Cranfield University

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MODELLING INFORMATION FLOW FOR ORGANISATIONS DELIVERING MICROSYSTEMS TECHNOLOGY

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ABSTRACT

Motivated by recent growth and applications of microsystems technology (MST), companies within the MST domain are beginning to explore avenues for understanding, maintaining and improving information flow, within their organisations and to/from customers, with a view to enhancing delivery performance. Delivery for organisations is the flow of goods from sellers to buyers and a classic approach to understanding information flow is via the use of modelling techniques.

Problem statement – Driven by the need for research to improve information flow during the delivery of MST, the problem statement of this research is formulated as follows: 'can a technique be developed to model information flows for organisations delivering microsystems technology?' Modelling information flows in organisations offers opportunities for analysing the current state of information flow, identifying and eliminating redundant and ineffective information flows, and improving future internal/external communication and overall organisational performance.

Research aim and objectives – The main aim of the research is 'to develop a technique for modelling information flows in organisations delivering MST'. Its objectives are:

(a) To review existing techniques and tools for modelling information flow in organisations;

(b) To capture industry practice in the use of modelling tools by organisations delivering MST and carry out an industry study of information flow during the delivery phase of real-life organisations delivering MST;

(c) To propose a technique for modelling information flows during the delivery phase of organisations delivering MST; and

(d) To evaluate/validate (c) through case studies of organisations delivering MST studied in (b).

Methodology – An ‘analytical-conceptual-applied’ methodology was adopted for the research in four phases: literature review, industry scope, proposed technique and case studies. The research began analytically with a literature review of existing techniques and tools for modelling information flow in organisations followed by a study to establish an industry scope through: (i) an industry survey to capture industry practice in the use of modelling tools by organisations delivering MST, and (ii) an exploratory study to understand how information flow is managed and current information flow modelling needs of organisations delivering MST. A technique for modelling information flow was then conceptually proposed, evaluated and validated through case studies within real-life MST companies. The proposed technique is developed based on a research methodology that establishes the industry scope and is informed by the literature review.

Findings and conclusions – The main findings of the research is a technique for modelling information flows during the delivery phase of organisations delivering MST that *diagrammatically* visualises information flow through an ‘information channel diagram (ICD)’ tool and *mathematically* analyses information flow through an intra-organisational collaboration (IOC) model. The ICD is made up of a set of diagrammatic primitives for depicting delivery interactions, delivery processes, information flow coordination and information flow streamlining. Using the processes and role description provided by the ICD as a starting point, the IOC model is developed as a network of human collaborators and processes. The IOC model analyses the topologies, vertices and edges for collaboration and provides indicators for assessing teamwork, decision-making and coordination.

The thesis concludes with remarks that: (i) analysing collaborations requires modelling for a combination of tasks and teams, (ii) delivery information flow for firms is non-monolithic and dependent on companies’ strategies for maintaining firm competitiveness, (iii) a demarcation of roles is vital to modelling information flow, (iv) the use of colour improves representations, (v) simplified communications is necessary for effective operations, (vi) information managers offer a useful avenue for improving delivery performance, and (vii) a review of the flow of information is important to maintaining firm competitiveness.

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INTRODUCTION

Recent years have witnessed an enormous growth and application of a sector of the semiconductor industry that is known by two main names: micro-electro-mechanical system (MEMS) – in America; and microsystems technology (MST) – in Europe; the term used in this thesis. By concentrating on the flow of information in the delivery phase, MST companies can promote collaboration among personnel for effective communication and documentation tasks, improved customer interactions and enhanced delivery performance.

In this chapter, the concepts of MST, organisations, delivery, information flow and modelling will be introduced as a background to this research. The research motivation and goals will then be presented. The chapter also outlines the problem statements, research strategy and research conributions followed by a description of the outline of the thesis.

1.1. RESEARCH BACKGROUND

In this section, the concepts of MST, organisations and delivery are introduced as a background to the research. The section also introduces and provides a definition for information flow within the context of organisations and modelling. These concepts were identified at the outset of the research and are integral to the research activities undertaken in the development of this research thesis.

1.1.1. Microsystems technology

According to the European Union (1996), an MST, as shown in Figure 1-1, is a 'miniaturised system comprising sensing, processing and/or actuating functions'. An MST achieves these functions by combining two or more phenomena such as: electrical, mechanical, optical, chemical, biological, magnetic, or other properties.

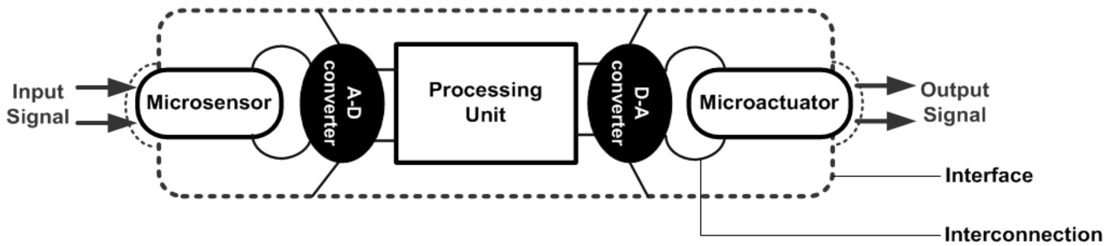


Figure 1-1: Microsystems architecture

Miniaturisation and integration are the two main techniques applied for the production of MST. *Miniaturisation* in MST means that the dimensions of functional parts and features of the devices are within the range of 1-100 micrometres (Wood, 1999). MST *integration* is concerned with the combination of subsystems and components at chip-, package-, module- or board-level (Tummala, 2004). Devices fabricated and manufactured in this way (or micro-integrated devices) can be applied in areas such as: automotive, aerospace and defence; process control, water and gas supply; medicine, pharmaceutical and health care industries; bioinformatics and biotechnology; telecommunication and information technology; consumer goods and electronics; environmental monitoring and air conditioning technologies.

1.1.2. Organisations and delivery

Citing Watson (1980), Honour and Mainwaring (1982) defined organisations as 'social and technical arrangements in which a number of people come, or are brought together in a relationship where the actions of some are directed by others towards the achievement of certain tasks'. 'Organisations thus include banks, firms, hospitals, prisons but exclude families, tribes, social classes and spontaneous friendships' (Watson, 1980). If an organisation is in commerce and is profit driven, it is known as a business (Wamba and Boeck, 2008).

Delivery for organisations is the flow of goods 'from the seller to the buyer' (Wang and Das, 2001). This flow is part of a transaction that is 'finally committed as soon as the seller delivers appropriate goods to the buyer'. Cappels (2004) noted that this phase in projects 'may account for 1 to 15% of the total effort'. In software based firms and divisions, the delivery phase 'concludes the development process of the product and delivers the technological solution' (Oktaba and Piattini, 2004).

1.1.3. Information flow

Within organisations, information flow is the movement of information between: (i.) individuals in an organisation or organisations, (ii.) organisational departments, (iii.) multiple organisations, and (iv.) an organisation and its environment (Henczel, 2001). More recent definitions identify characteristics of effective and efficient information flows that the individual authors have focused on. This is reflected in the findings and conclusions of the individual articles from which these definitions have been identified.

According to Westrum (2004) information flow in organisations can be defined as timely, relevant and appropriate flow of information from a sender (transmitter) at point A to a receiver (recipient) at point B. De Wolf and Holvoet (2007) defined information flow as a maintained and updated stream of information from a source towards a destination. The stream of information may pass through various points resulting in the aggregation of new information that is integrated into the information flow. Atani and Kabore (2007) defined information flow as access to information resources.

1.1.4. Modelling

Modelling is a classic approach to understanding complex problems that produces models. A model is an abstract representation of a reality at a certain level of detail (Michael and Massey, 1997; Ball *et al*., 2004).

Modelling information flow is an important challenge for structuring team organisation (Chiu, 2002), for documenting phases of a product life-cycle (Stoyell *et al*.,

2001) and for intentional iterations in design (Pektaş and Pultar, 2006). It is realised in two main forms: diagrammatically, to introduce primitives and representations for visualising information flow (Ball *et al*., 2004), and mathematically, to introduce metrics and formulas for measuring uncertainty (or complexity), variability, equivocality, redundancy, consistency and ambiguity (Lo Storto *et al*., 2008).

1.2. RESEARCH MOTIVATION

Although the last two years witnessed low growth (6 per cent) in the MST industry, forecasts by organisations such as Yole Développement (2009) have projected continuous growth in the coming years. These forecasts suggest that by the year 2012 MST production sales will exceed 15 million US Dollars driven by a compound annual growth rate (CAGR) at 15 per cent. Apart from overall market growth, some MST sectors have been forecast with huge increases in sales for the coming years. For instance, by 2012, sales figures for medical based MST are predicted to increase by 200 per cent whereas sales for telecommunications based MST are expected to have quadrupled (Yole Développement, 2009). This is because MST production, over the years, has continued to be successful in converting researched designs into commercially viable high-tech products with micro-scaled functional parts. In addition, MST production continues to be underpinned by services offered through research and development competence houses and design houses (Wilkinson, 2000).

MST based products include fabrication tools, manufacturing equipment and miniaturised, integrated devices – that include microfluidic, microoptical, micromechanical, radio frequency (RF) and microwave structures and components (Madisetti, 2006). MST based services on the other hand can include the provision of microfabrication capabilities, computer-aided design (CAD) training and device packaging services.

MST production requires the involvement of multidisciplinary teams (Shen *et al*., 2008). Typical MST production could involve experts from various disciplines such as business analysts, electrical engineers, chemists (microfluidics) and physicists (micromechanical). Each discipline has a different perspective of system goals and product life cycle concerns (Kannapan and Taylor, 1994). It is for this reason that measures and techniques must be put in place to analyse the flow of information among MST team members. However, the first step in an information flow analysis methodology is the modelling of the current information flow in an organisation (Macintosh, 1997) to create a 'fingerprint' of the organisation's communication structure (Ciborra *et al.*, 1978; Ellis, 1989; Yazici, 2002; Michael and Massey, 1997).

Modelling information flows for organisations is important for three main reasons. Firstly, it aids organisations to analyse their current state of information flow. Secondly, it enables organisations to identify and eliminate redundant and ineffective information flows as well as minimising the duplication of information. Thirdly, it helps an organisation to make assessments and recommendations for improving future internal/external communication and overall organisational performance. This activity is useful for implementing organisational strategies such as resource allocation and job description. Furthermore, ISO TR 9007 maintains that models of information can provide a common basis for different working groups to represent, understand and manipulate the behaviour of a set of entities (Scheller, 1990).

To date, the main focus of research for modelling techniques within the MST domain has been on technological issues which relate to engineering science and application of the technologies. Many of these studies in particular have looked at proposing information flow models for use in MST design processes and production. However, very few studies, such as Myer *et al.* (2000) and Dickerhof *et al*. (2002), have considered the information flow for the organisation in which MST are being designed, developed and delivered. Furthermore none of these studies have considered the information flow or information flow modelling techniques for MST delivery.

1.3. Problem statement

Founded on the research motivation outlined in §1.2, the problem statement of this research is formulated as follows:

"Can a technique be developed to model information flows for organisations delivering microsystems technology?"

Within the MST domain, modelling the flow of information during the delivery phase in organisations is now particularly important since MST production is moving from a 'surprise to an enterprise' phase i.e. proof of MST concepts are increasingly being commercialised (Fujita, 2007; Durugbo *et al.*, 2009). Information flow modelling for MST delivery is also motivated by the need to improve accessibility to MST (Ohlckers and Jakobsen, 1998). The problem with accessibility to MST refers to market penetration where consumers are cautious in the use of new products and technologies. Analysing the flow of information during the delivery of MST based products and services could therefore offer a useful forum for MST companies to improve information exchanges with customers so as to highlight the benefits and potentials of MST. This is because traditionally, the analysis/management of information flow is vital for enabling information exchanges between customers and sales teams i.e. *customer service* (Iskanius *et al*., 2004).

1.4. RESEARCH GOALS

The main aim of the research is 'to develop a technique for modelling information flows in organisations delivering MST'. Its objectives are:

(a) To review existing techniques and tools for modelling information flow in organisations *(Chapter 2)*;

(b) To capture industry practice in the use of modelling tools by organisations delivering MST and carry out an industry study of information flow during the delivery phase of real-life organisations delivering MST *(Chapter 3)*;

(c) To propose a technique for modelling information flows during the delivery phase of organisations delivering MST *(Chapter 4)*;

(d) To evaluate/validate (c) through case studies of organisations delivering MST studied in (b) *(Chapter 5)*.

1.5. RESEARCH STRATEGY

The thesis seeks to address the need for research during MST delivery by proposing a technique for modelling information flow for organisations delivering MST. The research strategy adapted for this thesis, made up of four main phases as summarised in Figure 1-2, began with a literature review followed by a study of industry practice to establish an industry scope.

A technique for modelling information flow will then be proposed, evaluated and validated through case studies within real-life MST companies. The proposed technique is developed based on a research methodology that establishes the industry scope and is informed by the literature review.

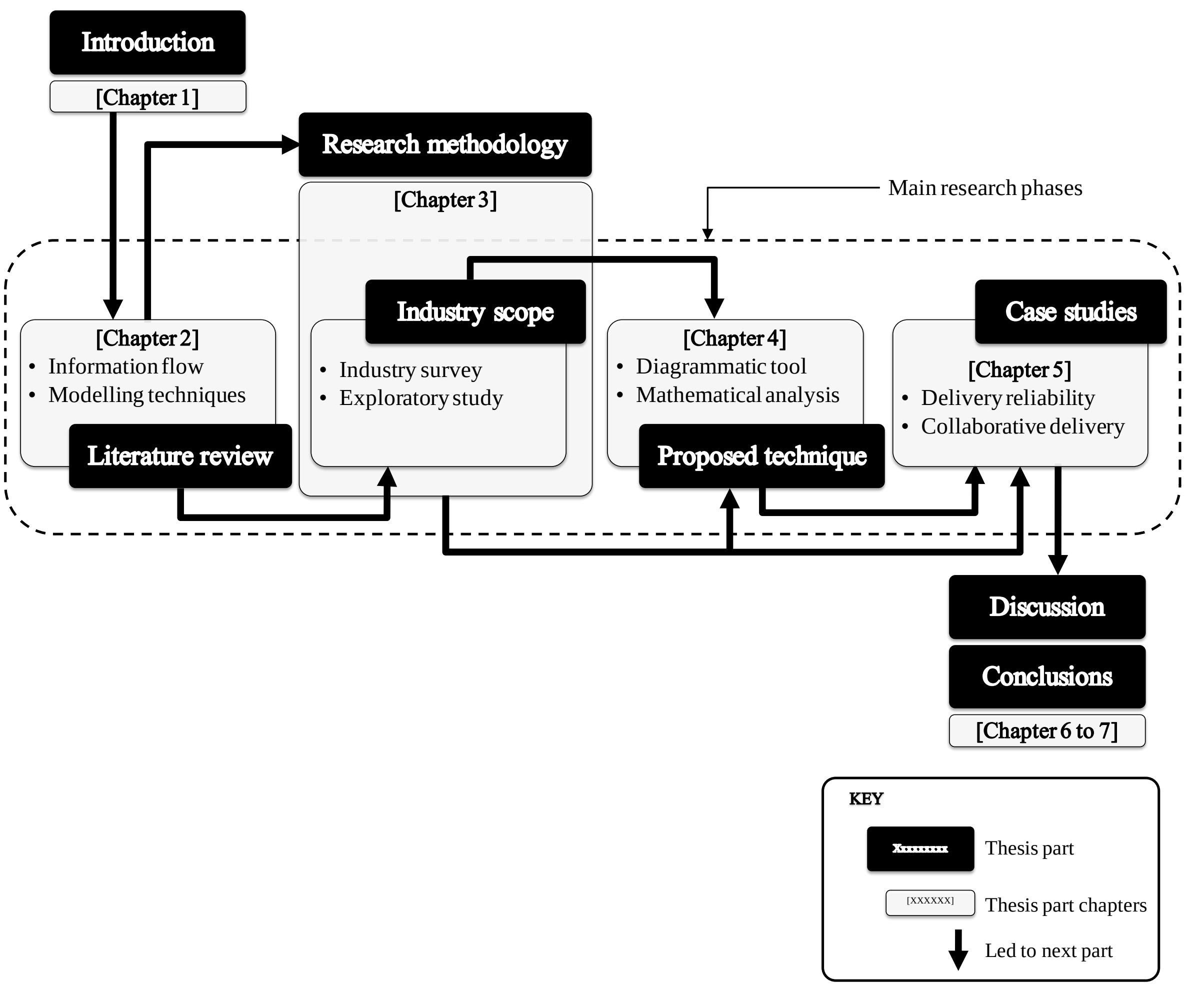


Figure 1-2: Research strategy

1.6. RESEARCH CONTRIBUTIONS

The main contribution of this research is 'a diagrammatic and mathematical modelling technique for analysing the state of information flow in organisations delivering MST'. In other to accomplish this, the research with carry out: (i) a scientific examination of the state-of-the-art in academic literature for techniques and tools for modelling information flow, and (ii) a study of industry practise in the use of tools and techniques for modelling information flow and how information flow is managed in MST companies. Insights provided by the review and study will then serve as the basis for the modelling technique.

1.7. THESIS STRUCTURE

This thesis is divided into 7 chapters, as shown in Figure 1-3:

- Chapter 1 [Introduction] introduces this research thesis by defining the main research concepts of microsystems technology, organisations, delivery, information flow and modelling. It describes the research motivation from which the problem statement is derived and the strategy used for the research. The chapter also identifies the research goals/contributions and outlines the structure of the thesis.
- Chapter 2 [Literature Review] presents a comprehensive review of literature on existing techniques for modelling information flow in organisations. An overview of information, information flow and organisations is first presented and the literature on delivery information flow is reviewed. The research gap for delivery information flow modelling highlighted in academic literature is also presented.
- Chapter 3 [Research Focus and Methodology] outlines the research focus derived from the research gap for delivery information flow modelling Chapter 2. The chapter also describes two studies used to establish as industry scope: an industry survey that captured industry practice in the use of modelling tools and an exploratory study that examined how information flow is managed during the delivery phase of real-life organisations. The methodology for fulfilling the research goals of Chapter 1 is also outlined.

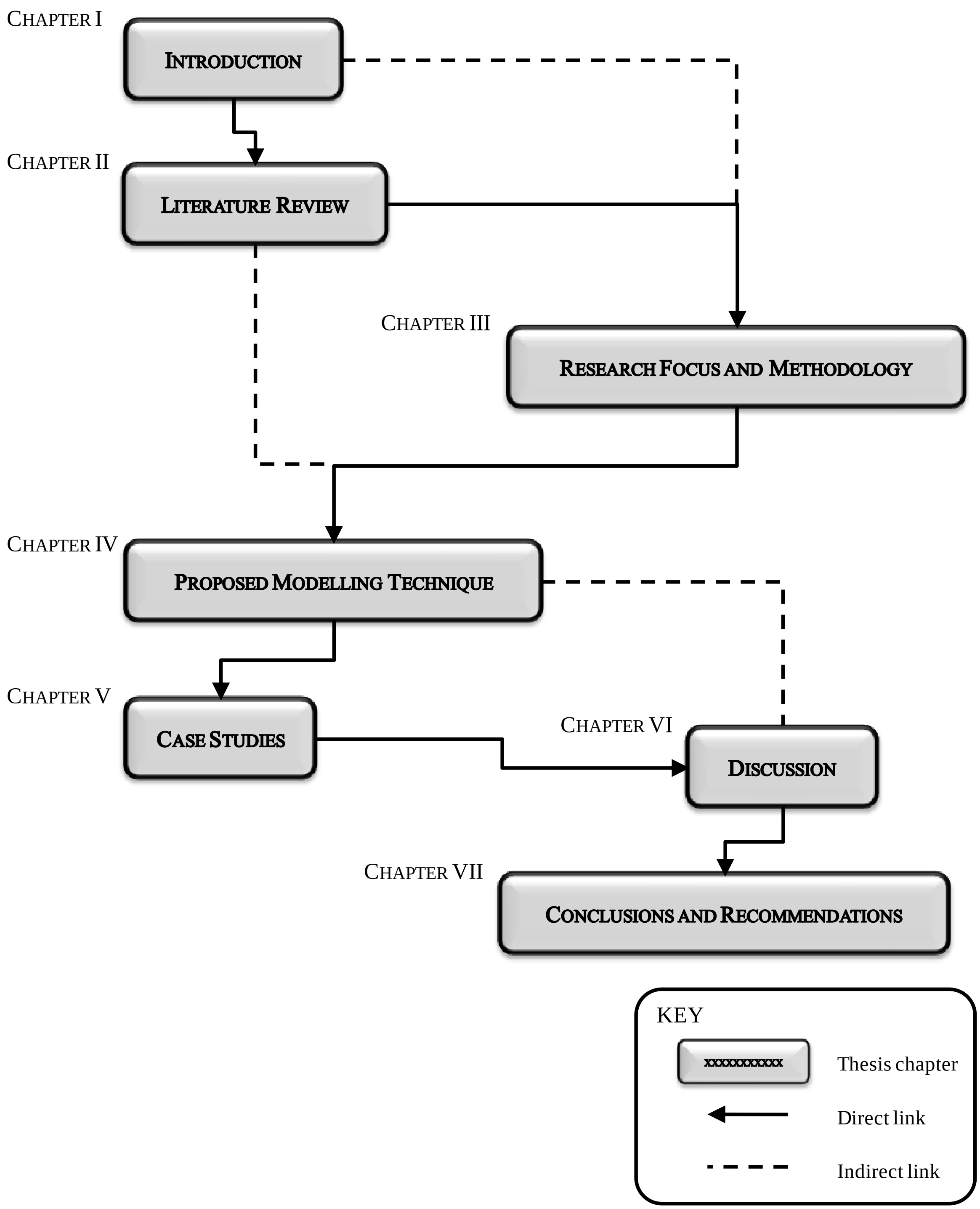


Figure 1-3: Outline of thesis

- Chapter 4 [Proposed Modelling Technique] proposes a technique for modelling information flow in organisations delivering MST that consists of a diagrammatical approach - the ‘information channel diagram (ICD)’ tool and a mathematical approach – the ‘intra-organisational collaboration (IOC)’ model.
- Chapter 5 [Case Studies] describes case studies that evaluate the use of the IOC model in analysing the current state of information flow and validate the ICD tool by comparing the tool with existing tools used in MST companies.
- Chapter 6 [Discussion] discusses the key observations of this research. It also discusses the applications, and limitations of the proposed ICD tool and IOC model.
- Chapter 7 [Conclusions and Recommendations] concludes this thesis by summarising the main outcome of the research and identifying possible directions for future research.

1.8. SUMMARY

In this chapter, the background of this research was presented through definitions for key concepts of MST, organisations and delivery, information flow and modelling. Next, the research motivation, problem statement, and research strategy were identified. A description of the aim, objectives and contribution of the research were then described. The chapter also outlined the structure of the thesis.

Chapter

2

LITERATURE REVIEW

This chapter presents a review of literature related to this research. A background on information, information flow for organisations and delivery information flow is presented in the first two sections followed by a comprehensive review of tools and techniques for modelling information flow in organisations. A critical review of current trends for modelling information flow for 'organisations as networks' is then presented followed by an analysis of the research gap for delivery information flow modelling.

