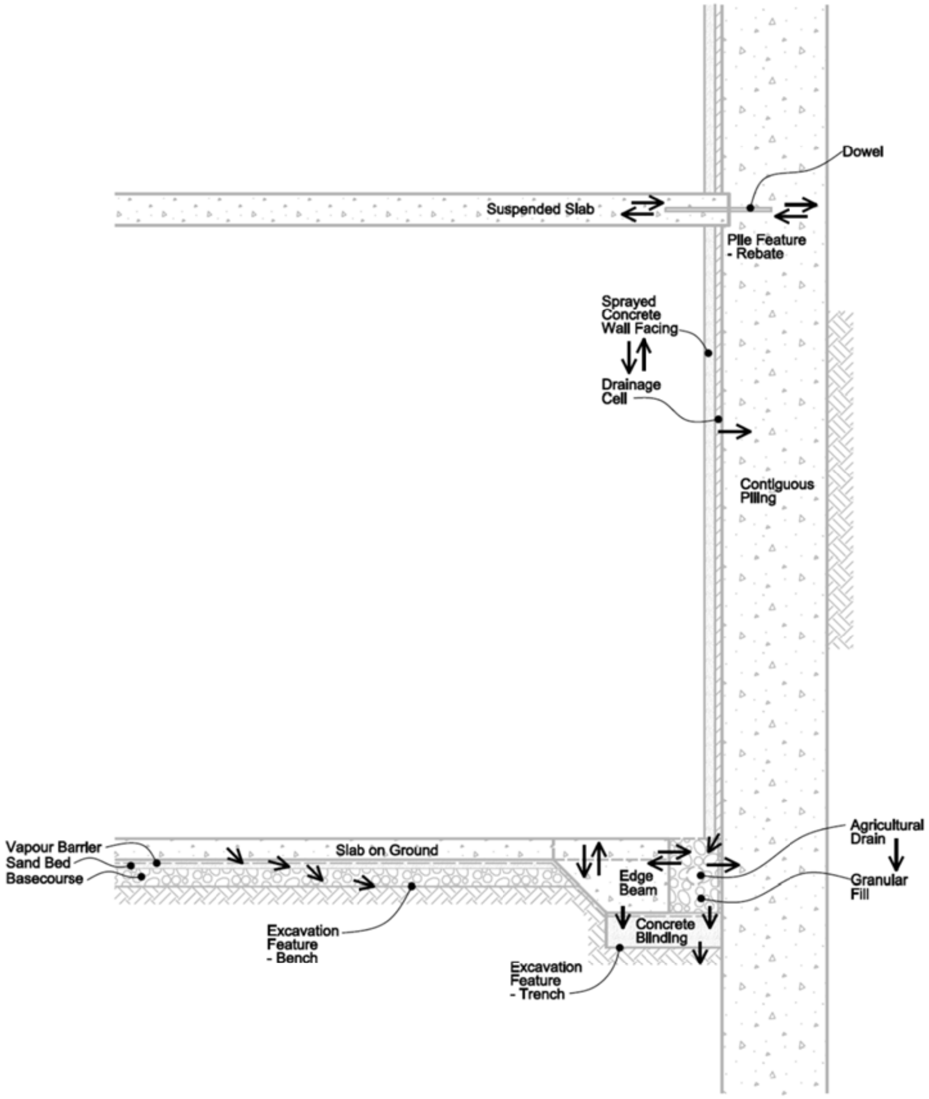
To illustrate the fifth modelling convention, pipework junctions are delivered to site and installed in the same form that they are purchased. The physical component and the node in the model are virtually one and the same. However, in the case of pipework, they are purchased and transported in standard lengths. They are joined on site to form runs of pipework between junctions and other components. A node in the model is a run of pipework, not individual pipe lengths, including couplings and other sundry physical components required to form the run. This principle is applied to many other components in the node-link functional dependency model. Another example is a brick wall – physical components are bricks and mortar but a node in the model represents a run of wall, not an individual brick. Bricks and mortar are considered sub-components of the node component and do not form part of the dependency scheme.

In addition to water supply, there are stormwater, drainage, power supply and data services in buildings, all of which have analogous components and are modelled in the same way.

Foundations & Piling

In the construction of a basement carpark, excavation is carried out after securing the perimeter with contiguous piling. Subsequently the ground slab is constructed, vertical structures on the ground floor and the suspended floor slab. Floor structures depend on perimeter piling to retain adjacent ground as well as for vertical support or restraint. In the modelling of contiguous piling, component nodes are defined as runs of piling, not individual piles.

Figure 8: Component interdependency overlaid onto architectural section through basement wall



The principle function of the ground slab is a structural one, to support the loads of occupation, from other structures, etc. In order to properly perform this function, it depends directly on several adjacent or nearby components.

1. Vapour barrier: In order to perform its function the ground slab must retain its own internal structural integrity. This requires remaining dry and preventing reinforcement from corroding, hence dependency on the vapour barrier, which prevents ground-borne moisture from rising into the slab. Excessive moisture can also penetrate the upper surface. A secondary function of the vapour barrier is to control the rate of moisture loss during curing of the slab. The ground slab also bears directly on the vapour barrier and therefore, technically at least, depends structurally on the vapour barrier, which in turn depends structurally on the sand bed, basecourse and, ultimately, the ground.
2. Agricultural drain: The agricultural drain around the perimeter of the ground slab drains water penetrating through the piling thereby keeping it off the surface of the slab and from building up behind the perimeter wall.
3. Slab beam: Slab beams stiffen the slab against excessive deflection.
4. Piling: Direct dependency can be said to exist between the floor slab and perimeter piling which retains the ground behind.

The principle function of the sand bed under the vapour barrier is to cushion the vapour barrier against penetration from coarse material underneath as well as to provide an even surface for laying the vapour barrier.

The principle function of basecourse material is to minimise the amount of rising damp reaching the vapour barrier. Secondarily, it forms part of the progressive development of flatness tolerance in bearing surface for the ground slab. A certain flatness tolerance is initially achieved with rolling of the ground surface, which is increased with the basecourse layer and further still with the sand bed layer, which provides the final bearing surface tolerance.

Structural loading is transferred from the ground slab via the vapour barrier to the sand bed, basecourse fill and to the ground.

The principle function of slab beams is a structural one – to transfer loads from the slab to the ground and to increase slab stiffness. In order to perform this function they must be placed on an even bearing surface. Undulations may reduce the effectiveness of beams or even encroach on structural design depth. Consequently, trenches for slab beams are often over-excavated and mass concrete blinding placed under beams is employed to make up height and increase the tolerance of the bearing surface of the beams. Therefore, the slab beam depends on the concrete blinding, which ultimately, again, depends on the ground as loads are transferred through slab beams to the ground via blindings.

The piling wall depends mainly on the ground and drainage cell. Dependency on the ground is the same for all foundation components. They transfer load to the ground. Dependency on drainage is related to structural dependency in that water draining through the wall of piles reduces pressure from the ground onto the piles. This is an example of cross-system dependency. Drainage is part of the hydraulics system and piling is part of the structural system.

The drainage cell layer depends on the sprayed concrete wall to remain in place. It also depends on the adjacent granular fill into which it drains. Water passes through the fill material and into the agricultural drain, which drains away, ultimately to the external stormwater mains.

Considering the granular fill, it is dependent on three separate components bounding its sides – piling, slab edge beam and blinding. It is also dependent on the agricultural drain, to drain water away to stormwater mains.

Considering drainage cell and sprayed concrete wall facing, it may be concluded that the drainage cell layer is held in place and protected by the sprayed concrete wall whilst the sprayed concrete wall depends on the drainage cell for backing support. Thus, there is mutual dependency.

Another pattern of dependency evident in this graph is triangular dependency. For example, the granular fill depends on the slab edge beam and blinding for bounding and support. In turn, the slab edge beam also depends on the blinding. Another example, with different directional configuration, is the granular fill, piling and drainage cell. Water flows from the ground through the piling wall, then drainage cell and into the granular fill. Meanwhile, the granular fill depends on the piling wall as a bounding surface.

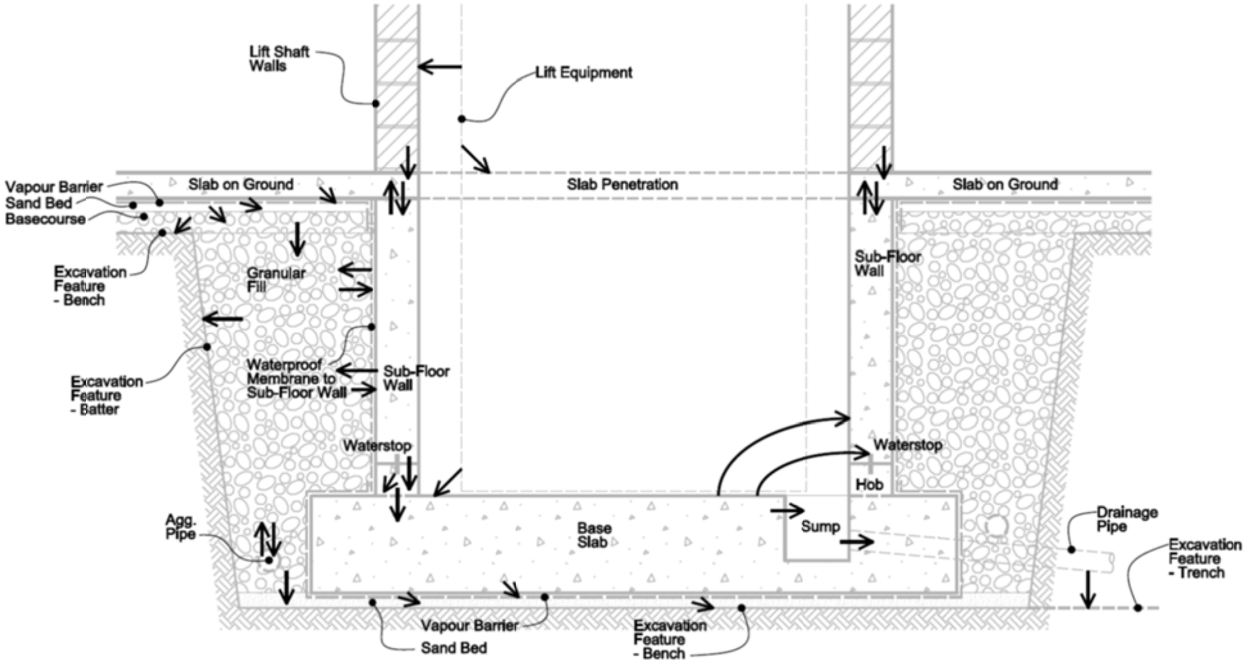
Triangular and mutual dependency can be viewed as special cases of circular dependency containing more than two or three nodes such as that between granular fill, piling, ground and blinding. The granular fill depends directly on piling and blinding as described above, both of which depend directly on the ground. The suspended floor slab depends on the dowel joint ,which in turn depends on the piling.

The piling component also illustrates the first convention of binary linkage. Some dependencies can be multi-variant, for example, the dependency of piling on the agricultural drain. In reality, the actual water pressure behind the piling can vary. If the drainage cell fails at a particular threshold of pressure, drainage may still be mostly effective. If the granular fill is clogged then perhaps less so, if the agricultural drain is blocked then even less. In this thesis, the policy of binary linkage is adopted, hence binary linkage only is considered, on the premise that it has significance independently of continuous linkage.

Lift Pit

The following diagram shows a cross-section through a typical lift pit design.

Figure 9: Component interdependency overlaid onto architectural section through lift pit



The base slab is placed on top of the vapour barrier and sand bed. Sometimes there are piers but in this case it is not required. Proper functioning of the base slab depends on the ground/subgrade, plastic sheet and perimeter piling (similar to main ground slab). Dependence on level (depth) and grading of subgrade and sand bed can be considered more direct here than in the case of the ground floor slab because there is no basecourse and in order to function properly the base slab must be at a certain level, have a certain flatness tolerance and therefore depends more directly on the vapour barrier, sand bed and subgrade.

Structural dependence of subgrade on vapour barrier is indirect as in the case of the ground slab. Also as per the ground slab, functional dependence on the vapour barrier is the prevention of ground water rising to the surface and thereby rendering the slab not fit for purpose as a floor surface. For the same reason, the base slab is considered to depend directly on the wall membrane to keep water from penetrating the walls and running on its surface. The hob depends structurally on the base slab directly and is integral with it. Lift pit walls depend for support on the hob and, similar to the base slab, depend on waterproofing membrane and waterstop to prevent water from penetrating through.

The waterproof membrane depends on granular backfill to reduce lateral pressure from ground water. The drainage of water from the granular backfill depends on an agricultural drain, which in turn depends on a water pump. The agricultural drain in turn depends on granular fill for support and bedding with falls. Waterproofing of the pit base also depends on a drainage sump to capture any stray moisture that may enter the pit in the even of membrane or waterstop deterioration or failure. The drainage sump in turn depends on the pipework leading to the pump out pit. The basement ground slab depends structurally on lift walls.

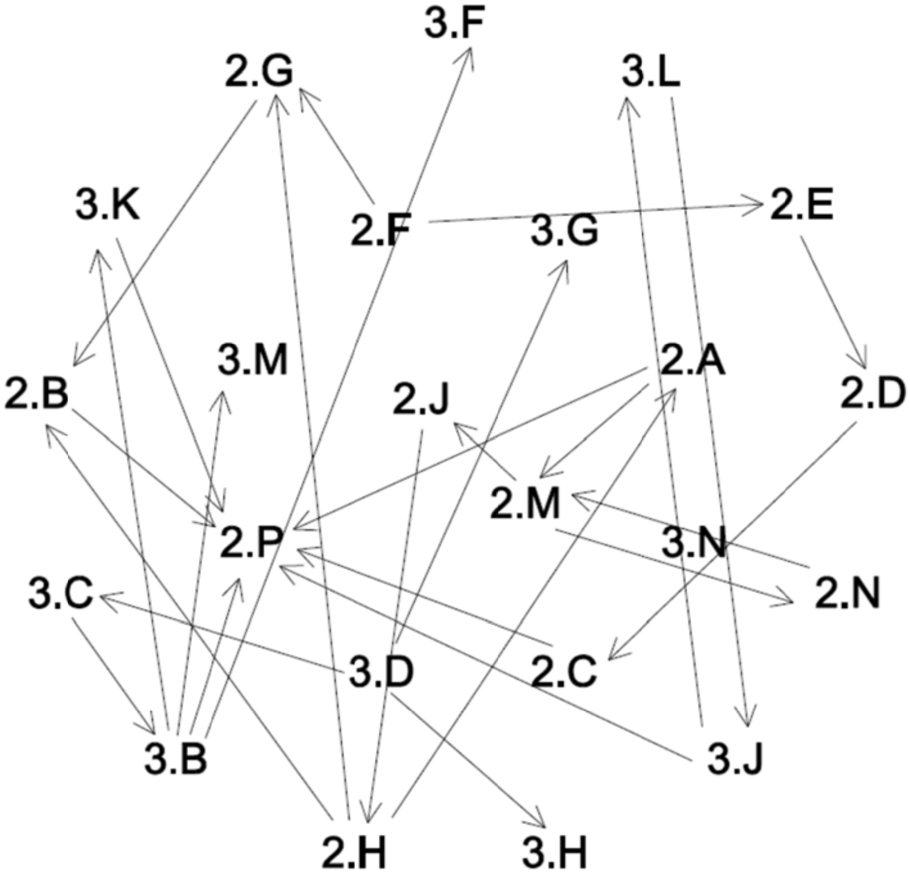
The following labels represent components in the process of assigning dependencies described in this section.

Table 1: Summary of codes and components for foundations, piling and lift pit.

Code	**Component**	**Code**	**Component**
2.A	Contiguous piling.	3.A	2.P
2.B	Mass concrete blinding.	3.B	Lift pit base slab.
2.C	Basecourse fill.	3.C	Hob.
2.D	Sand bed.	3.D	Lift pit wall.
2.E	Vapour barrier.	3.E	2.F
2.F	Basement ground slab.	3.F	Vapour barrier to lift pit base.
2.G	Slab beam.	3.G	Waterproofing membrane.
2.H	Granular fill.	3.H	Waterstop.
2.J	Agricultural drain.	3.J	Granular fill.
2.K	Suspended floor slab.	3.K	Sand bed.
2.L	Dowel joint.	3.L	Agricultural drain.
2.M	Drainage cell.	3.M	Drainage sump.
2.N	Sprayed concrete wall facing.	3.N	Drainage pipework.
2.P	Ground/subgrade.		

The following graph is produced as a result of the modelling procedure so far.

Figure 10: Graph of components for foundations, piling and lift pit.



The following eigenvalue centrality results for values exceeding 0.1 are provided to illustrate the application of an analysis method conducted on the above graph:

Table 2: Eigenvalue centrality of foundations, piling and lift pit components.

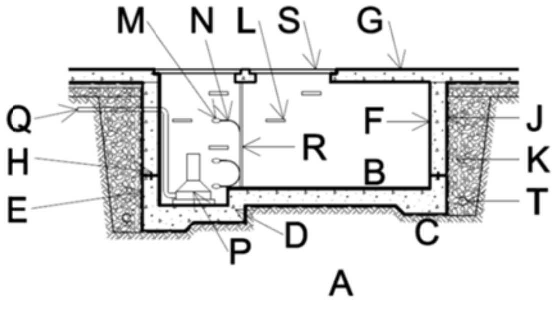
Code	Component	Eigenvalue Centrality
2.P	Ground/subgrade.	1.000
2.B	Mass concrete blinding.	0.383
2.M	Drainage cell to perimeter wall.	0.349
3.J	Granular fill to ground slab perimeter.	0.341
2.J	Agricultural drain to lift pit.	0.275
2.N	Sprayed concrete wall facing.	0.275
2.H	Ground fill to lift pit.	0.214
2.G	Slab beam.	0.175
2.A	Contiguous piling.	0.166

Using a similar method to that described above, further examples are given below.

Pump Out Pit

There are various types of pump out pits in buildings, commonly for stormwater, sewer and fire services. The main function is performed by a heavy duty pump which forces fluid from a low level to a higher level in order to connect with mains and drain away by gravity into the city's infrastructure.

Figure 11: Component dependency overlaid onto section through pump out pit.



A	Ground/ subgrade.
B	Base slab.
C	Slab beam.
D	Slab upturn.
E	Hob.
F	Pit wall.
G	Ground slab.
H	Waterstop.
J	Vapour barrier.
K	Granular backfill.
L	Step rung.
M	Float sensor.
N	Float sensor cable.
P	Pump.
Q	Pump outlet.
R	Power supply pole.
S	Grate cover.
T	Agricultural drain.

In this project, a stormwater pump out pit under the basement ground slab having two pumps is used to collect water from basement floors and pump it upwards and out through the perimeter piling by one or both pumps to a height where gravity drains it to stormwater site mains.

In order to function, the pumps must be surrounded by a certain depth of water, in this case 200mm. To achieve this, pumps are installed within a sump formed by the pit base slab, similar to the sump in the lift pit but larger in a dedicated pump out pit, in the order of 900-1200mm square. Consequently, there is not only a structural dependency from pump to base slab but also one of providing a minimum depth of water with which the pump can operate.

The pumps also depend on three float sensors, each of which triggers a specific response when the water level triggers float switches. The first one is at 200mm and switches both pumps off if the water level is less than 200mm. The second is 300mm above the first and starts one of the pumps when the water level reaches that level until the water level reduces to the 200mm mark. The third is located approximately 450mm above the second float. The third float sensor triggers the second pump so that both pumps are on and activates an alarm.

The alarm consists of a strobe light at the vehicular entrance to the basement. It is powered by a direct connection to the distribution board and battery backup. Statutory signage indicating pump failure is also required adjacent to the strobe light. This demonstrates the seventh convention, that of non-physical dependency. In this case, human interaction forms an essential part of functional dependency. An alarm system alerts people to physically attend to the pump and a sign informs people about the alarm. Though there is no physical inter-dependency between the signage, alarm and pump, the functioning of the pump out pit depends on the alarm and sign for human intervention in the event to overflow, and an architecture is identifiable.

Another example where human interaction is part of the definition of functional dependency between components are the step irons. They have no direct dependency on the functioning of any component in the pump out pit. Functional dependency is directly with humans in that they reduce the risk of injury when accessing the pit without a ladder. In this sense it is an end user component like a washing machine or window, which should depend on at least one other component. Step irons depend on the wall for support. However, no other components depend directly on the step irons for their functioning, which consequently form an end node in the node-link model.

It can be construed that without step irons the speed and ease with which maintenance personnel can access the pit would be reduced and may discourage people from entering the pit, therefore leading to neglect. There is an indirect functional dependency, however weak, from the pumps, alarm and other components, which may need human intervention, to the step irons. This is not considered a strong enough dependency to include in the model because maintenance does not depend as such on the step irons. Access can be achieved with a normal ladder or, depth permitting, without.

Stormwater Detention Tank

In some cases, space restrictions produce the need for a suspended stormwater detention tank instead of the more common in-ground tank. This precludes the need for certain components such as backfill, vapour barrier, excavated pit, whilst requiring others such as waterproofing.

Typically an on-site detention tank has two openings covered with metal grates fitted into rebated openings into the tank. When flush with surrounding pavement these openings are formed in the lid slab of the tank. In the example studied, the tank is covered with a planter, so the inlet openings are formed by tank walls and upstands. Cover grates permit the ingress of water through the penetration whilst enabling traffic over and preventing objects larger than a certain size from falling into the tank and hindering the flow of water or clogging the outlet. Upstands are supported on and, therefore, depend on the tank lid slab which doubles as a planter base. In turn, the tank lid slab is supported by tank walls. Some tank walls perform the dual function of beam and wall, supporting the tank base slab, whilst others are supported by the base slab.

The main outlet depends on an orifice cover plate and a perforated metal screen for proper functioning, that is, to pass on the appropriate water composition. A screen filters out general debris that penetrates the grate and the orifice cover plate filters finer particles. A sump collects water adjacent to the sump such that it can readily drain into it. This depends on a depression in the base slab, surrounding beams and adjacent slab. An overflow outlet controls the flow of water in the event of main outlet blockage. Both overflow and main outlets depend on the wall in which they are formed.

Ladder rungs are necessary to enable accessing the tank internally for maintenance. No single component depends on them directly although the overall functioning of the tank does. The rungs themselves depend on tank walls for support.

Structural Columns

A column on the lowermost level depends structurally on the pad footing on which it sits, which in turn depends on the ground and potentially a pier under. Upper columns depend on the floor slab and column, beam or wall under. In this case, starter bars may be considered separate components because other components depend on them directly.

Structural Walls

Similar to a column, a structural wall on the lowermost level depends on a supporting strip footing, which in turn may depend on a run of piers. Upper walls and roof may depend on walls and columns under, potentially also beams. Starter bars are also required for concrete walls and may be considered separate dependency nodes because although they are cast into a concrete component, they are configured not according to that component but according to the walls they are associated with. Hence, they are an intermediate element, which can be considered separately, particularly as their proper setout and timing of placement needs to be coordinated.

Staircase

A staircase may be considered one component including flights and landings, which depends on support under and above. The lowermost staircase depends on a footing under. Staircases on upper levels depend on the floor slab and beam for support at top and bottom of the staircase. If flights and landings are considered individually, the lower flight depends on the footing and landing. The landing depends on the lower flight and upper flight, and the upper flight depends on the landing and the slab above.

The functioning of a staircase also depends on a void or absence of floor above. The function of a void in a slab over a staircase relates to human use of the staircase. Without the void, a staircase is useless because the stair flight and the upper floor being served by the staircase are inaccessible. This raises the question of whether a void should be considered a node component in this model. The conclusion drawn here is that it should, thereby illustrating the sixth modelling convention.

To explore the rationale behind this conclusion, consider two alternative configurations of a staircase from one floor to another, one incorporating a void in the slab, another not requiring a void because there is no slab over. The void in the first configuration is a morphological feature of a physical component, the floor slab, not a physical component itself. However, without the void, configuration one is not functional. Component two is functional without the void. The two configurations are two architectures, one of which requires the void. Consequently, the void must be an architectural component.

Roofing, Roof Plumbing & Framing

In this project the roof is designed as a steel-framed roof with steel sheet roofing. Analogously to walls, areas of roofing rather than individual roof sheets are designated as node components. Roofing sheeting is fixed onto purlins, which are fixed onto rafters, which are fixed directly to concrete walls or columns or to steel beams, which are in turn fixed on to concrete walls or columns. Ridge cappings are considered separate components,, which depend on adjacent roof areas. Similarly, flashings which may also depend on walls.

A gutter depends on a fascia to which it is affixed and downpipe outlets into which water drains. A downpipe depends on a gutter outlet, the supporting wall or column and a sump or connection to a drainage pipe. Downpipes penetrate through the ground slab and feed into suspended pipework in the basement level, leading to the first flush system and then into the rainwater tank.

At this point another modelling principle is introduced, that various types of dependence can be identified but that functional dependence is the main concern. For example, between a gutter and area of roof there needs to be a spatial relationship in order for water to drain into the gutter. There is also a quantitative relationship between the roof area and cross-sectional area of the gutter. In isolation a gutter can function to drain water irrespective of whether a roof exists or not as long as it is held in a particular way and can adequately discharge water.

Insulation

Insulation is an end-node component. A roof insulation blanket depends on a support mesh to keep it in place as well as roofing sheeting and sarking to protect it from the weather. Similarly, roof sarking depends on the insulation on which it is laid and, to a lesser degree, protection by roof sheeting. Insulation batts in external walls depend on stud wall framing or cladding support framing for support and on sarking and external cladding for protection from the weather.

Herein is another example of design dependency. Wall insulation may be considered to have design dependence on the internal wall lining and wall cavity in order for the wall to provide the required insulation value (R-value). However, for the insulation component itself to perform its own insulation function it does not depend on the wall lining or cavity, it just depends on whatever secures it in position.