2.1. INFORMATION AND INFORMATION FLOW FOR ORGANISATIONS

In literature, the term 'information' is used in four different ways: as a resource, as a commodity, as perception of patterns, and as a constitutive force in society (Braman, 1989). *As a resource,* information is interpreted as content from which knowledge is captured, described as data represented, or structured for meaning (Loos and Allweyer, 1998; Gavirneni *et al.*, 1999; Juric and Kuljis, 1999; Hicks *et al*., 2006; Ni *et al*., 2007; Wamba and Boeck, 2008). *As a commodity*, information is highlighted from the perspective of businesses where the flow of information (usually computerised) is used as trans-organisational communication (Iskanius *et al.*, 2004; Demiris *et al.*, 2008). *As a perception of pattern*, information is viewed as the reduction of uncertainty in a system (Ellis, 1989; Durugbo *et al.*, 2009). This reduction of uncertainty is useful as it saves organisational time and cost by minimising alternate decisions that arise due to uncertainty. *As a constitutive force in society,* information is viewed as a key element for shaping the structure and behaviour of organisations (Childerhouse *et al.*, 2003; Westrum, 2004; Dimitriadis and Koh, 2005; Berente *et al.* 2009). In this context the flow of information is used to determine the nature of expression and complexity of the social structure of the organisation.

Information is important to the existence of organisations much so it is likened to oxygen for human life (Al-Hakim, 2008). In profit driven organisations (i.e. businesses), information is a critical factor that determines growth and prosperity (Krovi *et al*., 2003), and information flow is considered the lifeblood of processes such as product development (Eppinger, 2001). Information flow is defined by the logic of a distributed system that is made up of agents and the relationship in the distributed system i.e. information only flows between two separated parts that are connected or related and is defined by a set of rules (Bremer and Cohnitz, 2004; Barwise and Seligman, 1997; Corrêa and Agustí-Cullell, 2008). In organisations, information flows in verbal, written or electronic form (Yazici, 2002), from a sender to a receiver (Westrum, 2004) and is dependent on access to information resources (Atani and Kabore, 2007).

Prior to the 1950s, communication and information flow was viewed as a one way process from a sender to a receiver (Clegg *et al.*, 2005). However, the emergence of cybernetics has resulted in a change of attitudes towards information flow by highlighting feedback in the communication and documentation process (Ellis, 1989; Durugbo *et al.*, 2009). This change in attitude is largely due to information theory research by academics such as Claude E. Shannon, Ralph Hartley and Andrey Kolmogorov. Feedback paths offer useful avenues for businesses to use information for making decisions with a view to accessing individual levels of trust, acceptance of responsibility, job demands and work satisfaction (Moller, 1997).

In organisations, information flows person-to-person, person-to-machine and machine-to-machine, from sources such as electronic data interchange and face-to-face conversations, and through channels for communication such as letters, reports, audio files and video recordings (Moller, 1997; Hicks *et al*., 2006). These channels offer the means for a company to communicate internally and externally so as to achieve its business objectives such as the delivery of products and services (Durugbo *et al.*, 2010a). However, the role of human judgement in the use of media forms is vital to maintaining business operations in general. This is because human judgement is required to consider the fulfilment of customer requirements without jeopardising business objectives of firms (Patel *et al*., 1996).

Information flow is an important part of work flows (Al-Hakim, 2008) that requires a synergy between humans and computer systems in modern organisations (Burstein and Diller, 2002; Hinton, 2002). Information flow is based on information gathering by means of textual, audio, video and graphical media forms (Perry *et al*. 2001). These media forms are used for communication within an organisation (Doumeingts, 1989), for description of processes (Martin and McClure, 1985), for analysis of systems (DeMarco, 1979) and for the documentation of ideas, activities and processes (Katzan, 1976).

Within research, studies focused on information flow have been undertaken in science and engineering fields such as organisational theory, management science, economics, artificial intelligence, ecology, control engineering, sociology, and computer science (Albino *et al*., 2002; Ehsani *et al*., 2010; Braha and Yaneer, 2007).

Within organisational theory and management science, the focus of research has centred on the analysis of information flow. This is because a widely recognised challenge for organisations is how to better understand and manage processes for capturing, storing and retrieving information (Lo Storto *et al*., 2008). Thematic analysis (Blackburn, 2001), ECCO (Episodic Communication Channels in Organisations) analysis (Zwijze-Koning and De Jong, 2005), functional decomposition (Friesdorf *et al*., 1994), structured analysis (Feinstein and Morris, 1988; Hansen *et al*., 1978) are examples of methodologies applied for analysing information flow in organisations.

2.2. Delivery information flow

The role of information for delivery is two-fold: firstly, as an *input parameter* for strategising the delivery process and secondly, as a *control measure* for achieving high levels delivery performances (Fawcett *et al.*, 1997; Hicks *et al*., 2006). And focusing on how information affects delivery, concepts such as the Capability Maturity Model (CMM) and Maturity Index on Reliability (MIR) have been proposed for classifying information (Humphrey, 1988; Sander and Brombacher, 1999; 2000). CMM originally proposed for assessing the maturity of software development process maturity can also be used to rank information according to a 1-to-5 rating scale (1-initial, 2-repeatable, 3-defined, 4-managed and 5-optimising). MIR also applies a five point scale from 0 to 4 (0-no information available, 1-how much problems, 2-where do problems originate, 3-what is the root cause of problems, 4-what can be done to prevent reoccurrence of problem) for classifying information but concentrates on the capability of firms to manage reliability.

Processes during delivery include: 'the physical delivery of a product to the customer's site, final inspection and test at the customer's site, training the customer, and honouring the warranty period (e.g. service calls, replacements)' (Cappels, 2004). In order to accomplish these processes, interactions are required to harmonise delivery schedules and delivery conditions and to fulfil customer expectations by delivering products and services "as soon as possible", providing order status information, on-time delivery, and stipulating return conditions (Reponen, 2003). To support these facilities, businesses are now adopting logistic- and customer-focus information systems and software suites for managing supply chains: Enterprise Resources Planning (ERP), Materials Requirement Planning (MRP), Quick Response (QR), Efficient Consumer Response (ECR), Vendor Managed Inventory (VMI), Point of Sale (POS), Collaborative Planning, Forecasting and Replenishment (CPFR), Business Process Reengineering (BPR), Component Supplier Management (CSM), Manufacturing Execution Systems (MES), Customer Relationship Management (CRM), and Supply and Planning Management (SPM) (Ou-Yang and Chang, 2000; Wamba and Boeck, 2008).

Supply chains are dynamic in nature and require a constant flow of information, material, cash, product, process, product/service value and market accommodation (Dimitriadis and Koh, 2005). These flows are vital to the success of businesses especially for maintaining competitive advantages and for enabling the exchange and sharing of information (Wamba and Boeck, 2008). Improved information sharing has been beneficial for defining and establishing relationships with a view to minimising uncertainty in supply chains (Zhang and Liu, 2008, Childerhouse *et al.*, 2003). These cooperative, collaborative or coordinated relationships are based on regular and effective flows to team members and the wider organisation (Barua *et al.*, 1997; Burstein and Diller, 2002). However, the emergence of the World Wide Web (WWW) has shifted the power of delivery information and communication from manufacturers to customers (Malecki, 2002). This is because the internet offers a wealth of readily accessible resources that present users with a wide range of information such as the business competitiveness, sales records and company policies and fiscal reports. Consequently, to support interactions during delivery, modern supply chains adopt a customer-focused approach based on a 'new digital business design' that is supported by the concurrent flow of information (Iskanius *et al.*, 2004). In this approach information flow via the WWW and e-commerce, plays an integral role for realising value and for supporting networked infrastructure.

Modern supply chains and delivery processes also adopt a logistic-focused approach centred on operational *information coordination* (Qing and Zhixue, 2008). Information coordination is applied for harmonising internal and external channels for information flow or the span and depth of information flow in organisations. The concept of information coordination however goes beyond communication and considers dependencies especially for conflict management during collaboration (Ouertani, 2008). Loos and Allweyer (1998) suggested that effective information flow must be coordinated for feed forward and feedback paths between logistics and engineering during planning and execution phases of business organisations.

To facilitate coordination during delivery four main roles are identified: laboratory role that tests new products and provides feedbacks, consultant role that assists customers to solve problems associated with a product, dispatcher role that communicates with internal and external parties to facilitate logistical endeavours, and showroom role that aids in the marketing and sales of product through on-site tour and off-site services (Youngdahl and Loomba, 2000).

In literature, empirical studies, based on interviewing company personnel, have examined the role of information flow for enhancing delivery within organisations. Table 2-1 summarises some of these studies and the remainder of this section reviews each study.

Table 2-1: Related work on information flow for enhancing delivery.

Author	**Motivation**	**Focus**	**Delivery information flow challenges**
Nicholson (1982)	Improving delivery management for batch production	Process modelling and Inventory management	Information coordination
Konijnendijk (1993)	Analysing the coordination of delivery in small and medium enterprises	Process coordination and logistics management	Information coordination
Vaughan (2000)	Enhancing the delivery of results from agricultural laboratories	Process improvement and cost effectiveness	Information flow bottle-necks
Iskanius *et al.* (2004)	Analysing information flow transparency in steel companies	Agent modelling and digital design	Information distortion
Boersma *et al*. (2005)	Improving service delivery by service and call centres	Quality management and organisational reliability	Information loss
Chen (2005)	Strategising delivery of meals in restaurants	Process improvement and mass customisation of services	Information reliability and redundant information use
Klein and Rai (2009)	Analysing conditions for strategic information flow during delivery between buyers and suppliers	Defining supply chain relationships and characterising flow exchange	Information sharing
Pedroso and Nakano (2009)	Assessing the flow of technical information in the delivery of pharmaceutical drugs	Process modelling and supply chain management	Information management

An early study by Nicholson (1982) investigated the role of production information in the delivery of batch manufactured products by five companies. The purpose of the study was to develop a design (process-flow grid) for information management. Nicholson also emphasised the importance of effectively using computer scheduling systems and of applying trade-offs in capacity, total order intake and lead times.

Konijnendijk (1993) investigated the connection between the coordination of delivery and logistics of four small and medium enterprises. The study analysed the effect of information flow at tactical and operational levels of three logistics structures: make-to-stock, make-to-order and engineer-to-order. Konijnendijk concluded that information flow was a problem for operations and that sales information was largely non-technical whereas production information contained cost and technology data. He also recommended that coordination between production and sales must be systematised to ensure effective operation.

Vaughan (2000) undertook a case study of an agricultural laboratory and explored the communication of results between laboratory analysts and clients. The focus of the study was to identify problems of information flow and to make recommendations for rapid and accurate information flow. The main information problems centred on missing/ inadequate information and recommendations were based on applying better structured information sheets and reports.

Iskanius *et al. (*2004) studied the transparency of information flow in the supply chains of steel companies in Northern Finland. They used the findings of their study to identify the elements of a new business design for supply chains. These elements include: customer-alignment, collaboration, systematisation, agility, scalability, fast-flow and digitalisation. Iskanius *et al.* also suggested agent-based technologies for managing this new supply chain thinking. They argued that this will improve the flexibility of supply chains and overcome problems of the "bullwhip effect" (i.e. information distortion as it passes through the business network).

Boersma *et al.* (2005) examined information flow for service delivery in the service and call centres of a multi-national electronics company. Following interviews with call agents, the authors made use of the MIR to propose two new business models for enhancing information flow. The models centred on reducing information losses, encouraging the use of knowledge databases and improving information quality.

In a case study of a Chinese restaurant, Chen (2005) analysed the flow of information involving products, process and people (3 'P's). The purpose of the study was to explore how the restaurant could deliver a broad range of meals that meet customer needs in a manner that is prompt, economical and flexible. By mapping the service process within the restaurant, Chen identified problems of information flow relating to: (i) reliability of oral information exchanged between staff during the delivery of meals, and (ii) redundancies in the use of information as a resource to offer variety in meal selections for customers.

Pedroso and Nakano (2009) studied the flow of technical information in the supply chain of four pharmaceutical companies. Based on the findings of case studies at the companies, the authors drew a distinction between order information (simple, upstream and timely) and technical information (rich, downstream and early). Pedroso and Nakano also suggested that effective information flow management is dependent on effective logistic processes.

2.3. Modelling information flow

Modelling information flow is the process of describing how information is transferred point-to-point along communication channels in an organisation (Hibberd and Evatt, 2004; Black and Brunt, 1999) done through the use of a mathematical (Collins *et al*., 2010) and/or diagrammatic (Albino *et al*., 2002) technique to aid organisations in ranking information, prioritising information flow and defining how budgets can be managed (Pentland, 2004). This activity is typically preceded by the collection of data about organisation processes via data collection techniques such as interviews, surveys and questionnaires (Cerullo, 1979; Macintosh, 1997; Pingenot *et al.*, 2009; Stapel *et al*., 2007).

Modelling information flow for organisations is a challenging task. This is because an organisation by nature is a 'communicating entity' i.e. it is a made up of constructs in which people can have access to information and speak to each other (Clegg *et al*., 2005). Within an organisation, communication for the flow of information can involve different groups, processes, individuals, communication channels and so on.

Modelling information flow for organisations is motivated by the need to better understand how to: organise and coordinate processes, eliminate redundant information flows and processes, minimise the duplication of information and manage the sharing of intra- and inter-organisational information (Szczerbicki, 1991; Howells, 1995). It is also required to understand communication barriers among departments that results in sub-optimal and inflexible organisational processes (Chiu, 2002; Hansen *et al*., 1978; Sander and Brombacher, 2000; Friesdorf *et al*., 1994; Krovi *et al*., 2003; O'clock and Henderson, 1994; Barua *et al.*, 1997). This is because models aid analysts to effectively communicate complex design issues (Hansen *et al*., 1978) and a better understanding of organisational processes is vital to assessing the performance of an organisation (Hsieh and Woo, 2000; Hartley *et al.*, 2002).

It is however important to note that information flow is a partial view of an information model which in itself is a partial view of an organisation (Ou-Yang and Chang, 2000; Collins *et al.*, 2010). Other views required to create a 'complete picture' of an organisation include organisational, functional, and process views.

This section reviews the main approaches to mathematically and diagrammatically modelling information flow in organisations. Diagrammatical modelling produces conceptual models for analysing the information needs and problems of an organisation (Ewusi-Mensah, 1982). These conceptual models are constructed to visually represent and aid in the analysis of organisational data, decisions, procedures or transactions (Albino *et al*., 2002). Mathematical modelling is carried out to analyse attributes of information flow such as ambiguity, equivocality, redundancy, consistency and uncertainty (Lo Storto *et al*., 2008). It uncovers statistical properties that underlie organisational structures and functions (Collins *et al.*, 2010) for the creation of models based on economics and computer science, team theory and decentralisation of incentives (Creti, 2001).

2.3.1. Diagrammatic modelling of information flow

The use of diagrams to model information flow makes it easier for organisational personnel to relate to and understand organisational requirements (Juric and Kuljis, 1999; Sen, 1992). It offers a unique opportunity to assess the impact of operations, management and support processes by capturing activities and interactions (Ball *et al*., 2004).

Hungerford *et al*. (2004) have asserted that diagrams or diagrammatic reasoning are better suited to solving problems created by increasing complexity in systems when compared with text-based (sentential) representations. They highlight three main reasons for this assertion. Firstly, diagrams promote information clusters (grouping of information), thus eliminating the need to conduct large amounts of searches associated with problem-solving inferences. Secondly, diagrams promote information clusters based on a single element, hence eliminating the need to match symbolic labels. Thirdly, diagrams offer facilities that support a wide range of perceptual inferences, which are simple and easy to use.

Becker *et al*. (2008) have suggested that standard models (as-is models) should be identified and serve as a starting point for models of planned systems (to-be-models). This sub-section presents, as a first step towards this approach, an analysis of some key diagrammatic information flow models. Diagrammatical tools beyond the scope of information flow, for example models for timeline orientation (UML sequence diagrams), process orientation (flow chart diagrams) or state orientation (state transition diagrams), are omitted.

The information flow diagrammatic models identified from literature are tabulated in Table 2-2. They include data flow diagrams, Integrated DEFinition method of modelling functionality and information modelling (IDEFØ and IDEF1), Graphes à Résultats et Activités Interreliés (GRAI) grids and nets, Petri nets, Input-Process-Output diagrams and design structure matrices. Each modelling approach has its strengths and weaknesses, which must also be taken into consideration by organisational designers and operators.

Table 2-2: A list of function-oriented information flow diagrammatic models found in literature

Modelling Tool	Description	Literature
Data flow diagrams	Analyses information flow within and between organisations or systems; applied for the design and deployment of information systems.	(Martin and McClure, 1985; Hungerford *et al.*, 2004; Canfora *et al.*, 1992; Tucker and Leonard, 2001; DeMarco, 1979; Du *et al.*, 2000; Ross and Schoman, 1997; Turetken and Schuff, 2007; Butler *et al.*, 1995; Gane and Sarson, 1979)
Integrated DEFinition method of modelling functionality and information modelling (IDEFØ and IDEF1)	Illustrates information flow along with constraints and mechanism which affect system functions; developed from the (Structural Analysis and Design Technique) SADT approach.	(Colquhoun *et al.*, 1993; Knowledge Based Systems Inc., 2006; Federal Information Processing Standards, 1993; Software Engineering Standards Committee of the IEEE Computer Society, 1998; Sullivan, 1991; Ang *et al.*, 1995; Kusiak *et al.*, 1994; Bernus and Schmidt, 1998; Ho *et al.*, 1994; Lingzhi *et al.*, 1996; Chen *et al.*, 2004)
Graphes à Résultats et Activités Interreliés (GRAI) grids and nets	Supports information flow in decision communication, feedback and review; part of the GRAI methodology.	(Butler *et al.*, 1995; Ho *et al.*, 1994; McCarthy and Menicou, 2002; Doumeingts, 1989; Merlo and Girard, 2004; Wainwright and Ridgway, 1994; Doumeingts *et al.*,1998; Vernadat, 1996; Leondes, 1995)
Petri nets	Represents automated and event-driven information flow in systems.	(Hilt *et al.*, 1994; Zhou and DiCesare, 1993; Bonney *et al.*, 1999; Ou-Yang and Lee, 2000; Murata, 1989; Lien, 1976; Varadharajan, 1990; Wakefield and Sears, 1997)
Input-process-output (IPO) diagrams	Describes and documents the organisation and logic of information flow; integral to the Hierarchy plus Input-Process-Output (HIPO) approach.	(Martin and McClure, 1985; Stay, 1976; Katzan, 1976; LaBudde, 1987; Nosek and Schwartz, 1988; Davis, 1998)
Design structure matrix	Depicts dependency, independency, interdependency and conditionality of information flow for organisations.	(Eppinger, 1991; Browning, 2001; Helo, 2006; Syed and Berman, 2007; Steward, 1981; Oloufa *et al.*, 2004; Farid and McFarlane, 2006; Yassine, 2007)

2.3.1.1. Data flow diagrams

Data flow diagrams (DFDs) are very popular diagrammatic models (Hungerford *et al*., 2004; Canfora *et al*., 1992) used in describing information exchanges in a variety of organisations (Tucker and Leonard 2001). They were developed by DeMarco (1979) in the late 1970s as a tool for analysing sequential information flows (Sommerville, 1992; Du *et al*., 2000). DeMarco defined DFDs as 'network representations' of automated, semi-automated or manual systems. DFDs describe how information flows logically or physically in a system. The logical view describes how information flow is expected to happen, while the physical view refers to what actually happens. In some cases, both the physical and logical views may be the same.

Although a wide range of symbols are used in DFDs, most authors use a notation for DFDs which involves four key features: processes, external entities, data stores and data flows (Du *et al*., 2000; Turetken and Schuff, 2007; Butler *et al*., 1995) as shown in Figure 2-1a.

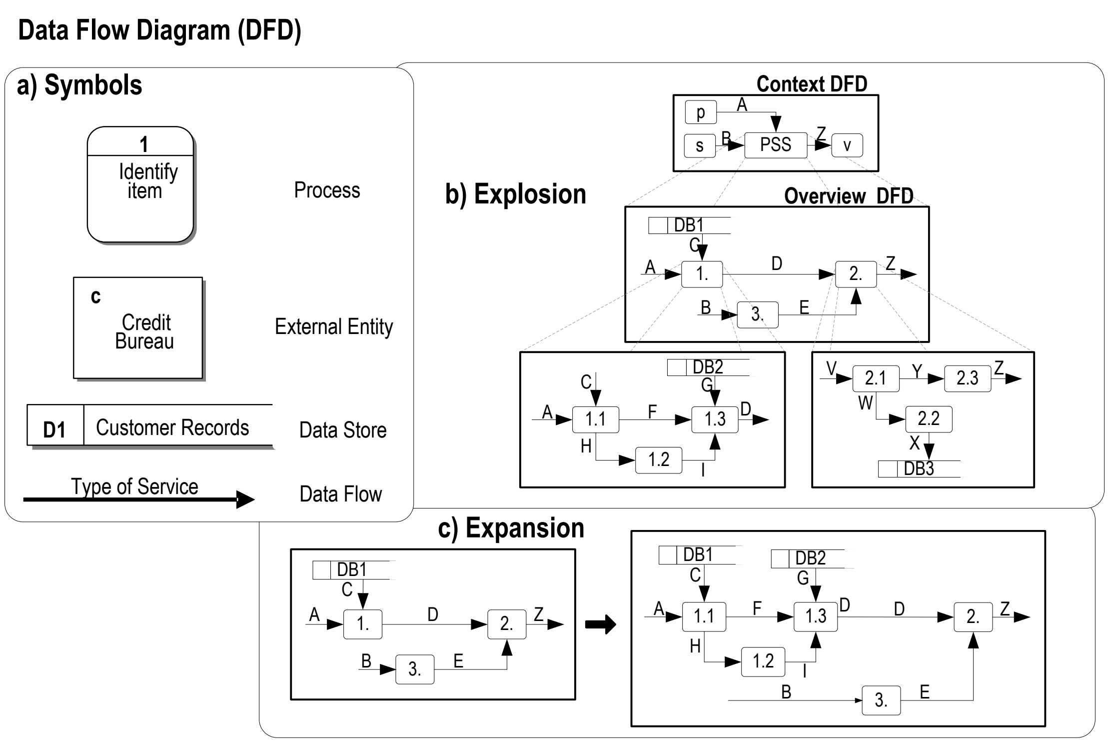


Figure 2-1: Approaches for Data Flow Diagrams (DFDs): (a) DFD representations; (b) Explosion approach to DFD development; and (c) Expansion approach to DFD development

With regards to design approaches, Du *et al*. (2000) identified two main schemes for designing DFDs (see Figures 2-1b, 2-1c). The *expansion approach* described by Gane and Sarson (1979) is the first scheme. It applies a single DFD, which is iteratively expanded till the entire system has been comprehensively modelled. In the other scheme, the *expansion approach* as explained in DeMarco (1979), a single diagram is created initially. This diagram is known as the context DFD. The system within this context DFD is then exploded to give the overview DFD. After these first two steps, multiple DFDs are constructed, with each successive model derived as an explosion from a single activity step in a parent or preceding diagram. This process is continued till the entire system has been comprehensively modelled. A slight variation of the explosion approach is employed in the Structural Analysis and Design Technique developed by Softech, Inc (DeMarco, 1979).

2.3.1.2. IDEFØ and IDEF1

The IDEF technique is an approach to modelling and analysing systems and enterprises. It is made up of a suite of models which contain a hierarchy of diagrams, text and glossary (Knowledge Based Systems Inc, 2006). These models include IDEFØ, IDEF1, IDEF1X, IDEF3, IDEF4 and IDEF5.

The IDEFØ or the Integrated DEFinition method of modelling functionality is a widely used technique employed by organisations, industries and governments to support their enterprises and applications (Federal Information Processing Standards, 1993; Software Engineering Standards Committee of the IEEE Computer Society, 1998). Sullivan (1991) asserted that the IDEFØ approach was borne out of the need for structured techniques which can be applied in systems, such as manufacturing systems, involving information flow.

The foundation for the IDEFØ modelling technique lies in the Structural Analysis and Design Technique (SADT) developed by Douglas T. Ross at SofTech, Inc in the early 1970s (Federal Information Processing Standards, 1993; Sullivan, 1991; Ang *et al*., 1995; Kusiak *et al*., 1994; Bernus and Schmidt, 1998). SADT is a function-oriented approach which adopts an all-inclusive modelling framework, unlike data flow diagrams, which concentrate on information flow in an organisation (Bernus and Schmidt, 1998). In 1978, the U.S. Air Force adopted the SADT as its modelling technique to support its Integrated Computer Aided Manufacturing (ICAM) programme (Software Engineering Standards Committee of the IEEE Computer Society, 1998; Kusiak *et al*., 1994). It is this approach, later revised by SofTech, which now exists as the IDEFØ modelling approach. Consequently, IDEFØ can be used for all kinds of function-oriented modelling for system-based applications, such as operation, activity, process or behavioural modelling needed by a system such as an organisation.

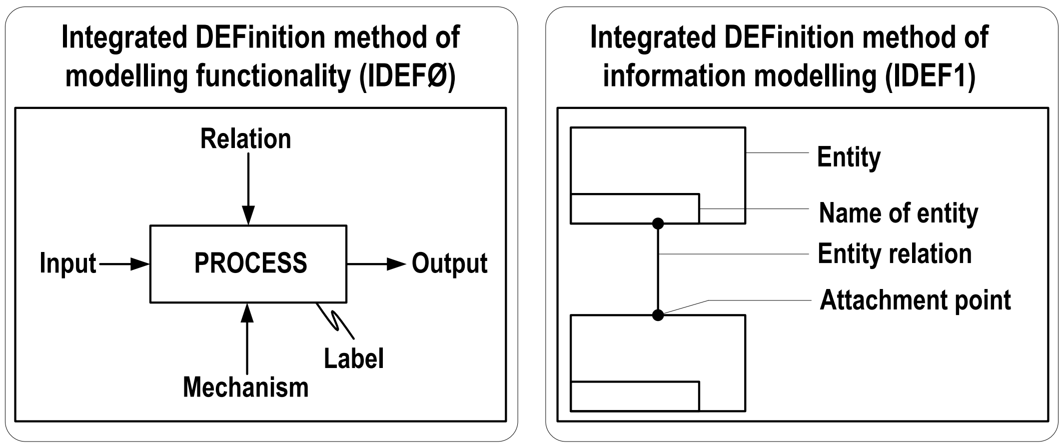


Figure 2-2: Representations for Integrated DEFinition method of modelling functionality and information modelling (IDEFØ and IDEF1)

IDEFØ models contain two main diagrammatic modelling components: boxes and arrows (Knowledge Based Systems Inc, 2006; Software Engineering Standards Committee of the IEEE Computer Society, 1998; Bernus and Schmidt, 1998) as shown in Figure 2-2. The idea in an IDEFØ model is to begin with a single top-level diagram (tagged as AØ) which provides a complete but abstract depiction of the system (Federal Information Processing Standards, 1993). This top-level diagram is then decomposed into a series of child diagrams, applying the explosion approach (see Figure 2-1b). Ho *et al*. (1994) suggested that decomposition in IDEFØ modelling should continue until a complete description of the organisation has been attained. This process, they contend, removes ambiguity and aids its use and implementation.

Based on the definition of information flow for this thesis, the IDEFØ approach can be used to model information flow. In other words, the IDEFØ approach illustrates the movement of information. For information modelling to complement the IDEFØ approach, the IDEF1 (Integrated DEFinition method of modelling Information) is recommended (Lingzhi *et al*., 1996). IDEF1 offers basic primitives for describing information that must be managed for an organisation to fulfil its objectives (Chen *et al*., 2004). It identifies how functions described in IDEFØ can share data/information. It also offers three main modelling primitives: boxes that depict system functions, arrows that indicate data, information and object interface, and attachment points between arrows and points that represent types of interface (input, output, control or mechanism) described in the IDEFØ model.

2.3.1.3. GRAI grids and nets

The GRAI (Graphes à Résultats et Activités Interreliés) Engineering method was developed by GRAI Laboratory at the University of Bordeaux in the 1970s (McCarthy and Menicou, 2002; Doumeingts, 1989). Figure 2-3 shows the GRAI Modelling Technique which is based on a hierarchical conceptual model (the GRAI model) for supporting decision-making processes during manufacturing and establishing information flow for facilitating these decisions (McCarthy and Menicou, 2002; Doumeingts, 1989; Merlo and Girard, 2004; Wainwright and Ridgway, 1994). In Doumeingts (1989), the GRAI model is divided into two parts: a macrostructure which displays the architecture of the overall system arranged in a hierarchy and a microstructure for system components which are identified in the macrostructure. The **macrostructure** of the GRAI model (see Figure 2-3a) decomposes the system to be designed into three sub-systems (Merlo and Girard, 2004; Doumeingts *et al*., 1998; Vernadat, 1996). The *technological system* presents the means for delivering products and services such as people, machines and materials. It is also concerned with information flows associated with these tangible/intangible offerings for meeting customer expectations. The *decision system* details the locus of decision in the hierarchy. This hierarchy is arranged according to decision-making levels which contain blocks known as decision centres. The *information system* links the decision and physical system and the enterprise environment. It also transforms and memorises information. The **microstructure** is concerned with decision centres in terms of their intelligence based on recognising the need for a decision to be made, their modelling capabilities of derived or gathered information, and their choice for selecting appropriate solutions based on criteria, constraints and context.

Two main diagrammatical tools are used in the GRAI model: GRAI grids and GRAI nets (Ho *et al*., 1994; Doumeingts, 1989). The latter is designed to pinpoint discrepancies at the macrostructure, while the former reveals inconsistencies at the microstructure. Ho *et al*. (1994) contended that the intention of these tools is for system designers or decision makers to review iteratively the GRAI model until discrepancies and inconsistencies are resolved or within acceptable limits of defined goals and objectives. Both tools are designed to model activities in systems. Doumeingts (1989) defined an activity in a GRAI model as an operation which changes an initial state into a final state. Several GRAI grids can be developed based on requirements for realising goals and objectives or according to the complexity of the system (Doumeingts, 1989; Leondes, 1995). These grids are also characterised by cells for decision centres and relationships between these decision centres (Leondes, 1995).

Relationships are used in GRAI models to specifically describe information flow and decision flow for co-ordination and synchronisation of activities in an organisation or system (Doumeingts *et al*., 1998). Relationships are depicted diagrammatically as arrowed lines (see Figure 2-3b). Decision flow between two decision centres can be represented as large, emboldened lines, while information flow can be depicted as small dashed lines.

GRAI nets are developed after GRAI grids and describe the activities in a decision centre (Wainwright and Ridgway, 1994). They are done to complement GRAI grids which give high-level diagrammatic representations of decisions without providing information about how decisions are made (Doumeingts *et al*., 1998). GRAI nets, as shown in Figure 2-3c, are made up of three constructs: states, activity and supports. States are represented by circles or ovals. Activities are represented as directed arrows, while the supports (information and technological resources) are represented as rectangles.

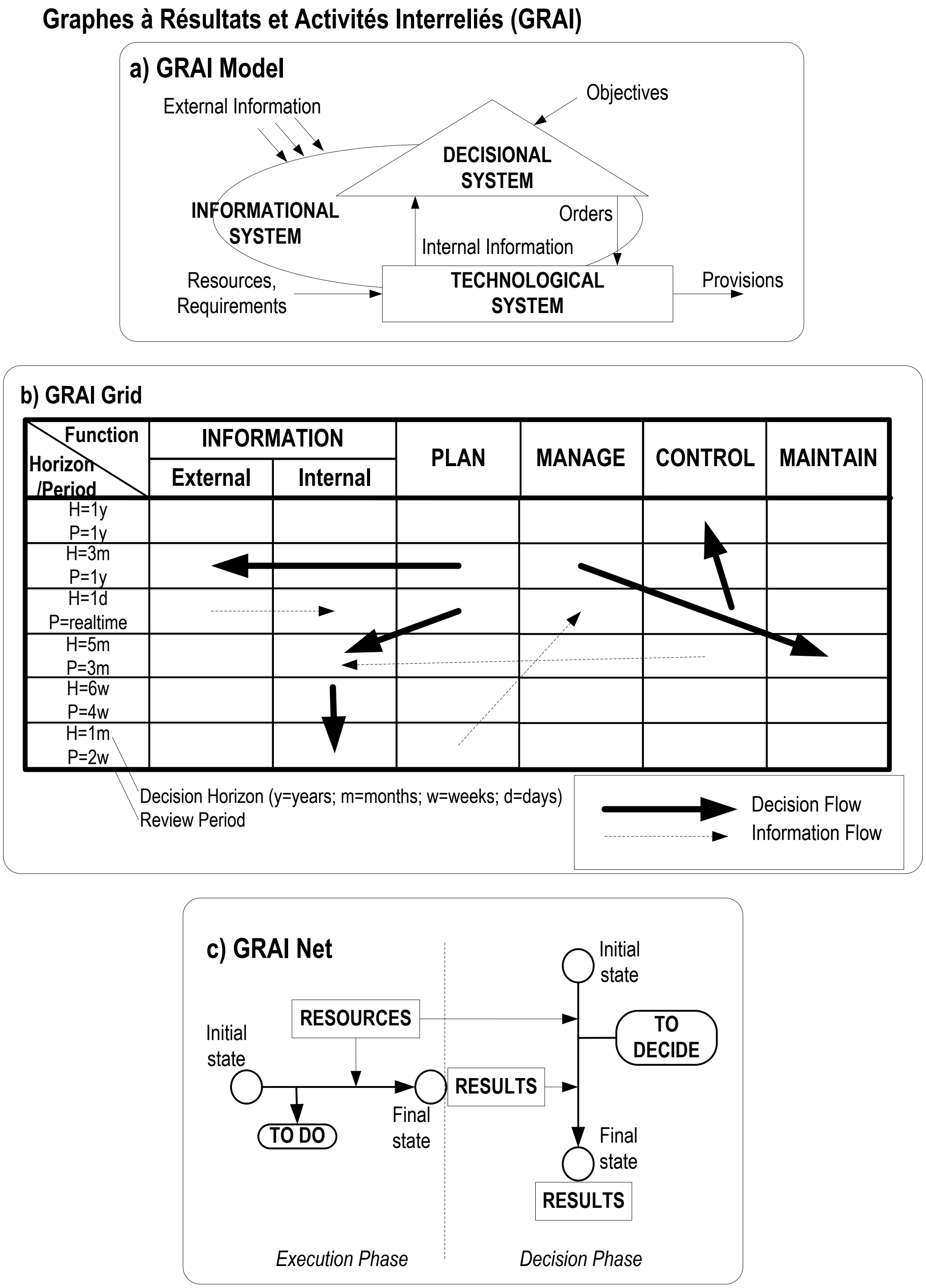


Figure 2-3: Graphes à Résultats et Activités Interreliés (GRAI) Modelling Technique

GRAI grids show information flow but do not represent or model them. GRAI nets on the other hand can be used to model this information flow. GRAI nets represent information flow by means of events or sequences of events in the manufacturing process or system. GRAI nets also depict states and state changes. Although originally designed for the development of production management systems, GRAI models can be used where a system is required among different groups or processes (Tucker and Leonard, 2001) like an organisation.

2.3.1.4. Petri nets

Petri nets (PNs) or place-transition nets were first proposed by Carl Adam Petri in 1962 for modelling processes in an event-driven system (Hilt *et al*., 1994; Zhou and DiCesare, 1993). These systems exhibit a wide range of characteristics such as non-determinism, concurrency, synchronicity as well as distributed and/or parallel features. PNs can also be used for representing the information flow in development and simulation of automated manufacturing systems (Bonney *et al*., 1999; Ou-Yang and Lee, 2000). Murata (1989) described PNs as useful mathematical and diagrammatical tools for representing control flow in systems.

Diagrammatically, PNs can be used to methodically describe and communicate ideas among designers and implementers. A PN is depicted as a directed, weighted, bipartite graph made up of four main symbols as shown by Figure 2-4. *Black dots* represent tokens. Tokens may be resources, counters, metrics or attributes. *Circles* show places and are marked with a non-negative integer *k* of token. *Bars* depict transitions, while *arcs* connect places to transitions. In the modelling of PNs, transitions represent events in a system, while places illustrate conditions for occurrence. The tokens provide the premise for the conditions just as input and output places offer pre- and post-conditions for the event respectively.

Mathematically, PNs are presented as tuples (Hilt *et al*., 1994; Zhou and DiCesare, 1993). A tuple is a fixed, ordered list of elements or objects. Tuples may contain multiple occurrences of elements and objects. A Petri net is defined as a quad-tuple (*P*, *T*, *I* and *O*) where:

P is a set of places i.e. $P = \{p_1, p_2, p_3, \ldots, p_n\}$;

T is a set of transitions i.e. $T = \{t_1, t_2, t_3, \ldots, t_n\}$, with $P \cap T \neq \phi$ and $P \cup T \neq \phi$ ('ø' refers to a tuple with no elements or objects);

I is an *input function* specifying *Arcs* directed from places to transitions i.e. $I:(P \times T) \rightarrow N$ (where N is a tuple of non-negative integers); and

O is an *output function* specifying *Arcs* directed from transitions to places i.e. $O:(P \times T) \rightarrow N$.

By applying these definitions, state and algebraic equations can be derived to define the behaviour and mathematical models which govern the behaviour of systems.

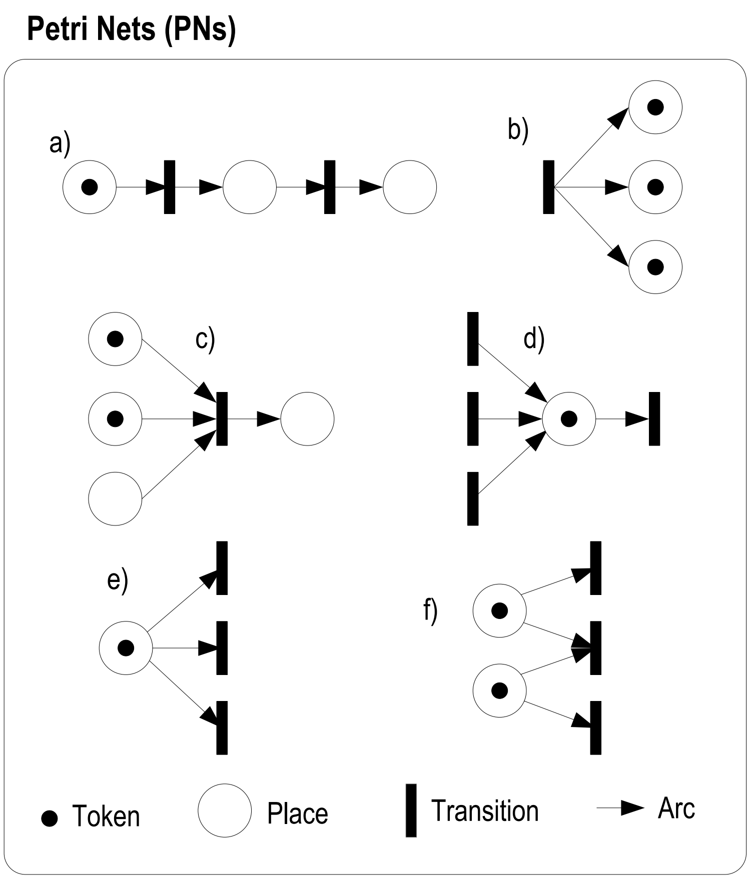


Figure 2-4: Petri net representations and constructs: a) Sequential execution; b) Concurrency; c) Synchronisation; d) Merging; e) Conflict; and f) Confusion

Lien (1976) described two main principles applied in Petri-net theory: transition enabling and transition firing. A transition is enabled or fireable if its input places all hold at least one token. A transition can be fired by two processes. First, one token is removed from each input place and secondly, the addition of a token to an output place. These symbols and configurations used in PNs can assist designers in describing some important system characteristics. These and other related principles, theories and formulae are extensively covered in literature (Zhou and DiCesare, 1993; Murata, 1989; Varadharajan, 1990)

Wakefield and Sears (1997) identified six possible constructs during the development of PNs. These constructs are depicted in Figure 2-4 and can be described in terms of information flow as follows. *Sequential* execution imposes precedence in the flow of information; *concurrency* shows parallel information flow; *synchronisation* coordinates information; *merging* combines information required to carry out a function; *conflict,* in which multiple functions request access to transactions are enabled but firing is disabled; and *confusion* which allows conflict and concurrency to coexist. The two latter issues can be remedied by assigning priorities or associating probabilities to appropriate transitions (Murata, 1989).

2.3.1.5. Input-process-output diagrams

The HIPO (Hierarchy plus Input-Process-Output) technique was developed by IBM's System Development Division (SDD) in the late 1970s (Stay, 1976; Katzan, 1976). It offers diagrammatic and textual representations for the documentation of systems, programs and processes. The HIPO technique is made up of two main components (Stay, 1976; Katzan, 1976; LaBudde, 1987; Nosek and Schwartz, 1988; Davis, 1998): Visual Table of Contents (VTOC) and Input-Process-Output (IPO) diagrams (See Figure 2-5).

The VTOC is represented as a chart showing how functions of a system or modules of a program are decomposed in a tree format. It offers a top-down analysis of a program, system or process and is made up of three main parts as shown in Figure 2-5b. The hierarchical diagram contains an echelon of numbered and named boxes which correspond to IPO diagrams and is read from left to right. A legend and an optional description for each function may also be included in the VTOC.

IPO diagrams are developed after the VTOC has been constructed. They describe functions (or modules) in the VTOC in terms of their inputs and outputs by means of processes which may be enclosed or encapsulated in the system. IPO diagrams are presented as pages in a form of pseudo-code showing local or functional information flow (Nosek and Schwartz, 1988). A page is developed for each function (or module). Each page (IPO diagram) contains three main blocks labelled as input, process and output as shown in Figure 2-5d. The idea is to show what is used (input) by the module; processing performed (translations and transactions) by the module represented as a high level textual representation pseudo code; and fields changed or written to (output) by the module (LaBudde, 1987; Nosek and Schwartz, 1988; Davis, 1998).

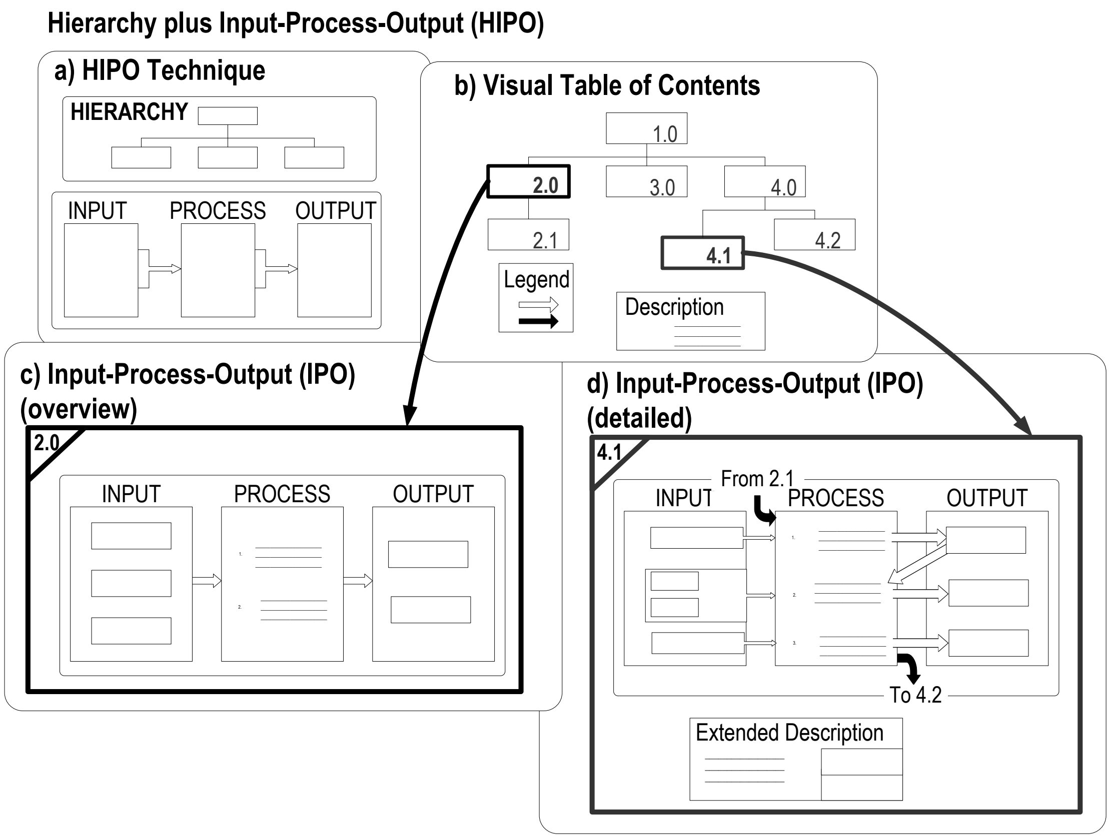


Figure 2-5: The Hierarchy plus Input-Process-Output (HIPO) technique and Input-Process-Output (IPO) diagrams

Stay (1976) traces the origin of the HIPO approach to structured design which offers methods for transforming a description into a functional, modular program structure. He identifies two important concepts of structured design exploited by the HIPO technique: module strength (relationships within a module) and module coupling (relationship between modules). Originally designed for the documentation of programs (Stay, 1976; Davis, 1998), its use can also be extended for other system related activities. The activities can include planning, development and implementation where the HIPO technique can offer information about the functions or 'what a system does' (Katzan, 1976). Martin and McClure (1985) also suggested its use for both the analysis and the design of systems. They recommend its use during analysis to aid definition of various system components as a means of kick-starting the design process. For design, they highlight its use as an enabler for describing procedures of system components.

2.3.1.6. Design structure matrix

The Design Structure Matrix (also known as problem solving matrix, dependency structure matrix and design precedence matrix) is a compact, visual, generic matrix-based framework for the graphical and numerical analysis of decomposition and integration in systems (Eppinger, 1991; Browning, 2001; Helo, 2006).

Syed and Berman (2007) traced the history of the Design Structure Matrix (DSM) approach to earlier concepts such as matrix mathematics, network precedence diagrams, network relationship diagrams and Interface-to-interface (N-to-N or N2). However, DSM in its current form was developed by Donald Steward as a tool 'to analyse the flow of information' in the design, development and operation of systems (Steward, 1981; Oloufa *et al*., 2004).

The DSM is implemented as an N-square matrix (See Figure 2-6) which represents functions and processes of systems in constructs of four forms: sequential, concurrent, coupled or conditional (Browning, 2001; Syed and Berman, 2007; Farid and McFarlane, 2006). This representation can be applied to depict information flow among types of systems and organisations. These system and organisational types can contain *elements* in the form of components or parameters or resources of the system, development phases, position or responsibilities of members in an organisation and so on.

A DSM can also be configured according to *attributes of marked cells* such as between binary DSM and numerical DSM (Browning, 2001; Steward, 1981; Yassine, 2007). Binary DSM typically involves the presence or absence of a mark (‘X’ or ‘●’) while numerical DSM could be applied to indicate importance or probability of repeating an element. In the DSM example in Figure 2-6, system elements or components are represented along the shaded diagonal. Off-diagonal ‘X’ marks and numerical values indicate dependency i.e. of one element on another. The labelled ‘X’ symbol in Figure 2-6a indicates the dependency of element E on element F.