Rainwater Tank & External Water Supply

In the subject project, water is collected from the roof and stored in a tank for supply to outdoor hose taps and irrigation. The supply of rainwater from the tank is supplemented by the general cold water service. An automatic changeover device manages the sourcing of water between rainwater tank and main cold water service. The collection of water into the rainwater tank is via a first flush diverter, which filters out undesirable material from rainwater which, being collected externally, carries suspended material.

Water incident on the roof runs off the roof sheeting and is collected in gutters, which drain via outlets into downpipes, which in turn connect to suspended pipework in the basement level, which connect to a dropper feeding into a first flush diverter within a plant room. Rainwater pipework from the first flush diverter drains filtered water into the rainwater tank. A submersible pump pushes water out from the tank, through a changeover device and into a reticulation system consisting of risers and horizontal pipework terminating in hose taps and irrigation points.

The changeover device consists of various valves and electrical controls. Rainwater pipework from the tank passes through a check valve followed by a T-junction where the cold water service line is connected whereby a lack of supply from the tank is supplemented with water from the cold water service if necessary. This is controlled by means of a float valve within the rainwater tank, which is wired to a solenoid valve along the cold water service line, which passes firstly through an isolation valve, then a double check valve, then solenoid valve and finally another isolation valve before reaching the T-junction with the rainwater supply line from the tank.

In addition to internal dependencies between equipment, pipework, wiring, etc., each component depends on a structural element for support, whether engineered such as a floor slabs or secondary structures such as non-load-bearing walls and penetrations within them. In some cases, pipework between the first flush diverter and tank may span between equipment.

Domestic Cold & Hot Water

Horizontal pipework at each level, connected to a main riser, feed a strata point at each unit. Internal reticulation pipework within each unit connects tapware to the strata point. This pipework is fixed mainly to walls.

Risers are fed at street level by horizontal pipework, which passes from the connection to the city mains through a site isolation valve within a cast-iron path box, then through a service meter and onto the risers. This pipework is either within backfilled trenches or above ground suspended between two droppers.

Hot water is provided by gas fired water heaters. Each hot water heater depends on cold water supply, gas supply, power supply, a pump, an exhaust flue, return hot water, concrete base plinth, isolation valve, non-return valve, pressure limiting valve and relief valve. Tempering valves within units control water temperature. Hot water equipment is supported on concrete plinths.

Pipework from hot water heaters connect the heating equipment to unit reticulation pipework and hot water taps. Hot water pipework from heaters as well as cold water supply pipework from risers is suspended under the slab over a level or fixed to walls and concealed with bulkheads, ceilings, soffits linings and wall claddings.

Fire Hydrants

Water supply pipework for fire hydrants is initially taken off the domestic supply main before the meter. From there, it passes through an isolation valve, double check/reflux valve, booster valve assembly, then directly to two hydrants at street level and subsequently to risers which feed other levels. At each level, pipework from the riser connects directly to a hydrant.

Fire Sprinklers

Water supply for sprinklers depends on a separate connection to the city main supply. Pipework passes through a site isolation valve and then to a booster valve assembly and alarm within the hose reel cupboard at each level. From the booster valve, assembly pipework connects water supply to a sprinkler head above each window.

Gas Supply

Similar to water supply, gas pipework connects to city mains, then passes through an isolation valve, meter and riser feeding each level from which horizontal pipework connects the riser to service fixtures. However, in the gas supply system there is a separate meter and riser for each apartment. Fixtures requiring gas service in the design data reviewed are hot water heaters, air-conditioning units and BBQs.

Sewer

The sewer system drains soiled water from sanitary fixtures, internal floor wastes and tundishes into the city sewerage system. Sanitary fixtures are the end nodes in the sewer drainage system just as taps are end nodes in the water supply system, thus the points at which two systems converge.

The kitchen sink functions to contain and drain water issued from the kitchen sink taps. The sink is connected to a trap connected to a dropper which penetrates the floor slab and connects with horizontal pipework leading to a vertical riser which is connected to sub-floor pipework, ultimately to site mains and external service mains. Pipework carries water from the main site connection in the ground via a trench to a riser within the building. From the riser supply reticulation takes cold water directly to the cold water tap and into the hot water system which is connected to the hot water tap. Similarly, most sanitary fixtures such as laundry tubs, showers, bath tubs, basins, washing machines and dishwashers drain into a trap, then a dropper connected to horizontal subfloor pipework leading to a riser, which carries the fluid down to the external reticulation system leading to the connection point with city mains.

A trap provides a barrier against the backflow of sewer gases and depends on a vent pipe further downstream, which prevents flow pressures from siphoning water out of the trap and rendering it defunct. A trap is associated with every sanitary fixture and a boundary trap near the connection to city mains provides an initial barrier for the entire site. A toilet pan has an integral S or P trap which feeds into a sewer drain pipe, which feeds into a riser, which in turn feeds into a site main. Cold water is supplied to the cistern via a cistern tap and pipework.

Floor wastes and air-conditioning tundishes require drainage but no direct supply. The air-conditioning system is supplied with water. They rely on a trap, similar to sanitary fixtures, and are part of the sanitary fixtures drainage system, sharing the same vent stacks and risers.

Stormwater

The stormwater system consists of various types of drainage outlets connected by mainly subsoil pipework leading to a silt arrestor pit, which is connected to the stormwater main. Drainage outlets drain water from pavements, planters, balconies and terraces. The rainwater tank also drains into a stormwater drainage pit. Drainage pits are precast concrete and channel drains in-situ concrete. Their dependencies are the ground, inlets, outlets and cover grate.

The balcony waste outlet utilised in the subject project is a proprietary bottle trap connected to a gully trap with pipework cast into the floor slab. The gully trap is near a downpipe to which it is connected with an s-junction.

The silt arrestor is a large pit, similar to drainage pits but with some additional components. An energy dissipater reduces water velocity. Weep holes drain excess water into a basecourse of granular fill under the pit. A metal trash screen filters outgoing water prior to leaving the pit. Subsoil pipework carries outgoing water from the pit into the stormwater main.

Planters

The mulch topping is defined as the end node, which depends firstly on soil fill having the dual function of providing moisture and nutrients whilst draining excess water. Adequate draining depends on a sand bed to act as the first line of filtering, followed by geotextile fabric as a fine filter. Water filtering through the fabric then either passes into the drainage cell directly or runs down the wall membrane and into the drainage cell which directs the flow of water into the drainage outlet. This depends on the waterproof membrane to contain water within the planter. Planter base and bounding walls also depend on the membrane in order to keep water out of the base and walls themselves. The membrane depends on a protection board, which prevents sharp aggregate or plant roots from damaging the membrane.

Concrete planter walls not integral with the slab depend on a waterstop to stop water from penetrating through the pour break. Block planter walls depend on a bond breaker for block walls, which permits the membrane to be continuous over the joint between block and concrete hob under by preventing fracturing of the membrane due to differential movement between concrete and blockwork.

Balconies, Terraces & Wet Areas

The end nodes associated with balconies are paving tiles and floor wastes. A balcony or terrace area including pavers and grouting is considered a node component, not individual pavers. Floor wastes are covered in the previous section. The function of balcony and terrace paving is to provide a trafficable and habitable floor surface. A secondary function is to drain rainwater incident on the balcony into an outlet connected to the stormwater system.

In order to achieve its functions, balcony and terrace paving must be laid to falls. This is achieved with bedding mortar. As pavers and mortar are porous materials, water penetrating them must be contained and directed into the drainage outlet. This is achieved with a waterproof membrane installed on the balcony or terrace floor and continuous skirting around its perimeter. In effect, a balcony or terrace is constructed as a shallow waterproof tank. This may require building up a hob with concrete, blockwork or other means, or incorporating a step in the slab. A flashing angle or other bond breaker is installed around the perimeter of the balcony or terrace over which the waterproof membrane is applied and upon which the integrity of the membrane depends.

Wet areas, in this case internal bathrooms, are similar. Instead of pavers, tiles are laid over a mortar bed graded to falls over a waterproof membrane, which extends to a degree onto bathroom walls such as behind the skirting, shower and basin. The membrane is usually of a different type than the balcony membrane, typically applied in liquid form. External membranes are typically sheet membranes made from reinforced bituminous polymer material torch applied directly onto the concrete substrate.

Power Supply

Power supply to the building is via the main switchboard, to which all distribution boards and devices are connected. The main switchboard in turn depends on the connection to the site mains cable, which is connected to the external service mains. A service protection device is installed between the main switchboard and service main connection in order to protect the site from a surge in the grid.

A distribution board in each apartment is connected with a submain cable connected to a meter via an isolator. A relay coil is installed between the meter and the main switchboard. Similarly, house supply is via a relay coil and metering transformer. An isolator serves all house boards except the passenger lift supply cable, which is taken off separately before this isolator, after the meter and has a separate isolator on the submain.

The house lighting submain has one isolator in addition to the main isolator. Similarly, submains to fire stairs, driveway/garage common areas, external lighting and landscaping, house power points, mechanical control panel and car lift. Submains to driveway/garage common areas, external lighting and external landscaping have two isolators. The emergency lighting submain is taken off the submain to the fire stair/ 24hr board.

The distribution board in each apartment contains circuit breakers for the various strata circuits and direct connections – lighting, power, oven, microwave, fridge, range hood, blinds, storage and garage lighting, security panel/smoke detection, audio visual rack, air-conditioning and car turntable. All these circuits and direct connections depend on the unit distribution board and consequently so do the appliances, fittings and equipment which they serve.

Communications & Intercom

The telephone communications system relies on a series of splitters and switches. The telephone company's line feeds initially into an MDF unit which splits it into a main line for each apartment which connects to a distributor within each apartment, which splits the line again into separate cables that feed into a patch panel within the same cabinet. One of the lines passes through an ADSL filter, which splits out an ADSL line for the modem and computer network switch. From the patch panel, telephone lines feed into a PABX, which maps lines to phones within the apartment.

The intercom system consists of a gate station, which leads into a floor distributor from which splits the line from the gate station into separate apartment lines, each of which feeds into the PABX in an apartment and from there to the intercom station.

The MDF resides within a dedicated service cupboard in the common areas, supported on a rack, fixed to the back wall or floor mounted. Similarly floor distributors, patch panels and PABX are housed in a dedicated cabinet within a cupboard in each apartment. Similar to power supply cables, communications cables are fed through conduits, which are fixed to cable tray, cable ladders or directly to walls.

3.3.2. Design Data Model

In the previous section, a set of conventions was proposed for the 'networkification' of building components in terms of their functional dependency. In this section, the same is proposed for design data. Again, the guiding principle is interdependence of function, which, in terms of design data being an information system, involves cross-referencing.

Design data consists firstly of packages by discipline – architectural, structural, electrical, etc., each of which in turn consist of drawings, text documents (specifications) and tabulated data (schedules). Drawings are organised onto sheets with title blocks. Specifications are bound into a book format with chapters, that is, trade sections. Schedules are tabulated and bound as appendixes to the specification documentation or issued as a separate document. Some specifications and schedules may appear on drawing sheets and some drawings may appear in specification appendixes.

As a building is a complex three-dimensional artefact represented by two-dimensional graphical and alphanumeric data, cross-referencing is required between the various design data components. Various types of cross-referencing can be identified, arising from various types of interdependency within design data components. Design data, in a sense, must form a cohesive whole just as a building is a cohesive whole.

The message or concept a design data component is intended to convey is not complete without making reference to another design data component. That is, its function is not fulfilled without further clarification or being read in combination with another data component. This need not involve literal representation or reproduction of the referenced data component, only the reference. For example, "refer engineer's details for footing requirements" – in this case a general reference to "engineer's details". A cross-reference may also be specific to a particular detail. For example, "refer drawing 1 on sheet S06".

Another type of cross-referencing is where a design data component partially comprises literal content or reproduction of content from another data component. An example of this between text components is a citation – text is inserted verbatim into another text within quotation marks. Similarly, a background drawing to another drawing is a form of cross-referencing. Likewise, depicting the overall outline of an element and cross-referencing parts of it elsewhere to a blown up version showing more detail.

Having established a basis for linkage, the definition of design data components, the nodes in the network, presents two initial possibilities – whether a design data node is a page within a document or a drawing or chapter/section within a document.

It is possible to define a node as a design package and only consider cross-referencing between packages. For example, a note on a drawing in the architectural package refers to a detail in an engineering package – the two packages are nodes and a link is established between them by the cross-reference. This is discarded because only the ex ante part of design data would feature, thereby precluding the need for modelling.

Similarly, the possibility of defining documents within packages as nodes – a set of drawings, a specification document, schedules – is discarded would produce a very small network with multiple sub-linkage embedded within single links.

Another option is that pages within documents are nodes. The problem here is that the composition of pages is unrelated to the structure of content. If a designer chooses a larger page size, then more drawings and information can fit on each page than in a smaller format, depending on the scale of the project, but in principle, this rules out pages because we are interested in the structure of content not on a superstructure related to format.

Having ruled out what might arguably be described as the first three tiers in the overall structure of design data, the next level of content is where components are defined. That is:

1. Individual drawings and blocks of specifications, notes and schedules within drawing sheets.
2. Trade sections within the package specification documents.
3. Individual schedules – external finishes schedule, internal finishes schedule, door schedule, door hardware, etc.

The question remains on whether to go to the next level – individual clauses in the specification, individual annotations within drawings, single lines in the schedules. This is discarded because of the potential to lead to data distortion. For example, there is no standard for the extent or method by which drawings should be annotated. Some designers use very few notes on drawings, whereas others are quite verbose. Similarly, although there are standard formats for specifications, there are several in use within the industry and the degree to which they are customised varies greatly between designers. There is potential for excessive duplication as much text on drawings are repeated between drawings.

Systemic Discrepancies

The proposition of design data architecture serving as a proxy for design organisation architecture is not investigated in this thesis but may be a possibility in future investigations. A potential for discrepancy is foreseeable where organisational interactions are not embedded in design data or design data dependencies are not captured in organisational interactions (Cabigiosu and Camuffo, 2011). These are briefly discussed below.

At the design data component level, design team interaction is subject to discrepancy. For example, some important interactions between teams involve data exchanges early in the design process which are eventually embedded in the final data but may be encapsulated in an obscure note on a drawing or not represented as a cross-reference at all.

A notable example is the design of structure. In building construction and increasingly in some types of infrastructure projects such as bridges, basic parameters are initiated by the architect because they are derived from the initial layout and concept. For example, the outline of floors, the levels of floors, and positioning of vertical structures (walls, columns and staircases). This is typically embedded in design data in the form of notes on the engineer's drawings such as: "Refer Architect's drawings for steps, falls and levels", "Verify all setting out dimensions with the Architect" and "All set out dimensions and levels, including those shown on these drawings shall be in accordance with the Architect's drawings and verified on site". In general, a dependency link exists by default between engineers' layout plans and the architect's floor plans. In the case of electrical, mechanical and hydraulics engineers, the architect's floor plan is usually referred to by literal inclusion as a background. The reason for this is that these defining geometric parameters, dimensions, shape, levels, etc. are not derived on engineering criteria but have to do with the use, positioning and size of space, circulation between space, planning authority requirements, relationships between interior and exterior, etc., which the architect synthesises into a floor plan that is subsequently engineered for loads and other engineering criteria.

In some cases, no cross-referencing may be present at all but team interaction must be inferred by the nature of the content and of the design process. For example, where there are non-conventional materials or systems. Although structural materials and systems are engineered by a structural engineer, the selection of which ones to use is the domain of the architect because it relates to the aesthetics and spatial conception. In many cases, this is a matter of industry practice. For example, the lowermost floor of a building, including houses, is invariably a concrete slab. However, the architect might decide on whether it is to be a waffle slab, raft slab or infill slab. The architect's concept may call for steel columns instead of concrete for example. In general, beyond the requirements of statutes, industry practice or economics, there is often still a choice of system and material, which an architect may decide on. Even when not exposed, where the engineer may decide on system selection, requirements of height or span imposed by the architect would frame the decision.

Another example is where structural elements are exposed to view. Unless an exposed structural element is within a plant room, car park or other "back-of-house" area, any exposed structure will have been intended to be exposed by the architect and therefore be evidence for design data exchange because, in those cases, structure is inextricable with aesthetic.

On the other hand, cross-referencing between design data may not be evidence of design team interaction.

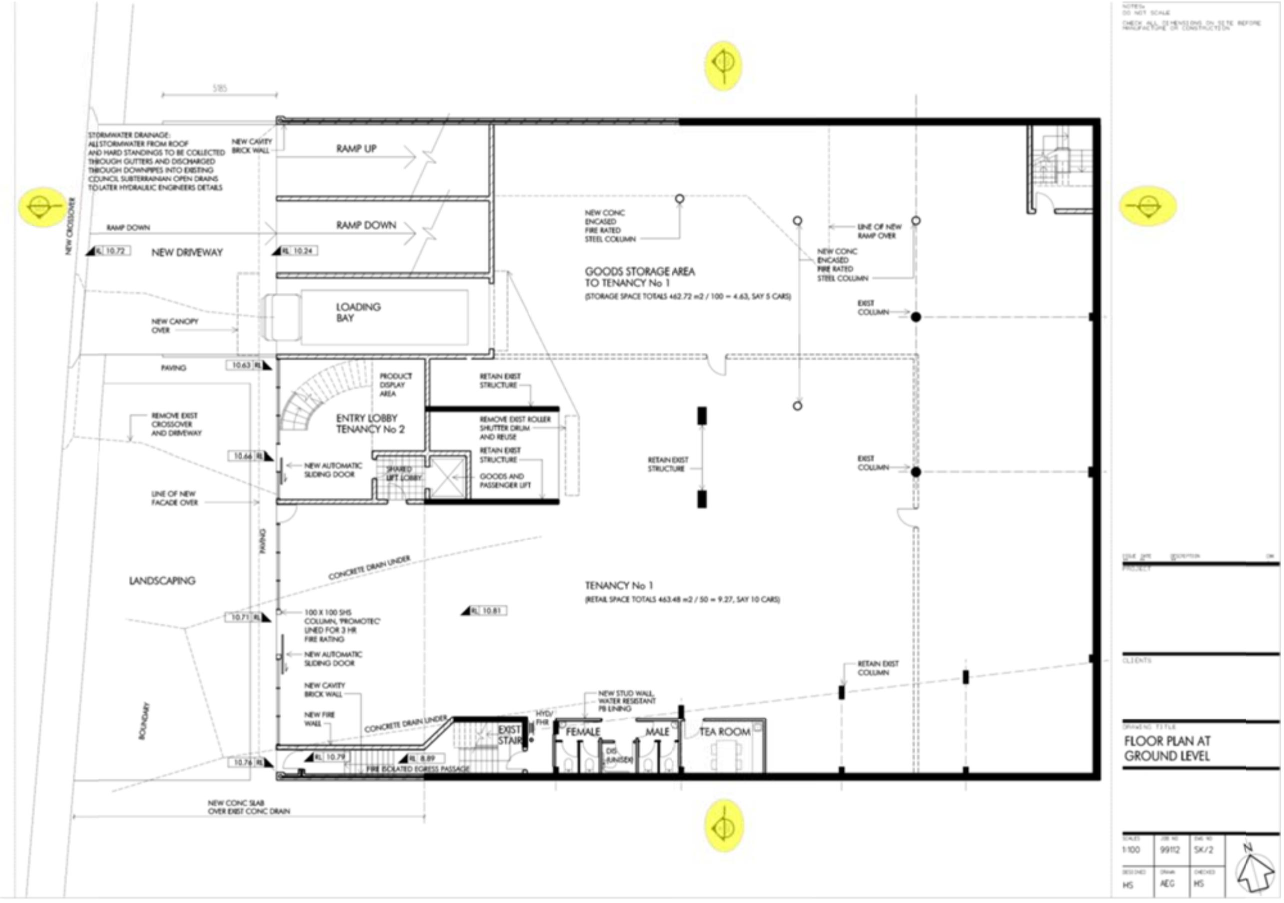
For example, a mechanical drawing that has a note that reads, "smoke detector within duct to electrical engineer's requirements", need not be accompanied by any interaction between mechanical engineer and electrical engineer if there is no direct exchange of drawing between them. The mechanical drawing might be issued to a third party charged with the role of design coordination, such as a design manager or project manager, who would reissue the drawing to the electrical engineer. The interaction would, in effect, be via a coordination agent and no interaction would occur between the two engineers. Even without a third party design coordinator, there may be no interaction if it is something that occurs by default or required by statute. In the case of the smoke detector, the mechanical engineer knows that it is required in that case and that it needs to be referred to the electrical engineer. As far as their scope of work is concerned, the mechanical engineer has fulfilled it by including the note in the drawing and does not have to actually inform the electrical engineer. Similarly, the electrical engineer knows that a duct of a certain size under certain circumstances needs a smoke detector and will know to include it in their design data. There is an established pattern which precludes the need for interaction. On the other hand, a direct interaction might nevertheless occur in a general design meeting with both engineers present.

3.3.3. Examples

Example 1

In this example, a cross-sectional drawing is referred to from a plan drawing.

Figure 12: Example of design data linkage mechanism highlighted – 'call-out bubbles'.



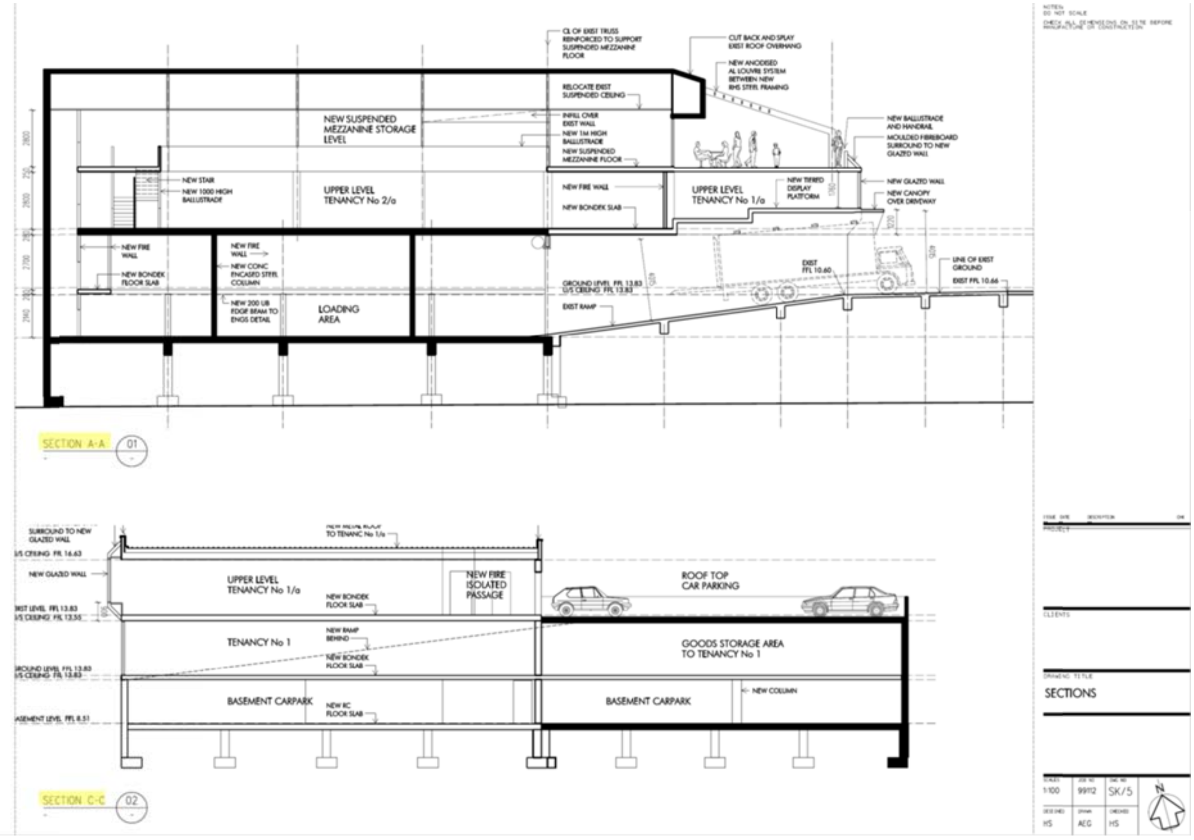
Following is a blow up of the call-out symbols highlighted in the floor plan above.

Figure 13: Detailed view of call-out bubbles.

Following is the sectional drawing referred to. Notice the sheet number (SK5) and section labels (A and B).

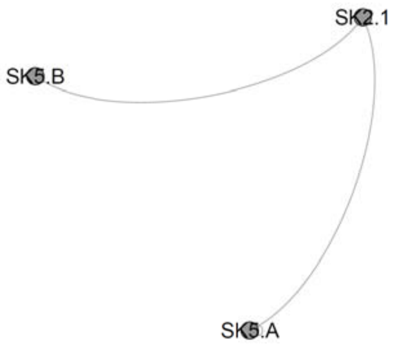
In this case, section labels are referred to instead of drawing number (01 and 02).

Figure 14: Drawing titles associated with call-out bubbles.



The following node relationships are generated.

Figure 15: Graph of design data linkage.