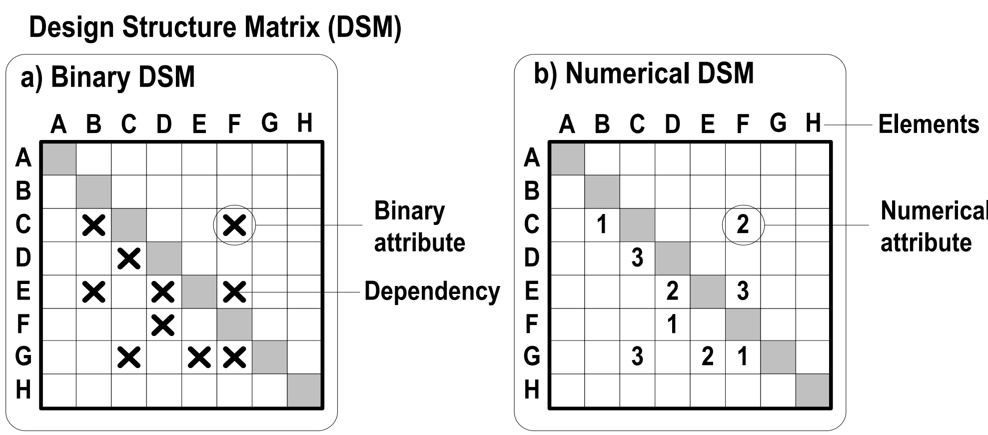


Figure 2-6: Design structure matrices according to attributes of marked cells

2.3.2. Mathematical modelling of information flow

Approaches for mathematically modelling information flow in organisations can be classified according to two main categories: *flow analysis* that propose quantities and information levels for assessing and improving organisational performance and *organisational analysis* that idealise organisations as different constructs for improving information flow. These approaches as shown in Table 2-3 make use of mathematical theories based on coordination, probability, complex networks, vectors, fluid flow and so on.

Table 2-3: Mathematical techniques for modelling information flow

Mathematical technique	Focus of technique	Mathematical field	References
Complex self-organisation network model	Analyse the trails left by information agents for: observation and recovery, and system normalisation	*Probability theory* *Network theory*	Costa *et al*. (2007)
Control network model – 'control net'	Analyse offices with regards to information processing	*Graph analysis* *Probability theory*	Ellis (1989)
Control network model - 'information tree'	Analyse the sequence of organisational procedures with regards to optimal control	*Vector analysis*	Feinstein and Morris (1988)
Control network model - 'spanning tree'	Analyse reliability and availability of flows	*Graph analysis* *Probability theory*	Kumar and Aggarwal (1989)
Decision network model	Analyse the organisational structure for uncertainty and complexity of networks	*Fuzzy possibility theory*	Ehsani *et al* (2010)
Feedback control model	Analyse delays of information flows and feedback	*Control theory* *Network theory*	Caldwell (2008)
Epidemic model of a scale-free network	Analyse information generation and transmissibility in social organisations	*Network theory*	Wu *et al*. (2004)
Information coordination model	Analyse coordination between decision units	*Nash equilibrium*	Barua *et al.* (1997)
Information-decision network model	Analyse and improve organisational decision support	*Interaction matrices*	Hansen *et al*. (1978)
Logistics network model	Analyse relationships based on geographical spaces	*Graph analysis* *Economic model*	Aoyama *et al* (2005)
Management fundamentals framework	Analyse relationship flows for improved management performance	*Probability theory*	Lin and Cheng (2007)
Network model of a company	Analyse coordination of hierarchical networks	*Network theory* *Graph analysis* *Organizational theory*	Almendral *et al*. (2003), López *et al.* (2002)
Parameter-based framework	Analyse relationships within organisations and environmental factors	*Fluid flow*	Krovi *et al* (2003)
Flow evaluation model	Analyse the functioning of groups for enhancing decision making	*Probability theory*	Szczerbicki (1991)
Production network model	Analyse firm relationships and process characterisation	*Nash equilibrium* *Economic model*	Creti (2001)
Production operations model	Analyse coordination in terms of uncertainty, variability and equivocality	*Coordination theory*	Albino *et al* (2002)
	Analyse and simulate relationships and flow patterns in new product development	*Organizational theory* *Probability theory*	Braha and Yaneer (2007)
	Analyse inventories in an	*Probability theory*	Datta and

	organisation in terms of parallel and serial flow, and production stages		Chaudhuri (1977)
Optimal level of information	Analyse organisational hierarchies with regards to productivity and information processing	*Probability theory*	Ben-Arieh and Pollatscheck (2002)
	Analyse organisational hierarchy for side-links and information control	*Graph analysis* *Organizational theory*	Helbing *et al.* (2006)
Organisation network model	Analyse flow patterns and relationships	*Network theory* *Organizational theory*	Merrill *et al.* (2008)

2.3.2.1. Flow analysis

The work by Datta and Chaudhuri (1977) concentrated on serial and parallel information flow in operation inventory systems for manufacturing organisations. The term ‘operation inventory system’ was used by Datta and Chaudhuri to describe a chain of manufacturing operations separated by inventories under periodic review of base stock systems of ordering. They developed a mathematical model for deciding on the optimum mix for operations that achieve the greatest efficiency.

Four information flow parameters suggested by Krovi *et al*. (2003) offer useful quantities for assessing the level of performance of an organisation. Information node density, the first parameter, deals with the complexity of information flow and is computed as the number of intermediate nodes that are present in an information processing channel. Information velocity is the second parameter and deals with the rate at which information is received at a node. Information viscosity, the third information flow parameter, is concerned with the level of conflict at a node i.e. the presence of contradictory information. The fourth parameter, information volatility describes uncertainty in the content, format or timing of information.

Szczerbicki (1991) modelled internal and external information flow in the functioning of groups and proposed a quantity for evaluating the value of information structures. Based on a simplistic example of an industrial production situation, Szczerbicki demonstrated the use of the model and concluded that rules based on the model can be applied in the development of group decision support systems.

Aoyama *et al.* (2005) modelled information (and commodity) flow in organisations with independent but linked sub-networks. They focused on logistics networks that incorporate methodologies for just-in-time manufacturing and inter-period network storage. These logistics networks in modern businesses incorporate web technologies (particularly the internet) in e-logistics for overcoming factors such as language barriers, and time zone and spatial constraints. Aoyama *et al.* studied the characteristics of logistics in geographic/ virtual spaces and concluded that intermediaries (such as middlemen) can still be important elements in the logistics industry.

Wu *et al*. (2004) developed an epidemic model for assessing the spread of information in social organisations. The model concentrates on analysing networks that are scale-free. Wu *et al*. concluded that the discovery of information hubs in an information network is not sufficient enough to guarantee that information transmitted from a source will spread to a large section of an organisation.

Creti, (2001) proposed a model for information that flows horizontally in organisations. These flows, termed ‘side-links’, were applied in the analysis of two forms of organisations: M-form (according to divisions in an organisation) and U-form (according to product-lines in an organisation). Creti treated the flow of information as a variable with unit cost, and concluded that information flow (primarily for demand and external communication) is an important factor that determines the profitability of functional and product-based organisations.

Helbing *et al*. (2006) modelled side-links in organisations made up of multiple agents with complex non-linear interactions. The model much like the one proposed by Creti (2000) proposed side-links for information flows. But unlike Creti, the model focused on hierarchical, regular area-filling kinds of organisational subdivisions according to triangular, quadratic and hexagonal configurations. Helbing *et al*. demonstrated how short-cuts and temporary links in hierarchical organisations can contribute to efficient and effective information flow during crisis or disaster response management.

Ben-Arieh and Pollatscheck (2002) proposed a model for identifying the optimal level of information required to flow in an organisation. The model consists of a productivity function and information processing parameters for assessing the hierarchy of three forms of organisations: homogeneous, semi-homogeneous and non-homogeneous. In the homogeneous organisation all employees independent of the hierarchical level possess the same information processing rate. The semi-homogeneous organisation is governed by a common productivity function but different information processing parameters for each hierarchical level. In the non-homogeneous organisation, the levels of hierarchy are governed by different productivity function and different information processing parameters.

Braha and Yaneer (2007) analysed the topology of information flow networks within the context of large-scale product development. The model makes use of statistical properties inherent in complex networks to identify parallels in social, biological, and technological networks. Braha and Yaneer concluded that properties within a firm (intra-organisational) can be expanded and applied in improving interactions involving multiple organisations (inter-organisational).

Kumar and Aggarwal (1989) proposed an approach that utilises spanning trees as a measure for determining the overall reliability of networks. They identified spanning trees as a minimal set of links required to maintain network connectivity. Kumar and Aggarwal applied PNs and matrix multiplication in deriving a list of spanning trees for a network that could be used to compute the ‘'overall reliability' of networks for analysing information flow.

In the study by Almendral *et al*. (2003) and López *et al.* (2002), the traditional hierarchical topologies of organisations were analysed to examine organisational efficiency in terms of: group sizes and information propagation. In both studies the concept of a coordination degree was introduced as a quantity that measures the ability of individuals in an organisation to exchange information.

Focusing on coordination theory, Albino *et al*. (2002) analysed the production operations in an organisation. The model proposes a ‘coordination index’ derived from uncertainty (or complexity), variability and equivocality in an organisation’s information system. Albino *et al*. defined information systems as manual or computer-supported communication and decision-making processes.

Motivated by game theory, Barua *et al.* (1997) developed an information coordination model for analysing the exchange of usable intra- and inter-organisational information between decision units (individuals or groups that are assigned tasks). The model is based on the idea of cheap talk (communication within the context of game theory that costs nothing and is non-obligatory) as a mechanism for partially coordinating inter-organisational activities.

Costa *et al.* (2007) developed a mathematical model of information for complex networks made up of human-made structures. The model analyses trails left by information flow for identifying contamination sources, strategies for immunization and optimal routing paths.

Caldwell (2008) developed a 'feedback control' model that analyses the delay between the time information is sent from a source and received at a destination. The model introduces a task time quantity for assessing the use of information and communication technologies (ICTs) for supporting human-human communication and for improving task coordination.

2.3.2.2. Organisational analysis

Drawing on graph theory principles, Hansen *et al*. (1978) developed a technique for analysing organisations when idealised as information-decision networks. The aim of the technique was to propose a 'reachability matrix' for determining if two units are reachable from each other.

Ehsani *et al*. (2010) modelled organisations as distributed decision networks. The model contained definitions for decision information, informational dependence of decision makers and informational complexity of the network. Ehsani *et al.* used the model to assess the structure of organisations in terms of the network complexity and uncertainty, and concluded that relations in a distributed decision network contribute to organisational efficiency.

In the work by Lin and Cheng (2007) an organisation is idealised as 'a kind of special system' made up of connected parts that relate to its environment by means of 'relationship flows'. These relationship flows include information flows, matter flows, energy flows, fund flows and personnel flows. Lin and Cheng also suggested that these flow are fundamental to the existence and survival of organisations and the role of management science is to optimise the flows so as to improve organisational performance.

Feinstein and Morris (1988) focused on the ‘state’ of information in an organisation and developed an ‘information tree’ model to assist organisational personnel in understanding the effects of introducing new information systems. The information tree model views complex organisations as information processing systems that are made up of people, equipment, activities, and procedures, that receive/transmit information as inputs/outputs.

Organisations modelled as complex information processing entities are also the basis for the work by Merrill *et al*. (2008). The information processing entities contain internal structures and processes that change subject to environmental effects. However, unlike the approach by Feinstein and Morris (1988) the work by Merrill *et al*. concentrated on analysing networks for organisations in terms of internal structures and processes. The result of the network analysis is a report that contains network measurements to complement information flow diagrams.

Ellis (1989) proposed a mathematical model, an ‘information control net’, for describing information flow in offices. In the model, offices are idealised as complex and highly interactive processing information systems. The purpose of the information control net was to rigorously describe organisational activities, test underlying diagrammatic descriptions for flaws and inconsistencies, and suggest possible office restructuring permutations.

2.4. MODELLING INFORMATION FLOW FOR ‘ORGANISATIONS AS NETWORKS’

Existing approaches to modelling information flow for organisations, identified in §2.3, have explored two main idealisations: ‘organisations as information processors’ (Ellis, 1989; Feinstein and Morris, 1988) and ‘organisations as networks’ (Merrill *et al*., 2008). The information processing idealisation analyses internal structures and processes that change subject to environmental effects whereas the network idealisation identifies patterns of relations and involvement (centralized and decentralized) within and between organisations.

Recently, complex network has been favoured by academic researchers due to its usefulness for delineating organisations with a view to identifying innovation networks and topologies capable of tapping knowledge from external sources. This is due to on-going studies and renewed interests in organisational/network theory that are driven by the proliferation of web-based systems and technologies such as: e-mail, peer-to-peer and grid computing, video-conferencing and mobile/broadband connectivity (Anderson, 2002; Cross *et al*., 2002; Wang *et al*., 2002). Furthermore, the mind-set of 'an organisation as a network' is widely considered in research as a useful approach for promoting organisational flexibility and adaptability, particularly in the *quality* and *sharing* of information (Oberg and Walgenbach, 2008). It is for this reason that complex networks can offer useful insights into how people work together based on media choice (depending on the context and needs of information flow), and communication media that influence information sharing (Grippa, 2009; Gregg, 2010).Consequently, complex network concepts have been used to analyse organisational characteristics such as hierarchies (López *et al*., 2002; Ben-Arieh and Pollatscheck, 2002) and decision making (Ehsani *et al*., 2010).

A complex network can be described as a graph $G = (V, E)$ containing a set of vertices V (called nodes or points) that are associated by edges E (called links or lines) (Boccaletti *et al.*, 2006) as shown in Figure 2-7. The vertices represent entities within a network whereas edges indicate interactions based on relationships in which the entire graph is connected (i.e. for a vertex i in the graph, there is a path made up of edges to another vertex j) or disconnected. A complex network can contain a subgraph (G') = (V', E') – a subset of G where V' and E' are subsets of V and E respectively. In Figure 2-7, subgraphs can be created between sets of vertices (A, B, C, D), (A, D, G), (B, C, D, F) and so on. Vertices, edges and topology (that depicts how vertices and edges are arranged) are the main concepts used to characterise information structures for analysing domains such as the World Wide Web, social networks, brain networks and genetic networks (Boccaletti *et al*., 2006).

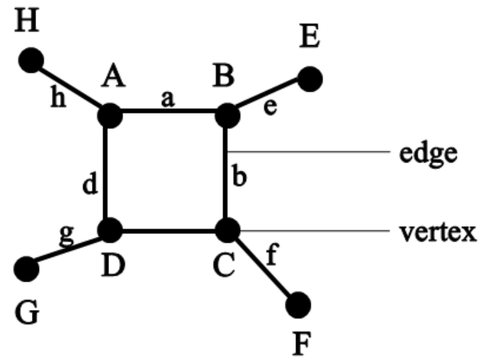


Figure 2-7: A complex network as a graph

Within complex network research, social network analysis (SNA) is the main approach adopted by researchers to study and understand relationships, social roles and social structure in organisations (Anderson, 2002; Hawe *et al.*, 2004; Wu *et al.*, 2004; Hatala and Lutta, 2009; Boccaletti *et al.*, 2006; Schultz-Jones, 2009; Wi *et al*. 2009). Examples of the use of SNA in characterising organisations include *friendship networks* for informal interactions and friendships (Newman 2001) and *hierarchical networks* for filling administrative layers (López *et al.*, 2002; Ben-Arieh and Pollatscheck, 2002).

Whilst the concept of organisations as networks is viewed by some social network researchers as a 'counter-model' to the bureaucratic organisation (Anderson, 2002; Oberg and Walgenbach, 2008; Pryke and Pearson, 2006), other authors have argued and shown how organisations, at least for administrative purposes, can be analysed as hierarchical networks (López *et al.*, 2002; Ben-Arieh and Pollatscheck, 2002).

SNA is often associated with organisation theory (Milward and Provan, 1998) and is used to identify clear patterns of relations and involvement (centralized and decentralized) based on gathered data such as the age, gender, and race of actors (Milward and Provan, 1998; Hatala and Lutta, 2009; Anderson, 2002). It makes use of techniques from sociology and mathematics for the representation and quantification of an organisation's information structure (Hawe *et al.*, 2004; Milward and Provan, 1998). Although networks can be represented as a matrix or a graph, most researchers prefer graph representations in which vertices represent actors within networks, and edges indicate the relationships between the actors with a view to improving processes and performances (Valente *et al.*, 2008).

However, the use of the term 'actor' is open to the interpretation of researchers. For instance, Pryke and Pearson (2006) used the term actor to represent a 'role-holding firm' whereas Van Der Aalst *et al.* (2005) applied the term actor as individuals within an organisation.

Quantitatively, SNA is based on sociocentric (whole) approaches in which groups and group interactions are studied, and egocentric (personal) approaches in which an individual and an individual's interaction is assessed (Hatala and Lutta, 2009; Valente *et al*., 2008; Clarke, 2005). Sociocentric and egocentric approaches are primarily studied through cohesion and centrality respectively (Hawe *et al.*, 2004) for characterising the **information behaviour** of social networks (Chen, 2007; Schultz-Jones, 2009). *Cohesion* is a network attribute that characterises the structural interconnectedness of two vertices *i* and *j* in a network and is assessed in terms of: **distance** between vertices computed as the sum of edges along the shortest path between *i* and *j*, **reachability** between vertices that establishes if *i* and *j* are linked directly or indirectly, and **density** between *i* and *j* that compares number of actual edges to the number of possible edges. *Centrality* is a network attribute that characterises the structural prominence or importance of a vertex *i* within a network and is evaluated with regards to: **degree centrality** that is computed as the number of directly connected vertices to *i*, **closeness centrality** that is measured as the inverse of the distance between *i* and network vertices, and **betweenness centrality** that is calculated as the amount of times *i* connects other vertices to each other. These quantitative concepts offer a useful avenue for giving exact meanings and mathematical definitions for terms that ordinarily can only be described metaphorically using phrases such as 'social role' and 'prominence' (Milward and Provan, 1998).

2.5. RESEARCH GAP

An analysis of the academic literature on delivery information flow in §2.2 and information flow modelling in §2.3 reveal two important lacunas relevant to this research: the need for delivery information flow analysis and for information flow model selection and suitability.

2.5.1. Delivery information flow analysis

Firstly, strategies for managing information flow during delivery have been examined in literature but none of the past studies have isolated and investigated information flow or information flow modelling for delivery phases. Furthermore, few studies in literature have isolated and investigated delivery processes and interactions for firms primarily because: (i) delivery performance (reliability and speed) is customarily viewed as an important measurement in the overall logistics scorecard of businesses (Handfield and Pannesi, 1992; Vachon and Klassen, 2002), and (ii) delivery management is usually integrated in supply chain management strategies (Zhang and Liu, 2008; Youngdahl and Loomba, 2000). In addition, supply chain management is required to coordinate delivery processes and other key business processes that run from the customer as an end user through to the manufacturer as a supplier of products (Themistocleous *et al.*, 2004). Supply chain management also considers the provision of services and information for added customer value (Youngdahl and Loomba, 2000). During delivery, these services may include product installation, online and telephone staff to support product use (Sundin, 2009).

2.5.2. Information flow model selection and suitability

Recent studies by authors such as Shankaranarayanan *et al*. (2000) and Stapel *et al*. (2007) have identified the need for creating or customising information flow modelling tools and techniques to meet new or specific characteristics of organisations. Furthermore, as earlier highlighted, each modelling approach has its strengths and weaknesses. Table 2-4 highlights some strengths and weakness of the diagrammatic information flow modelling tools described in previous sections. The table highlights relative ease of use, ease of interpretation, time taken to construct and ability to model aspects of a system.

New requirements for modelling arise due to evolution of organisations that can be attributed to advances in information systems. Most modern organisations manage the flow of information by means of a synergy between humans and computer systems (Hinton, 2002). The synergy raises new challenges for competitive networking particularly in terms of how to use information and ICTs. Competitive networking refers to the ability of firms to leverage ICTs for achieving organisational objectives (Malecki, 2002). ICTs also known as telematics (Boer and Walbeek, 1999) are information / telecommunication devices and applications for data storage and information retrieval, such as the internet, electronic mail, mobile phones and video conferencing (Owens *et al*., 1997). These devices and applications currently dominate information flow in modern businesses but have not been able or are likely to replace face-to-face interactions (Malecki, 2002). This is because face-to-face interactions still remain the best form of information flow due to the richness of information conveyed (Choe, 2008). Conversely, while face-to-face contact is viewed as an important form of information flow, it is still largely affected by the geography or location of personnel (Howells, 1995). In addition, the flow of documents (letters, memos etc.) remains a vital part of information flow and must be considered in any strategy for analysing or modelling information flow (Stapel *et al*., 2007).

Table 2-4: Strengths and weaknesses of information flow diagrammatic models

Modelling tool	Strengths	Weaknesses	Related tool
Data flow diagrams	Suitable for sequential representation of information flow	In large systems such as enterprises, these models may become	-
	Flexible and easy to maintain	Cumbersome in representation	
	Readily available context makes it easy to translate and read	Difficult to interpret	
	Varying levels allows focus on area of interest	Time consuming in construction	
	Popularly used and supported in industry	Ignores time dependent events or event driven processes	
Integrated DEFinition method of modelling functionality and information modelling (IDEFØ and IDEF1)	Suitable for analysing a business	Can be time-consuming and inconsistent	IDEF modelling technique
	Ideas and concept are easy to grasp and apply		
	Allows for controlled and incremental system description	Can be difficult to integrate related methodologies	
	Supported by standards and widely used in industry		
	Supported by closely related methodologies such as IDEF3 for process flow	May not be suitable for system development and documentation	
	Makes use of limited notation making them easy to interpret		

Graphes à Résultats et Activités Interreliés (GRAI) grids and nets	Suitable for supporting decision making processes in manufacturing enterprises	Only concentrates on the information flow related to decision making processes	GRAI modelling technique
	Highlights opportunities for synchronicity and concurrency in systems by depicting the durations for the system processes	Fails to provide structure details such as: enterprise processes, the distribution and use of resources and the organisation or enterprise being modelled	
	Enhances enterprise performance by offering diagnosing mechanisms which can identify defects in operation and reasons for management gaps		
Petri nets	Suitable for automated or event-driven systems	Tough to learn and popularize	-
	Based on a solid mathematical foundation	Easily becomes too complicated even in reasonably sized systems	
	Allows for extensions and modifications		
Input-process-output (IPO) diagrams	Suitable for hierarchically structured programs	Can quickly become cluttered in big programs or systems; becoming difficult to interpret	HIPO (Hierarchy plus Input-Process-Output) modelling technique
	Presents a useful avenue to begin program and system designs	Can be bulky since it uses a page for each module irrespective of module size	
	Provides ready-made documentation of a system after its implementation	Lacks support for loops, conditions, data structures or data links	
	Identifies procedural flow from input to output	Not widely used in industry	
	Offers clear definitions	Difficult to maintain	
Design structure matrix	Suitable for representing the entire range of interactions among functions	Difficult to construct since data may not always be available	-
	Compact and clear representation	Data required may be vast and difficult to assimilate	
	Can assist a company identify and focus on key issues	Do not include task duration, time lines or estimates for task duration	
	Supports continuous learning, development and innovation		

2.6. SUMMARY

In this chapter, academic literature was reviewed with regards to information and information flow for organisations, and delivery information flow. Next, literature was reviewed to identify existing techniques for modelling information flow for organisations.

Mathematical modelling makes use of mathematical theories based on concepts such as coordination, economics, graphs, probabilities, networks, vectors, and fluid flow, for flow analysis and organisational analysis. Flow analysis studies focus on quantitative measures for analysing the level of information in organisations and production inventories whereas organisational analysis researchers have attempted to improve operational performance of information systems in terms of innovation, efficiency, and competitiveness.

Key diagrammatical information flow models were also identified. DFDs can be used in organisations to propose information flow path (logical view) and to represent actual flows (physical view). DFDs do this by depicting processes, external entities, data stores and flows in sequential representations. Information flows in manufacturing organisations can be highlighted by the IDEFØ/IDEF1 approaches which make use of boxes (representing functions) and arrows which indicate relations, input, control, output, and mechanisms associated with the function. GRAI grids and nets provide information flow descriptions to support decision making processes in an organisation. Petri-nets deliver representations of information flow in the development and simulation of event-driven and automated manufacturing organisations. IPO diagrams offer information flow descriptions in programs but can also be extended to describe organisations with varying complexity. DSMs present compact, visual, matrix representations for systems analysis, offering a roadmap of system level knowledge.