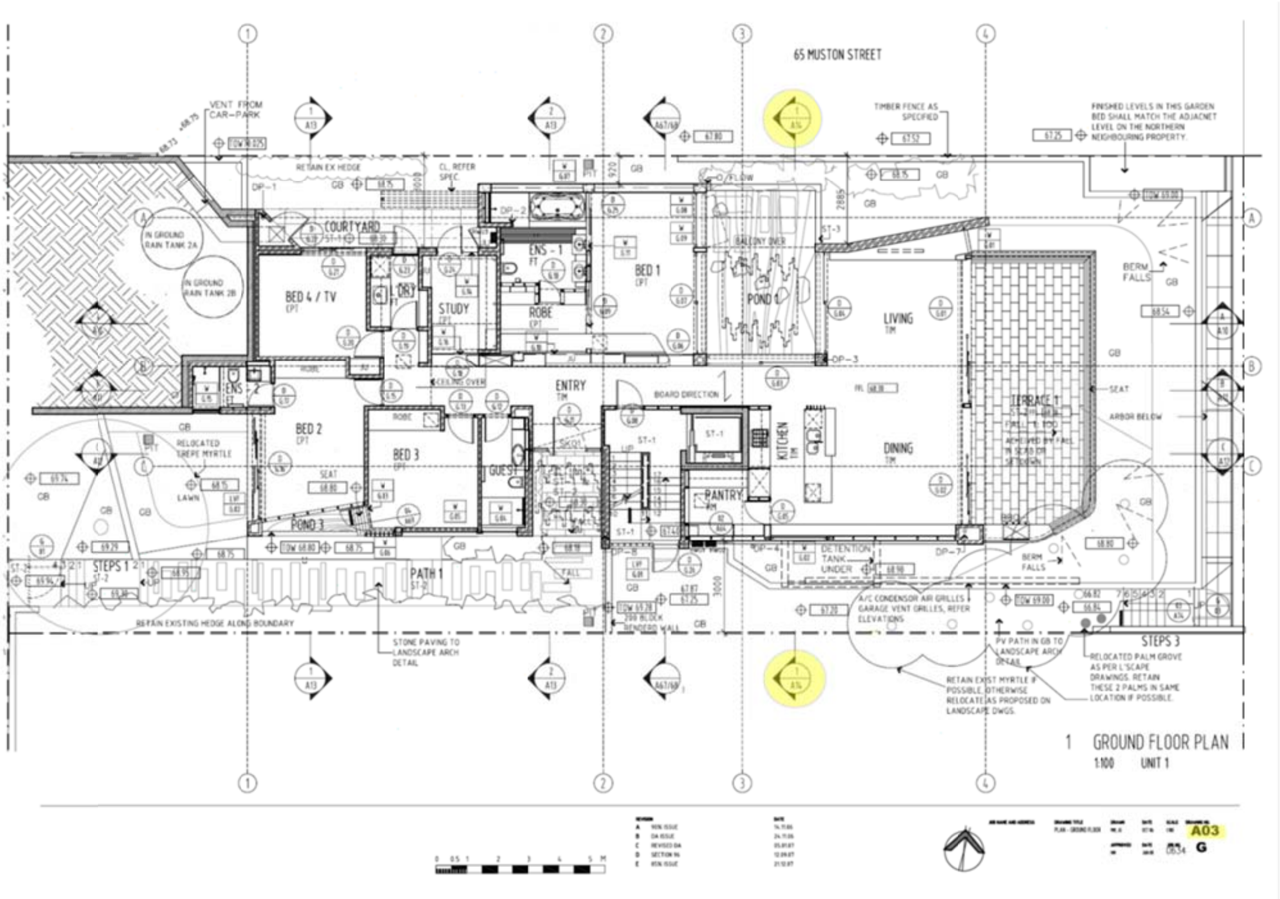


Example 2

In this example, a cross-sectional drawing is referred to from a floor plan drawing, as in the example above.

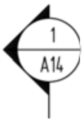
In turn, a detailed drawing is referred to from the overall cross-sectional drawing. Following is the floor plan:

Figure 16: Design data linkage mechanism example 2 – call-out bubbles highlighted.



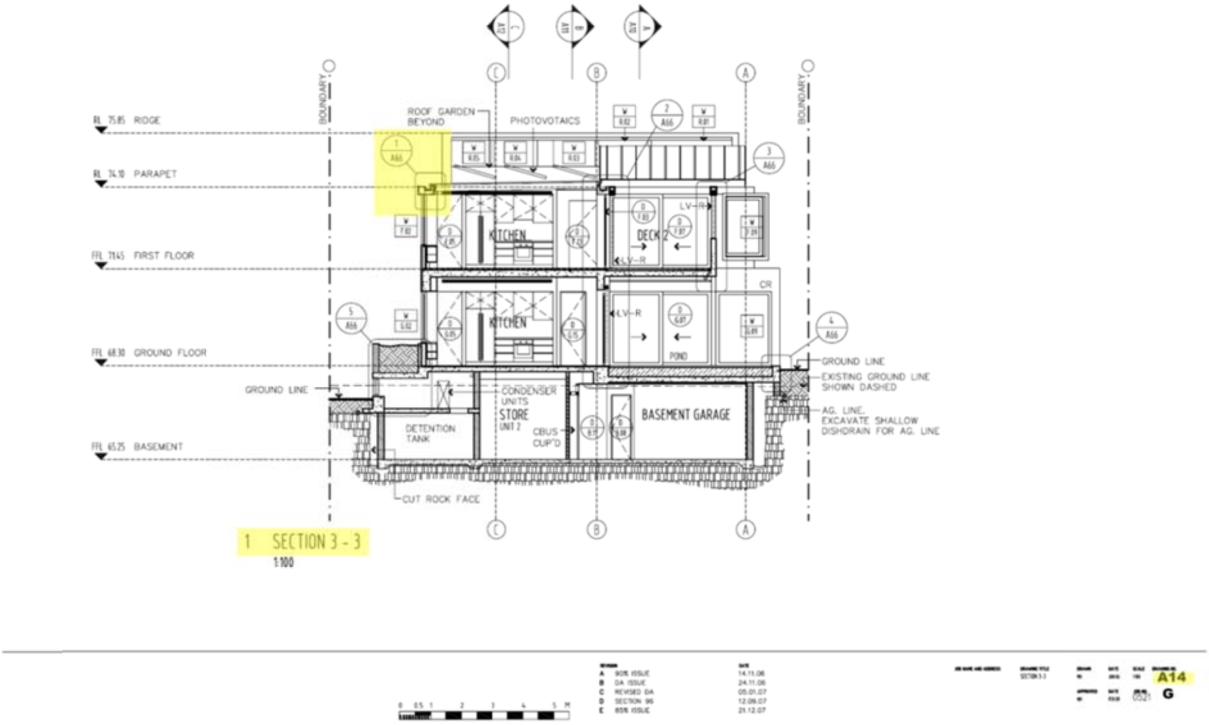
Following is a blow up of the call-out symbols highlighted in the floor plan above.

Figure 17: Design data linkage mechanism example 2 – detailed view of call-out bubble.



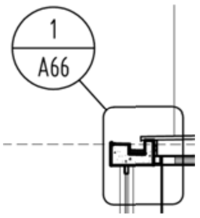
Following is the sectional drawing referred to. Notice the sheet number (A14) and drawing number on the sheet (1). It is section 3-3 but drawing number 1 on the sheet.

Figure 18: Target drawing of example No. 2 and highlighted second tier call-out bubble.



Following is a blow up of the call-out symbol highlighted above.

Figure 19: Detailed view of call-out bubble referring to detailed drawing.



Following is the detail referred to by the above drawing. Notice the drawing number (A66) and drawing number (1) on the sheet.

Figure 20: Final target in example No. 2 linkage sequence – detailed drawing of roof to window junction.

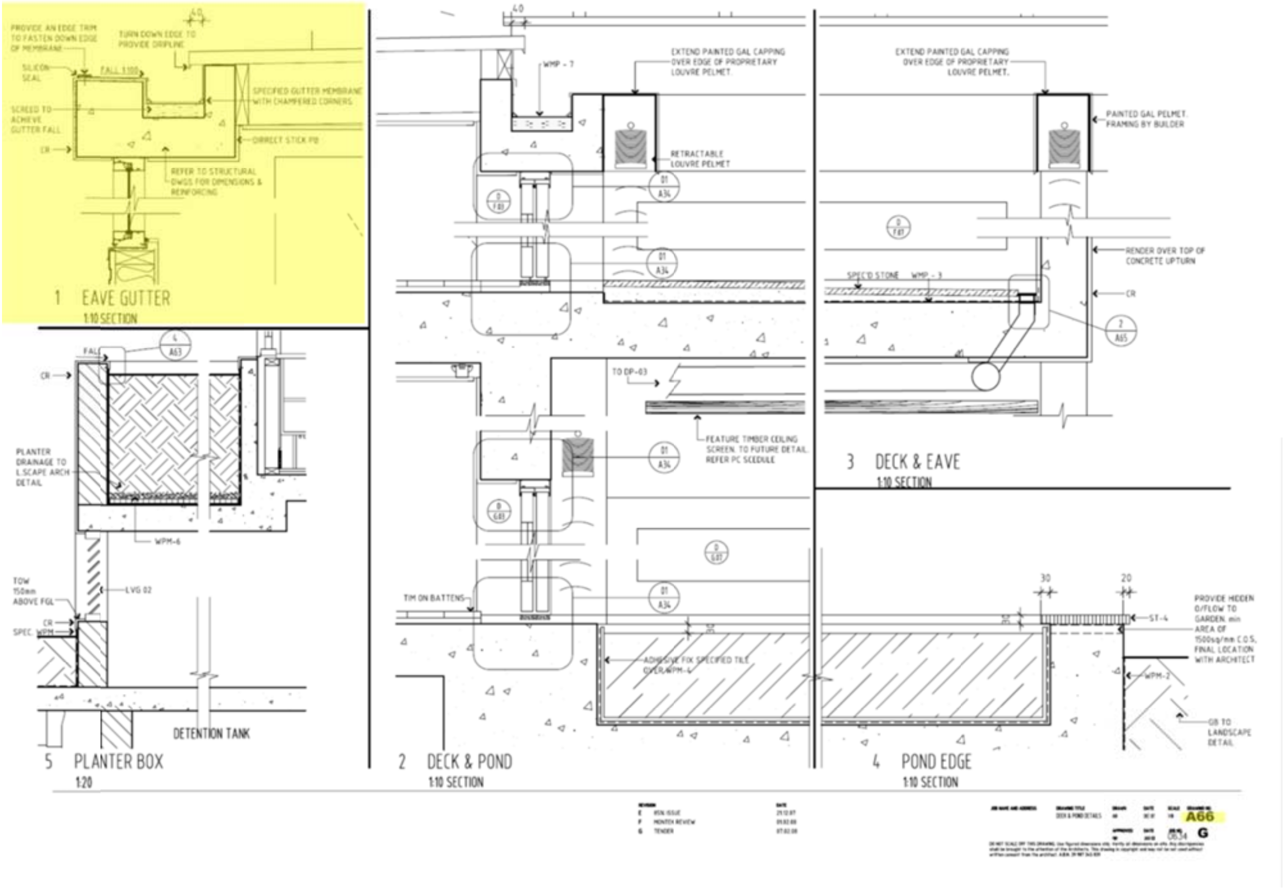
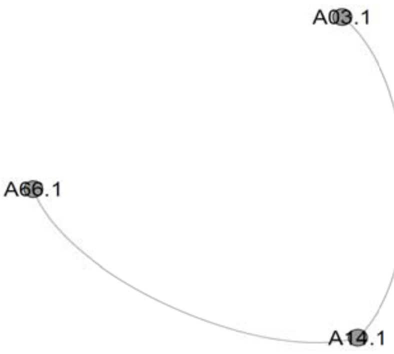


Figure 21: Graph of design data linkage example No. 2



Example 3

The floor plan, finishes schedule and specification are interdependent in the definition of a vinyl floor covering. Floor finish types are designated to areas on the floor plan by the use of single word or short labels such as “Vinyl”, “Floor Tiling”, etc. In the finishes schedule, specific products are designated to particular rooms and a core set of specifications are given, typically, the manufacturer, product and basic parameters such as colour and thickness. In turn, the specification provides further details on installation, associated standards, procedural and contractual requirements for the type of finish. In this case, the specification is a standard format applying to vinyl flooring generally.

Example 4

This example is a variant on the previous one defining a vinyl floor covering component. Similarly, the floor plan, schedule of finishes and specification are interdependent in the definition of the component. This time, instead of a generic label, a unique code identifies the floor covering. Again, a line in the finishes schedule defines basic specifications such as manufacturer, product, colour and thickness. However, in this case, the finishes schedule need not designate rooms to types of vinyl floor covering because each type has a unique code, each of which is shown on the floor plan where they apply. In this case, the specification may contain a dedicated clause to each code as well as general clauses applying to all vinyl flooring types.

Example 5

The architect’s floor plan is reproduced as a background in engineering plans, each of which show a particular system on the subject floor of the building such as power and data points, lighting, security, drainage and water supply.

Example 6

An architect’s floor plan and the corresponding engineers slab plan. As explained above, although the engineer may omit the architect’s background drawing, dependency must be inferred because of various defining parameters: level, grids and geometry. A note referring to the architectural floor plan is often found somewhere amongst the engineer's specifications.

Example 7

A general reference is made to engineer's drawings and a general reference is made from engineer's drawing to architect's drawing. As explained above, these are not necessarily evidence of communication because they are standard requirements that are well known and routinely implemented.

4 Results

4. Results

4.1. Network Models

The components network model has 2061 nodes and 3109 edges (0.001 density).

The design data network model has 651 nodes and 1678 edges (0.008 density).

The following visualisations are generated with Netdraw.

Figure 22: Model Visualisations

Visualisations by Netdraw - Borgatti, S.P., (2002). NetDraw Software for Network Visualization. Analytic Technologies: Lexington, KY..

Two models constructed as node-link networks according to the methodology described in the previous chapter are analysed and the results presented in this chapter. The first model, referred to hereafter as the "components model", "components graph", "components network" or "components matrix", represents the functional dependency between building components in the subject project. The second model, referred to hereafter as the "design data model", "design data graph", "design data network" or "design data matrix", represents the functional dependency between design data components.

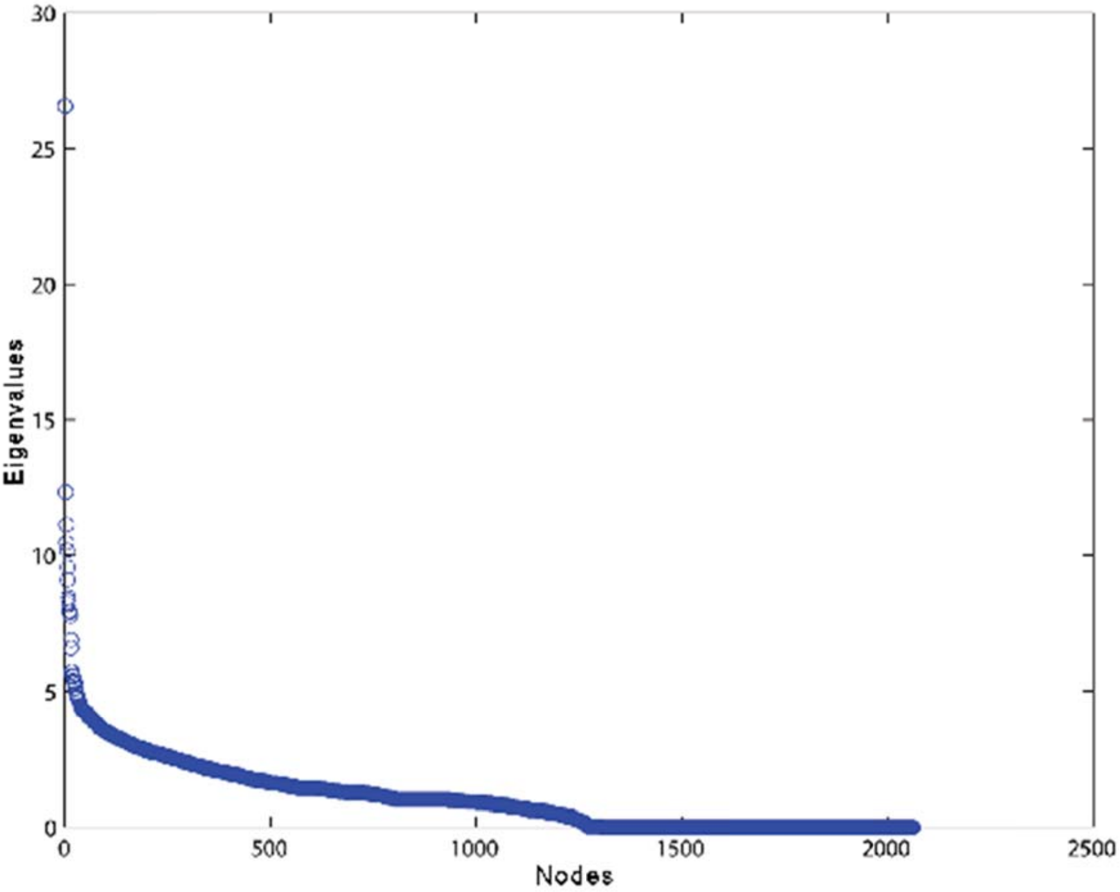
In this thesis, the term 'topological' properties refers to centrality and other structural measures and does not include 'modularity'. In the literature this definition varies and may include modularity.

4.2. Components Model

4.2.1. Spectral Analysis

The following chart shows modularity spectra of the components network.

Figure 23: Spectral graph of components models.

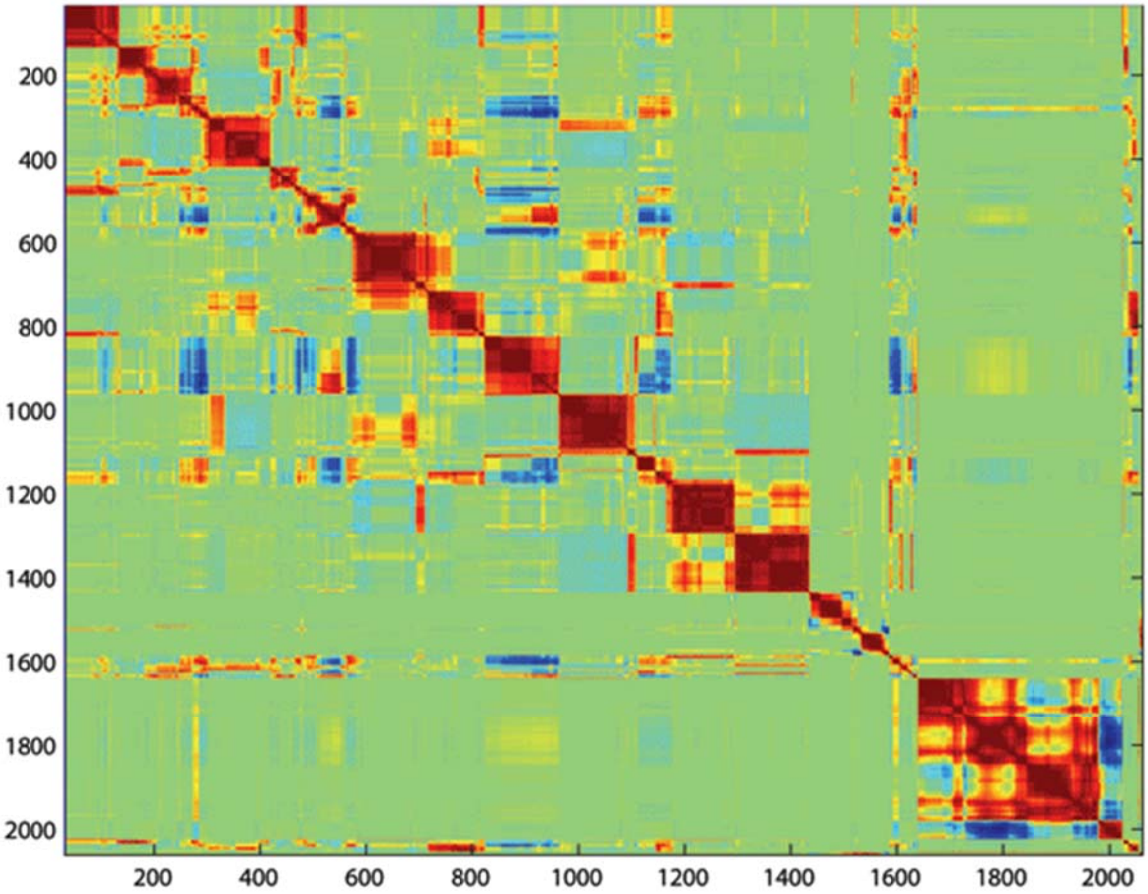


Refer Sarkar et al. (2014) for algorithm.

4.2.2. Reordered Cosine Angle Matrix

The following chart is a reordered cosine angle matrix of the components network. Darker colours represent greater cosine angles which correspond to stronger edge relations.

Figure 24: Reordered cosine angle matrix of components model.



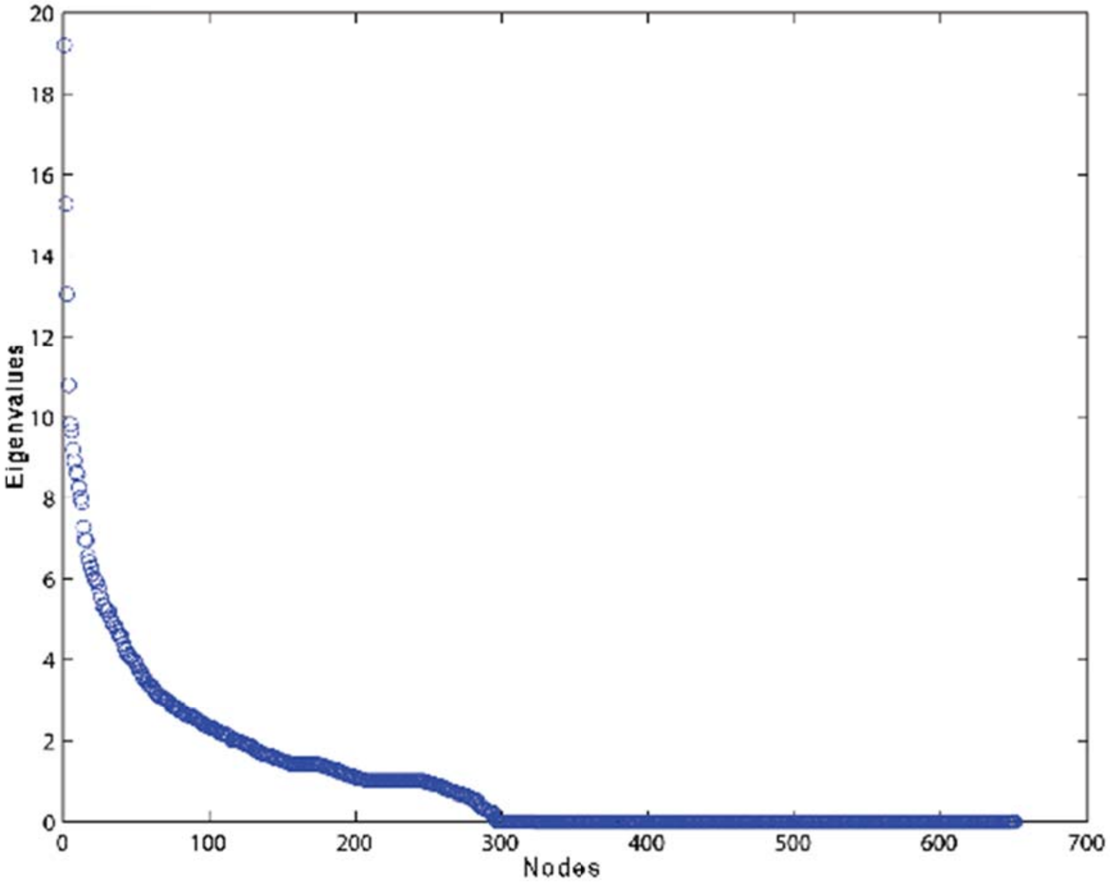
Refer Sarkar et al. (2014) for algorithm.

4.3. Design Data Model

4.3.1. Spectral Analysis

The following chart shows modularity spectra of the design data network.

Figure 25: Spectral chart of design data model.

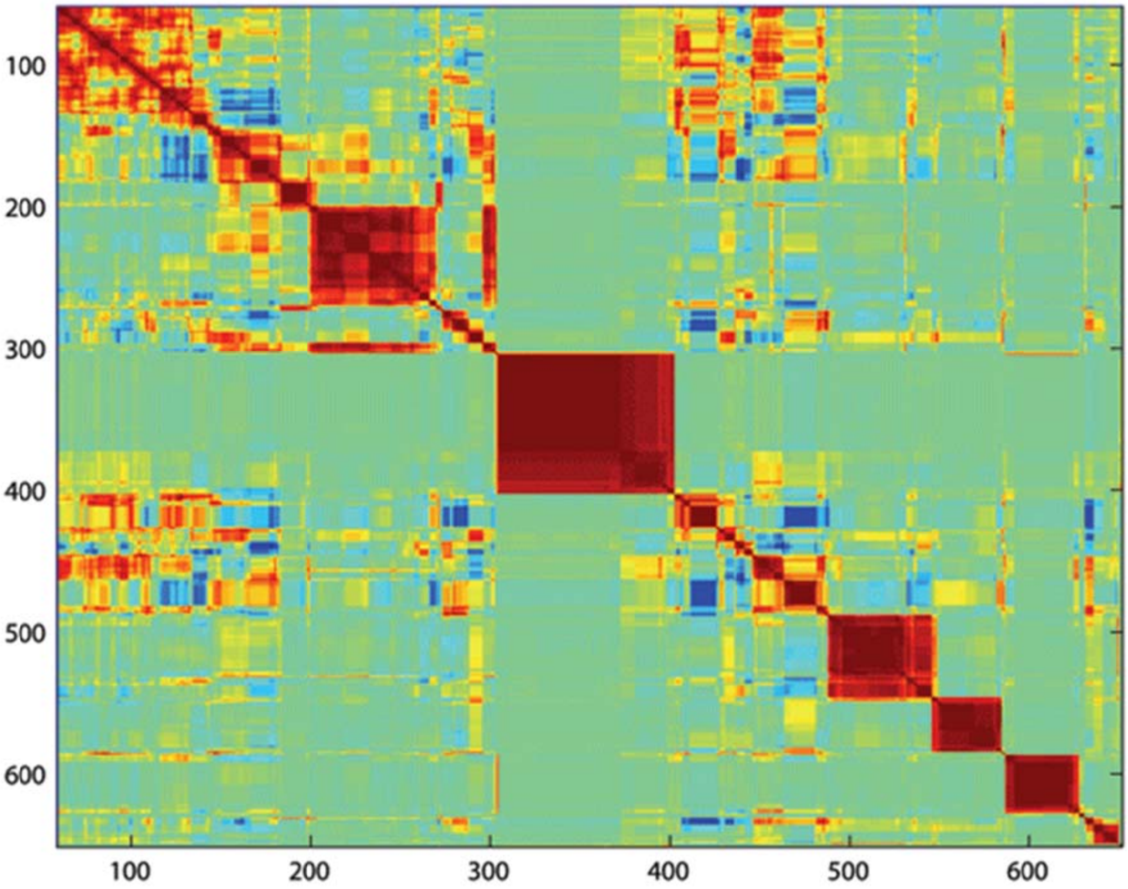


Refer Sarkar et al. (2014) for algorithm.