Based on the review, research gaps relevant to the research were identified with regards to the need for analysing delivery information flow characteristics and the need for evaluations that determine information flow model selection and suitability.

Chapter

3

RESEARCH FOCUS AND METHODOLOGY

Driven by the literature review of Chapter 2, this chapter identifies the research focus, establishes the industry scope and outlines the research methodology. The research focus is defined based on analysis of the research gap from academic literature (§2.5) to determine current opportunities for modelling information flow in organisations. The research scope is established based on an analysis of the research needs relevant to the microsystems technology (MST) domain, as captured through an industry survey and an empirical study. The chapter also includes the overall research methodology for the development of the proposed technique that addresses the gap.

3.1. RESEARCH FOCUS

Informed by the research gaps identified in §2.5 the focus of this research is to: (i) analyse the characteristics of delivery information flow based on industry practice, (ii) evaluate the suitability of existing techniques to model delivery information flow, and (iii) to make use of these characteristics to propose, evaluate and/or validate a set of diagrammatic primitives and a mathematical model for modelling information flow. In order to accomplish this, current industry needs for information flow modelling during delivery will be analysed to establish an industry scope. Focus on relevance for industry ensures models are effectively used by organisational analysts and managers.

Addressing the need for effective use of techniques for modelling information flow, is the goal of: (i) studies by Ellis (1989) and Feinstein and Morris (1988) that proposed 'control nets' and 'information trees' respectively for modelling information flows in offices, and (ii) more recent approaches such as: the 'information product map' by Shankaranarayanan *et al*. (2000) that is designed to model the quality of data in an organisation and FLOW notation by Stapel *et al*. (2007) that offers diagrammatic primitives for modelling the flow of documents in manufacturing processes.

To guide information flow analysts/managers, diagrammatical tools can include prescribed steps for creating models. For instance, a data flow diagram can be developed based on two different approaches: explosion (also applied in the Integrated DEFinition (IDEF) methodology) in which each successive model is derived as an explosion from a single activity step in a parent or preceding diagram, and expansion in which a single diagram is iteratively expanded till the entire system has been comprehensively modelled.

Also, for effective use of diagrammatic models in design, it has been suggested that existing diagrammatical tools be assessed based on their ability to aid perceptual (for thorough grasp of meaning) and conceptual (for hypotheses development) cognitive processes (Hungerford *et al*., 2004). This assessment aids designers and researchers in systematically identifying modelling requirements of intended tool users that may then be applied in: selecting tools that meet user requirements, combining tools to create a hybrid version for use in modelling organisation characteristics, modifying tools to meet user requirements, or developing new tools to fill existing gaps or fulfil user requirements.

Furthermore, the mathematical modelling of information flow is also required to reveal mathematical properties that underlie organisational structures and processes (Collins *et al*. 2010). It is for this reason that several works (such as Feinstein and Morris (1988), Hansen *et al*. (1978) and Ding *et al.* (2007)) have complemented or combined diagrammatical models with mathematical models to create a clearer description of information flow in organisations.

3.2. INDUSTRY SCOPE

This section seeks to establish an industry scope for the research based on studies of industry practice. In other to accomplish this, two studies were carried. First, an industry survey of 40 companies was conducted to capture industry practice in the use of modelling tools (identified from §2.3) by organisations delivering MST. Second, an exploratory study was conducted with 3 of the 40 companies to understand current information flow modelling needs of organisations. Based on the established scope, a set of modelling goals will then be defined for charactering delivery information flow and for developing the proposed technique.

3.2.1. Industry survey of organisations delivering microsystems technology

An industry survey was carried out to establish if there are correlations in the information flow modelling tools proposed in literature and those actually employed in industry. The industry survey centred on a sample of 100 MST companies[1]. The sample was made up of a random selection of members of organisations (MEMS Industry Group, IVAM and SEMI) for companies aiming to carry out business transactions within the MST industry. These companies are headquartered at locations in Europe (56%), North America (38%) and Asia (6%), as shown in Figure 3-1.

Figure 3-1: Geographical distribution of survey sample

[1] An initial analysis and findings of industry practice in the delivery of MST by the sampled companies was presented in 'Durugbo C., Tiwari A., Alcock J.R., 2011, Service delivery for microsystems production: a study. *CIRP Journal of Manufacturing Science and Technology, DOI: 10.1016/j.cirpj.2011.02.005*'.

A questionnaire[2] was developed and distributed with pre-defined responses (and the option of a user-defined response) from participants over a period of 3 months. The questionnaire enquired about the use and the purpose of using modelling tools (Data flow diagrams (DFDs), Integrated DEFinition method of modelling functionality and information modelling (IDEFØ and IDEF1), Graphes à Résultats et Activités Interreliés (GRAI) grids and nets, Petri nets (PNs), Input-Process-Output (IPOs) diagrams and design structure matrices (DSMs)) in these organisations through questions such as 'What modelling techniques have you used as part of your duties?' and 'What are these tools used for?' An additional enquiry was also made regarding how MST companies described the processes and functions in their organisations. Questions were also posed to companies to establish the nature of information flow (through the use of media forms)[3] and responsibility for managing information flow.

Responses to the questionnaires were solicited in three ways: firstly, via electronic mail containing the questionnaire, secondly, by means of an online survey site for which participants were allocated a unique ID to maintain traceability and confidentiality, and thirdly, by means of follow up telephone calls. *40 companies responded to the survey and completed the questionnaire*. A breakdown of the types of companies that completed the questionnaire is presented in Table 3-1. Responses to each question in the survey were aggregated and presented in a column chart that compared the aggregated responses.

Table 3-1: Breakdown of industry survey respondents.

Type of Company	Number of Survey Respondents
Microsystems technology (MST) foundry	8
MST manufacturer	22
Computer-Aided Design (CAD) developer	3
Intellectual Property (IP) company	2
Consulting firm	2
MST distributor	3

[2] Please refer to Appendix A for questionnaire used in the survey.
[3] Appendix B shows additional findings of the study that captured the characteristics of functions / processes and information flow responsibility in MST companies.

3.2.1.1. Industry survey findings

For information flow models, the survey showed that 17 of the 40 respondents applied DFDs as part of their duties, 4 of the 40 respondents made use of DSM while 17 of the 40 respondents did not make use of any of the information flow models identified in §2.3.1. All respondents that made use of DSMs also made use of DFDs. None of the respondents made use of IDEFØ, Petri Nets, GRAI or IPO charts as shown in Figure 3-2.

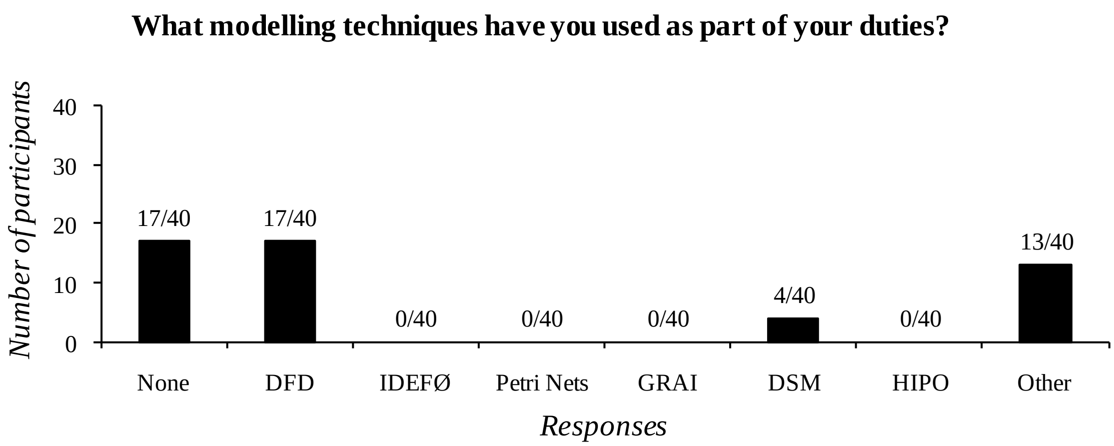


Figure 3-2: Diagrammatic models for microsystems technology production

13 of the 40 of the respondents noted the use of other forms of diagrammatical tools such as engineering block diagrams, Gantt charts, timing diagrams, software development tools, enterprise resource planning tools and project management tools based on methodologies such as PRINCE2 (**PR**ojects **IN C**ontrolled **E**nvironments).

In relation to the purpose of using modelling tools, the study showed that 20 of the 40 respondents applied modelling tools for the design and development of products as shown in Figure 3-3. 6 of the 40 respondents made use of modelling tools to design services while 7 of the 40 respondents made use of modelling tools to develop services. Other purposes of use identified by 5 of the 40 respondents include: for customer support, for quality planning, for managing the life of software development, to explain products and services to customers, for research and quality control, and for the delivery of services and products.

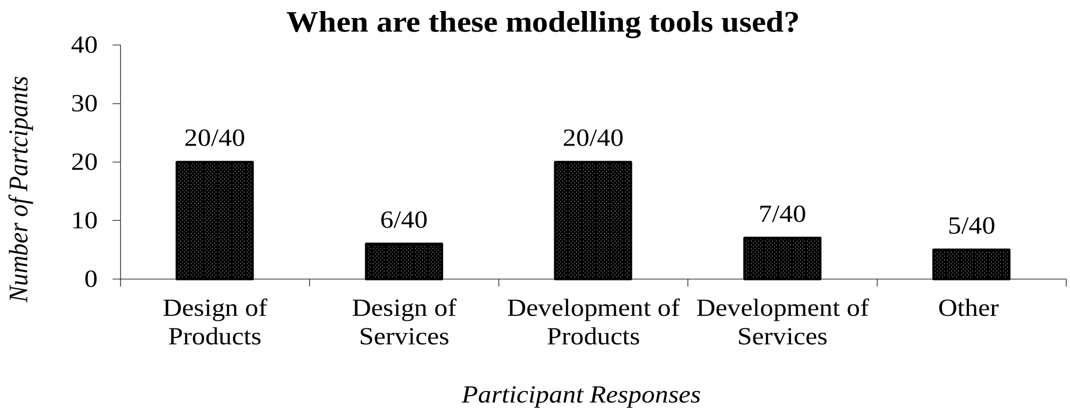


Figure 3-3: Application of diagrammatic models during microsystems technology production

When asked 'How are functions and processes carried out in the company?' participants responded, as shown in Figure 3-4. The figure showed that collaboration was chosen by 36 out of 40 respondents, 4 of the 40 respondents chose automation, 17 out of 40 chose networked, 5 out of 40 chose hierarchical, 2 out of 40 chose centralised, and 8 out of 40 chose distributed.

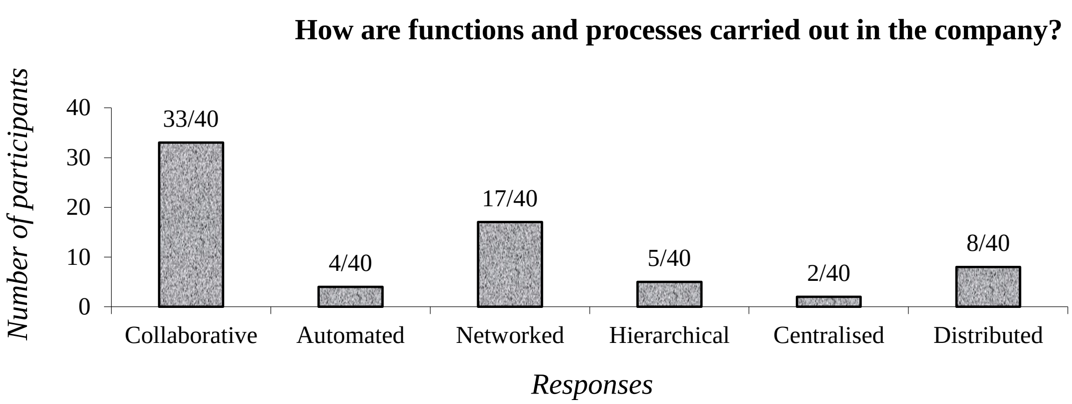


Figure 3-4: Description of functions/processes for microsystems technology companies

3.2.2. Exploratory study of organisations delivering microsystems technology

An empirical study of 3 MST companies was undertaken to explore how firms manage the flow of information and the nature of information flow during the delivery of MST based products and services. The MST companies represent a subset of participants the from the industry survey sample that agreed to take part in the study. All are based in the United Kingdom with a targeted global market and customers that are mainly original equipment manufacturers (OEMs) or academic institutions. The names of the companies remain anonymous for confidential purposes.

1) **Company A,** is a company that operates with 14 staff for the delivery of microfluidic and microoptical solutions. Products delivered by **Company A** include microlens arrays for flat panel displays, and lab-on-a-chip microfluidic devices for industrial automation, cell analysis and drug delivery. The case study focused on delivery by the entire company.
2) **Company B,** is a semiconductor based company that is headquartered in Europe and the case study focused on its software division which provides software for a wide range of MST. **Company B,** operates based on in-house capabilities to deliver microoptical and micromechanical prototypes. The software division has 200 staff. The customers of the software division at **Company B** are internal divisions or subdivisions that make use of MST-based products (mostly accelerometers and gyroscopes) for developing mobile phones and television set up boxes.
3) **Company C,** delivers microfluidic solutions with 30 employees split equally into subdivisions for manufacturing and R&D (research and development) where the case study was conducted. Products delivered are similar to the range of products offered by **Company A** and include lab-on-a-chip systems for DNA analysis, drug delivery and clinical diagnostics. In addition, **Company C** offers design services for planning the production of MST structures/components and project management services to assist customers in managing new product development.

Similar services delivered by all the research participants include technical advice on the applications of MST for developing consumer products and the outsourcing of MST production based on the company's industrial contacts and networks.

3.2.2.1. Exploratory study approach

An exploratory approach (Marshall and Rossman, 1999) was adopted for the study because it is designed to captured 'what' and 'how' existing firms manage the flow of information during MST delivery. Exploratory studies identify important variables for further analysis by means of explanatory or predictive research (Marshall and Rossman, 1999) and it is common practice for the (empirical) study to be carried out using three cases (Darke *et al*., 1998). Driven by the exploratory approach, a three staged scheme was adopted for the study: framework selection, semi-structured interviews and comparative analysis of findings.

3.2.2.1.1. Framework selection

A framework in the form of a chart proposed by Demiris *et al.* (2008), and containing the main dimensions of information flow (information access, information exchange and documentation) as shown in Figure 3-5, was used for capturing information flow in the study. Demiris *et al.* recommended the use of the chart for: capturing interactions within an organisation and identifying possible barriers to information flow. The chart was selected for use in this study for three main reasons:

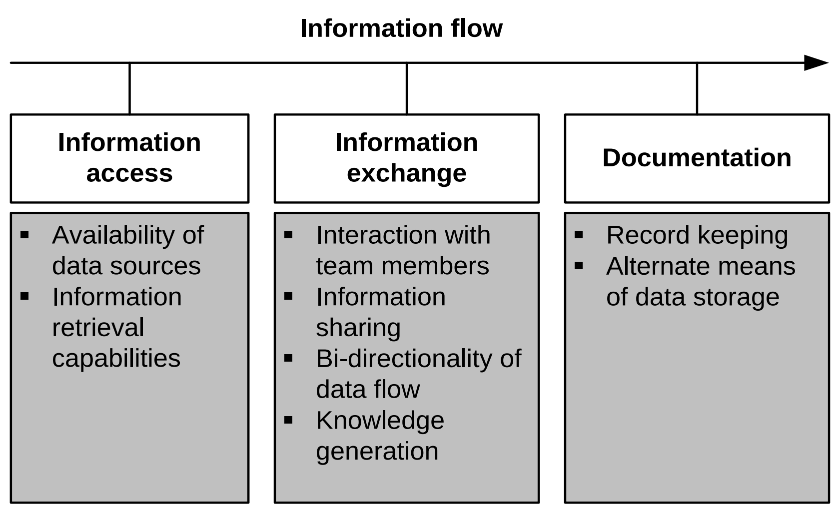


Figure 3-5: Dimensions of information flow (Demiris *et al*., 2008)

1) *Multidisciplinary approach* - As earlier mentioned in §1.2, MST production is a multidisciplinary endeavour that could involve business analysts, electrical engineers, chemists (microfluidics) and physicists. The chart is therefore suitable for this study because it was developed through an extensive research of multidisciplinary team communications contained in Larson and LaFasto (1989).
2) *Simplicity* - The chart characterises the flow of information in a simple and compact manner.
3) *Inclusiveness* - The chart can be applied to study a wide range of information flow properties because its concepts are rudimentary and contribute to the manner in which information can be classified using concepts such as Capability Maturity Model (CMM) or Maturity Index on Reliability (MIR). For instance, within the CMM, the manner in which information is accessed and exchanged within a company can be used to rank information in terms of if the number of accesses by staff is known but exchange duration is not known – giving a CMM scale of 0. Similarly, if number of staff accesses and duration times are known but the origin of access problems are not known then the CMM scale can be given as 1.

Within the context the exploratory study, information access, the first dimension of the chart, affects delivery information flow because it relates to the presence of delivery data and ease with which delivery information can be retrieved. This delivery data and information is based on the order book of a firm relative to flow policies that govern lead times and capacity allocations (Nicholson, 1982).

Information exchange is linked to delivery data flow, team interactions and the generation of knowledge, and affects delivery by enabling suppliers to share critical and proprietary information (Wamba and Boeck, 2008) that may be based on generic inventory control policies or specific weekly manufacturing schedules (Gavirneni *et al.*, 1999).

Documentation involves recording/storing delivery data and affects delivery information flow through regular data entry, worksheets, acquisition, recommendations, and report forms that guide suppliers and inform customers about important delivery data such as order status, customer enquiries, and lead times (Vaughan, 2000).

3.2.2.1.2. Semi-structured interviews

Using the framework in Figure 3-5 as a guide, semi-structured interviews were conducted with engineering and non-engineering staff responsible for managing the flow of information during the delivery of products and services. Four members of staff in total were interviewed: one at **Company A** (customer support manager), two at **Company B** (business director and systems engineer), and one at **Company C** (business and commercial directors). These interviewees were provided by the company directors (at each of the companies) following initial telephone conversations to request permission to visit the companies. The directors designated the interviewees as personnel responsible for managing the flow of information during MST delivery. All interviews were conducted on-site at the participating companies for durations ranging from 45 to 60 minutes, and interviews were recorded and fully transcribed. The semi-structured interviews were designed to determine the nature of staff responsibility and identify the requirements of managing the flow of information during product delivery.

The following questions were prepared and posed to interviewees to initiate the semi-structured interviews: With regards to delivery in your company how: “are data sources made available?”, “is information retrieved?”, “do team members interact?”, “does the company share delivery information?”, "is data flow bi-directionality supported?”, “is knowledge generated?”, “are records kept?”, and “are alternate means of data storage catered for?”.

3.2.2.1.3. Comparative analysis of findings

Using comparative analysis, responses to the posed questions were then used to populate an empty chart containing only the headings for the chart to create charts characterising the flow of delivery information in **Company A**, **Company B** and **Company C**. The idea behind the analysis was to distinguish what gets done as part of a job (in this case information flow as shown in Figure 3-5) and what is done by staff as part of their duties to manage the flow of information (the findings of the data collection in Figures 3-6, 3-7 and 3-8).

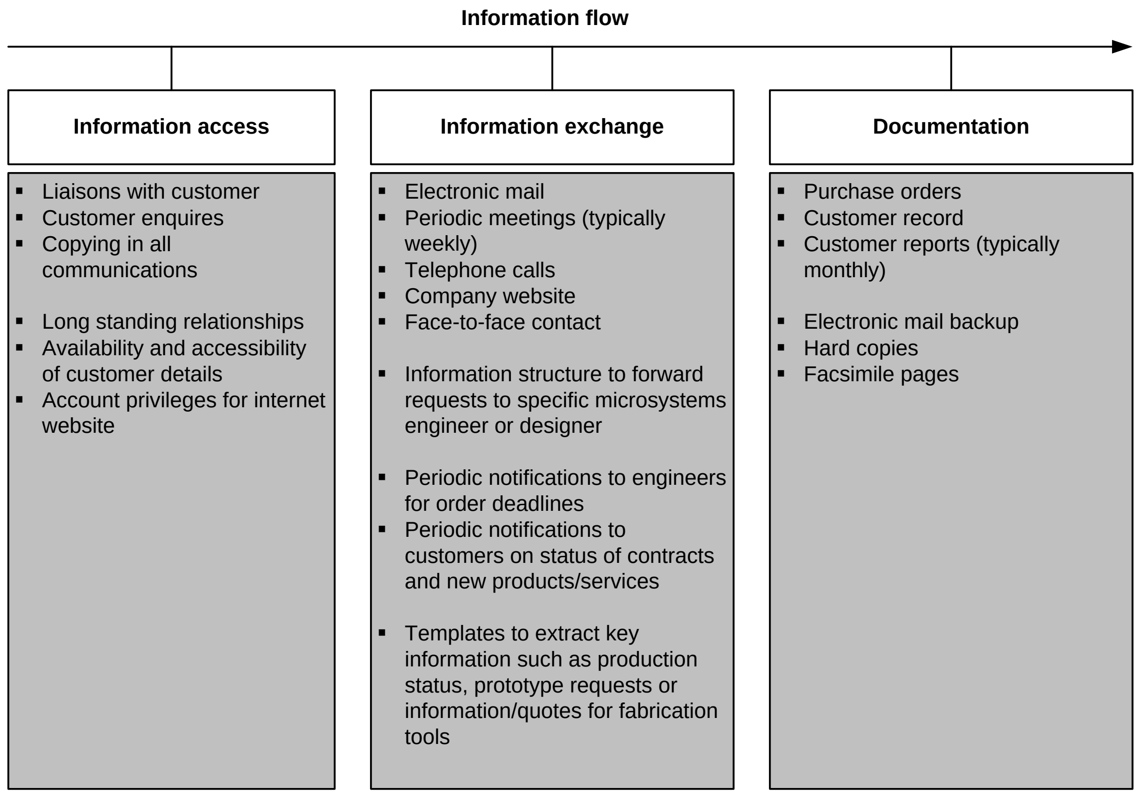


Figure 3-6: Information flow at Company A

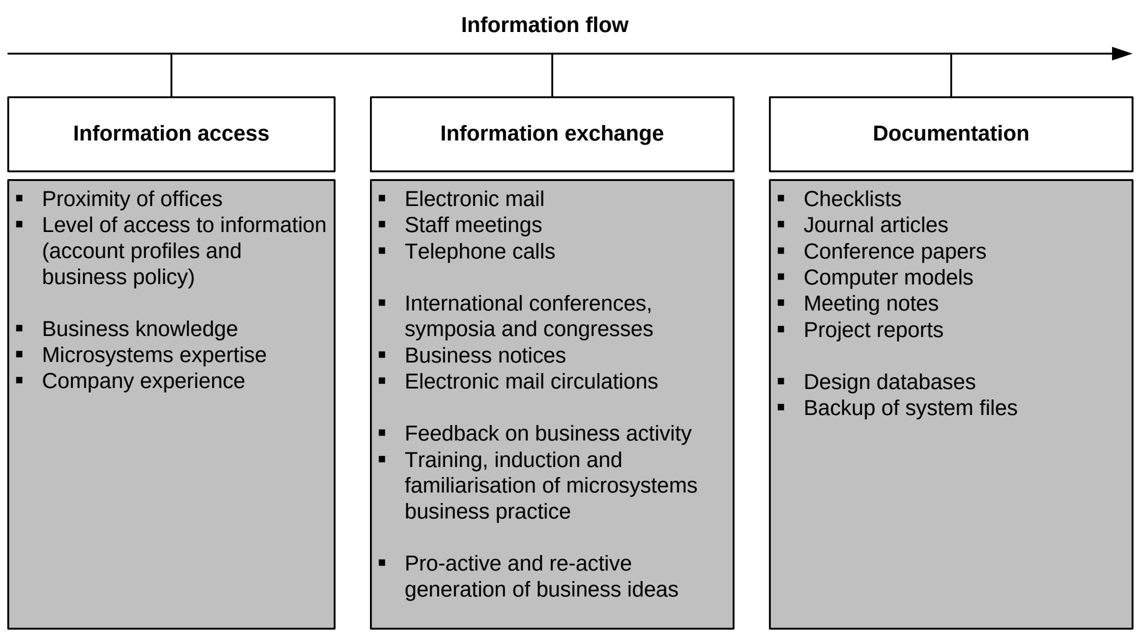


Figure 3-7: Information flow at Company B

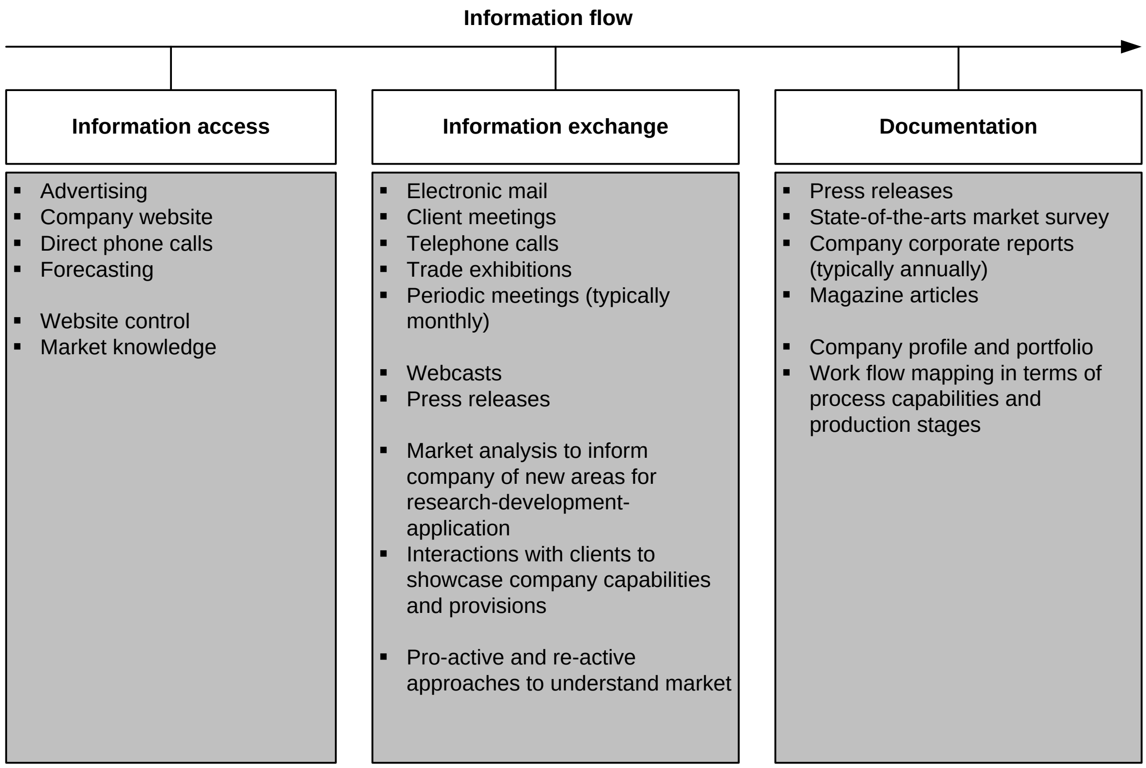


Figure 3-8: Information flow at Company C

3.2.2.2. Exploratory study findings

Captured information flow in the studied companies is shown in Figures 3-6, 3-7 and 3-8. The main difference noted in the studied companies was the variation in motivators for information flow management. The presence of various motivators for information flow management supports the contingency theory (Fawcett *et al.*, 1997), which suggests that firms within a competitive environment tend to modify their operations so as to enhance performance and maintain firm competitiveness. Three different motivators were identified in the case studies: technological-perspective, customer-perspective and market-perspective. The differences in motivators are reflected in the manner in which the studied companies allocate the role of managing information flow. Possible explanation for this difference in motivations for managing information flow could be attributes to factors such as the maturity of the business, market competition and the experience of information flow manager.

3.2.3. Delivery information flow characteristics

Four main characteristics of delivery information flow captured from the industry survey and exploratory study are now highlighted.

3.2.3.1. Delivery interactions

The first characteristic centres on **interactions** during delivery in an organisation. This involves understanding the *roles* of company personnel and how these roles contribute to the flow of information during delivery. The importance of roles in organisations delivering MST was highlighted by the customer support manager at **Company A** as she noted that MST companies:

> "tend to work in teams but everyone has an understanding of what everyone is doing."

Delivery interactions also involve recognising the presence of *multiple channels* and *possible paths* for information in modern organisations and exploring how these channels factor in the free flow of information. As shown in Figures 3-6, 3-7 and 3-8, the findings from the industry survey presented in §3.2.1 and Appendix B, MST companies make use of multiple channels (or media forms) to enable the free flow of information. These channels include text formats (electronic mail, facsimile and text files), graphical representations (diagrams and charts) audio/video files, telephone/mobile phone conversations and weekly meetings. **Company A** and **Company B** also made use of telephone conferencing for external communication with clients.

Participants in all the companies studied, described an information flow path within their companies made up of eight main phases as shown in Figure 3-9. The phases within the information flow path are: *requirement phase* to capture customer requirements, *research stage* to investigate if design is possible or already exists, *proposal phase* detailing cost and time and the formation of a project, *prototype phase* to design, develop and test MST prototypes, *fabrication phase* for manufacturing and assembling devices in a cleanroom based on the characterisation of the fabrication process and verification of manufacturing steps for reliability, *packaging phase* to enable electrical interfacing, *marketing phase* to yield capital returns from MST based products, and *support phase* to assist customers and potential clients in the use of current and future products.

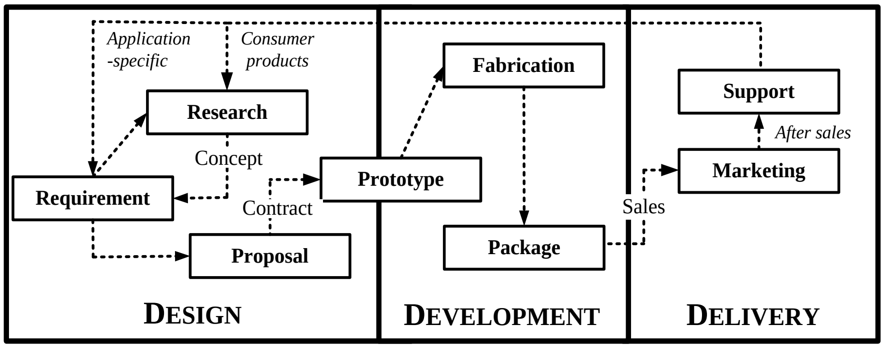


Figure 3-9: Information flow in microsystems technology companies

In all cases (the companies where the interviews were conducted - **Company A**, the MST division at **Company B** and **Company C**) the flows were identical with slight differences in the terminology used to describe some phases as follows:

- **Company A** use the term feasibility phase *in lieu* of the research phase and described three parallel paths during this phase – feasibility aspect definition, feasibility financial project planning resources and legal contractual obligation
- **Company B** split the proposal phase into three sub-phases – Conceptualisation, state-of-the-art survey (intellectual property (IP) space and solution) and design feasibility)

These phases can be initiated within the company for the delivery of MST based consumer products in which case the risk sits with the manufacturer, and marketing is crucial to achieving return on investment. Alternatively, design and development can be initiated by a customer request for the delivery of application-specific MST in which case the risk largely sits with the customer.

3.2.3.2. Delivery processes

The second characteristic focuses on delivery **processes** in an organisation. This involves investigating and comparing the impact of information flow in single- and multi-disciplinary teams on the timeliness of company processes. The business director at

Company B described timeliness of processes as key to the operations of MST companies. He remarked during the semi-structured interviews:

> 'in terms of the most important consideration for processes, the business (upper management) would say what is delivered is delivered on time and that it is correct.'

He described the two factors as the driving force for interactions during processes and further explained that the reason for the second consideration (correctness of MST design) is that:

> 'the cost of fault in design can be astronomical. And of course is tied in with the first (time to deliver) because effectively if you find a fault you're late'.

Another area that could offer insights into processes involves exploring the role of information flow in *collaborative delivery* by companies. As shown by the industry survey, when asked 'How are functions and processes carried out in the company?' participants responded as shown in Figure 3-4. The figure showed that collaboration was the dominant description for functions and processes in MST companies as provided by 36 out of 40 (90.0%) surveyed companies. Company staffs are therefore required to collaborate by establishing full commitment to shared goals wherein MST delivery is closely linked to MST design and development within the organisation.

3.2.3.3. Information flow coordination

The third characteristic focuses on **coordination** of information flow during delivery in an organisation. This characteristic entails exploring how companies: (i) internally *synchronise* communication channels, and (ii) *harmonise* internal and external flows.

Synchronisation of communications is necessary to regularise the flow of information due to the presence of multiple media forms. As noted by the systems engineer at **Company B**:

> "we have this nice preferred communication (emails) … when it all goes wrong, just resynchronise, pick up the phone and say 'what I wanted was …'"

In terms of harmonising flows, the commercial director at **Company C** noted that as part of her role as an information manager she needs to consistently harmonise internal flows within the organisation and external flows with customers. This according to her is necessary to:

> 'understand customer needs, know where to direct them … to be able to say "yes it can be done", "yes, we cannot do it but we know who can", and "yes we can"'

3.2.3.4. Information flow streamlining

The fourth characteristic deals with **streamlining** information flow during delivery in an organisation. This involves understanding how the information flow in organisations impacts on the manner and ease with which information is *shared* during delivery. The customer support manager at **Company A** remarked that information sharing is important particularly for an enquiry (by a customer) that is:

> '…kept open as it moves through the company and terminated when it can no longer be supported or is not in the company's area of expertise'

Streamlining also considers how information flow can be *contextualised* to suit different company staff and scenarios for delivery. According to the business director at **Company B** the channels for communication differ depending on the context of use:

> 'It is important that we are able to manipulate information automatically and mechanically…it is feasible to do that by textual information, very difficult to do that with anything else. For a more general explanation, a video or audio would be more appropriate.'

The customer support manager at **Company A** also commented on the contextualisation (and simplification) of information:

> 'where possible the flow of information should be simplified … relate to people in level they understand.'

In order to do this, she recommended an understanding of the structure of the company and its area of expertise. This ensures that the information flow and communication between information managers and customers are transparent so as to gain customer confidence. The same also applies for internal information flow and communication with staff. For instance ‘problem customers’ or ‘high order customers’ may require more flows during delivery to aid the use of MST. Technical manuals, delivery confirmation sheets/emails must therefore be customised so as to improve information flow with these types of customers.

3.3. RESEARCH METHODOLOGY

An analytical-conceptual-applied research methodology (Kumar, 1996) was adopted for the 4 phases of the research strategy outlined in §1.5. These phases are: literature review, industry scope, proposed technique and case studies. The research began analytically to capture and evaluate delivery information flow characteristics and delivery phase, and the information used during this evaluation was derived from the literature review (Chapter 2) and industry scope studies (§3.2). Using the identified characteristics as a set of criteria, the current state of existing techniques was evaluated and the identified gaps were then formulated as ‘modelling goals’ for conceptualising a diagrammatical tool and mathematical approach that were applied in case studies. The research methodology is used in the research phases to fulfil the research objectives as summarised in Table 3-2.

Table 3-2: Relationship between research objectives and research strategy phases

	Research objective	Research strategy phase
(a)	To review existing techniques and tools for modelling information flow in organisations *(Chapter 2)*;	literature review
(b)	To capture industry practice in the use of modelling tools by organisations delivering MST and carry out an industry study of information flow during the delivery phase of real-life organisations delivering MST *(Chapter 3)*;	industry scope
(c)	To propose a technique for modelling information flows during the delivery phase of organisations delivering MST *(Chapter 4)*;	proposed technique
(d)	To evaluate/validate (c) through case studies of organisations delivering MST studied in (b) *(Chapter 5)*.	case studies

3.3.1. Literature review methodology

To achieve objective (a), review existing techniques and tools for modelling information flow in organisations, a review of academic literature was carried out through a 3-stage analytical process: *plan*, *source* and *study*.

In the first stage, a plan was drawn up in which the aim, motivation and focus for the literature review were defined. This also included questions which the review would seek to answer as well as the initial or planned structure for the review. For the second stage, academic publications (journal articles, conference proceedings and other materials) were sourced and selected using SCOPUS (www.scopus.com) an online database for literature, and the Cranfield University Kings Norton Library (library catalogue and electronic resources). The third stage involved studying the sourced publications and re-examining the sources from stage two. The literature review plan drawn up in the first stage was also reconsidered during this stage.

The 3-stage process to achieving objectives (a) was adopted to cope with the novelty of the research topic. This novelty was due to two main factors that account for limited related research. Firstly, few studies (such as De Grave and Brissaud, 2007; Kannapan and Taylor, 1994; Myer *et al.*, 2000; Dickerhof *et al*., 2002) within the MST domain have examined 'non-technology' related research such as organisational collaboration or MST business models. Secondly, the analysis of information during multi-tasking activities (such as product/service delivery) is a new and significant area in human behaviour with limited research or investigation (Spink and Park, 2005).

3.3.2. Industry scope methodology

To accomplish objective (b), capture industry practice in the use of modelling tools by organisations delivering MST and carry out an industry study of information flow during the delivery phase of real-life organisations delivering MST, two studies were conducted: industry survey and exploratory study.

An industry survey of MST companies was conducted in three analytical phases, as described in §3.2.1: *plan*, *sample*, and *administer*. In the first phase, a plan was drawn up in which the goals of the industry survey were defined using findings from the literature review. For the second stage, the World Wide Web (WWW) was used to select the survey sample. During this phase, the WebPages of each participant (i.e. company) in the sample were examined to determine the types of delivered products and services. The sample was selected for use in this study to provide a representative sample of the MST domain and all sampled companies delivered integrated MST products and services offerings. During, the third stage, a multiple-choice questionnaire was prepared and presented electronically to participant in the sample. The choice of electronically administered questionnaires was made to cope with the cost and large sample size and geographical proximity of a large portion of the sample, as shown in Figure 3-1. Multiple-choice responses were adopted for simplicity purposes.

The exploratory study involved semi-structured interviews with personnel responsible for managing information flow at 3 MST companies, based on the dimensions of information flow proposed by Demiris *et al.* (2008), as described in §3.2.2. The semi-structured approach was adopted to accommodate any additional information flow concepts that 'information flow managers' may suggest or introduce during the interviews. In addition, MST companies were selected from the United Kingdom based participants of the survey sample to minimise travel costs. The companies were then contacted by email and telephone to request access to information flow managers.

3.3.3. Proposed technique methodology

To accomplish objective (c), propose a technique for modelling information flows during the delivery phase of organisations delivering MST, a diagrammatical approach (information channel diagram (ICD) tool) and a mathematical approach (intra-organisational collaboration (IOC) model) for modelling information flow in organisations were proposed.

3.3.3.1. Diagrammatic approach methodology

The ICD tool is proposed through five main stages: characteristics identification, tools evaluation, approach development, approach demonstration, and approach comparison with pre-existing tools, as shown in Figure 3-10. The stages adopted in this development of the ICD are typical of diagrammatical tool development approaches such as DeMarco (1979) for DFD and Doumeingts (1989) for GRAI. In these approaches, researchers have initially captured the practice in industry through exploratory studies, evaluated existing tools in terms of current needs and proposed new tools to meet current needs through the reuse, adaptation and introduction of diagrammatic primitives.

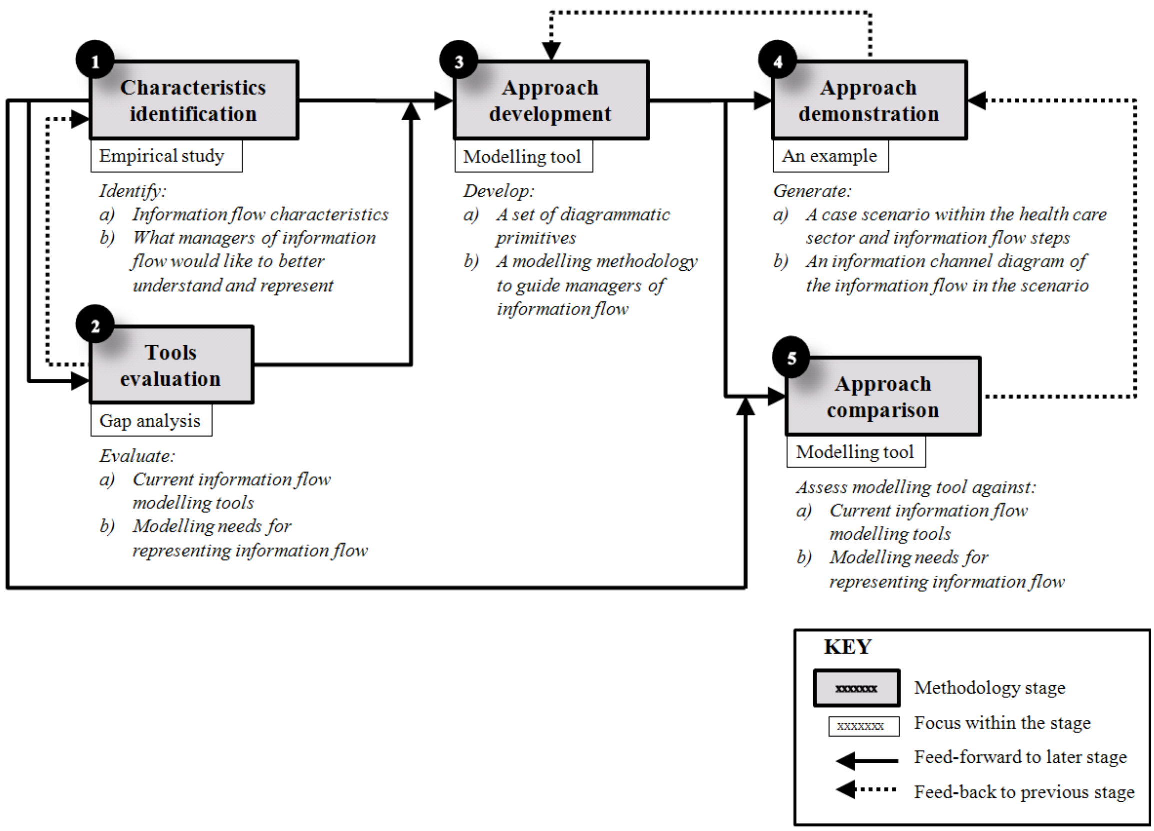


Figure 3-10: Information channel diagram methodology

The ICD tool is proposed to fulfil the design goal of 'assisting information managers effectively represent and understand delivery phase information flow'. To fulfil this goal, ICD offers two elements, firstly, a set of diagrammatic primitives to depict information flow, secondly, a user method for using the primitives to create information flow models.

3.3.3.1.1. Characteristics identification

Focusing on MST delivery, the research scope of §3.2 identified four main delivery information flow characteristics. In Table 3-3, these characteristics are summarised and the findings from §3.2 are described with regards to 'what managers of information flow during the delivery of MST would like to better understand and represent'.

Table 3-3: Delivery information flow characteristics (table data taken from §3.2.3)

Information flow characteristics	**Representation required by managers of information flow**
Delivery interactions	1. roles of company personnel
	2. information flow path
	3. multiple channels
Delivery processes	4. timing of processes
	5. collaborative processes
Information flow coordination	6. synchronise communication channel
	7. harmonise flows
Information flow streamlining	8. contextualised information
	9. information sharing

3.3.3.1.2. Evaluation of current modelling tools

The information presented in Table 3-3 represents a set of criteria - the required representations of information flow - which can be used to assess currently available tools.

These criteria were used to evaluate each of the modelling tools identified in §2.3.1 i.e. data flow diagrams (DFDs), Integrated DEFinition method of modelling functionality and information modelling (IDEFØ and IDEF1), Graphes à Résultats et Activités Interreliés (GRAI) grids and nets, Petri nets, Input-Process-Output diagrams and design structure matrices. The output of this assessment is presented in Tables C1-C6 (see Appendix C).

The evaluation showed that for two required representations, roles of company personnel and multiple channels, primitives were not present in any of the tools. Furthermore, for another six representations, primitives were inadequate for effective representation. This evaluation is summarised in Figure 3-11.

3.3.3.1.3. Diagrammatic primitives

To create the primitive set, the approach outlined in Figure 3-11 was followed. Diagrammatic primitives were reused, modified, adopted or introduced as follows:

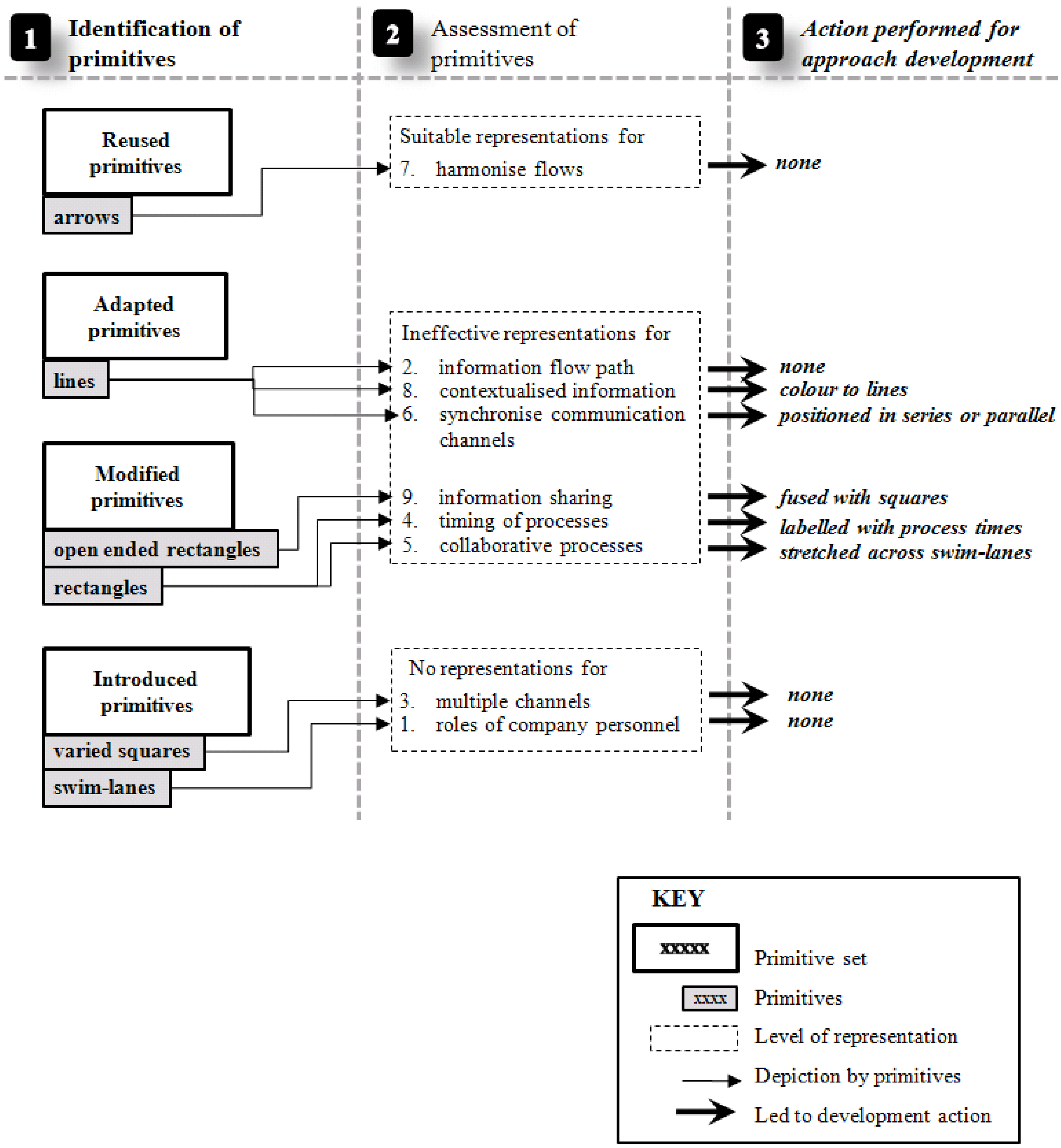


Figure 3-11: Evaluation of current diagrammatic modelling tools

- *Roles of company personnel*: ‘swim-lanes’ were adapted from existing literature to depict roles during interactions. Swim lanes are primitives commonly used in business process modelling (e.g. Kim *et al.* (2005)) to represent ‘what’ or ‘who’ is involved in a process.
- *Multiple channels*: three forms of squares, novel primitives, were introduced to depict verbal, written and electronic forms that are the main communication channels in modern organisations (Yazici, 2002). Verbal forms refer to face-to-face interactions and word of mouth, written forms include paper copies of documents such as newsletters, receipts and reports, while electronic forms consist of electronic mails, spreadsheets and so on.
- *Timing of processes*: to represent timing of processes, rectangles used to depict processes in modelling tools such as DFDs and IDEF were modified by including a label within each rectangle to indicated estimated process time.
- *Collaborative processes*: to show collaborative processes, rectangles indicating processes were allowed to stretch across multiple swim-lanes
- *Harmonising flows*: to represent internal and external flows arrows used in existing modelling tools were reused.
- *Information flow path*: lines used in existing tools were adapted for use in the ICD tool to depict links for flow paths between processes or people. The purpose of adopting lines in the ICD tool was to extend their use to fill multiple identified gaps. These depicted links offer avenues for enabling what Lin and Cheng (2007) have termed ‘relationship flows’.
- *Contextualised information*: lines were assigned colour-coding to show how information can be contextualised.
- *Synchronised communication channels*: to show how communication channels can be synchronised, lines used to depict links were allowed to contain squares that are positioned in series or parallel.
- *Information sharing*: open ended rectangles that indicate data stores in DFDs were modified by fusing each data store with a square to depict information sharing in terms of both the means for sharing the information and the information source (data store).