4.3.2. Reordered Cosine Angle Matrix

The following chart is a reordered cosine angle matrix of the design data network. Darker colours represent greater cosine angles which correspond to stronger edge relations.

Figure 26: Reordered cosine angle matrix of design data model.

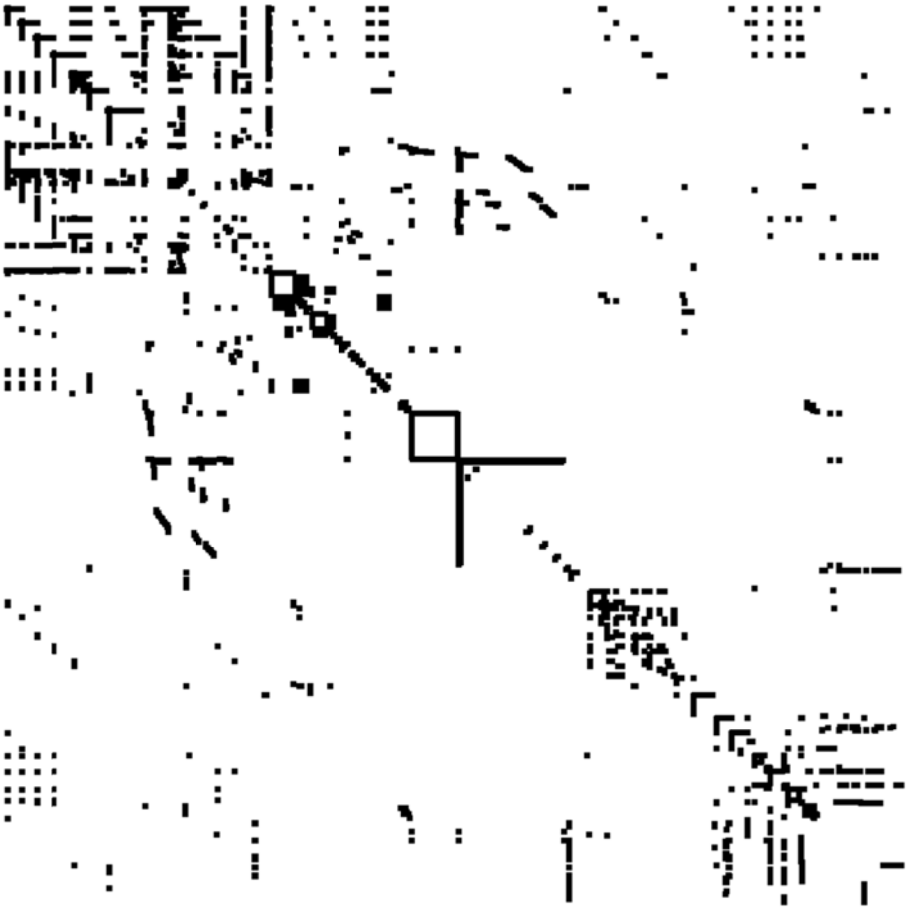


Refer Sarkar et al. (2014) for algorithm.

4.3.3. Design Interface Matrix

Utilising codes representing design disciplines prepended to node labels, this design structure matrix was prepared of the design data network

Figure 27: Design structure matrix of preordered design data model.



Refer Sosa et al. (2003). Implemented with Java.

4.4. Combined Results

4.4.1. Basic Network Properties

Table 3: Basic network properties.

Metric	Components Model	Design Data Model	Percentage Difference
Number of nodes:	2061	651	104.0%
Number of edges:	3109	1678	59.8%
Density:	0.001	0.008	155.6%
Average path length:	6.788	6.836	0.7%
Average weighted degree:	3.017	5.155	52.3%
Diameter:	21	8	89.7%
Degree centralisation:	10.065	10.148	0.8%
Closeness centralisation:	13.810	6.472	72.4%
Betweenness centralisation:	31.38%	16.49%	62.2%
Eigenvector sum change:	0.059	0.036	48.4%
Eigenvector maximum:	29	59	68.2%
Modularity coefficient:	0.814	0.704	14.5%
Clustering coefficient:	0.051	0.313	144.0%

Percentage difference is a simple quantitative method of comparing two numbers. It is calculated with the following formula:

Equation 3: Percentage difference.

$$Percentage\ Difference = \frac{|a-b|}{|(a+b)/2|} \times 100$$

4.4.2. Centrality of Structural Slabs

The following figures were generated by Gephi (Bastian et al., 2009).

Table 4: Centrality of structural slabs.

Average Node Centrality	Structural Slab Nodes	Other Nodes	Percentage Difference
Degree:	71.4	3.5	181.3%
Closeness:	5.8	3.2	47.6%
Betweenness:	87025	1137	194.8%
Eigenvector:	0.194	0.015	171.3%

4.4.3. Centrality of Modules by Design Discipline

The centrality measures summarised in Table 5 below are provided to permit assessment of 'centrality mirroring', as discussed in the Literature Review. They are the centralities of predefined modules corresponding to design disciplines. This was enabled by the method of node labelling explained in 3.1 on page 41.

The calculation of degree centrality was carried out from the original node models by iterating through each node and summating links between design disciplines whilst ignoring links within them, implemented programmatically using Visual Basic. This effectively provides a measure for node based degree centrality of design discipline modules within the model.

For the calculation of the other centrality measures, a new model was constructed consisting of nodes representing design disciples. Undirected links were, again, determined programmatically. These models were analysed within network software, UCINET (Borgatti and Freeman, 2002) and Gephi (Bastian et al., 2009), to produce closeness (UCINET), betweenness (UCINET) and eigenvector (Gephi) values.

Table 5: Centrality measures by design discipline.

By Design Discipline	Degree	Closeness	Betweenness	Eigenvector
Component Model				
Architectural	391	0.455	5.0	1.000
Structural	404	0.455	3.0	0.887
Mechanical	96	0.357	3.0	0.338
Hydraulics	78	0.455	0.5	1.000
Fire Protection	56	0.167	0.5	0.435
Electrical	72	0.385	0.5	0.756
Design Data Model				
Architectural	191	0.500	4.5	1.000
Structural	97	0.417	1.5	0.707
Mechanical	24	0.417	0.5	0.707
Hydraulics	21	0.455	0.5	0.899
Fire Protection	17	0.167	0.5	0.256
Electrical	60	0.385	0.5	0.373

4.4.4. Norm Comparison

The components matrix, being more than three times the size as the design data matrix, was scaled down to match the dimensions of the design data matrix. This was achieved by setting the values in the scaled down version to averages of values within regions of the larger matrix where region size equals (the row dimension of the larger matrix / the dimension of the smaller matrix).

Table 6: Norm comparisons

Model	1-Norm	2-Norm	Sup-Norm	Frobenius Norm
Components – scaled to match design data	133	73	137	154
Design Data	146	96	146	183
Percentage Difference	9.3%	27.2%	6.4%	17.2%

5 Discussion

5. Discussion

The discussion chapter is divided into four sections. Some results from auxiliary analyses are presented in-line with this discussion instead of the main Results chapter because they were carried out subsequently to the main analysis and formed part of the process of interpretation.

The first section is the assessment of the hypothesis by comparing the two models, component model and design data model, based on the spectral module detection method, concluding that the two do not mirror, that is, that the hypothesis of this thesis does not hold. In the second section, interpretations are made of the result. In the third section, contributions and implications for future research arising from the results are presented. The fourth section is a discussion of errors.

5.1. Hypothesis Assessment - Comparison of Component Model & Design Data Model

The following charts are reduced versions of Figure 24 and Figure 26 in the Results chapter. Their juxtaposition suggests a natural modular structure between the two models that is visibly differently distributed, though perhaps within a similar range of degree of modularity.

Their respective modularity coefficients, 0.814 and 0.704 with a percentage difference of 14.5%, also attest to a comparable degree of modularity, whilst their clustering coefficients, 0.051 and 0.313 with a percentage difference of 144.0%, are quite different (refer Table 3).

It is concluded that, by visual assessment, as in Sosa et al. (2003), the architectures of the subject component and design data models do not demonstrate a significant degree of mirroring with respect to modularity and that the hypothesis, therefore, does not hold in this case.

Figure 28: Cosine angle matrix of components model

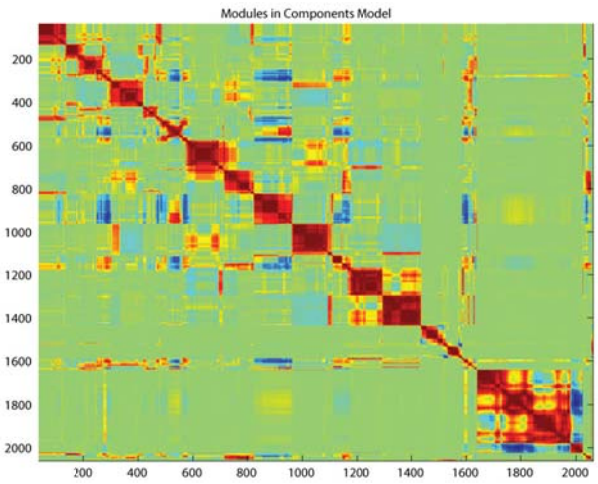
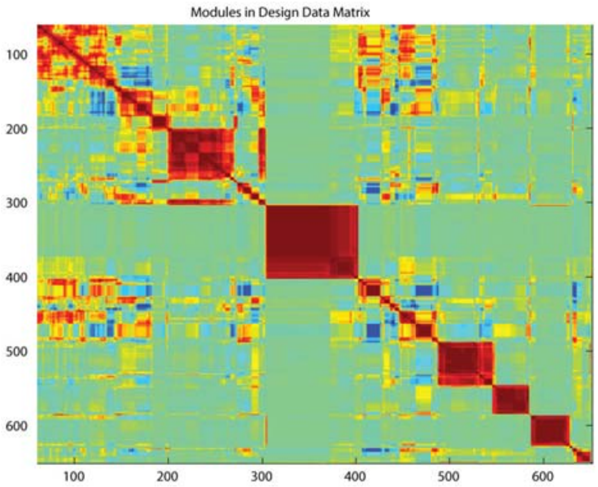


Figure 29: Cosine angle matrix of design data model



Reordered cosine angle matrix according to the method in Sarkar et al. (2014).
Charts produced by Andy Dong (darker colours represent greater cosine angles).

The following overlays show possible modular hierarchy demarcations.

Figure 30: Modular demarcation of components matrix.

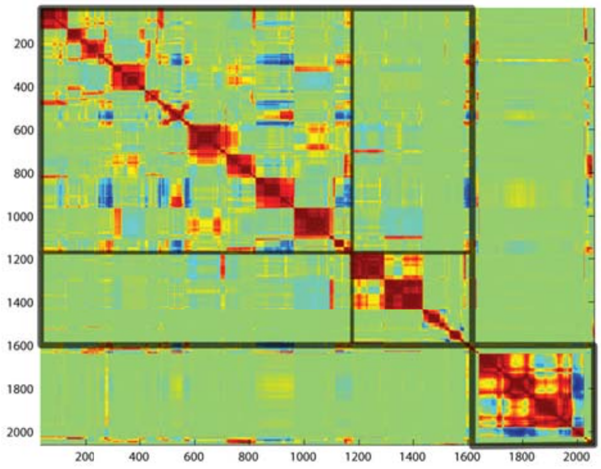
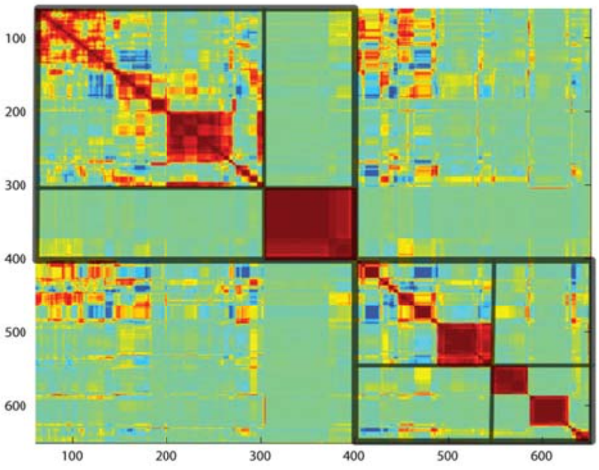


Figure 31: Modular demarcation of design data matrix.



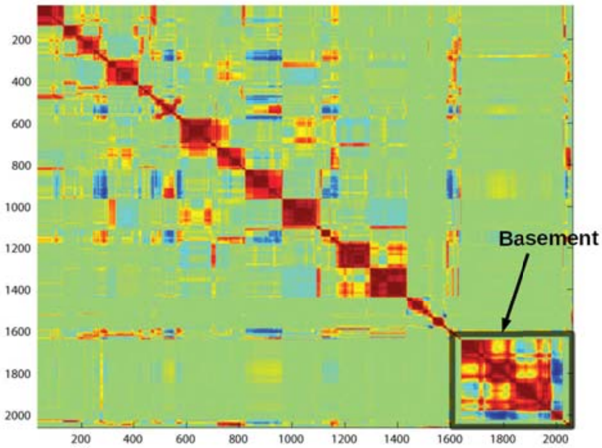
Interpretation of natural modules in building components network and design data network.
Reordered cosine angle matrix according to the method in Sarkar et al. (2014). Charts produced by Andy Dong (darker colours represent greater cosine angles).

5.2. Interpretation of Results

5.2.1. Component Model

Figure 32 below is a reduction of Figure 24 and shows the rendered cosine matrix from the module detection analysis. Darker colours represent greater cosine angles which correspond to stronger edge relations. A distinct module on the bottom right corner of the components matrix is identifiable. With an assessment of node labels in the output matrix, this module is associated with components in the foundations and basement of the building.

Figure 32: Preliminary interpretation of components matrix.



Interpretation of natural modules in building components network and design data network.
Refer Sarkar et al. (2014) for algorithm.
Charts produced by Andy Dong (darker colours represent greater cosine angles).

The following extract from the output matrix demonstrates how this association was determined. Positional indices returned by the reordering procedure permit the identification of original nodes in their new positions within regions of a reordered matrix. In the above assessment of region associated with certain components, node labels within this region are identified with a master legend, which decrypts node label codes. The following table is an extract from the reordered matrix, rows 1990-2000, within the region identified above. All the nodes are found to be associated with structure within the substructure of the building.

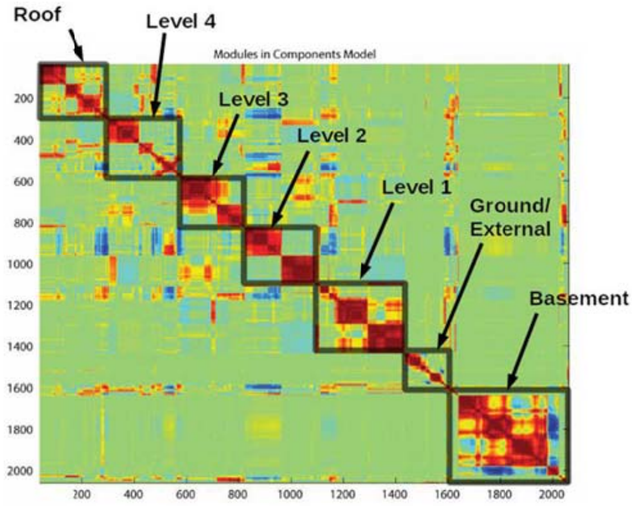
Table 7: Extract from output matrix.

Reordered Row Number	Original Row Number	Node Label	Expanded Label
1990	1875	S.SIB-08	Structure – Slab Internal Beam # 08
1991	1605	S.ADR-02	Structure – Agricultural Drain Riser # 02
1992	1904	S.PCB-04	Structure – Piling Capping Beam # 04
1993	1659	S.SWDP-03	Structure – Stormwater Drainage Pit # 03
1994	1660	S.GFDT-09	Structure – Ground Drainage Trench # 09
1995	1662	S.GFDT-11	Structure – Ground Drainage Trench # 11
1996	1661	S.GFDT-10	Structure – Ground Drainage Trench # 10
1997	1877	S.SEB-16	Structure – Slab Edge Beam # 16
1998	1665	S.EFBN-01	Structure – Excavation Feature Bench # 01
1999	1664	S.BC-01	Structure – Ground Drainage Trench # 01
2000	1663	S.GFDT-12	Structure – Ground Drainage Trench # 12

By following this procedure, nodes within the region corresponding approximately between 1600 and 2061 were identified mostly with the basement level and foundations. This method is followed in the remainder of this chapter for the identification of region constituency.

Further assessment of the components model indicates that modules are clustered around floor levels of the building – basement, floors and roof, as suggested in Figure 33 below.

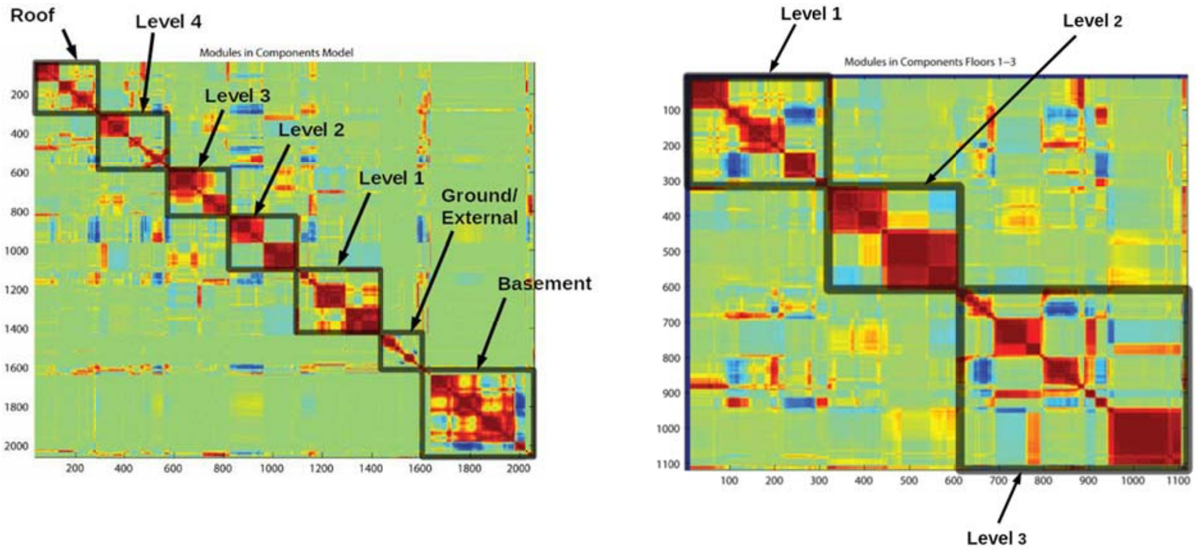
Figure 33: Components model interpretation.



Interpretation of natural modules in building components network and design data network.
Refer Sarkar et al. (2014) for algorithm.
Charts produced by Andy Dong (darker colours represent greater cosine angles).

To further investigate this possibility, a separate analysis was carried out on the regions indicated above as Levels 1 to 3. The results matched those of the main analysis, that according to an assessment of node labels as demonstrated above, a strong predominance of components associated with Level 2 are identified within the region marked Level 2 in the component model interpretation. In the areas marked Level 1 and Level 3, there was lesser correlation between node labels and interpreted regions. It is possible that the reordering procedure switched the position of floors. This does not affect the result because there is no reason why the order of the modules within the reordered matrix should match the physical order of levels in the building. Figure 34 below shows alternative interpretation for Level 1 and Level 3, juxtaposed with the original overall interpretation.

Figure 34: Detailed analysis of Levels 1 to 3.



Spectra method showing interpretation of natural modules in building components network and design data network.
Refer Sarkar et al. (2014) for algorithm.
Charts produced by Andy Dong (darker colours represent greater cosine angles).

In general, a high degree of correlation was found in the regions marked Basement and Level 2. A lesser degree of correlation, though significant, was found in other regions. Consequently, it is concluded that the natural module detection algorithm appears to have decomposed the component model into modules clustered around the design levels of the building, that is, basement and foundation, upper floors and roof, an unexpected result but one which makes intuitive sense.

A kitchen bench cupboard on Level 1, for example, should not be coupled directly with Level 4 in a network model because it is physically either unconnected or indirectly connected by several degrees of separation to anything on Level 4. There would be indirect connection via paths of other components such as kitchen sink, taps, pipework and riser, similarly, via the electrical system and structural system. However, in terms of the definition of modularity, its nearest neighbours should be other components on Level 1.

This also reflects construction sequence, which, in the subject project, being a low-rise multi-storey residential building, would progress from the ground up. A different result may be obtained on a model of a warehouse building, for example, where structure and roof may be erected prior to other superstructure components.

Another observation of the component matrix is that each floor levels appears to consist of two distinct sub-modules, one of which contains a clustering of horizontal components such as floors and ceilings, and the other a clustering of vertical components such as walls, columns and stairs.

5.2.2. Design Data Model

Meanwhile, an assessment of node labels in the design data model finds a predominance of nodes associated with the joinery package to reside in the strongly articulated region at the centre of the matrix (Figure 35 below). This is further corroborated by comparison with a design structure matrix generated from pre-ordered data (Figure 36 below) as in Sosa et al. (2003; 2004), prepared to aid this analysis.

Figure 35: Interpretation of design data matrix.

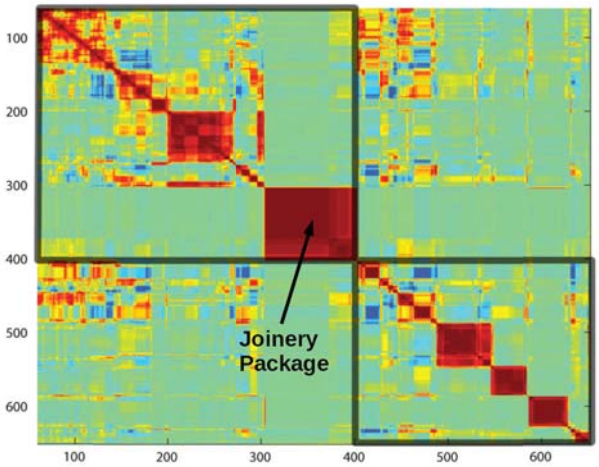


Figure 36: Design structure matrix based on preordered data.

Refer Sarkar et al. (2014) for cosine angle module detection. Joinery design data predominance in the region indicated. Background chart produced by Andy Dong (darker colours represent greater cosine angles).
Design Interface Matrix as in Sosa et al (2003). Chart produced using Java bitmap class.

Other regions in the natural module data have a lower degree of correlation but significant enough to make the interpretation that the natural module detection algorithm appears to have successfully identified the overall scheme of design packages by discipline as well as, to some degree, in the second tier of the hierarchy, sub-packages such as joinery.

Again, this makes sense from a consideration of design data in real terms. Interdependency between design data elements within the joinery package should exceed that between the joinery package and windows package, for example, because the joinery package represents components that are physically adjacent in the components model and the package is intended to provide the joinery trade contractor with complete and integrated design data independently of other design data.

Similarly, within a design discipline package, the degree of integration is far higher than between packages because each package is produced by a design team within an organisation and represents a functionally integrated sub-system such as the water supply system. A design data sub-system package is typically cross-referenced to produce an integrated package, again, intended for a particular trade contractor or pertaining to a physically integrated system such as the external enclosure of a building. References between disciplines do not have the same integration role. They are often notes and are very limited between engineering disciplines. As discovered in the centrality analysis, the degree of linkage to and from the architectural package is disproportionately high. This is because architectural components are less specialised, being everything that is not engineered. They are also at the end-user interface level, which engineering systems serve. End-user components typically interface one or two engineering systems. For example, an electrically operated roller shutter must interface with the structural system as well as the electrical system. A sink interfaces with the water supply and drainage system as well as the electrical system via the hot water unit.

5.2.3. Summary of Interpretation

From the above interpretations, it is concluded that the natural detection algorithm has, in the components network model, captured a modules clustered around building design levels, and, in the design data network model, identified design data packages associated with design disciplines as well as packages within disciplines, as depicted in the following.

Figure 37: Components matrix interpretation.

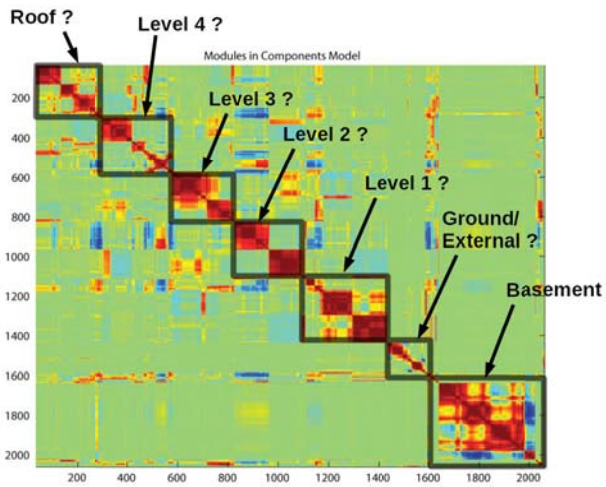
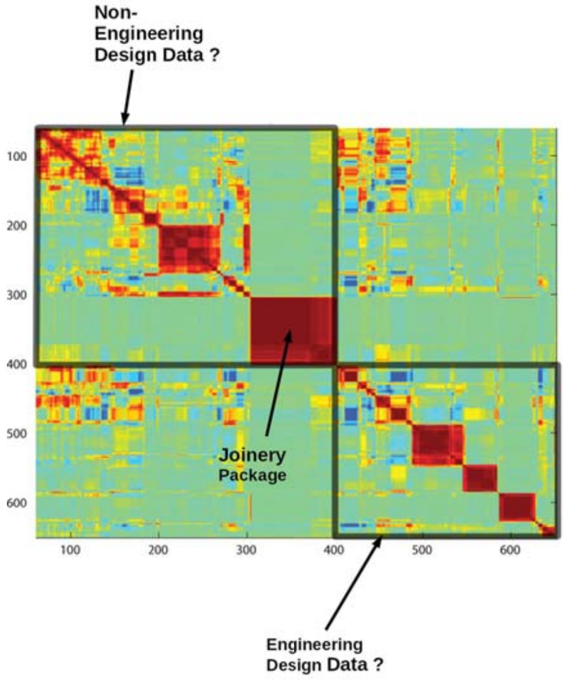


Figure 38: Design data matrix interpretation.



Interpretation of natural modules in building components network and design data network.
Refer Sarkar et al. (2014) for algorithm. Charts produced by Andy Dong (darker colours represent greater cosine angles).

5.3. Contributions & Implications for Future Research

5.3.1. 'Dual Architecture'

The interpretation of results suggests that natural modules detected by the algorithm from Sarkar et al. (2014) in the two models represent two distinct categories of decomposition.

In the case of the components networks, the module detection method appears to have detected modules clustered around floors, which is consistent with, firstly, the spatial proximity of components in a building given the physical scale of a building relative to each component as well as the short average path length of the network. Secondly, structural dependency requires the main structural components to be in place in the construction sequence before other components can be affixed. In the case of the subject building project, a four-storey apartment building, this would be floors then walls, column and stairs at each level. The detected decomposition reflects this.

In the case of the design data network, the module detection method appears to have detected a similar modular structure to that observable in the corresponding pre-ordered design interface matrix and consistent with the naturally pre-ordered structure of design data by virtue of, firstly, separate design discipline packages produced by professionally and organisationally separate design teams – architects and engineers. Secondly, the need for packaging of design data for trade contractors, which corresponds to sub-packages within each design discipline. For example, the joinery package within the architectural package. Another example would be the lighting sub-package within the electrical engineer's package. Each of these sub-packages may correspond to a separate trade contractor or all of them sublet to one subcontractor. The need for such packaging is necessary also in the traditional organisational model, though in management contracting systems to a greater degree.

Another way of viewing the decomposition of design data is that it generally corresponds with sub-systems which span throughout the building, some of which are physically integrated and contiguous according to some kind of flow – electrical current or fluids, generally engineered systems. For example, the power supply system, the communications system, cold water supply, hot water supply, sewer drainage and stormwater drainage. Sub-systems can also exist as sets of strongly related components which may not be contiguous. These are typically part of the architectural package. For example, joinery, windows, ceilings, internal walls and doors. The architect also deals with the integrated and contiguous system of external enclosure – the external surfaces of a building, which must be integrated in order to form a barrier against weather and other prevailing factors.

This leads to the concept of 'dual architecture' or two architectures in one. Buildings and products can be viewed as having a dual architecture, one of parts and one of sub-systems, just as the human body can be decomposed into arms, legs, torso, etc., (parts) on the one hand, and skeleton, digestive, nervous, cardiovascular, etc., (sub-systems) on the other. Two architectures exist simultaneously within the one system and are inextricable though distinguishable.

It is proposed that in this investigation the module detection method detected modules in the architecture of parts within the components model, similarly in the design data model but that design data parts modules represent design disciplines, which, in turn, represent sub-systems in the building. It appears that dependencies within sub-systems are subsumed within dependencies associated with physical connection.

Furthermore, this suggests that design data acts to transpose two architectures – that of the design organisation to that of sub-systems within the product architecture, at least at the uppermost hierarchical level of the design organisation associated with design discipline packages.

The notion of multiple architectures in one is recognised in quantity surveying practice in Australia. Two component classification standards govern the preparation of cost estimates: the 'NPWC' elemental system for preliminary estimates, effectively an architecture of parts – substructure, upper floors, roof, external walls, internal walls, etc., and 'ASMM5' for detailed estimates, divided by trade, which in turn broadly coincides with sub-discipline design packages – joinery, structural steel, windows, concrete, etc.

Implications for Future Research

An implication for future research of this result is the potential development of a method or algorithm to identify sub-system clusters within a dependency model. This can be achieved with the spectral algorithm employed in this thesis by incorporating flows into the network model by means of multiple parameter links. However, this would be an ex ante method. Research into sub-system architectures might reveal certain features or morphological patterns that could enable ex post identification within another network. For example, sub-system structures may strongly conform to a definition of tree structure.

Another implication relates to organisational design. As explained in the literature review, the manner in which design data is divided into packages is integral to differentiation between organisational models. In management models of organisational design, the importance of autonomy of sub-disciplinary design packages is greater in than the traditional method, resulting in a greater decoupling of design data. The move to delegate detailed design to trade contractors, as in Gray and Flanagan (1984), further decouples design teams and design data into something resembling complex product development, a rare phenomenon in construction. Consequently, the role of design data as a third system, in addition to organisation and product architectures, might continue to be investigated in future mirroring studies.

5.3.2. 'Centrality Mirroring'

This thesis adopts a broad definition of the mirroring hypothesis, leading to a departure from mirroring in terms of architecture and modularity and consideration of topological properties of network models.

Given the proliferation of topological measures, an exhaustive evaluation is not proposed but a specific one. Centrality is selected for two reasons. Firstly, it is the first metric in a lineage of literature going back to the early small group studies movement (e.g., Bavelas, 1950). Secondly, recent research indicates that centrality is a potent indicator of coordination potential in a construction context (Hossain, 2009), and coordination is a key part of management and organisational design.

The results of this investigation with regards to mirroring are not consistent between different algorithms. However, significant corollaries emerge, thereby making a contribution to the subject.

One corollary relates to the positional potential for coordination within organisational systems. Referring to the Results chapter, Table 5 reveals relatively high centralities for modules associated with Architectural and Structural design disciplines in components model. Within the design data model, the centrality of the Architectural module is relatively higher again over all metrics.

Implications for Future Research

As well as the notion of centrality being associated with potency for coordination, also concluded in Hossain (2009) is that betweenness centrality and out-degree are particularly associated with potency for coordination (Hossain, 2009). As this thesis is based on undirected data, betweeness centrality was incorporated in the investigation but in-degree versus out-degree was not. Consequently, future research into this matter might utilise directed data and incorporate in-degree versus out-degree.

The second implication for future research is the modelling of organisational architecture as nodes of individuals, as in Hossain (2009), rather than nodes of organisations. The architecture of organisational nodes is important in this thesis because it has an ex ante relationship with that of design data.

The third implication for future research is the investigation of design discipline centrality on engineering construction projects. Potentially, different outcomes might result between project sub-types – roads, bridges, tunnels, sea walls, etc.

The fourth implication for future research is the significance of design data node attributes. In network analysis, there is much emphasis on the notion that topological properties have significance independently of node attributes. From an organisational design perspective, outcomes cannot be achieved with topology or mirroring alone. Nevertheless, like any design pursuit, through organisational design, optimum solutions should be sought regardless of whether they are subsequently fully availed of. Consequently, the relationship between node attributes, such as whether a design manager has design training, and network topology may form the subject of future research.

Implications for Design Management

An implication of this observation relates to the function of design management within the traditional system of organising projects when implemented with project management. In particular, if centrality mirroring has significant value for coordination and if coordination is significant for management, and if a particular pattern of centrality is manifest intrinsically in design data architecture, then it follows that the design of the associated design organisation should mirror design data architecture with respect to centrality.

More generally, if a topological principle has significance for management and if such a principle is manifest in a product architecture, then it follows that the design of the associated organisation should recognise the topological principle.

More particularly, in this investigation the implication is that the design organisation associated with the most centralised design data package should have the highest potential for management of design during the production of design data and should be designated a central organisational position. If a project management firm or other actor which does not participate directly in design production is designated a more central position, then a misalignment occurs between product architecture, in this case, design data architecture, and organisational architecture, with the risk that the function of design management is either not performed or performed poorly. This is not uncommon in the Australian context at the present time.

The end result of this is greater potential for degradation of design data quality, with consequent negative effects on projects (Akintoye, 1994; Doloi, 2008), the opposite of what was envisaged in the pursuit of alternatives to the traditional method. That is, rather than being mitigated by project management, cost escalation, delay and conflict are likely to be exacerbated by such a misalignment of topologies.

This has several implications for organisational design practice in relation to the traditional method where employed with project management. Certain strategies may serve to mitigate this risk. Firstly, in the case of building projects, harkening back to the traditional method prior to the rise of project management, the architect can be formally assigned a dual role of designer and design manager, thereby maximising mirroring alignment as well as the coordination potential of the design organisation.

The secondly implication on organisational design is that, where the responsibility of design management rests on the project manager, hence a mirroring misalignment, the project management firm could appoint an individual within their firm who has design background or subcontract a specialist design management firm to manage the design process in conjunction with the architect organisation. This may serve to bridge the misalignment and consequent reduced coordination potential in the network.

The advent of project management brought much needed management expertise into the centre of project organisations, interfacing between buyer, design and construction organisations. This role entails several functions, two major ones being design management and head contract administration. It is argued here that where a project manager has construction or quantity surveying background, the latter is well served. However, the former is neglected. Nowadays, architects continue to perform a significant degree of design coordination informally anyway but without contractual mandate or responsibility and can be greatly hindered by a formally designated project manager who doesn't understand the design coordination process.

5.3.3. Effects of Node Attributes on Topological Properties

A striking observation is made in the results with respect to degree of difference between centrality measures of structural slabs compared to other nodes in the components model (refer Table 4). In three of four measures, the percentage differences are between 170% and 195%.

The average degree centrality of floor and roof slabs is 71.4 and of other nodes is 3.5, a percentage difference of 181.2%. The average closeness centrality is respectively 5.8 and 3.2, a percentage difference of 47.6%. The average betweenness centrality is respectively 87025 and 1137, a percentage difference of 194.8%. The average eigenvector centrality is respectively 0.194 and 0.015, a percentage difference of 171.3%.

An explanation for this is conceivable upon consideration of real-world factors, in particular the physical attributes of large concrete slabs. Although integral features such as beams and upstands are modelled as separate nodes, modelling conventions result in concrete slabs being modelled as single nodes because of their shape and contiguousness, and which, by virtue of their location, disproportionate size and surface area, have a greater potential for adjacency. They are also a main structural component. It follows that they should have disproportionately high degrees of connectivity with other components in physical space and hence centralities within the model. This is also consistent with the idea that naturally occurring modules should cluster around floors as suggested in sub-section 5.2.1.

Implications for Future Research

A potential topic for future research is the question of what are the implications for construction management of this high centrality of floor slabs as opposed to breaking down floors into smaller sections with lesser centrality. The subject project is representative of Australian practice where contiguous floor slabs are common because of the predominance of in-situ concrete as a structural material, as opposed to steel, in many building types – offices, apartments, hospitals, etc. This relates to fire protection standards, relative cost and other factors, although there are many examples of the use of modular floor systems such as custom precast or proprietary hybrid systems. In the US, where steel as a structural material in buildings is more prevalent, considerable time saving has been achieved by modularising product and organisational design (Gray and Flanagan, 1984). A related topic for future research would be to investigate how this might be achieved with concrete structures.

Another topic for future research would be the inter-relationship between modularity and centrality. In this investigation, modules appear to cluster around certain nodes with a relatively high degree of centrality. However, it is possible for nodes with relatively high centrality to be outside the most distinct module clusters.

Future research may also further investigate the effects on topology of the physical and spatial attributes of nodes in product architecture models. An analogy can be drawn in social network models. The reason an individual may have a central position might relate to the attributes of that person, being a better communicator or socialiser than others in the network. The emphasis in social network theory is usually on the effects or potentials of structural position independently of actor attributes. A node attributes perspective may lead, for example, to the ability to assess the relative potential of nodes to end up in certain positions in certain networks based on their attributes. Similarly, algorithms based on node attributes may provide further insight into the properties of product architecture models.

5.4. Potential Sources of Error

Given the lack of precedence in certain aspects of this investigation, there are several types of errors that could be addressed in future research in this topic.

1. The quality of design data.
2. Input error.
3. Node and link definition.
4. Extrapolation and interpolation.
5. Software development.
6. Data uncertainty and interpretation.
7. Conceptual error.
8. Discrepancy between real-world and data.

5.4.1. Quality of Design Data

Design data configuration, quality and scope varies between organisational models in construction. In some cases, design data might be minimal, as would actual design team interaction. The best design data for this type of investigation is from a project delivered under the traditional method, as was the case in this thesis, because design data is fully detailed and likely to be obtainable as a fully package. In other methods design data would be less complete, distributed amongst multiple organisations and more difficult to obtain.

5.4.2. Input Error

The potential for input error exists at least at two points in the process. Firstly, misinterpretation in the extraction of component data from design data. Secondly, misinterpretation in the extraction of design data nodes and cross-referencing. Both of these can be mitigated by the development of quality procedures such as cross-checking by others, marking off after input, following a standard sequence, the development of manuals and checklists, etc.

5.4.3. Node & Link Definition

In this thesis, a contribution was made to the degree of objectivity in hitherto literature on organisational design in construction by reducing the degree of subjective opinion embedded in primary source data. This is the consequence of mirroring hypothesis methodology whereby a functional dependency model of components is the basis of investigation.

Sources of error in this approach are also identifiable. Node and link definitions are the basis for a network model and, therefore, an essential part of the process that establishes basic parameters affecting properties. This is seen as a long-term question and the conventions developed in the Methodology chapter are proposed as a starting point of investigation. The basis for constructing a functional dependency model is seen as relatively objective and yet low density networks are produced, although this is considered to be primarily attributable to network size, materiality and spatial aspects of the subject. Modelling policies nevertheless have an influence in this regard and there is much potential for their development and refinement into a standard methodology.

5.4.4. Extrapolation & Interpolation

The extrapolation and interpolation of data is inevitable to some degree on all projects. Though related to input error, where an error can occur on data that is not extrapolated or interpolated, this problem arises from the natural incidence of discrepancy in design data and the need to make assumptions in the modelling process. Here again, standardised methodologies can help in some cases. In situations not covered by standard methodologies, it may be that only expert advice will provide a resolution. For example, the isolation of a sub-section of a network in order to analyse separately as in section 5.2.1. The following charts show cosine angle module detection for Level 1 data isolated from the components model.

Figure 39: Reordered cosine matrix of Level 1 region

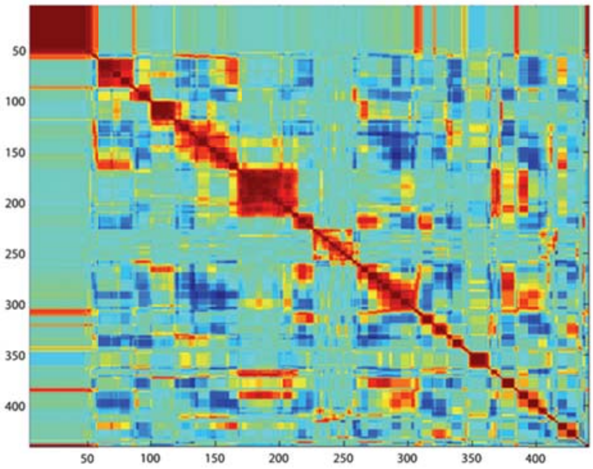
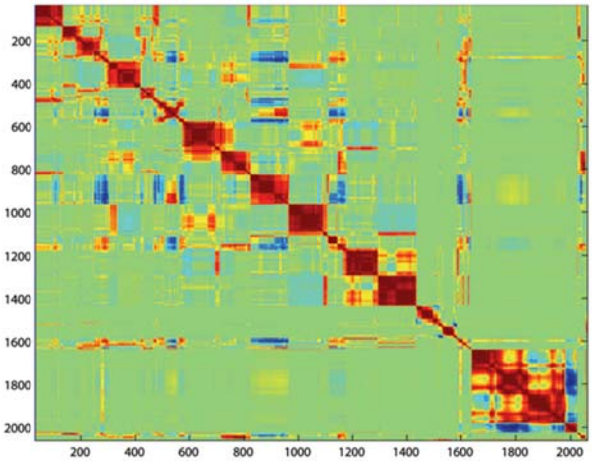


Figure 40: Reordered cosine matrix of components model



Spectra method showing natural modules in building components network and design data network.
Refer Sarkar et al. (2014) for algorithm.
Charts produced by Andy Dong (darker colours represent greater cosine angles).

Natural modularity results shown on the left-hand chart here contradict what is interpreted as the Level 1 region in the main component model chart. Two distinct modules of similar size were expected. Instead, from node index data, the larger module on the top-left corner contains the floor slab together with components closely connected with it, including columns (verticals). This makes sense because they are directly connected components but it is not consistent with the overall chart and neither with the proposition that floor level modules each resolve into two main sub-modules where one contains components fixed to the floor and the other components fixed to columns, walls and stairs.

This anomaly may be due to the isolation of network data. To generate this chart, nodes tagged as being on Level 1 were simply isolated into a separate matrix file for analysis. This might be problematic in terms of connections to other modules. For example, in the main model, ceilings and cornices tagged on a level were found associated with the level above. This makes sense because they are fixed to and supported by the floor structure over the level on which they are tagged. However, in an isolated floor level network these would form a module with components missing the floor above, likewise, the module containing the floor on that level because components such as the ceiling below would be missing.

5.4.5. Software Development

As this analysis is heavily reliant on software processing, algorithms, transcriptions and conversions feature highly in the process and may present a significant challenge where there is lack of precedence. In this project, a simple AJAX utility was employed to construct the models, which were saved as delimited text in network list format, which was subsequently converted to delimited matrix format utilising Gephi (Bastian et al., 2009).

'List format' refers to delimited text in which each line begins with a node label followed by labels of nodes with which it is connected. This differs from 'matrix' format, which consists of a literal delimited text matrix. Again, the first element in each row is a node label but instead of being followed by labels of edge nodes, the remainder is a vector containing matrix edge values and the first row contains a transpose of the node labels.

Matrix format in delimited text was imported into Matlab, which was utilised to perform the single value decomposition, cosine angle calculation, reordering operations and visualisation. A counterpart in Java was also developed but the result was not consistent with that produced by the original Matlab code.

The need to utilise a diverse range of tools and techniques is due to a lack of software for this specific purpose. One deficiency in particular is a lack network construction tools. Gephi (Bastian et al., 2009) has 'Add Node' and 'Add Edge' functions but they are cumbersome to use. Similar features in other network analysis software were found to be crude and not practical. The AJAX tool provided text recognition capability with the 'autocomplete' method, which accelerated the process of constructing network data.

JAVA code was developed by interpreting a Matlab script, which turned out to be 3-4 times larger than the Matlab script. Persistent problems were encountered in reduction and reordering of the matrix. In hindsight, the JAMA library is limited and required constructing support methods, which, in Matlab, are already part of the environment. This may be alleviated in future with the use of alternative, more powerful matrix libraries such as UJMP or COLT.

5.4.6. Data Uncertainty & Interpretation

As the output of the method in Sarkar et al. (2014) represents naturally embedded structures, the interpretation of such output can be diverse. In the data generated here, interpretation rested on the preservation of node labels and, in turn, line indices in the output matrix. This enabled the identification of module constituency. However, much of the data was obfuscated, presumably due to module overlap. The highest degree of certainty obtained was in the identification of basement level nodes in the main components model, the identification of a predominance of Level 2 components in the module comprising Levels 1 to 3 and the identification of joinery components in the design data model. The rest was relatively uncertain.

This error risk is contingent on data quality but must also be accepted as inherent in anything involving the identification of naturally embedded information, along with the high degree of uncertainty associated with low density networks (refer Appendix 1 and 2 for explanation of uncertainty in low density networks).

The following example shows alternative module delineations which could have been made in Figure 30 and Figure 31 in Section 5.1.

Figure 41: Components model

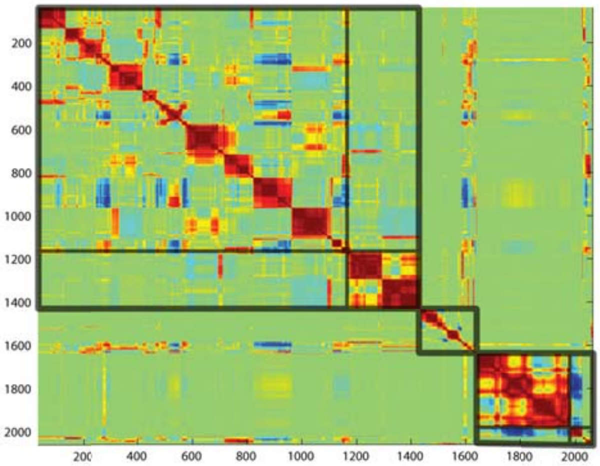
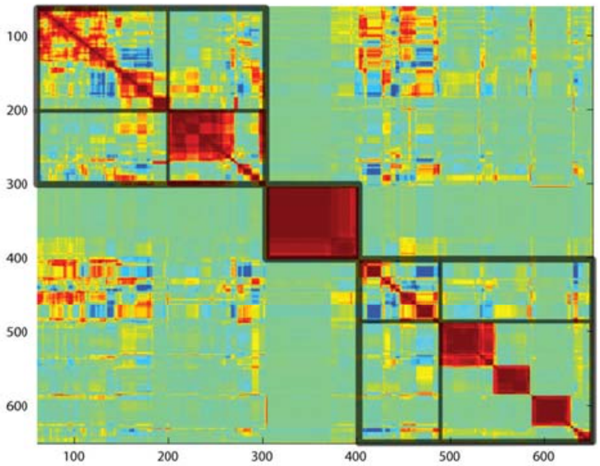


Figure 42: Design data model



Interpretation of natural modules in building components network and design data network.
Reordered cosine angle matrix according to the method in Sarkar et al. (2014). Charts produced by Andy Dong (darker colours represent greater cosine angles).

Figure 43: Components model

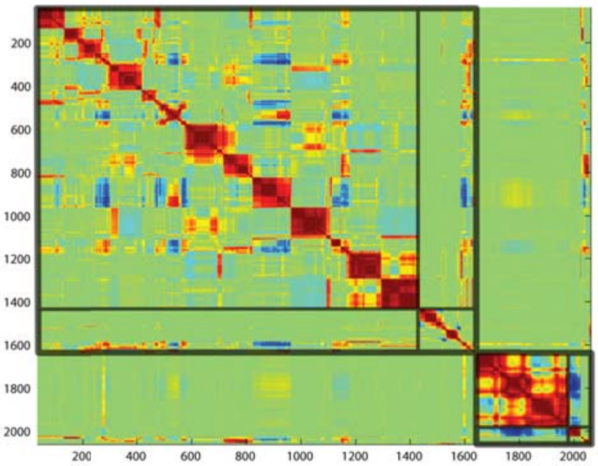
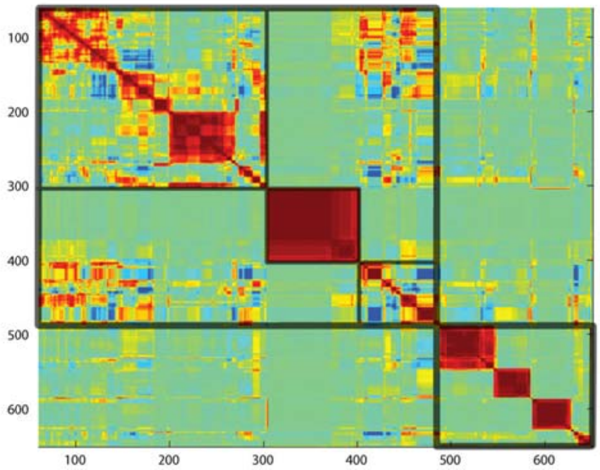


Figure 44: Design data model



Interpretation of natural modules in building components network and design data network.
Reordered cosine angle matrix according to the method in Sarkar et al. (2014). Charts produced by Andy Dong (darker colours represent greater cosine angles).

Another error which may arise in comparing two networks is where the relative number a size of modules may have a high degree of congruency and yet not be evidence of coupling. For example, the data analysed in this project could have yielded, on the one hand, a components network comprising a larger module consisting of basement components and four smaller but approximately equal in size modules containing Levels 1, 2, 3 and roof components. On the other hand, design data could have yielded a similar modular structure, one larger module containing non-engineering design data and four smaller and similar sized modules corresponding to structural, electrical, hydraulics, mechanical design data.

The interpretation could be made that the two networks are highly coupled. However, as modules represent different content, that is, nodal constituency, this might not be the case and the interpretation would be erroneous. This can be considered a separate problem to that of interpretation and, rather, one of conceptual error in the notion of modularity. Similar errors can be made in relation to other measures.

An implication for future research is the development of an algorithm for comparison of matrices or networks with respect to modularity and topological measures. In this thesis, norms measures supplemented visual comparison but with inconclusive results and there was no basis for the interpretation of norm figures. For example, what numerical value would correspond to a high degree of modularity or what percentage difference would constitute similarity vis-à-vis mirroring?

5.4.7. Conceptual Error

There is potential error in the notion of design data as a proxy for team interactions. In this thesis, the focus was on the organisational level and, whilst there is a logical basis for the proposition that design data architecture may serve as a proxy for design team interactions in that certain types of cross-referencing in design data cannot occur without a transfer of design data between teams, hence interaction, the degree to which this type of interaction is represents all types of interaction is unknown. This is a potential topic for future research.

Inherent limitations in methods present scope for conceptual error. For example, meaning and dogma assigned to network measures, such as the notion of centrality as an indication of power. Relying on centrality or any metric exclusively to represent complex features of networks may lead to error.

5.4.8. Discrepancy Between Real-World & Data

Cabigiosu and Camuffo (2011) identify two error types which would also apply to this project (where design data substitutes for team interaction):

1. Evidence of team interaction where there are no design interfaces between components or modules.
2. Design interfaces between components or modules but no corresponding team interactions.