3.3.3.1.4. Deriving the prescribed steps for creating information flow model

Deriving the prescribed steps for creating an information flow model was a two stage process. In the first, existing literature methods were assessed and one selected. *Functional composition* (Jorgensen, 1995) was selected from the literature, because, unlike existing methods used in creating information flow models (such as explosion and expansion), composition enables users to methodically populate models by increasingly adding and connecting primitives for creating a chain of primitives. Outside the information flow domain, functional composition is a well-established practice in software development, in which chains of functions are increasing added to create subroutines and procedures.

In the second, this method was adapted in detail as a user method for creating ICDs. To adopt functional composition as a method for ICD, a set of design steps (i.e. procedures) was formulated by the authors: (i) to initially represent diagrammatic primitives with associations to other primitives within the ICD tool (i.e. primitives with higher dependencies) and (ii) to increasingly add diagrammatic primitives with a view to creating a complete ICD. This user method is detailed in §4.2.2.

3.3.3.1.5. Approach demonstration

An example scenario from literature (Durugbo *et al*., 2009) of information flow in the delivery phase of a major healthcare organisation is used here as an example to show the creation of an ICD. The example was selected for familiarisation and simplicity purposes. In the demonstration of the ICD, the scenario for the delivery phase within the health sector is identified, the steps for information flow are captured and an ICD based on the steps is produced.

3.3.3.1.6. Comparison of the ICD approach with pre-existing tools

To compare the ICD approach against pre-existing tools, ICD was assessed against the original criteria (Table 3-3) used to assess existing modelling tools. This evaluation is presented in Table C-7 of Appendix C and is based on the star-based system[4], with regards

[4] Please refer to Appendix C for a description of the star-based system

to the representations required by managers of information flow. The table demonstrates coverage of the required representations for the delivery phase in organisations.

3.3.3.2. Mathematical approach methodology

The IOC model is proposed through four main stages: characteristics identification, social network analysis evaluation, model conceptualisation and demonstration, as shown in Figure 3-12. The stages are typical of mathematical model development approaches such as López *et al.* (2002) that proposed the coordination degree model for hierarchical networks and Ehsani *et al.* (2010) that proposed decision networks. In these approaches, researchers have mainly extended or formulated new aspects of existing network models.

3.3.3.2.1. Characterising collaboration

The main characteristic adopted for the mathematical approach was collaboration due to its importance to MST production as suggested by 90.0% of the industry survey respondents. Collaboration, although not a new organisational characteristic, has become a critical factor that determines the success of businesses (profit-driven organisations) (Beyerlein *et al*., 2003). It means working together in group(s) to achieve a common task or goal (Chiu, 2002; Wang and Kilduff, 1999; Beyerlein *et al*., 2003; Maher *et al*., 1998) and irrespective of geographical separation (Anderson, 2002; Wu *et al*., 2004). This task or goal is often beyond the capabilities of the participants involved in the collaboration.

Within the MST domain, collaboration is also an important aspect of the design process due to 'technological imperatives' of miniaturisation and integration[5] (Myer *et al*. 2000). Due to these technological imperatives, the MST design process is best approached by *multidisciplinary* (Shen *et al.*, 2008) and *interdisciplinary* (Tay, 1999) teams in organisations that are flatter and less hierarchical. Collaboration in the MST design process is a high-level consideration for: sensing, thinking, acting and communication within MST design teams (Myer *et al.*, 2000) and conflict resolution in perspectives of team members and for designs to have a context (Kannapan and Taylor, 1994).

[5] Miniaturisation and integration within the context of MST have been described in §1.1.1.

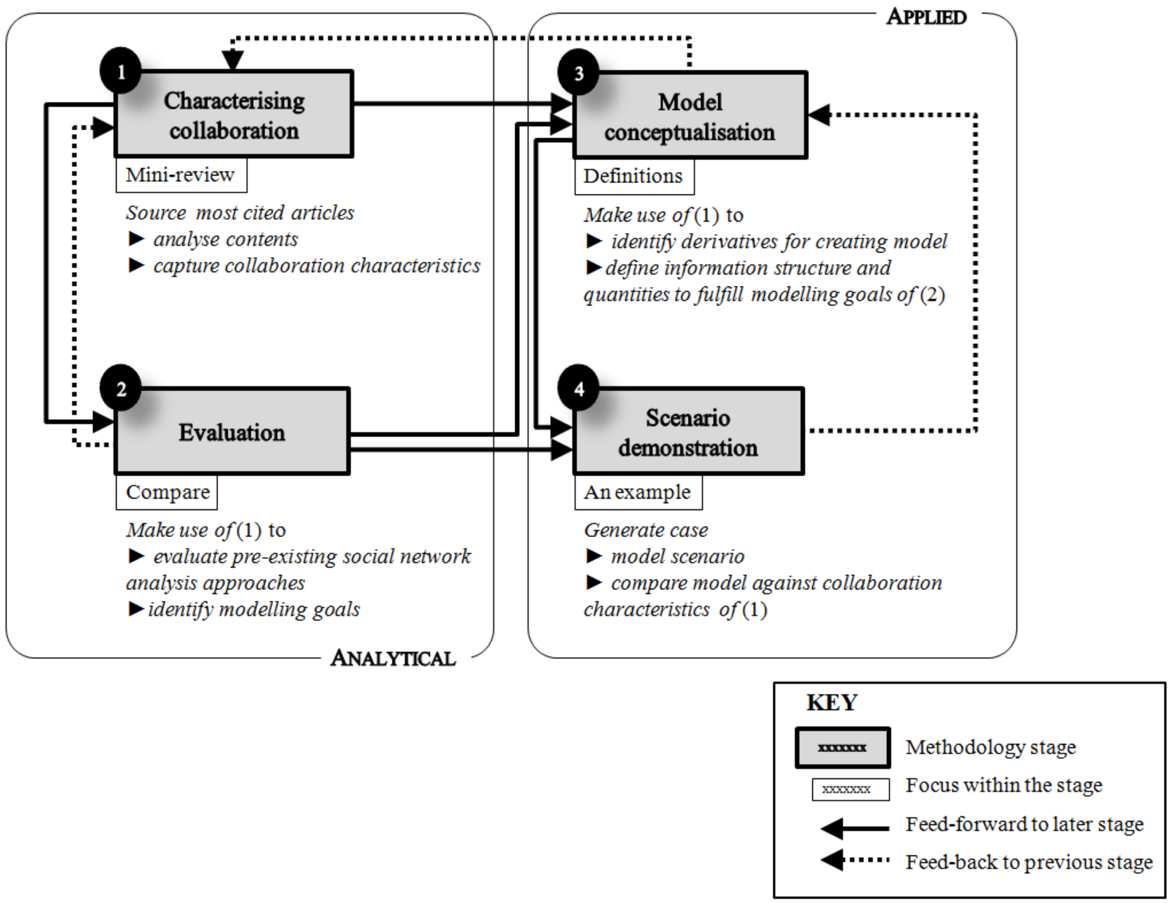


Figure 3-12: Intra-organisational collaboration model methodology

Consequently, the first step in the development of the mathematical approach focused on identifying collaboration characteristics as seen through the perspective of collaborative design research. To determine these characteristics, some key collaboration articles (according to SCOPUS an online database for literature accessible via www.scopus.com), relevant to this work, were sourced using keywords ‘collaborative design’. Of the top ten cited articles returned by the search, seven were relevant to this work. The review paper on collaborative design by Wang *et al.* (2002) was also analysed to capture key characteristics of collaboration. The idea behind this search and analysis of articles was to ground the model within collaborative design research. Based on the search, the following collaboration characteristics were summarised from literature:

C1. Collaboration requires a network in which individuals/ groups are interconnected (Pahng *et al.*, 1998; Wang *et al*., 2002; Xu and Liu, 2003) i.e. a social network.

C2. Collaboration requires a network in which tasks/processes are linked (Klein and Dellarocas, 2000; Wang *et al*., 2002) i.e. an activity network.

C3. Collaboration is required to explore and integrate differences of group members who take part in solving problems of allocated tasks that contribute to a common goal (Sonnenwald, 1996; Shyamsundar and Gadh, 2001; 2002; Xu and Liu, 2003).

C4. Collaboration is closely connected and dependent on decision making, teamwork, and coordination that typify relationships and communication roles (Sonnenwald, 1996; Kvan, 2000; Stempfle and Badke-Schaub, 2002; Xu and Liu, 2003).

Coordination involves harmonising interactions between individuals to achieve a common goal (Clarke, 2005) while decision making refers to how choices are made based on rules and procedures (Clarke, 2005; Pryke and Pearson, 2006). Teamwork involves pooling skills and resources (Wang and Kilduff, 1999) and forms the basis for collaboration within organisations (Beyerlein *et al*., 2003).

3.3.3.2.2. <u>Social network analysis evaluation</u>

In Table 3-4, a set of modelling goals based on the collaboration characteristics identified in §3.3.3.2.1 was used to assess the current state of social network analysis (SNA). SNA represents current research for modelling information flow for ‘organisations as networks’, as presented in §2.4 of the literature review. Using SCOPUS, a search for articles with keywords ‘collaboration’ and ‘social network analysis’ returned **18** related articles that were analysed to determine the focus and current implementations in research that relate to the set of criteria. The evaluation demonstrated that no visualisation for linked processes and indicators for coordination, decision making and teamwork, within the context of this research, were available in SNA research. In addition, the analysis showed that current models were inadequate for characterising formal relationships that symbolise collaboration roles and responsibilities.

These formal relationships are defined by formal work practices for which tasks and events need to be defined particularly for process-intensive organisations (Gregg, 2010;

Cain, 1996; Klein and Dellarocas, 2000) and information is usually stored in a more structured form (Van Der Aalst *et al*., 2005). It is for this reason, that existing structures studied in SNA may not be enough to model collaboration. Nevertheless, the SNA is a flexible approach in which basic SNA concepts can be adapted by researchers to propose new attributes/indicators to characterise phenomena and systems (Pryke and Pearson, 2006). Consequently, for the approach proposed in this research, the SNA approach has been augmented with adapted techniques from other domains and novel indicators for characterising collaboration.

Table 3-4: Evaluation of social network analysis using collaboration characteristics

Research modelling goals	Social network analysis focus	Implementations in literature	Gaps in Social network analysis
Interconnected groups (C1)	relationships between social actors in organisations	• Informal relationships that characterise friendships, and affiliations (Newman, 2001; Hatala and Lutta, 2009; Cross *et al.*, 2002) • Formal relationships that typifies administration in firms through hierarchies (López *et al.*, 2002; Ben-Arieh and Pollatscheck, 2002)	Inadequate descriptions for formal relationships that symbolise roles and responsibilities during collaboration
Linked processes (C2)	–	–	No representation or descriptions
Decision-making, Teamwork and Coordination (C3 and C4)	egocentric and sociocentric approaches for individual and group interactions	*Similar concepts –* **Centrality** that refers to the importance or prominence of actors and concentration of individuals with decision making rights (Pryke and Pearson, 2006), **Cohesion** that refers to the interconnectedness of groups (Hawe *et al.*, 2004) **Coordination score** (White, 2008), a central tendency score, and **coordination degree** (López *et al.*, 2002) that measures the ability of actors to interchange information	No quantities to specifically measure decision-making, teamwork or coordination within the research context

3.3.3.2.3. Model conceptualisation

The next phase in the research involved making use of the identified collaboration characteristics to conceptualise the mathematical model, as shown in Figure 3-13. To do this, two main derivatives (D1 and D2) were identified based on the analysis of literature in §3.3.3.2.1 that produced C1-C4:

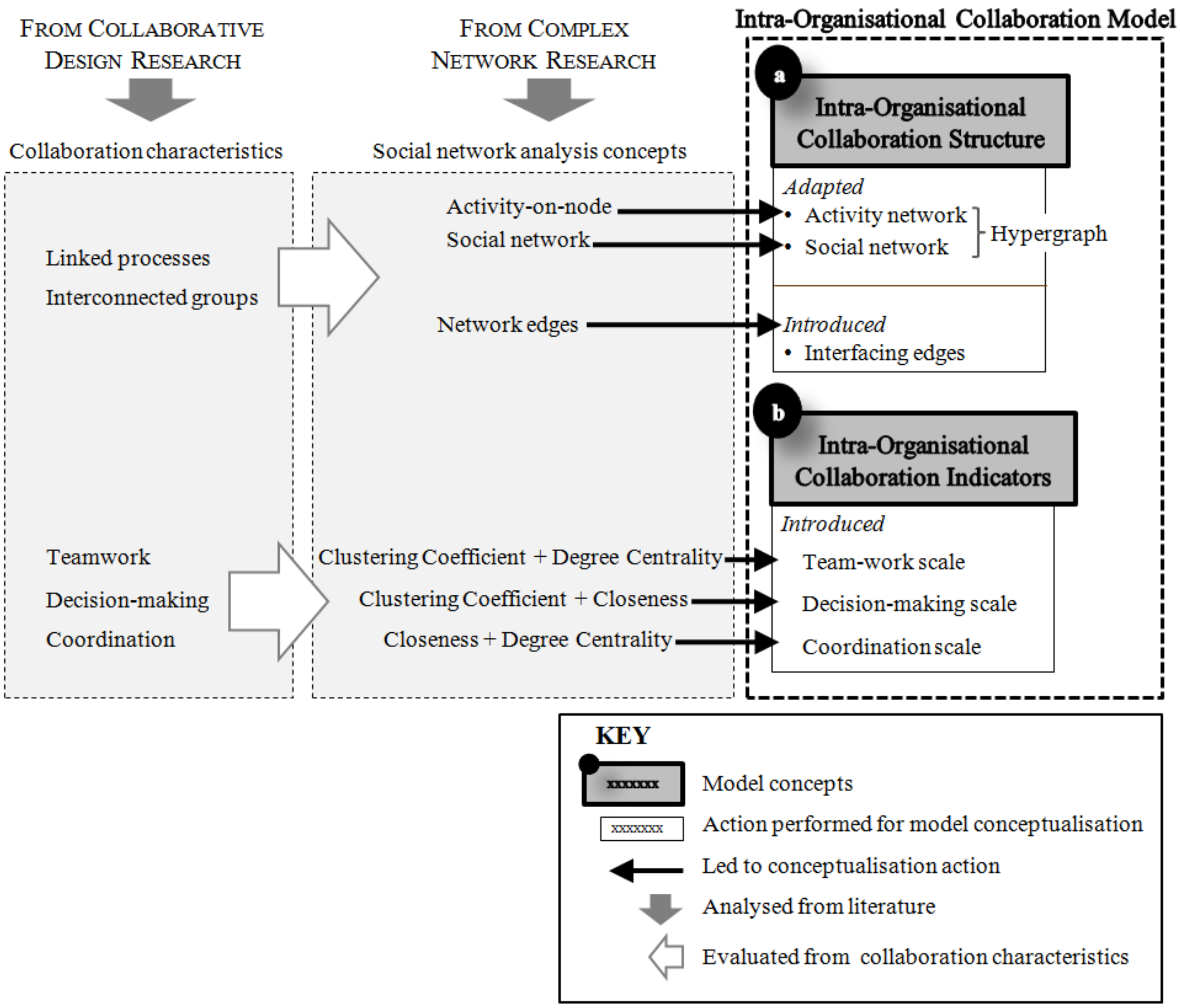


Figure 3-13: Intra-organisational collaboration model conceptualisation

D1.Intra-organisational collaboration information structure consists of: social and activity networks (C1, C2 and C3),

From this derivative, the main information structure concepts for analysing collaboration were then obtained as a combination of social vertices and edges for individuals/groups (C1 and C3), and activity vertices and edges for tasks/processes (C2 and C3).

To derive topologies of the social network for collaboration, some possible configurations for the dictator, mutual and exclusive collaboration forms captured in Maher *et al.* (1998), and were investigated and adopted to: (i) illustrate the potential use of the model, (ii) simplify the model, and (iii) align the model with existing collaborative design research.

The topologies of the activity network in the proposed model for collaboration were based on the activity-on-node (AON), a traditional activity network employed in the widely used Project Evaluation and Review Technique (PERT) and critical path method (CPM) for the (Yassine *et al.*, 1999). It selection for use in the model was based on the popular use of the AON in the design and management of collaboration related tasks such as organisational projects.

AON representation makes use of dependencies for organising activities according to two main configurations: series and parallel configurations (Cook, 1966). Dependencies exist if subsequent activities must wait for preceding activities to finish. In addition, within AON representations, a process occurs once with no feedbacks or loops (Cook, 1966).

To conceptualise formal relationships that symbolise roles and responsibilities, a set of edges was introduced for interfacing social vertices with activity vertices. The introduced 'interface edges' represent relationships that are associated with individuals, teams and organisations for involvement in linked processes that contribute to a common goal.

The need to include and analyse networks made up of tasks is evident in current studies by authors such as Batallas and Yassine (2006), in which the analysis of social networks was complemented with design structure matrices for analysing tasks, and Collins *et al.* (2010) that examined task networks for product development. These studies have mainly concentrated on isolating and analysing social and task networks separately or making use of one technique to analyse the other. An inspection of these techniques suggests that potentially some links and flows may be omitted. For instance, a human operator working as part of a team may access or transfer some information necessary for collaboration (such as number of products to be manufactured) with a manufacturing process. This interaction may not require the participation of a team member or may be accessed by another team member through the process without a direct link to the original source of the information i.e. the first human participant.

D2. Intra-organisational collaboration requires indicators for authority (decision making), teamwork, and coordination within topologies, vertices and edges (C3 and C4).

Based on this derivative, a set of novel indicators for collaboration was proposed by the authors, and to compute each indicator a constant is introduced to quantify the strength of network relationships and the availability of collaboration information. The introduced constants are as follows: coordination constant (α_i), decision constant (β_i) and teamwork constant (γ_i). These constants are subjective probabilities that are based on the availability of a vertex *i* to: harmonise interactions (α_i), make choices (β_i) and pool resources (γ_i).

The proposed collaboration indicators for a vertex *i* include: decision-making scale (δ_i), coordination scale (χ_i) and teamwork scale (τ_i). These identified indicators are consistent with existing studies in complex network research where decision making measures have been introduced for agent-based systems (Ehsani *et al.*, 2010) and coordination of edges between vertices have been investigated for hierarchical networks (López *et al.*, 2002; Ben-Arieh and Pollatscheck, 2002).These collaboration indicators are proposed because existing quantities for decision making, teamwork and coordination identified in literature have been used in different contexts to those applied in this research as defined in §3.3.3.2.1. For instance, the **coordination degree** by López *et al.* (2002) measures the ability of a vertex *i* to interchange information with another vertex *j* within a network and the **coordination score** by White (2008) assesses the degree to which networks are concentrated around important vertices. The indicators as shown in Figure 3-13 are derived as sums of existing SNA measures for clustering coefficient, closeness and degree centrality. These quantities were selected because they reflect interconnectedness within groups, individual connections for relationships and activity of individuals respectively (Hatala and Lutta, 2009; Valente *et al*., 2008).

The **degree centrality** (Dc_i) is a ratio of number of directly connected vertices to the number of possible vertices in a network and can be computed as:

$$Dc_i = \frac{[\deg]_i}{N-1} \qquad \textbf{(1)}$$

Where, N is the number of vertices in the network and $[\deg]_i$ is the number of vertices directly connected to i.

The **clustering coefficient** assesses the density between vertices and represents the tendency for vertices to cluster together. If a vertex i, connects to b_i neighbours, and the number of possible edges between the vertices is given as $b_i(b_i - 1)/2$, then the clustering coefficient (Cc_i) of i can be computed as:

$$Cc_i = \frac{2n_i}{b_i(b_i - 1)} \qquad \textbf{(2)}$$

Where n_i is the number of edges between b_i neighbours.

The **closeness** between vertices defines the order with which one vertex connects to another vertex. It is computed as the inverse of the geodesic distance (d_{ij}) between a pair of vertices i and j. The geodesic distance is the number of edges along the shortest path between i and j. Closeness (c_{ij}) can be calculated as:

$$c_{ij} = \frac{1}{\sum_{i \neq j \in N} d_{ij}} \qquad \textbf{(3)}$$

For instance, if an individual connects directly to another collaborator (i.e. participant in a collaboration), the closeness is given as 1, if an edge is established as a result of connecting to a third vertex k acting as a hub or by dictator collaboration (Wang *et al.*, 2002), then vertex i has a closeness of 0.5 to vertex j.

In the proposed model, configurations proposed in D1 were used to develop eqns. (4-7) that analyse the information structure for social and activity networks. Eqns. (4-7) were then combined with eqns. (1-3) to formulate the collaboration indicators of eqns. (8-13).

3.3.3.2.4. Scenario demonstration

To demonstrate the use of the model for analysing collaboration in organisations, an example from literature was presented and analysed. The example was selected for familiarisation and simplicity purposes. In the example, case scenarios of collaboration will be generated and possible topologies, vertices and edges based on the proposed model will be investigated. Coordination, team-work and decision making indicators for each case scenario will then be compared and used to make suggestions as to the most suitable information structure for enabling collaboration within the different scenarios. In Table 3-5, the IOC model introduced as part of the proposed technique is evaluated based on the characteristics of collaboration identified in §3.3.3.2.1, with regards to the information structure and behaviour for organisations. The table demonstrates coverage of the required characteristics for collaboration in organisations.