This has the potential to confound research but would occur to a significant degree in all construction projects and can be explained as misalignments, discrepancies between real-world facts and the information exchanges that occur in relation to them.

The first misalignment arises often in construction where members from two separate design teams, that is, representing different design disciplines, typically an architect and engineer, are both involved in the detailed design of one component. For example, a floor structure is effectively designed by both architect and engineer and would be modelled as one component, hence revealing no design interface. In a building project, the architect would typically select the floor system type – concrete, steel, timber, etc., mark out its dimensions, level (height) and features such as steps, upstands, etc. However, the engineer would calculate the size of beams and thickness of concrete, strength grades of materials, support and bracing, reinforcement, etc. Two teams must interact to design separate aspects of the one component. Another example would be a distribution board. The determination of its final location is the result of an interaction between architect and electrical engineer. There are many such components in a building project.

The second misalignment case is also very common in construction and arises from two factors. Firstly, where components and interfaces required for statutory compliance or manufacturer's warranty and are prescriptively defined by standards, regulations or manufacturer's instructions there may be no interaction required between design teams because each would rely on their respective criteria. An architect would designate the pitch of a roof according to the roof sheeting manufacturer's criteria. The structural engineer would design roof members according to a statutory standard and manufacturer's criteria if applicable and the two designers do not need to interact in order to design the roof. Another example is a smoke detector required inside certain air-conditioning ducts. Both the mechanical and electrical engineer are aware of the requirement and could each potentially incorporate it into their designs independently of each other, without the need to interact.

Secondly, much of the detailed design required for compliance is carried out by the construction side of the industry. For example, shop drawings for formwork, structural steel, metal fixtures and joinery. Electrical and mechanical installations are also sometimes designed by the installer. In addition, many interfaces are not designed but solutions are improvised on site. The identification of these types of component interfaces may be identified as part of a research project but corresponding design team interactions would not be necessarily identified.

6 Conclusion

6. Conclusion

The hypothesis that product architecture mirrors design data was found to be false in this investigation where 'product architecture' refers to that of a construction project. This conclusion is based on prevailing definitions of product architecture (Ulrich, 1995) and the mirroring hypothesis (Sosa et al., 2003). The identification of modular structure was achieved by employing a spectral algorithm based on the notion of 'naturally existing' modularity (Sarkar et al., 2014).

A components model representing product architecture and a model representing design data architecture were constructed by using methods adapted from the literature. Matrix representations of modular structure were compared visually as in Sosa et al. (2003). The labelling of nodes enabled their identification within reordered cosine matrices produced by the spectral algorithm, leading to the conclusion that the most visibly distinct modules detected by the algorithm correspond to an 'architecture of parts' within the subject building, as they do in the design data as an information system, which in turn corresponds to an 'architecture of systems' within the subject building, hence the falsification of the hypothesis.

It is argued that design organisations correspond with design disciplines, which correspond with the first division of design data into packages. Hence, being defined ex ante, the testing of mirroring between design organisation and design data at the level of design disciplines is redundant but may permit the use of the latter as a proxy for the former. Together with the results, this leads to the general notion that, being an information system which models a product, design data also transposes between two architectures intrinsic within the product. It also permits the use of a pre-modularised design structure matrix to corroborate the results of design data natural module detection, which was done and which did corroborate.

The primary aim of this thesis was to investigate the hypothesis in a manner which closely matches precedence in the mirroring hypothesis literature, albeit adapted for construction. A secondary aim was to heuristically explore a more generic notion of mirroring in relation to organisational design in construction.

This was achieved by considering the correlation of centrality, hence the notion of 'centrality mirroring', to supplement architectural mirroring, which is embroiled chiefly with modularity.

This thesis makes several contributions to the literature, commencing with the falsification of the hypothesis. These are presented here in the order they appear within the thesis, together with some implications for future research. Other implications for future research are presented in the Discussion chapter.

The second contribution is the introduction of the mirroring hypothesis as a new theoretical perspective into the field of organisational design in construction. An implication for future research is the call for continued development of this genre. Future research could involve several projects executed under different organisational models or capture design team interactions and compare with design data model.

Future research might also investigate the development of an algorithm for the detection of sub-systems such as the power supply system within a building. This arises from the notion of a dual architecture – parts and sub-systems. In this investigation, it was found that functional dependency modelling combined with the spectral algorithm tends to reveal an architecture of parts but obscure that of sub-systems.

The third contribution is the introduction of research methods from mirroring hypothesis and related literature, thereby achieving a higher degree of objectivity in the relationship between primary data and conceptual modelling. Instead of asking management experts for their opinion on the rating of multi-value variables, technical experts are queried on matters of dependency between components, simplified, as in this study, to permit binary evaluation and corroboration. An implication of this for future research is to further develop and simplify this process.

The fourth contribution is the methodology developed to define nodes and links, hence network models of a building and of design data as an information system. Lacking specific precedence in the literature this was adapted from functional dependency modelling in manufacturing. An implication of this for future research is that the functional modelling methodology employed in this investigation might be further developed or adapted to suit a construction context.

Another implication for future research is the possibility of establishing a public database containing network models for building components and design data. Such a facility might be web based and provide tools, algorithms and literature.

The fifth contribution is to supplement the visual comparison of modules in reordered cosine matrices with norm algorithms. An implication for future research is the development of more reliable algorithms for comparing two network models of architectures as well as reference criteria. In this investigation, visual inspection was the primary comparison method, consistent with literature precedence. Norm comparisons were applied inconclusively in the absence of reference criteria. That is, what percentage difference should represent a cut off for mirroring?

The sixth contribution is to utilise an ex ante method, in this case, the design structure matrix of design data re-ordered into design package modules, to corroborate the results of an ex-post method, the spectral algorithm and resorted cosine matrix. The implication for future research is to emphasise this approach in researching the mirroring hypothesis or at least be attentive to opportunities for adopting it.

The seventh contribution is to apply centrality measures to architecture models, thereby giving rise to the notion of 'centrality mirroring' and the effects of physical node attributes.

An implication for future research is that directed data could be used instead of undirected data in future research, thereby to test the third hypothesis in Hossain (2009) that out-degree is associated with a higher propensity for coordination effectiveness.

Another implication is to investigate organisational level centrality in engineering construction projects – roads, tunnels, bridges, etc.

A further implication for research and for organisational design practice is that 'centrality mirroring' leads to a focus on design management, which, being critical for project success and central activity within the design organisation, should be taken seriously in its own right. Consequently, in response to the findings of this thesis, in the design of building projects, mirroring alignment on an organisation level can be achieved by designating the role of design management to the architect. Alternatively, where design management is part of the project manager's contractual responsibility, the resultant mirroring misalignment can be mitigated by the project manager designating to the role of design management, an individual or consultant with design background as opposed to construction or quantity surveying background which is often the case. This strategy can be applied to any organisation design model.

Appendix 1 – Basic Network Theory

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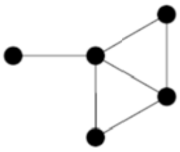
A network or graph is a set of nodes with potential connections between them.



Simple Graph

In a social network, nodes represent people or actors and connections between nodes represent relations between actors. An actor may also be a group or organisation, that is, a network. Every network within the network of humanity is a sub-network and also consists of sub-networks down to the level of the individual, by the notion of self-linkage, may also be considered a network. This perspective offers unique concepts in the study of organisational structure, such as the focus on connection rather than attributes of actors, interdependence, the notion that structure alone affects substantive outcomes and emergent effects (Borgatti, 1998).

6.1. Linkage Types

Given a group of actors, various network dimensions can be investigated as defined by the nature of links. For example, if links represent communication linkage, then the network is a communication network. Examples of relational types are friendship, trust and acquaintance. An ever-increasing range of quantitative properties and metrics of networks are available for the assessment of patterns within network structures and congruency between them.

This section explains some basic metrics in network analysis: geodesic, diameter, paths, density, centrality and modularity.

6.2. Basic Concepts

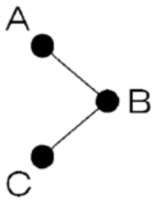
In a network, *nodes* are also referred to as *vertices* or *points*. *Connections* are typically also referred to as *ties, links, relations, lines* or *edges*. Ties may be *one-way* or *two-way*. Two-way ties are also referred to as *directed* and one-way links are referred to as *undirected*. The numerical value of ties may be *binary* (0 or 1), denoting whether a link exists or not or *variable* and represented by integers or real numbers.

Ties may also be *multiple category/parameterised* representing multiple sub-parameters in the connection. Thus, ties may be modelled with software by means of data objects. Networks are typically represented graphically as dot and lines or as a matrix.

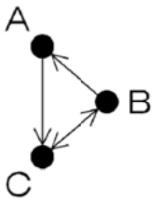
6.2.1. Graphical Representation

As mentioned above, in the graphical representation of a network, nodes are represented as filled or unfilled circles or shapes typically labeled with letters, numbers or names; ties are represented as connecting lines, directed shown with arrows, undirected without. A directed graph is also referred to as a *digraph*; as follows:

Sample Network 1 - Graph



Sample Network 2 - Digraph



6.2.2. Matrix Representation

The following matrix maps a network of three actors, A, B and C, in which the links are *binary* and *undirected*. Links are assigned a value which is either, *binary* (0 or 1), denoting whether a link exists or not, in which case the values in the matrix cells are either 0 or 1. Links may also be a *multi-variant value* or *multiple category nominal measure* representing multiple sub-parameters in the connection, in which case the values in cells may be integers or real numbers.

Sample Network 1 – Undirected

	A	B	C
A	-	0	1
B	0	-	1
C	1	1	-

The preceding matrix may also be represented as follows:

	A	B	C
A	-	0	1
B	-	-	1
C	-	-	-

Notice that the total number of potential connections is (3 x (3-1)) / 2 = 3, thus:

	A	B	C
A	-	0 [1]	1 [2]
B	0 [1]	-	1 [3]
C	1 [2]	1 [3]	-

The following matrix shows *directed* data in which some links are not reciprocated.

Sample Network 2 – Directed

	A	B	C
A	-	0	1
B	1	-	1
C	0	1	-

A group of three actors, A, B and C, have 3 x (3 -1) = 6 potential connections. The subtraction of 1 from the multiplier excludes self-ties from the equation, as illustrated in the following table:

	A	B	C
A	-	0 [1]	1 [2]
B	1 [3]	-	1 [4]
C	0 [5]	1 [6]	-

Potential links that are not links correspond to 0 cells in the matrix.

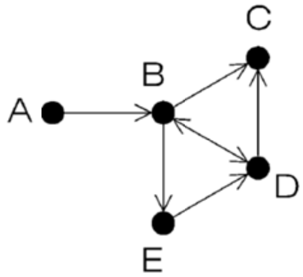
6.3. Properties of Networks

The quantifiability of networks gives rise to the calculation of network properties for which the computational power of software can be harnessed. This research project is proposed to be software intensive. That is, the capturing of raw data, conversion to network data, calculation of network properties and assessment of outcomes is envisaged to be handled predominantly by means of software. In the following section, various properties of networks are discussed together with explanation of the algorithms involved in their calculation.

6.3.1. Geodesic & Diameter

In network analysis, several types of distances between nodes are measured according to various trajectory definitions, summarised in the table below. Consider the following graph.

Network 3



The *length*, according to each definition, is the number of connections passed through.

If a trajectory begins and ends with the same actor then it is referred to as *closed*.

An undirected network will generally contain more potential trajectories than a directed equivalent because each link can carry two directions of flow.

Distances Between Actors (Hanneman and Riddle, 2005)

Path Type	Definition	Example from Network 3
Walk	Any unbroken trajectory between two actors. Links and actors can be passed through any number of times. A closed walk is called a *cycle*.	ABEDBE
Trail	A walk in which each connection can be passed through only once.	ABEBD
Path	A walk in which each connection and each actor can be passed through only once.	ABEDC
Geodesic	The shortest possible path between two actors.	From E to C is EDC.

Dimensional Properties of Actors & Networks (Hanneman and Riddle, 2005)

Property	Definition	Example from Network 3
Eccentricity	An actor's largest geodesic distance.	Actor A's largest geodesic is 2, which is the same for ABC, ABD and ABE.
Diameter	A network's largest geodesic.	Several cases: ABC, ABD, ABE, BDC, BED, DBC, DBE, EDB, EDC

Where multiple cases satisfy the geodesic and diameter measures there is network *redundancy,* which is indicative of efficiency. The more redundancy, the higher the likely level of efficiency because there is more than one option for flow connection.

6.3.2. Density

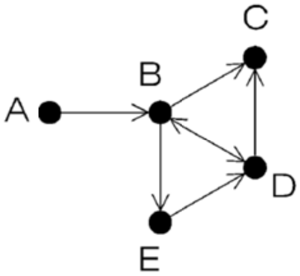
The density of a network is the extent of links present in a network relative to the number of potential links.

In matrix representation, network density is the extent to which cells have non-zero values, the ratio of 0s to 1s in the binary connectivity matrix. In graphical terms, network density is the extent to which dots are connected by lines. Density is related to network size in that the number of potential connections increases exponentially with network size, that is, number of actors. Therefore, the tendency for lower densities also increases.

6.3.3. Density & Volatility

Density is also related to statistical volatility. The standard deviations associated with connection and non-connection may be thought of as interchangeable with an intuitive notion of volatility and predictability of a network. To illustrate, consider the following network.

Sample Network 3



The corresponding matrix is:

	A	B	C	D	E
A	-	1	0	0	0
B	0	-	1	1	1
C	0	0	-	0	0
D	0	1	1	-	0
E	0	0	0	1	-

The data is directed binary data, hence an asymmetrical matrix. However, directed networks also have a concurrent undirected dimension, represented by an *adjacency matrix* containing the undirected links for the network, which in this case is the following:

	A	B	C	D	E
A	-	1	0	0	0
B	1	-	1	1	1
C	0	1	-	1	0
D	0	1	1	-	1
E	0	1	0	1	-

A simple calculation of undirected density yields the mean density of the network, thus:

Total number of possible ties: 10

Ties present: 6

Overall network density: 6 / 10 = 0.6

Generally, for directed data, the maximum number of ties is n(n-1) where n is the number of actors. Therefore, for undirected data, it is n(n-1)/2, in this case 5 x 4 /2 = 10.

Density factors for each actor can be analysed in turn. For each actor, the maximum number of ties is n-1, in this case 5 -1 = 4:

	(a) **No. of Ties**	**(b)** **Possible No. of Ties**	**(c)** **a / b**
A	1	4	0.25
B	4	4	1
C	2	4	0.5
D	3	4	0.75
E	2	4	0.5

The value of a / b is therefore the density of each actor's *ego-network* or *neighbourhood*, the sub-network comprising a node and its adjacent nodes. In terms of the matrix, this is a node's *vector* – the column or row associated with a node.

The mean of the entire set of ego-networks in a network is:

(0.25 + 1 + 0.5 + 0.75 + 0.5) / 5 = 3 / 5 = 0.6

This is the same as the mean density from the calculation of overall density:

6 / 10 = 0.6.

Notice that the density for each actor is numerically synonymous with the mean of that actors binary linkage data.

For example, the set of binary linkage values for actor A is:

{1, 0, 0, 0}

As a distribution of values, the mean is:

(1 + 0 + 0 + 0) / 4 = 0.25

This is numerically equal and the same calculation as density.

1 tie present / 4 possible ties = 0.25

Considering actor A's network data as a distribution of values, the variance can be calculated as follows:

Node	**Value**	**Value – Mean**
B	1	1 – 0.25 = 0.75
C	0	0 – 0.25 = -0.25
D	0	0 – 0.25 = -0.25
E	0	0 – 0.25 = -0.25
∑|x-m|		1.5
Variance ∑|x-m| / (n-1)		1.5 / 4 = 0.38

Similarly, the standard deviation can be calculated as follows:

Node	**Value**	**(Value – Mean)^2**
B	1	$(1 - 0.25)^2 = 0.56$
C	0	$(-0.25)^2 = 0.06$
D	0	$(-0.25)^2 = 0.06$
E	0	$(-0.25)^2 = 0.06$
$\sum (x-m)^2$		0.74
Standard Deviation $\sqrt{(\sum (x-m)^2 / (n-1))}$		$\sqrt{(0.74 / 4)} = 0.43$

Repeating this process for each actor yields the following:

	No. of Ties	**Mean/ Density**	**Variance**	**Standard Deviation**
A	1	0.25	0.38	0.43
B	4	1	0	0
C	2	0.5	0.5	1
D	3	0.75	0.38	0.43
E	2	0.5	0.5	1

Every scenario for n=5 is represented in this example network.

n-1 = 4

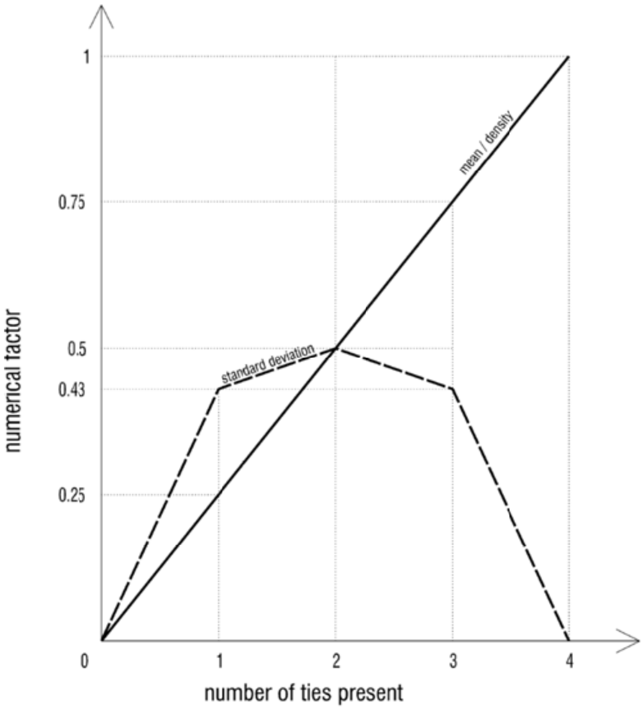
n-2 = 3

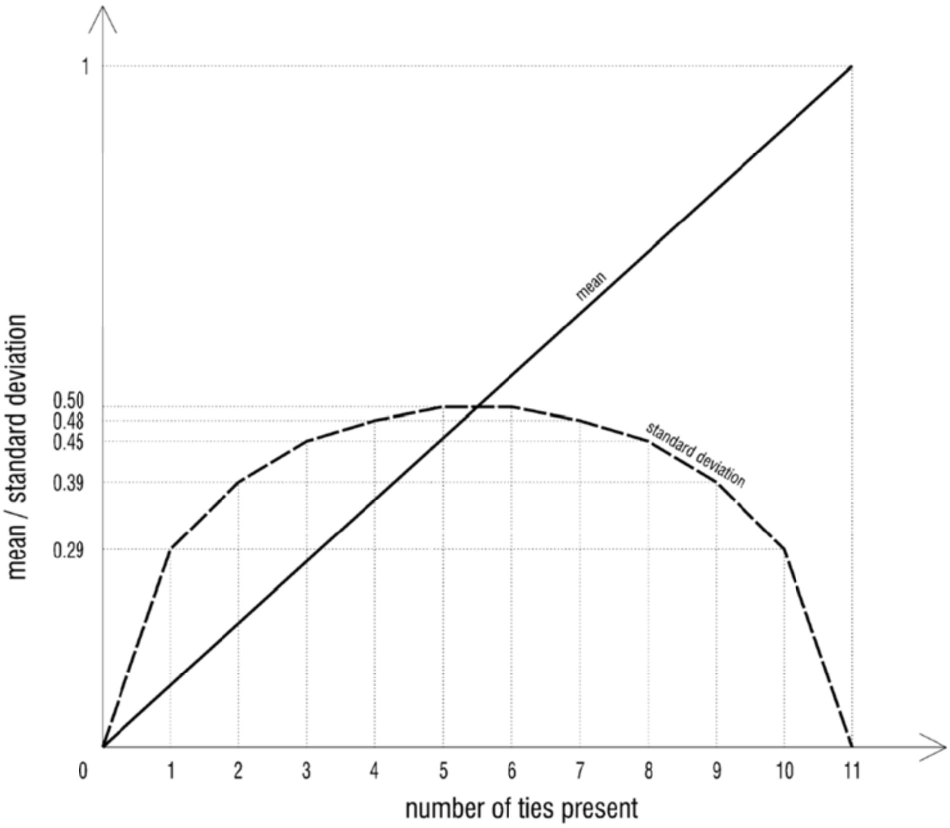
n-3 = 2

n-4 = 1

The only case not represented is the zero case {0,0,0,0}, which obviously yields all zero values.

Plotting variance and standard deviation against density of the distribution of ego-network linkage data yields the following graph:





Various analyses can be performed on these graphical and numerical results. For example, the standard deviation curve is steep towards the beginning and end and is, therefore, in the upper regions for most of the domain. It can be interpreted from this that any actor's density volatility is more likely to be higher than lower.

Other observations:

The standard deviation in binary data is not variable relative to the mean but is a function of the mean.

As standard deviation is generally regarded as an indicator of the degree of certainty or confidence in data, 0 being maximum certainty whilst 0.5 being minimum, in binary data the mean is a likewise indicator. As mean values approach 0 or 1, the standard deviation approaches 0 and the degree of certainty approaches a maximum. As mean values approach 0.5, the standard deviation also approaches 0.5 and the degree of certainty approaches a minimum.

Thus, the overall density of the network is an indicator of a certain *volatility* associated with the network, which, in social network analysis, for example, may translate into a certain *predictability* of actors *"in their behaviour toward any given other actor" (Hanneman and Riddle, 2005)*.

Evidently, as there is also a relationship between network size and density, network size can be thought of as carrying inherent degree of predictability, which, as the size of a network increases, would move through a threshold into a range of low predictability and then, irrevocably through another threshold beyond which the density would always approach 0 and the predictability would, therefore, theoretically increase indefinitely. This increasing *static* quality of large social networks can also be seen in terms of *inertia* associated with large organisations.

6.3.4. Application of Network Measures to Ego-Networks

By considering the network measure of density, the above example demonstrates the technique of applying an algorithm, usually a summation function (or integral), to each actor in a network and generating various types of numerical and graphical results. This may be performed separately on ingoing and outgoing links, as well as on a network's associated adjacency matrix. Network measures generally may be applied in this way, yielding various types of insight into a network.

6.4. Centrality & Centralisation

According to Freeman (1977), *"the original application of the centrality idea was in the study of communication in small groups. Bavelas (1950), Leavitt (1951), Shaw (1954) and Goldberg (1955) all reported studies of speed, activity and efficiency in solving problems and personal satisfaction and leadership in small group settings. All of these variables were demonstrated to be related to centrality in* *some way"*.

What is referred to here as "*centrality"* can also be referred to as *"centralisation"*, a property of a network as whole as distinct from that of a node relative to its network.

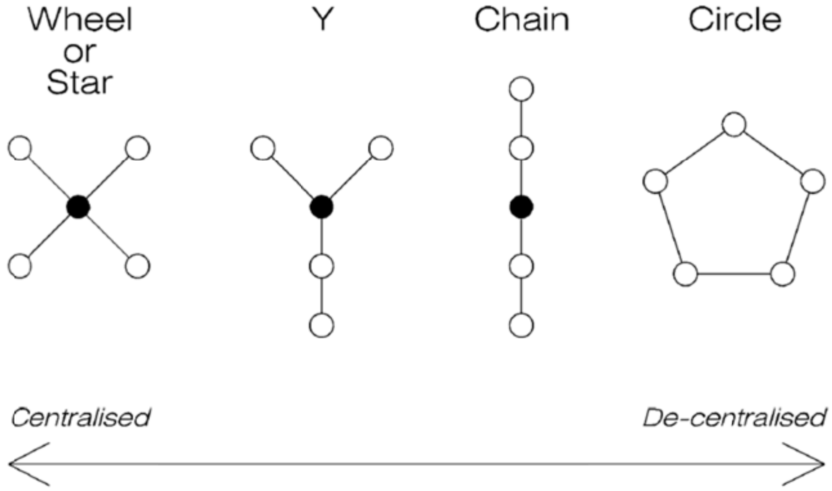
Historically, the study of centrality in modern social network analysis begins with the study of centralisation in the work of Bavelas and Leavitt.

6.4.1. The Bavelas-Leavitt Experiment

The Bavelas-Leavitt experiment, conducted in the 1940s at MIT, sought to investigate the effect of network structure on the performance of a group. The general conclusion was that highly-centralised structures resulted in lower completion times, therefore group performance is proportional to centralisation.

The experiment involved assigning a puzzle to a group of 5 people arranged in a predetermined structure and measuring the time it took for everyone to solve the puzzle. Each person selected 5 out of 6 symbols. The objective was for all members to find out a symbol common to the whole group by exchanging information with each other via a specific communication system by which those exchanges were made to conform to predetermined network structures. The communication system involved people in cubicles passing colour-coded written messages through slots in the cubicle walls configured to permit certain connections and not others thereby establishing the relevant structure. The process was timed and repeated with different network structures, of varying centralisation, such as the following.

Early Work on Structural Centrality as a Determinant of Performance



Filled nodes denote those with the highest degree of centrality.

Various comments can be made in hindsight about this experiment and conclusions.

The quantitative efficiency of communication is the output variable being measured, that is, the time taken for everyone to have the same relevant information. This is assumed to be proportional or synonymous with performance, an assumption which nowadays might be brought into question as the definition of the term "*performance"* might be context specific and may or may not depend on communication efficiency.

From a coordination point of view, there is *interdependency* of information consistency between members of the group, which is *managed* by means of the imposition of structure. Coordination itself is only relevant in the experiment insofar as the ranking of structures in terms of communication efficiency. The application value for real-world coordination problems is presumably that, upon such results, the definition of coordination is seen as the selection and imposition of structures according to their efficiency ranking, nowadays a relatively narrow definition.

The task itself is not varied in the experiment but considered a constant and immaterial to what is being investigated. In a sense, it might be said that the task was reverse engineered in order to contain the interdependency of information consistency for the quantification of communication efficiency. Different results may have been obtained by changing the nature of the task.

The needs of the Bavelas-Leavitt experiment called for ingenuity in the design of the apparatus, which nowadays can be achieved with web based techniques.

The Bavelas-Leavitt experiment initiated research into the concept of structural properties determining having significance and an effect on group behaviour independently of other factors. This can be seen as a kind of structural determinism.

6.4.2. Post Bavelas-Leavitt

In response to the Bavelas-Leavitt experiment, Guetzkow and Simon (1995) suggest that a *"sharp distinction be made between: (a) the effects of communication restrictions upon performance of the operating task; and (b) the effects of the restrictions upon a group's ability to organise itself for such performance"* and showed that *"centralized structures (e.g. wheel) improved the diffusion of information in simple tasks while decentralized structures (e.g. circle) delayed the diffusion of information"* (Cummings & Cross 2003). Later, Shaw (1964) demonstrates that *"groups with decentralized communication nets took less time to finish complex tasks than groups with centralized communication nets."*

With these and other studies, post-Bavelas-Leavitt development of social network theory sees translation of the notion of structural determinism of a network, in terms of centralisation, to that of individual nodes in a network, and thus increasing emphasis on centrality. For example, Lois Rogge demonstrates that leadership behaviour of an actor in a network can also be a function of that actor's structural position within the network (Borgatti, 1997).

6.4.3. Linton Freeman

In discussing the differences between mathematical simulation and computer simulation, Freeman (1971) suggests that whilst mathematical simulations provide abstract general solutions, the value of which is *res ipsa loquitur*, computer simulations *"are an attractive alternative to mathematical simulation"* because they provide specific *"numerical solutions which themselves have utility value"* and with *"equal strength and power of [mathematical] derivation"*.

Freeman (1971) argues that mathematical and computer simulations form the basis for ***"systematic cummulative theoretical systems"***, as in *"normal science"*, in contrast to behavioural science up to that point, a ***"descriptive"*** body of knowledge tending to *"develop rather than solve models"*. *"Most current knowledge in the social and behavioral sciences is descriptive. Much of our collective effort during the past several decades has been empirical. We have surveyed and experimented. We have observed, tested and measured. We have checked validity and reliability, devised elegant sampling designs and employed powerful statistical tests. We have done everything but organize our findings into systematic cumulative theoretical systems."* (Freeman, 1971)

Freeman laments that *"the sad fact is that application of descriptive information about past observations is of little utility in the attempt to solve new problems unless that information is organized into interrelated general principles"* and that *"we cannot hope to* ***explain*** *behavior as long as we are content with mere description"*. (Freeman, 1971)

The contribution of Freeman was in addressing this formidable conundrum and ultimately succeeding in establishing a pivotal point for social network analysis to become the systematic cumulative theoretical system that it is, vis-à-vis his formulation and compiling of centrality measures based on three basic types of centrality concepts (Freeman, 1979):

1. Degree.
2. Betweenness.
3. Closeness.

In doing so, Freeman also establishes a clear distinction between "*point centrality*", the *centrality* of a node within a network, which can be absolute or relative, and network *centralisation* which he terms *"graph centrality"*.

6.4.4. Degree Centrality

Degree centrality is an enumeration of a node's adjacencies. Freeman proposed Nieminen's (1974) algorithm as the most *"simple, natural and perfectly general measure of centrality based on degree"* (Freeman, 1979), as follows:

$$C_D(p_k) = \sum_{i=1}^{n} a(p_i, p_k)$$

$C_D(p_k)$ represents the degree centrality of point p_k.

$a(p_i, p_k)$ denotes the binary value of the link between points $p_i$and p_k, that is, if $p_i$and $p_j$are connected by a line then $a(p_i, p_k) = 1$, otherwise $a(p_i, p_k) = 0$.

The absolute degree centrality of a node is the sum of the link values between the node and all other nodes in a network. The algorithm is a simple summation of binary values similar to the one for the density of a node within its ego-network (discussed above).

The relative degree centrality of a node is its absolute degree centrality relative to the maximum number of links a node can have in a network, $n - 1$, and thus equal to the density of a node within its ego-network.

$$C'_D(p_k) = \frac{\sum_{i=1}^{n} a(p_i, p_j)}{n-1}$$

6.4.5. Degree Centralisation

Degree centralisation of a network is the sum of the differences between the largest degree centrality value, $C_D(p^M)$, and all other degree centrality values in that network, $C_D(p_i)$, as a ratio of that of a star network of the same size:

$$C_D = \frac{\sum_{i=1}^{n}[C_D(p^M) - C_D(p_i)]}{max\sum_{i=1}^{n}[C_D(p^M) - C_D(p_i)]}$$

The denominator can be simplified by considering that, in a star network the maximum degree centrality is that of the central node, which is $C_D(p^M) = n - 1$, and the value of all other nodes is $C_D(p_i) = 1$. Consequently, the value of the difference for each node in a star network (except the central one) is $(n - 1) - 1 = n - 2$ and the sum of the differences with the central node is:

$$(n-2)(n-1) = n^2 - 3n + 2$$

Therefore, degree centralisation is:

$$C_D = \frac{\sum_{i=1}^{n}[C_D(p^M) - C_D(p_i)]}{n^2 - 3n + 2}$$

6.4.6. Betweeness Centrality

According to Freeman (1977), *"the earliest intuitive conception of point centrality in communication was based upon the structural property of* ***betweenness****"*, which was *"introduced by Bavelas (1948) in his first paper on the subject"*. Although varying conceptions of betweenness centrality by Shimbel (1953), Shaw (1954) and Cohn & Marriot (1958) are proposed subsequent to Bavelas, Freeman (1977) suggests that, *"the importance of this conception of point centrality [betweenness] is in the potential for a point for* ***control*** *of information flow in the network. Positions are viewed as structurally central to the degrees that they stand* ***between*** *others and can therefore facilitate, impede or bias the transmission of messages."*

Freeman (1977) notes that, *"although earlier intuitive statements conceived of point centrality in terms of betweenness, measures based on this concept have not been reported",* but that "*such measurement, however, is rather straightforward"* and then proceeds to expound his measure of betweenness centrality.

Freeman's measure of betweenness centrality is based on the premise that the potential for betweenness control is mainly associated with geodesic paths, hence the initial formulation that if the number of geodesics between two nodes, $p_i$and p_j, is g_{ij}, the probability of a message or flow occurring along one of those geodesics is:

$$\frac{1}{g_{ij}}$$

If $g_{ij}(p_k)$ is the number of geodesics linking nodes $p_i$and $p_j$which contain the point p_k, then the betweenness of node $p_k$with respect to nodes $p_i$and p_j, denoted as $b_{ij}(p_k)$, is:

$$\frac{g_{ij}(p_k)}{g_{ij}}$$

The absolute betweenness of node $p_k$is therefore the sum of the betweenness values between all other points in the network:

$$C_B(p_k) = \sum_{\substack{i,j,k \leq n \\ i \neq j \neq k}}^{n} \frac{g_{ij}(p_k)}{g_{ij}}$$

The maximum betweenness centrality that any node can have in the network is the same as betweenness centrality of the central node in a star network of the same size. This is equal to the maximum number of possible connecting paths in a network, $n(n-1)/2$, because in each case, the betweenness value is 1, less those in which the node itseld is an endpoint, $n-1$, hence:

$$\frac{[n(n-1)]}{2} - [n-1]$$

$$=\frac{n^2-3n+2}{2}$$

The relative betweenness centrality of a node, $C'_B(p_k)$, is the ratio of its absolute betweenness centrality, $C_B(p_k)$, to the maximum betweenness centrality that any node can have in the network, that is:

$$C'_B(p_k) = \frac{2C_B(p_k)}{n^2 - 3n + 2}$$

6.4.7. Betweeness Centralisation

Freeman (1979) defines betweenness centralisation of a network as *"the average difference between the relative centrality of the most central point, $C_b(p^M)$, and that of all other points"*. In other words, the sum of the difference between the highest relative betweenness centrality in the network and all other betweenness centralities, divided by the number of such differences, that is:

$$C_B = \frac{\sum_{i=1}^{n}[C'_B(p^M) - C'_B(p_i)]}{n-1}$$

Substituting relative betweenness centrality expressions in terms of $C_B(p^M)$ and $C_B(p_i)$, that is,

$$C'_B(p^M) = 2C_B(p^M)/n^2 - 3n + 2$$

and

$$C'_B(p_i) = 2C_B(p_i)/n^2 - 3n + 2$$

yields the following for Freeman's betweenness centralisation of a network:

$$C_B = \frac{\sum_{i=1}^{n}[C_B(p^M) - C_B(p_i)]}{n^3 - 4n^2 + 5n - 2}$$

6.4.8. Closeness Centrality

With reference to closeness centrality measures by Bavelas (1948), Beauchamp (1965), Sabidussi (1966) Moxley and Moxley (1974) and Rogers and Agarwala-Rogers (1976), Freeman (1979) suggests Sabidussi (1966) as the *"simplest and most natural"* measure of closeness centrality of a node, namely that the closeness centrality of point p_k, $C_C(p_k)$, is the inverse of the sum of the lengths of all geodesic distances connected to the node:

$$C_C(p_k) = [\sum_{i=1}^{n} d(p_i, p_k)]^{-1}$$

Where $d(p_i, p_k)$is the length of the geodesic between point $p_i$and p_k.

Freeman (1979) explains that Bavelas (1950) and Leavitt (1951) interpret closeness centrality of a node as the extent to which it is not subject to other nodes in the relaying of messages whilst Bavelas (1948), Beauchamp (1965), Hakimi (1965) and Sabidussi (1966) conceptualise closeness centrality as a measure of time and cost efficiency on the presumption that time and cost efficiency, hence closeness, is inversely proportional to the number of links required for a node to reach all other nodes simultaneously.

Freeman (1979) attributes the algorithm for relative closeness centrality resolved by Bauchamp (1965), defined as the ratio of the absolute closeness centrality of a node to the total number of possible links to other nodes that it may have network, that is:

$$C'_C(p_k) \quad = [\frac{\sum_{i=1}^{n} d(p_i, p_k)}{n-1}]^{-1}$$

$$= \frac{n-1}{\sum_{i=1}^{n} d(p_i, p_k)}$$

6.4.9. Closeness Centralisation

Freeman (1979) suggests that closeness centralisation is *"some sort of index of homogeneity of distance"* and proceeds to develop a measure of closeness centralisation based on the rationale applied to betweenness centralisation. That is, the numerator is the sum of the differences between the maximum case node centrality present versus all other cases present in the network.

$$\sum_{i=1}^{n} [C'_C(p^M) - C'_C(p_i)]$$

In the maximum centrality scenario, the star network, the maximum sum of geodesics of the central node is 1 and of all other nodes is $1 + 2(n-2)$, that is, 1 to the central node plus 2 to all other nodes which are enumerated by (n-2), n less the central node and the node in question. Therefore, the relative point centrality of each node other than the central one is:

$$\frac{n-1}{1+2(n-2)} = \frac{n-1}{2n-3}$$

The difference between the central node and each other node is:

$$1 - \frac{n-1}{2n-3} = \frac{n-2}{2n-3}$$

Factoring by $n-1$ gives the sum of the differences as they are all equal to each other, that is:

$$\frac{n-2}{2n-3}(n-1) = \frac{n^2-3n+2}{2n-3}$$

Therefore, closeness centralisation is:

$$C_C = \frac{\sum_{i=1}^{n}[C'_C(p^M) - C'_C(p_i)]}{(n^2-3n+2)/(2n-3)}$$

6.4.10. Phillip Bonacich & Perron-Frobenius – Eigenvector Centrality

A significant development in centrality measures was that of *eigenvector centrality*, defined by Bonacich (1972) as the principle eigenvector of the adjacency matrix of a network. It is a recursive algorithm implementing the proposition that the centrality of a node may be conceived as proportional to the centralities of the nodes to which it is connected, thus reflecting a broader notion that centrality ought to be moderated somehow by adjacent centralities, arising from a basic intuition that the centrality of a node with connections to nodes with low centralities is not equivalent to one with connections to nodes having high centralities.

The eigenvector centrality, e_i, of a network with nodes, a_{ij}, is:

$$e_i = \frac{1}{\lambda}\sum a_{ij}e_j$$

Where λ is the maximum eigenvalue.

A descriptive algorithm for calculating eigenvector centrality is suggested by Borgatti (http://www.analytictech.com/networks/centrali.htm) is:

1. Start by assigning centrality score of 1 to all nodes (e_i=1 for all i).
2. Recompute scores of each node as weighted sum of centralities of all nodes in a node's neighbourhood: $e_i = a_{ij}e_j$
3. Normalize e_i by dividing each value by the largest value.
4. Repeat steps 2 and 3 until values of e stop changing.

The basis for this measure is the Perron-Frobenius theorem, which states that the principle eigenvector of a real square matrix, that is, the eigenvector with the maximum corresponding eigenvalue, must have positive members.

6.4.11. Borgatti & Everett

Borgatti and Everett (2006) propose that *"measures of centrality summarize a node's involvement in or contribution to the cohesiveness of the network"* and identify a 4x4 classification system as opposed to Freeman's (1979) three-tier classification. Instead of three types of measures, *degree*, *closeness* and *betwenness*, there is a primary classification of algorithm according to whether it is *radial* or *medial*, referred to as *type of involvement* or *walk position*, and a secondary classification according to *volume* and *length,* referred to as *walk property*.

Centrality Measures

Measure	Overview of Algorithm	Network Interface Features
Degree	Descriptive type: *Radial/Volume*. Definition: This is simply the total number of links from an actor (*out-degree*) or to an actor (*in-degree*).	Potential for activity within the network.
Closeness	Descriptive type: *Radial/Length*. Definition: The total geodesic distance from an actor to all other actors.	Potential for independence from control.
Betweeness	Descriptive type: *Medial/Volume* Definition: The number of trajectories which pass through an actor.	Potential for control of communication within the network. Brokerage potential.
For descriptive types, refer Borgatti and Everett (2006) p.11. For network interface features, refer Hossain (2009) p.26.		

The distinction between radial and medial is considered to be more profound than that between volume and length (Borgatti and Everett, 2006), hence the primary/secondary designation. Within the volume measures, there is also a distinction made between *walk type*: walk, trail, path or geodesic. Moreover, radial and medial measures are considered to be complementary in the sense that an aggregate approach should provide a more comprehensive result. In principle, the total involvement of a node should be thought of as a combination of its involvement in a radial manner (*degree* and *closeness*) and a medial one (*betweenness*) (Borgatti and Everett, 2006).

Borgatti and Everett propose that, ultimately, *"the key underlying concept [of centrality] is that of dyadic cohesion—the social proximity of pairs of actors in a network" (Borgatti and Everett, 2006. p.482),* and that *"there are two fundamental ways of analyzing cohesion. One is to seek regions of the network that are more cohesive than others—a focus on the pattern of cohesion. This constitutes the field of cohesive subgroups. The other is to attribute to individual nodes their share of responsibility for the cohesion of the network—a focus on the amount of cohesion. This constitutes the field of centrality measures. Within that, two fundamental approaches are discernable—the radial approach that directly partitions total cohesion by node, and the medial approach that assesses a node's contribution to cohesion by removing it. The other* *fundamental distinction—between volume and length measures—is essentially an argument about the meaning of cohesion" (Everett and Borgatti, 2000).*

6.5. Modularity – Groups/Sub-structures

From the point of view of sub-structures in social networks, a structure that is not a sub-structure is a misnomer because everyone has some connection to the rest of humanity, even if purely on the most basic level of connection, through bloodline. Even all of humanity alive at the present time cannot be considered strictly in isolation from the previous generation and so on back to the first man and woman.

Structure, therefore, is a recursive term, synonymous with sub-structure. The distinction arises, however, in the notion of structures within structures and the key question is what determines the boundary of inclusion and exclusion. This is the concern of groups or sub-structures in network analysis.

Borgatti recognises two types of methods for the investigation of sub-structures: data reduction and theoretical.

Data reduction, he suggests, can be undertaken in various ways, such as:

1. Identify dense regions within the network.
2. Cluster analysis of adjacency matrix.
3. Cluster analysis of other cohesion index such as geodesic or maximum flow.

This is performed with the aid of computer software, and in this project, a fourth means is utilised – the eigenvalues produced by single value decomposition (Sarkar et al., 2014).

Hanneman and Riddle (2005) outline two basic types of theoretical sub-structures, summarised below:

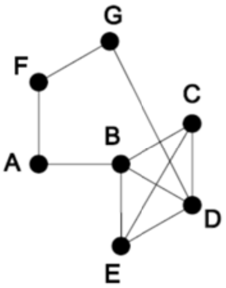
Bottom-up: N-Cliques, N-Clans, K-Plexes, K-Cores and F-Group.

Top-down: Components, Blocks & Cut Points, Lambda Sets & Bridges, Factions.

In both theoretical and data reduction techniques, cluster analysis is the principle mechanism for defining the criteria for sub-structure boundaries and hence sub-structure constituency.

Consider the following network:

Sample Network 4



The adjacency matrix is:

	A	B	C	D	E	F	G
A	-	1	0	0	0	1	0
B	1	-	1	1	1	0	0
C	0	1	-	1	1	0	0
D	0	1	1	-	1	0	1
E	0	1	1	1	-	0	0
F	1	0	0	0	0	-	1
G	0	0	0	1	0	1	-

6.5.1. Cliques

The simplest definition of a substructure is one in which all nodes are connected to each other, in the sample network above, *BCDE*. This is sometimes referred to as a *clique*. A clique is clearly distinguishable from its network context and conceptually simple. However, it is an extreme case, the other extreme being a completely unconnected set of nodes. This is classified as a bottom-up approach because it begins from the frame of reference of a dyad. Other sub-structure bottom-up approaches are essentially relaxations of criteria from this extreme case.

6.5.2. N-Cliques

An *N-Clique* is a structure in which all actors are connected by a maximum connection length of *n*. For example, if n=2 in sample network #4, then the entire network is an N-clique because all nodes within that structure are at most 2 nodes from any other node. A co-matrix membership shows the lengths of connections between nodes:

	A	**B**	**C**	**D**	**E**	**F**	**G**
A	-	1	2	2	2	1	2
B	-	-	1	1	1	2	2
C	-	-	-	1	1	3	2
D	-	-	-	-	1	2	1
E	-	-	-	-	-	3	2
F	-	-	-	-	-	-	1
G	-	-	-	-	-	-	-

Cluster analysis reveals that all members in the network may be considered part of the same N-clique.

Level	**A**	**B**	**C**	**D**	**E**	**F**	**G**
3			▨		▨	▨	
2	▨	▨	▨	▨	▨	▨	▨
1	▨	▨	▨	▨	▨	▨	▨

6.5.3. N-Clans

An *N-Clan* restricts the definition of an N-clique, requiring that connections must occur through members of the group. So, in sample network #4, the connection between A-G and C-F would not qualify, thus excluding

F and G from the N-clan *ABCDE.*

6.5.4. K-Plexes

In a *K-Plex* group, members qualify if they have connections to all nodes in the group less k number connections. If k=1, then a member qualifies by having connections to all but 1 member in the group.

In sample network #4, *ABFG* would be a K-plex where k=1.

6.5.5. K-Core

A *K-Core* is a group in which a member is connected to at least k members of the group. If k=2, then a member qualifies by having connections to at least 2 other members of the group.

In sample network #4, *ABDFG* would be a K-plex where k=2.

6.5.6. Components

A component is an isolated network or node, that is, one with no connections to other networks. Components are the most extreme case amongst the top-down approaches.

In sample network #4 there are no components except the entire network itself.

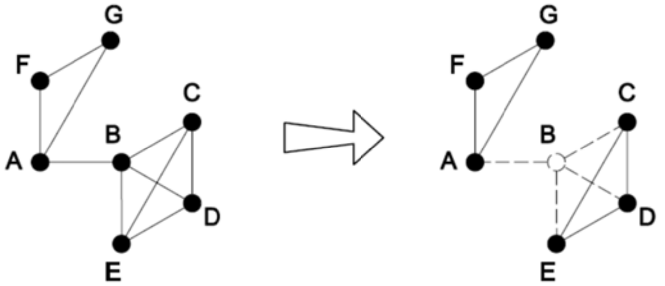
Further top-down approaches relax the definition of a component and thereby enable the identification of sub-structures with varying degrees of isolation.

6.5.7. Blocks & Cutpoints

A *cutpoint* is a node, which, if removed, would sever two or more sections of a network into isolated networks or *'components'*. Sub-structures connected to each other by cutpoints and hence subject to them for connectivity, are called *blocks*.

In sample network #4, no such cutpoint exists. However, in the variant example below, *B* is a cutpoint, and *AFG* and *CDE* are blocks, two triads.

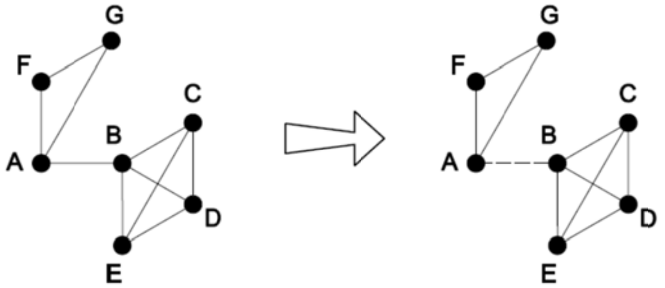
Sample Network #5 – Cutpoint B



6.5.8. Lambda Sets & Bridges

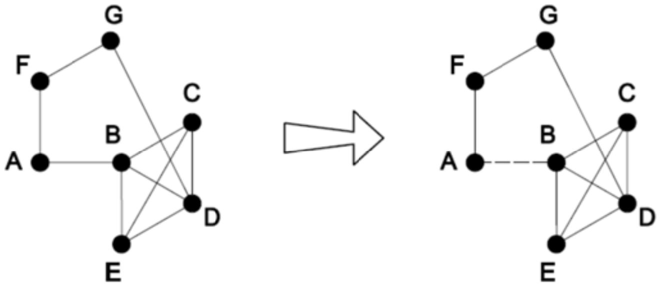
Lambda sets and bridges are analogous to blocks and cutpoints, respectively, except that the definition applies to connections instead of nodes. In simple terms, a *bridge* is a connection, which, if removed, would sever two or more sections of a network into isolated components. Sub-structures connected to each other by bridges and, hence, subject to them for connectivity, are called *lambda sets*. In sample network #5, AB is '*bridge',* which, if removed, would divide the network into the '*lambda sets' AFG* and *BCDE*.

Sample Network #5 – Bridge AB



However, lambda sets can also be a continuous measure. Consider sample network #4. By removing AB, the flow is greatly disrupted but flow can still occur through DG. Nevertheless, AFG and BCDE may still be considered lambda sets with bridge AB if the value of cohesion may be a real number between 0 and 1.

<u>Sample Network #4 – Bridge AB</u>



Appendix 2 – Granovetter & Burt

7. Appendix 2 – Granovetter & Burt

Granovetter's (1973) opening comments identify a need to model macro-level phenomena such as diffusion in terms of micro-level principles, hence, the importance of triads in the development of his theory, which commences with a basic assumption that if actors A and B are friends and C is a friend of one of them, then the stronger the tie between A and B, the more likely it is that C will become friends with the other. The strength of a tie is seen as the aggregation of time, emotional intensity, intimacy and reciprocal services.

Granovetter proposes that, consequently, the stronger the tie between A and B, the greater the overlap in the union set of A and B's friends.

The basic assumption that if A-B and, say, A-C are strong friendship ties, then B-C is likely to become a friendship tie is explained in terms of time and similarity.

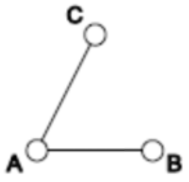
Firstly, if A-B and A-C are strong ties, it means the time they spend together is high, presumably relative to the total amount of time A has to spend with friends, and mutually related in that if A-B spends more time then less time is available for A-C. This increases the likelihood of B and C meeting each other.

The second part of this assumption is the assumption, citing various empirical evidence, that a high correlation exists between tie strength and similarity between two individuals. Thus if A-B and A-C are strong ties, there is also a high likelihood of similarity between B and C and, therefore, a high likelihood that B-C form a friendship tie upon B and C meeting each other.

Furthermore, Granovetter (1973) suggests that if B-C does not become a positive tie, there is strong evidence that there will develop a *"psychological strain"* on the situation arising from incongruency of feelings.

Granovetter (1973) proposes that, based on these assumptions, with the caveat that the evidence is *"less* *comprehensive than one might hope"*, the scenario of strong ties between A-B and A-C existing concurrently with no tie whatsoever between B-C (as in the following diagram) is highly unlikely and that there must exist a kind of weak tie between B-C by virtue of the strong adjacent ties, effectively, weak ties are synonymous with second degree ties.

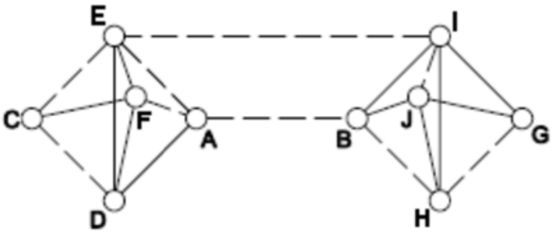
Granovetter's "forbidden triad"



The notion of bridges is brought to bear on the argument with the proposition that *"all bridges are weak ties"*. According to Granovetter, strong ties cannot be bridges because, if two strong adjacent ties are always closed by a weak tie, there is always an alternative route to an adjacent tie via a two degree step along a strong and weak tie combination. Consequently, all bridges are weak ties although not all weak ties are bridges.

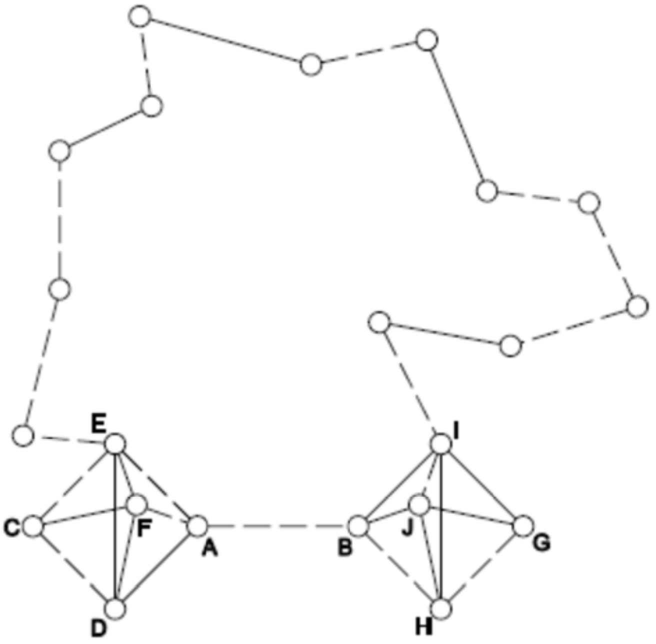
An alternative route can render a weak tie a bridge or not, depending on the length of the alternative route. For example, in the following hypothetical network, the weak tie A-B is not considered a bridge because the alternative route via A-E-I-B is not very long.

Alternative Route



Whereas in the following example, A-B would function as a bridge because the alternative route, regardless of its weak strong composition, exceeds the viable trade-off of using it.

Bridge



This diagram illustrates the fact that weak ties need not be part of a triad as in the A-B-C example above. Here, the weak tie A-B is between two nodes that have strong adjacent ties but not in a triad.

This gives rise to the conclusion that, although flow within dense networks occurs faster than between those networks, the flow between networks is dominated by weak ties. Therefore, weak ties, a micro-level phenomena, is a key factor at the macro-level.

Weak ties are considered an important factor from which an individual can benefit, such as in job seeking. In Granovetter's (1973) questionnaire study, 46% of respondents found their new jobs through a weak tie, that is, through someone they knew but did not see more often than a certain threshold.

Granovetter suggests that weak ties can also be important on the community level. Giving the example of an Italian community in Boston's West End which failed to form any organisational structure within which to oppose urban renewal development. Granovetter speculates that the reason for this failure was that, although there must have been weak ties in that community, perhaps they did not become bridges because of the lack of diversity manner in which they were formed. Contrasted with another community, which did organise and fight urban renewal development in their area, many work ties also existed in that case because people worked within the area. However, in the West End case, work ties were few because people tended to work outside the area. Granovetter proposes that, consequently, if the nature of formation and typology of weak ties can be better understood then so can this type of phenomena, which can be brought to bear in such community applications.

7.1.1. Granovetter versus Burt

According to Granovetter (1973) his theory of weak ties "does lend itself to *"elucidation of the internal structure of small groups"*. Burt et al. (2001) remarks that *"weak ties and structural holes describe the same phenomena"* and sees them as an opportunity for social capital by closing them. According to Granovetter, this should undermine the value of weak ties to the network because of their importance to diffusion.

Both theories rely heavily on the assumption that information flows within dense networks faster than between them.

Appendix 3 – Organisational Models in Management

8. Appendix 3 – Organisational Models in Management

8.1. Malone – Market/Hierarchy Models

Malone (1986; 1987) differentiates between emergent paradigms of coordination he observes within American business at the time and develops several models of coordination describing those paradigms:

1. Product hierarchies.
1. Decentralised market.
2. Centralised market.
3. Functional hierarchy.

Malone (1986) defines within each model a relationship between production costs, coordination costs and vulnerability costs:

1. *Production tasks* are *"the physical or other primary processes necessary to create the central products of the organization"*.
2. *Coordination tasks* are *"the information processes necessary to coordinate the work of the people and machines that perform the primary processes"*.
3. *Vulnerability tasks* are *"the unavoidable costs of a changed situation that are incurred before the organization can adapt to a new situation"*, also referred to as *failure*. The incorporation of vulnerability tasks in Malone's model accounts for risk and contingency.

Two essential types of coordination tasks are identified by Malone (1986) as "*simple, but fundamental, aspects of coordination"*:

1. *Product decisions: "deciding which tasks should be done to achieve the goals"*.
2. *Functional decisions:* "*deciding which processor should do each task"*.

Herein lies a parallel between Malone & Crowston's theories of coordination, social network analysis and a longstanding coordination tradition in construction projects, PERT (Program Evaluation and Review

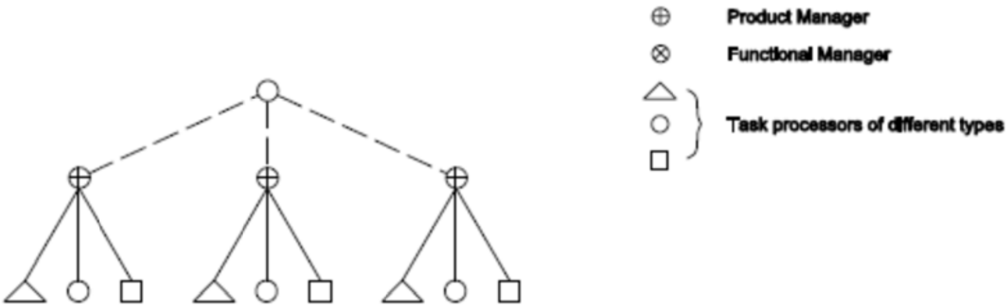
Technique). Coined in the development of the U.S. Navy's Polaris nuclear submarine project in 1957 and related to the critical path method, a PERT chart depicts activities as nodes in a network graph and links are directional dependencies from tasks to prerequisite tasks.

The two essential decisions in a PERT analysis are deciding which tasks are required (Malone's *"product decisions"*) and what is their sequential interdependency. Along with critical path analysis, resource levelling is an important allied technique within the framework of PERT. For resource levelling, the decision of who does each task (Malone's *"functional decisions"*) is fundamental. This is analogous to network analysis on a generic level, the definition of nodes and edges.

8.1.1. Product Hierarchies

A product hierarchy can be viewed as a vertically stratified structure in which each column contains a sub-hierarchy devoted to a product, geographical location, market segment, or other specialisation or *"mission-oriented lines"* Malone (1987).

Product Hierarchy



This is the form of the early automobile manufacturers where organisational divisions were each in charge of a particular car model. For example, General Motors had separate divisions for Pontiac, Chevrolet and Cadillac (Malone 1987).

Military structures are another example of structures that may be characterised as predominantly product hierarchies – army, navy, air force, etc. Within the product hierarchy, a sub-hierarchy is headed by a general manager who directs section managers and who, in turn, direct team managers and so on.

Product divisions are vertically integrated. All of the functions associated with the product division are contained within the division, design, engineering, manufacturing, finance, and so on. These resources are not shared with other divisions.

Malone (1986) summarises a typical coordination event: the division manager delegates a task to the appropriate section, which is, in turn, delegated to sub-sections. The cost of such delegation is minimal because there are pre-established delegation routes down to design and production lines.

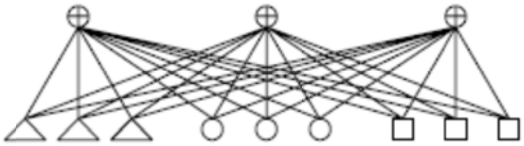
Risk of failure along a delegation trajectory only affects a division, not the entire organisation.

8.1.2. Decentralised Markets

At the other end of the spectrum are markets. In the market model, not all tasks are carried out within divisional hierarchies; they are outsourced to subcontractors.

In a decentralised market, subcontractors and buyers interface directly in tendering and transactions. There are no intermediaries.

<u>Decentralised Markets</u>



Malone (1986) suggests that, in a decentralised market, a large number of "messages" are required in tendering and transaction processes, hence the relatively high cost of coordination. In network terminology, what is being referred to here is network flow along links between nodes.

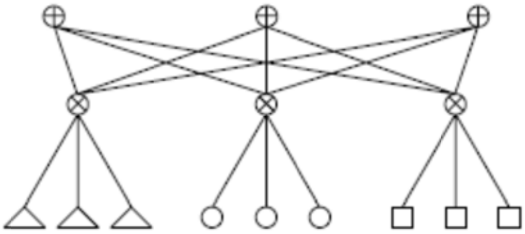
Risk of failure is again seen as limited, this time by option of terminating a failed subcontractor and replacing it with another.

8.1.3. Centralised Markets

A centralised market is also defined by outsourcing but operates with the aid of intermediaries or brokers.

In this way, the number of connections and transactions on the part of the buying organisation is significantly reduced and hence also the cost of coordination processes.

Centralised Markets



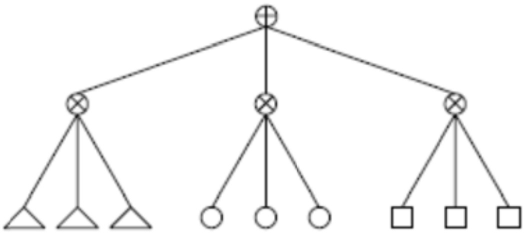
A typical task assignment in this model is via a broker who *"keeps track of the prices, capabilities and availabilities of all the subcontractors"* (Malone 1986).

The risk of failure in a centralised market, like in a decentralised market, is mitigated by the option of replacing failed subcontractors. In a centralised market, a broker can fail without affecting work production.

8.1.4. Functional Hierarchy

In a functional hierarchy, product divisions are overlaid with horizontal strata containing shared resources and services such as financial, engineering, marketing, research, etc. A reduction of input is achieved by the elimination of duplication across divisions and the opportunity for resource levelling - moving resources across divisions to fulfil varying production needs.

Functional Hierarchy



The coordination overhead associated with a functional hierarchy is considerably more than in a product hierarchy because delegation operates between layers of management rather than within the one hierarchy. When a division manager delegates to a functional department which is managed as a separate structure with its own head manager, the coordination transactions required involve those within the division, within the functional department and those between the two.

Malone (1986) gives examples of possible failure scenarios in the context of a car manufacturer.

The first is the failure of a car dealership, that is, a subcontracted activity, hence, a market type of failure, which is also mitigated as in a market structure, by replacement of subcontractor.

The second example is the failure of a departmental head, compared by Malone (1986) to a broker in the market model, which unlike the same, by failure can affect production of the entire organisation.

8.1.5. Example Application of Models

Malone (1986) presents a two-fold application of these models:

1. Historical analysis of observable change between organisational structure in American business between the mid-nineteenth century and the time of the paper in terms of relative production and coordination factors described by these models.
2. Analysis of contemporaneous change trends and, within reasonable extrapolation, prediction of the same, considering the effect of information technology on relative production and coordination factors.

The historical changes in American organisational business structure presented by Malone (1986) are broadly in three phases, as outlined as follows:

The first phase of historical change from 1850 to 1910 according to Malone (1986), citing Piore and Sabel (1984), Williamson (1981) and Chandler (1977), is the emergence of large functional hierarchies, superseding the previous paradigm characterised by small businesses in decentralised markets. The reasons for this change summarised by Malone (1986) are:

1. The development of production technology resulted in improved economies of scale in that *"large scale processors became more economical than small ones"*, of which reduction in per unit coordination costs is also a feature.
2. The growth of markets brought about by the development of railroad and other transportation systems on a continental scale.

The second phase of historical change from 1910 to the mid-20th century is continued growth of functional hierarchies. The reason for this development, according to Malone (1986), is the same as that proposed for why functional hierarchies emerged in the first phase, the economies of scale and reduction of unit coordination costs associated with production and growing markets.

The third phase of historical change from the mid-20th century to 1986 according to Malone (1986), citing Rumelt (1974), Williamson (1981) and Chandler (1977), is the superseding of large functional hierarchies by large product hierarchies. Malone (1986) suggests two reasons for this change.

1. According to Williamson (1981) and Chandler (1977), a threshold operates upon the processing capability of upper level management as an organisation grows, beyond which capacity is not increased by increasing the size of management.
2. The sustained growth of functional hierarchies brought about a significant reduction in production costs relative to coordination costs. *"Thus, product hierarchies, which economized on coordination costs at the expense of production costs, became increasingly attractive"*. According to Jonscher (1983), *"the proportion of "information workers" in the workforce increased from about 25% in 1920 to almost 50% in 1960"*.

Malone (1986) observes two broad contemporaneous developments in organisational structure change, which he explains from the point of view of the reduced cost of communication and hence coordination brought about by information technology.

1. Product hierarchies to functional hierarchies:
   - A. Some organisations, such as IMB and Kneale, are observed to be moving to a functional hierarchy structure presumably owing to reduced coordination costs brought about by reduction in unit costs of communications technologies such as email and cheaper long distance telephone calls.
   - B. This is expected where production cost minimisation is the overriding factor.
2. Product hierarchies to decentralised markets:
   - A. Owing to the reduced cost of communications afforded by information technology combined with increased need for flexibility in an environment characterised by increasing rate of change, Malone (1986) observes a trend from product hierarchies to decentralised markets and foresees an increase in this trend.

8.1.6. Summary

Malone (1986) proposes four structures of organisational form and evaluates them in terms of particular types of costs, namely, production, coordination and vulnerability. The application of this model to real-world situations is in organisational design. A situation is assessed in terms of these costs and a corresponding structure or hybrid is selected as the basis for the design of organisational structure. As an overall approach, this is a familiar pattern observable from the earliest research in the field such as Bavelas (1948).

The following table summarises the Malone's (1986) model of coordination:

Organisational Form	**Evaluation Criteria**		
	Efficiency		**Flexibility**
	Production Costs	**Coordination Costs**	**Vulnerability Costs**
Product Hierarchy	H	L	H'
Functional Hierarchy	L	M-	H+
Centralised Market	L	M+	H-
Decentralised Market	L	H	L

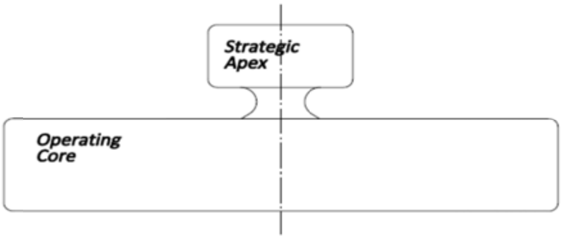
8.2. Mintzberg - Organisational Growth Model

Henry Mintzberg (1981) proposes various organisational structures based on a generic model of organisational growth rather than historical interpretation as in Malone (1986).

8.2.1. The Simple Structure

Mintzberg (1981) construes models of organisational structures as derived from a baseline structure he terms the *simple structure*. The locus of a simple structure begins as an entrepreneur with an idea who becomes a *"strategic apex"* upon hiring employees to undertake operational tasks, thus termed the *"operating core"*.

The Simple Structure



In a simple structure there is little or no standardisation, formalisation, planning, training or liason devices. Coordination is achieved with *direct supervision* by the top apex. As it grows the simple structure increases the number of operational staff and may incorporate a few middle managers. Many small businesses would fit this model.

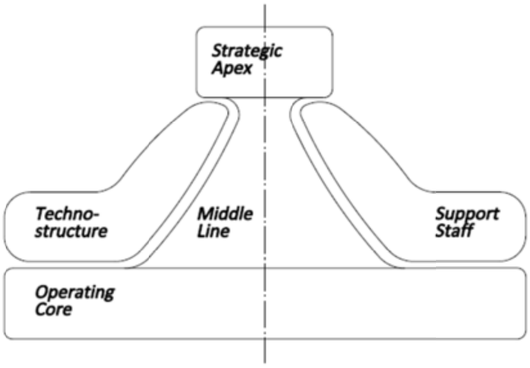
A simple structure is lean and flexible and, thus, able to compete with bureaucracies in volatile, dynamic environments and able to simple types of innovation. Mintzberg (1981) sees all organisational structures as beginning as simple structures and reverting back to their origin under hostile environmental conditions when *"systems and procedures are suspended as power reverts to the chief executive to give him or her a chance to set things right"*.

8.2.2. Machine Bureaucracy

By the growth of its administration component, a simple structure becomes what Mitzberg terms a *machine bureaucracy*. In a machine bureaucracy, the characteristic coordination mechanism is *standardisation of work*. An example of machine bureaucracy is the early Ford corporation which relied on the breaking down of tasks and reordering into more efficient sequences.

A sizable middle management component is required to develops and maintain the systems of standardisation, oversee the specialised work and resolve conflict in the growth process. According to Mitzberg, middle management attains a degree of power within an organisation because of the organisation's reliance on it, yet *"formal power is concentrated at the top"*, presumably because individuals within middle management are not indispensible. Middle management is accompanied in the mid-zone by a *"techno-structure"* comprising engineers and other professionals, and support staff.

Machine Bureaucracy



Standardisation of work was a key feature in scientific management or Taylorism (Taylor, 1911), nowadays considered the beginnings of modern management theory and the basis for the idea of a production line.

Taylorism is much criticised because this standardisation of results in an extreme specialisation of work to the point where a worker repeats one task continuously, hence, a kind of degradation of labour.

Mitzberg (1981) summarises the negative aspects of machine bureaucracy as *"legendary – dull and repetitive work, obsession with control (of markets as well as workers), massive size and inadaptability"*. Nevertheless, it is an important type in his model and remarks that *"bureaucracy has become a dirty word. Yet this is the configuration that gets the products out cheaply and efficiently"* and responds well to demand factors such as consistency, price and high demand. According to Mitzberg (1981) *"machine bureaucracy remains indispensible – and probably the most prevalent of the five configurations today",* and gives examples such as McDonalds, the Swiss railroad, insurance companies and automobile manufacturers.

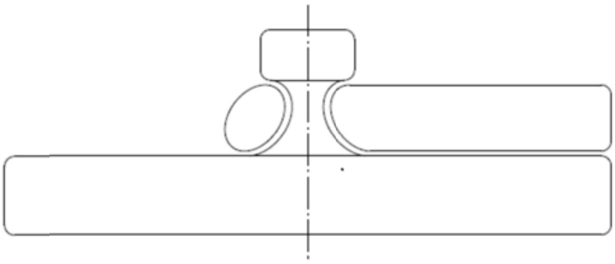
Mintzberg suggests that organisations tend to become machine bureaucracies in order to mitigate volatility in their environments or in response to control factors such regulation and having to perform to imposed criteria.

8.2.3. Professional Bureaucracy

In Mintzberg's model, a simple structure, depending on the nature of the business, may evolve into a *professional bureaucracy* instead of a machine bureaucracy. In a professional bureaucracy, coordination relies on the *standardisation of skills*. Examples of machine bureaucracy are hospitals, universities and consulting firms such as accountants. Whereas in a machine bureaucracy, the operating core comprises unskilled workers, in a professional bureaucracy, the operating core comprises highly trained professionals.

Mitzberg (1981) likens this configuration to a democracy because much of the power in making decisions is at the bottom, embedded in the operating core. Middle management is small or non-existent for this reason, similar to a techno-structure because most technical skills are contained in the operating core. Support staff may be significant in order to carry out administrative tasks shed by the professionals.

Professional Bureaucracy



Power in a professional bureaucracy is described by Mintzberg as bi-directional – bottom-up from professionals in the operating core, top-down from the apex to the support staff. A head manager in this arrangement is seen principally as the interface to the external environment rather than having a supervisory role. According to Mintzberg (1981), the professional bureaucracy is suited to complex environments which require highly skilled operators. However, internally, the professional operators need a high degree of autonomy and, hence, *"the production system must be neither highly regulated, complex nor automated"*.

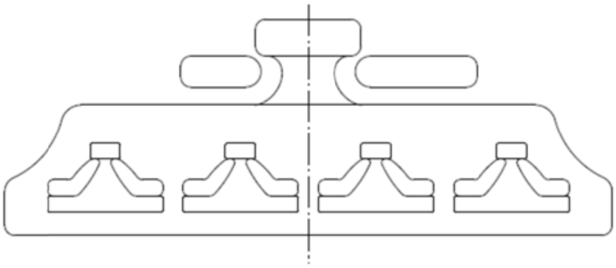
The operating core in a professional bureaucracy is seen by Mintzberg as highly trained with standardised skills such as engineering and accounting but not suitable for a high degree of subjective innovation such as in a film-making company, for example.

8.2.4. Divisionalised Form

The *divisionalised form* retains the simple structure as an outer layer but with the operating core consisting of machine bureaucracy sub-structures. According to Mintzberg, this structure comes about from an already large and mature organisation, presumably a machine or professional bureaucracy, in response to a diversification of products. This is analogous to Malone's (1986) *product hierarchy* in which each vertical division is entirely devoted to one product or line of products and both Mintzberg and Malone give the example of the General Motors corporation as epitomising the form.

Mintzberg emphasises that divisions are semi-autonomous and yet a divisionalised form is substantially a centralised structure because organisational strategic decision-making occurs at the apex, which is outside and above the divisionalised operating core. The techno-structure and support staff are seen as primarily related to the management of divisions.

Divisionalised Form



In a divisionalised form, coordination is achieved by *standardisation of outputs*, that is, quantified performance measures and metrics against which all divisions are assessed. Mintzberg proposes that the machine bureaucracy structure within divisions is a direct consequence of this standardisation of output because on the one hand, quantified goals imposed on a structure requires bureaucratisation in order to achieve them and, on the other hand, the head of division being held responsible for the outcomes of the division produces centralisation, the two factors together characterising a machine bureaucracy. This is consistent with the notion that machine bureaucracies can arise in response to external control factors.

This arrangement imposes a bias on divisions in favour of economic goals versus other considerations such as social, hence, this form is not recommended by Mintzberg as suitable for government.

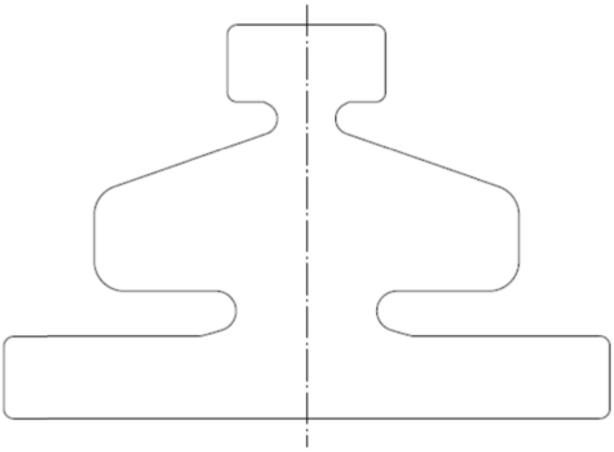
The divisionalised form is not recommended for any macro-structure likely to have divisions that require structures other than machine bureaucracies, such as multi-university structures, large hospital systems, unions and, again, government.

8.2.5. Adhocracy

An *adhocracy* is related to a professional bureaucracy in that it constitutes predominantly highly-skilled experts. However, whereas a professional bureaucracy utilises standardised skills to solve standardised complexity, an adhocracy deals with complex innovation in a complex and dynamic environment, therefore relying on unstandardised skills and flexible *"'project structures' that fuse experts drawn from different specialities into smoothly functioning creative teams"* (Mintzberg, 1981). In an adhocracy, the coordination mechanism is *mutual adjustment*. Examples of adhocracies given by Mintzberg are the aerospace and petrochemical industries, think-tank consulting and film-making.

In an adhocracy, power is based on expertise rather than authority; hence, the horizontal strata of the simple structure are merged. Strategy and decision-making is neither top-down nor bottom-up but distributed and via expert consensus, hence, adhocracies are genuinely decentralised. Strategy is always adapting and outcomes cannot be predicted.

Adhocracy



Adhocracies and professional bureaucracies can operate within the same market, differentiating themselves by whether standardised skills are applicable or not. The former is cheaper but limited in scope, hence, the need for adhocracies. Examples of this can be found in engineering within the construction industry. Some engineering consultancies can be commissioned to develop new environmentally sustainable systems or fire control systems whereas other firms can only offer to work with products and systems that are already developed and tested.

8.2.6. Summary

Mintzberg proposes five structures of organisational form and evaluates them in terms of various criteria including coordination, centralisation and mechanistic organic. The application of Mintzberg's model to real-world situations is in organisational design. A given scenario is assessed in terms of specific criteria and a corresponding structure or hybrid is selected as the basis for the design of organisational structure.

Some properties of the forms described in this section are summarised as follows (from Mintzberg, 1981):

	Simple	**Machine**	**Professional**	**Divisionalised**	**Adhocracy**
Coordination	Direct Supervision	Standardisation of Work	Standardisation of Skills	Standardisation of Outputs	Mutual Adjustment
Key Component	Strategic Apex	Techo-structure	Operating Core	Middle Line	Support Staff
Centralisation	Centralised	Limited Horizontal Centralisation	Decentralised	Limited Vertical Decentralisation	Selectively Decentralised
Mechanistic/ Organic	Organic	Mechanistic	Mechanistic	Mechanistic	Hybrid
Age & Size	Young, Small	Old, Large	Varies	Old, Very Large	Young
Centralisation here refers to the distribution of decision making.					

8.3. Market-Hierarchy vs. Organisational Growth Models

Mintzberg and Malone propose two sets of structures and two sets of criteria with which those structures are assessed in terms of performance. On one level, the models differ. Malone's focus is on a core set of strategic concerns whereas Mintzberg takes a broader perspective. However, the differences are mainly in the definition of structures and assessment criteria. From the point of view of research typology and application, the overall approach is the same. Structures are defined theoretically from observation and analysis. The research centres on the assessment of these predefined structures in terms of some kind of performance criteria. The application of resultant knowledge is presumably the reverse process of assessing a situation in terms of the model's performance criteria and upon that assessment establishing a structure or hybrid of structures as a basis for organisational design.

For example, a new engineering firm is created by a group of engineers. They are advised by their management consultants that their profile and circumstances closely matches the criteria associated with a professional bureaucracy. Therefore, they are advised to structure their new business accordingly. A similar process could be undertaken for a business undergoing changing conditions. The new conditions are matched to model criteria and a new structure suggested on that basis. It can be observed, therefore, that Malone and Mintzberg exemplify a particular paradigm in this field of research. As will be shown in the following chapter, this paradigm was established in the first investigations into the relationship between organisational structure and performance in the context of organisational design.

In this research project an alternative paradigm is investigated. Instead of predefining structure and testing according to performance criteria, using network analysis techniques structure is *"measured"* as an output variable.

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