Table 3-5: Evaluation of the intra-organisational collaboration model

Research modelling goals	Intra-organisational collaboration model focus	Implementations in the model
Interconnected groups (C1)	relationships between social actors in organisations and interfacing edges to processes	**Informal /formal relationships** within the social network of human actors **Formal relationships**, through interfacing edges, that symbolise roles and responsibilities during collaboration
Linked processes (C2)	Activity-on-node (AON) from the widely used Project Evaluation and Review Technique (PERT) and critical path method (CPM) (Cook, 1966; Yassine *et al.*, 1999)	Activity networks for serial and parallel configurations for sets of processes
Decision-making, Teamwork and Coordination (C3 and C4)	egocentric and sociocentric approaches for individual and group interactions	**decision scale** that measures the ease with which social vertices can make choices **teamwork scale** that measures the ease with which social vertices can pool resources **coordination scale** that measures the ease with which social vertices can harmonise interactions

3.3.4. Case studies methodology

To accomplish objective (d), evaluate/validate (c) through case studies of organisations delivering MST studied in (b), instances of the proposed diagrammatical and mathematical technique were evaluated and validated at the three MST companies where the initial exploratory study was conducted.

3.3.4.1. Semi-structured interviews

To capture the flow of information in the participating companies, semi-structured interviews were conducted via telephone with a customer support manager at **Company A** and two commercial directors at **Company B** and **Company C** and the main question posed to the personnel to initiate the semi-structured interviews was 'How does information flow during the delivery phase in your company?' The interviews lasted between 25 to 40 minutes.

Using the transcribed information provided by the interviewees, a set of formal information flow models (ICDs and the two techniques (DFDs and DSMs) used by organisations delivering MST as determined through the industry survey of §3.2.1.1) and information structures of the IOC model for **Company A**, **Company B** and **Company C** were produced for delivery phase scenarios captured in each company.

3.3.4.2. Empirical inquiry

Next, a questionnaire, as shown in Figure 3-14, was prepared and posed face-to-face to company staff involved in the delivery phase with a view to rating the ability of tools to represent MST delivery information flow.

QUESTIONNAIRE

ID	

1. Participant Description

Job title:	
Industry experience:	

2. With regards to representations provided by the three models:

		DSM	DFD	ICD
1	"Can the roles of delivery personnel be identified?"			
2	"Can delivery information flow paths be identified?"			
3	"Can multiple communication channels during delivery be identified?"			
4	"Can the timing of delivery processes be identified?"			
5	"Can collaborative delivery processes be identified?"			
6	"Can the synchronisation of communication channels during delivery be identified?"			
7	"Can the internal and external delivery information flows be identified?"			
8	"Can the context for delivery information be identified?"			
9	"Can be the sharing of delivery information be identified?"			

3. As a formal approach to modelling information flow:

	DSM	DFD	ICD
Which approach (es) best captures delivery phase flow communications?			
Which approach (es) would you consider using?			

Additional Comments (*if any*):

Figure 3-14: Questionnaire posed to participants during empirical inquiry

For each question, the unordered options were: DFD, DSM or ICD. Participants were required to choose one or more of each of these options in response to each question (by ticking the appropriate boxes). Participants were not made aware of which proposed tool (i.e. the ICD) was being analysed in an attempt to minimise bias.

Two additional questions were also posed to participants; "which technique(s) best captures delivery phase flow communications?" and "which technique(s) would you consider using?" During the inquiry participants were also asked if they had any pre-existing knowledge of DFDs and DSMs. Notes were made of any additional comments volunteered by participants. All questionnaires, presented to participants alongside a set of produced information flow models (to demonstrate the use of the tools), were completed on-site at the participating companies in durations ranging from 15 to 20 minutes.

The comparison of techniques using company personnel was done to assess the performance of the proposed technique. Also, the questionnaire was interviewer-administered with a view to encouraging company personnel to make suggestions for improving the technique and to capture additional data required for mathematically analysing information flow. Each instance was analysed with a view to populating the IOC model and evaluating the ability of the IOC to model information flow for organisations delivering MST. In other to populate the model, interviewees were asked to validate the description provided by the CSM. Interviewees were also asked to identify processes and other personnel that they were connected to for collaboration during delivery.

18 participants (6 from each company) took part in the study. Table 3-6 shows a breakdown of the job titles, MST industry experience and knowledge of DSM/DFD for the participants from **Company A** (Aa-Af), **Company B** (Ba-Bf), and **Company C** (Ca-Cf).

Table 3-6: Breakdown of case study participants

Participant	*Job Title*	Industry Experience (yrs)	Knowledge of DFD	Knowledge of DSM
Aa	*Production Assistant*	9	✓	
Ab	*Senior Chemist*	2		
Ac	*Software Engineer*	18	✓	
Ad	*Customer Support*	4		
Ae	*Project Engineer*	10.5	✓	

Af	*Managing Director*	15		
Ba	*Software Engineer*	12	✓	
Bb	*Software Engineer*	4.5	✓	
Bc	*Software Engineer*	3	✓	
Bd	*Design Manager*	17	✓	
Be	*Senior Software Engineer*	20	✓	
Bf	*Design Manager*	5	✓	
Ca	*Company Director*	9	✓	✓
Cb	*Head Of Engineering*	10	✓	✓
Cc	*Project Manager*	1		
Cd	*Chief Executive Officer*	9	✓	✓
Ce	*Sales Administrator*	1		
Cf	*Head of Operations*	5	✓	

3.4. SUMMARY

This chapter presented the research focus and two studies used to establish an industry scope. The first study, an industry survey, showed that 17 of the 40 respondents have used Data Flow Diagrams and 4 respondents have used Design Structure Matrices. None of the respondents made use of Integrated DEFinition (IDEFØ), Graphes à Résultats et Activités Interreliés (GRAI) grids, Petri nets or Input-Process-Output (IPO) charts. The second study, an exploratory study, showed that at the production level, information flow in microsystems technology companies is monolithic and contributes to the timely delivery of products that are functionally correct as well as services that underpin design and development processes. But, at the delivery level, the flow of information is non-monolithic and dependent on the company's strategy for maintaining firm competitiveness such as the technology being delivered and the customers or the market that demand the technology. Next, the chapter outlined the methodology that was adopted for the research. The chapter also described: (i) how each research objective is achieved through the research strategy that applies the research methodology, (ii) the approaches (tools and techniques) used and (iii) the reasons for using the approaches.

Chapter

4

PROPOSED MODELLING TECHNIQUE

This chapter presents the proposed technique for modelling information flow in organisations delivering microsystems technology (MST) that was developed based on the research methodology outlined in §3.3.3. The technique consists of a diagrammatical tool - the 'information channel diagram (ICD)' tool and a mathematical analysis approach – the 'intra-organisational collaboration (IOC)' model. The descriptions of the diagrammatical tool and the mathematical model conclude with examples demonstrating the use of the technique.

4.1. OVERVIEW OF PROPOSED TECHNIQUE

The purpose of this section is to propose a technique for modelling information flows during the delivery phase of organisations delivering MST. The technique *diagrammatically* visualises information flow through the ICD and *mathematically* analyses information flow through the IOC model, as shown in Figure 4-1.

The ICD is made up a set of diagrammatic primitives for depicting delivery interactions (roles of company personnel, information flow path and multiple communication channels), delivery processes (timing of processes and collaborative processes), information flow coordination (synchronisation of communication channels and harmonisation of flows) and information flow streamlining (contextualised information and information sharing). Using the processes and role description provided by the ICD as a starting point, the IOC model is developed as a network of human collaborators and processes. The IOC model analyses the topologies, vertices and edges for collaboration and provides indicators for assessing teamwork, decision-making and coordination.

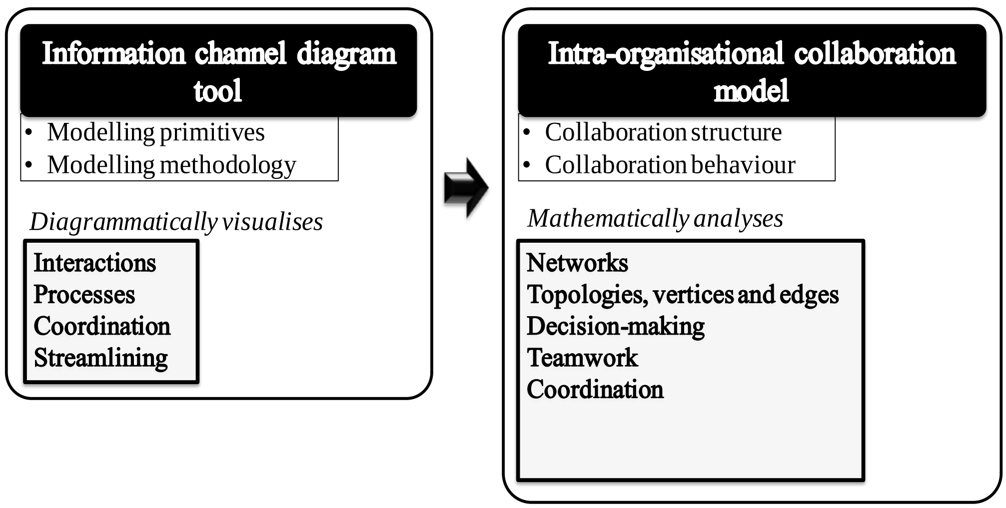


Figure 4-1: Overview of proposed technique

4.2. INFORMATION CHANNEL DIAGRAMS

In this section, the information channel diagram (ICD) approach is introduced as a modelling tool based on a set of diagrammatic primitives, and a prescribed set of steps for creating information flow models.

4.2.1. Diagrammatic primitives

Table 4-1 shows the nine diagrammatic primitives and the arrangements to fulfil the needs of the information flow characteristics of the delivery phase in an organisation. In the table, the first three diagrammatic primitives concentrate on representing interactions whereas the fourth and fifth focus on representing processes. The sixth and seventh diagrammatic primitives represent coordination while the eighth and the ninth represent streamlining. Each is now described below.

Table 4-1: Diagrammatic primitives and arrangements of the information channel diagram approach

Information flow characteristics	*Representation required by managers of information flow*	**Diagrammatic primitives**
Delivery Interactions	*1. roles of company personnel*	**Roles**
	2. information flow path	**Process links** **Flow direction**
	3. multiple channels	**Telematics** **Face-to-face** **Documentation**
Delivery Processes	*4. collaborative processes*	**Stretch across multiple roles** 1.1.1 Make enquiry t=1d **Process time**
	5. timing of processes	
Information Flow Coordination	*6. synchronise communication channels*	**Paralleled channels**
	7. harmonise flows	**Manager of Information Flow** **External** **Internal**
Information Flow Streamlining	*8. contextualised information*	**Coloured links and flows**
	9. information sharing	B Orders **Data Store with channel**

4.2.1.1. Primitive set 1 - Representing interactions

Each swim-lane in the ICD is labelled with task roles during information flow (such as information manager or principal engineer). The swim-lanes also contain processes that each role is responsible for.

Paths for information flow are shown as arrows along lines that link or network organisational processes. Each arrow is unidirectional and points in the direction to which information flows. If the direction of flow is towards a process, then the arrow is placed above the link whereas feedbacks are shown below the links. Arrows are also accompanied with a short description of the type of information that is flowing from one process to the next. The arrows used in the ICD offer features to aid managers of information flow to understand how information flow can be coordinated. Representing multiple channels of communication is proposed in the ICD approach by means of three types of labelled squares: completely shaded boxes to indicate information and communication technologies (ICT) such as emails, telephone or similar means for communication based on technology, clear boxes folded at the bottom right corner to indicate documented forms of communication i.e. document flow, and boxes containing intersecting diagonals to depict face-to-face interactions mostly one-on-one and group meetings.

4.2.1.2. Primitive set 2 - Representing processes

Processes for the ICD are represented as labelled rectangles. Each rectangle is labelled with a process number and the estimated time for each process is positioned below the bottom right corner of the rectangle.

The rectangles can be stretched across several swim-lanes to show collaborative processes. For instance, if a process is stretched across the swim lanes for a manager and systems designer, then it implies that the process may require collaboration between the manager and system designer.

4.2.1.3. Primitive set 3 - Representing coordination

Within the ICD approach, the representation of how communication channels can be synchronised is done: *in series* to show how one communication channel can be used to reinforce another channel, or *in parallel* to depict alternative channels that are available for information flow. For instance, if a customer can call, email or write to make an enquiry, then the available channels are in parallel. Similarly, if an information manager responds to an enquiry via email followed by a telephone call, then the communication channels are in series.

To aid in the representation of how internal and external flows can be harmonised, the swim-lane (role) of information managers can be depicted first, in the centre of the ICD. Next, external roles (particularly the customer), are depicted to the left of the information manager's swim-lane. Internal roles such as technicians and business directors are then depicted to the right of the information manager's swim-lane.

4.2.1.4. Primitive set 4 - Representing streamlining

Contextualised information is an option within the ICD represented by means of different colours for process links and flows. Colours to contextualise information can also be used for the label ascribed to each swim-lane (for roles) at the discretion of the ICD user.

The open ended rectangle, the primitive used to represent data storage in the DFD is adopted and customised for use in the ICD depicting information sharing. Each open ended rectangle labelled with a unique identifier (as in DFD) is also fused with squares, as shown in Table 4-1, to indicate the type of media form used to store and share information. For instance a completely shaded box would indicate data or information stored via telematics such as email, word documents or spreadsheets.

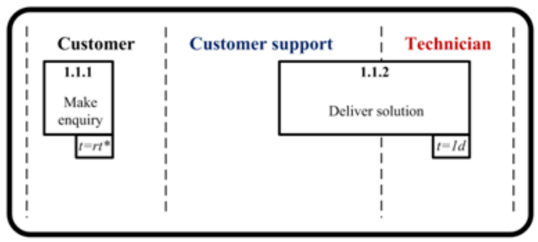
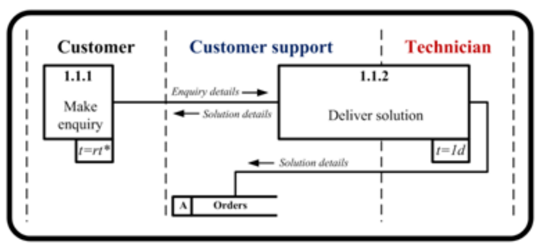
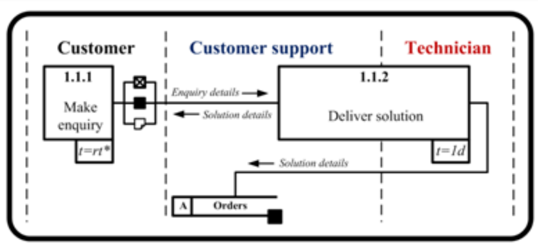
4.2.2. Prescribed steps for creating information flow models

For the creation of an ICD, four steps are prescribed, as shown in Table 4-2, to describe how collected data about information flow in organisations can be transformed into diagrammatic models. In each step, primitive sets are increasingly added to populate the ICD. These steps are now described as follows:

4.2.2.1. Modelling step 1 - Depicting roles

The creation of ICDs begins with identifying the roles in the organisational scenario(s) extracted from the data collection process. These roles are depicted as swim lanes positioned side-by-side with the option of using different colours for each swim-lane left to the discretion of ICD users.

Table 4-2: Composition steps for creating information channel diagrams

Method for creating model	**Information channel diagram composition**
Depicting roles - *1. Draw swim-lanes to show roles involved in the interactions* *2. Label each swim-lane with the names of the roles*	
Positioning processes - *1. Place processes (and stretch across to show collaboration) within swim-lanes* *2. Label processes*	
Introducing flow links - *1. Draw links between processes* *2. Place data stores within swim lanes where applicable* *3. Bring in labelled arrows to describe information*	
Representing communication channels – *1. Depict communication channels for processes and data stores* *2. Review and update*	

4.2.2.2. Modelling step 2 - Positioning processes

The next step in the development of the ICD involves positioning processes within a swim-lane or over multiple swim-lanes (to depict collaborative processes) for roles to take ownership and be responsible for processes. The estimated time for each process is also included. For each process, a number format is defined depending on the degree to which a function is decomposed. Three levels of decomposition (function → task → process) are applied as a guide for the technique to ensure a function can be sufficiently broken up into a set of activities.

Each level of decomposition is assigned an additional digit. This assignment is continued till the lowest level where processes are described. The first digit represents functions in the organisations; the second represents tasks carried out as part of the function; while the third represents processes. For instance, Figure 4-2 shows a process to 'check records' (labelled as 1.1.1.), that is part of a task to manage customer sales records (labelled as 1.1.), that is part of a sales function (labelled as 1).

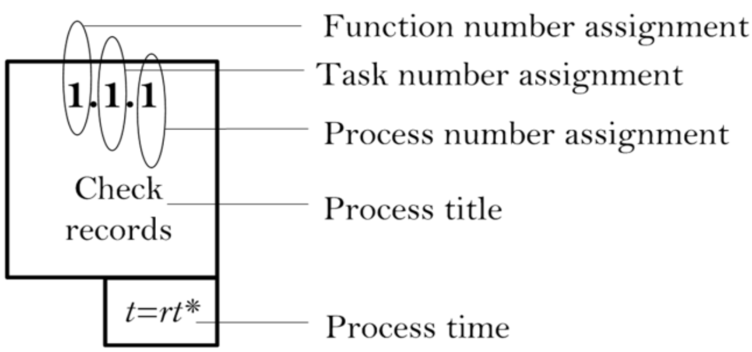


Figure 4-2: Process number assignment in the information channel diagram approach

4.2.2.3. Modelling step 3 - Introducing information flow links

Next, links are introduced to depict relationships that exist between roles during delivery processes. Since the focus of the ICD is for modelling information flows during delivery exchanges that involve customers and manufacturers, the links between processes are labelled with arrows depicting the flow of information. Labels that are above links represent feed-forward paths whereas labels below links depict feed-back paths. Also, depending on the scenario, information flow may involve the aggregation of new information or the extraction of information for storage. Where this is the case, links can be connected to other links to represent aspects such as access or exchange involving a data store, or modification of information for granularity / transparency.

The introduction of information sharing within an ICD follows the labelling of links and is done in a similar manner to step 2 i.e. introduced information sharing primitives are positioned in a swim lane for roles to take responsibility for storing and sharing information.

4.2.2.4. Modelling step 4 - Representing communication channels

The final step in the creation of the ICD is the representation of communication channels. In the ICD, different forms of communication channels can be used to describe available means for accessing and transferring information and can be represented in two ways: sequentially and concurrently. In sequentially represented communication channels, the flow of information involves the use of two or more media forms or interactions. For instance, a telephone call followed by an email would be considered serial communication channels in the ICD. Similarly, in concurrently represented communication channels, the flow of information entails the availability of alternate media forms or interactions. For example, a customer may send an email or make a phone call to make an enquiry. In some cases, succeeding processes may make use of the same communication channels as a preceding process. In these cases, it is not necessary to repeatedly depict the channels in the succeeding processes.

4.2.3. An example: delivery within the health care sector

Durugbo *et al.* (2009) used here as an example describes the operations of a major healthcare organisation that offers ‘service agreements’. This service agreement involves delivering mission-critical equipment backed, with 24 hour service for remote clinical and technical expertise. In the solution, products delivered to client businesses (i.e. customers) included X-ray machines, CT, MR, ultrasound and nuclear medicine imaging equipment, whereas services delivered included software updates, planned maintenance and parts replacement. In the scenario, a laboratory technician from a client business makes a request and receives replacement parts and maintenance for a CT machine. The focal point in the scenario is the information flow involving the support staff (as the manager of information flow) which contains eight steps: Technician requests service → Support staff checks service → Support staff checks orders → Support staff updates orders → Support staff places order for service → Support staff gives feedback (to technician) → Support Staff gets feedback (from service team) → Support staff updates record.

Using the methodology of §4.2.2, a description of information flow, as shown in Figure 4-3, can be presented using the ICD approach in four steps.

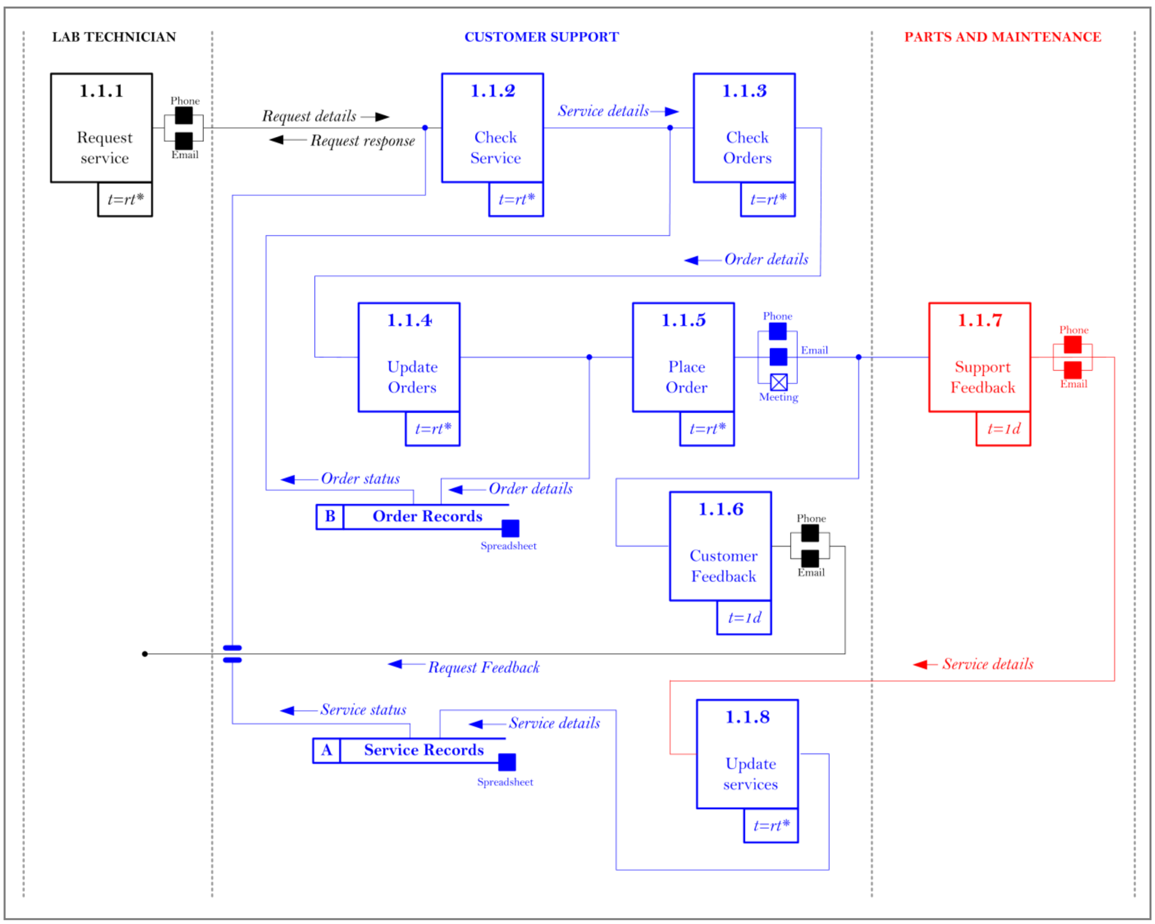


Figure 4-3: Information channel diagram for the customer enquiry scenario

For the first step, the three different roles identified in the scenario i.e. the lab technician, customer support and service team, are depicted in swim-lanes. The customer support role is positioned in the middle because it interacts with the lab technician, a role external to the healthcare organisation, and the internal parts/maintenance staff. Consequently, the swim-lanes of the lab technician and the parts/maintenance staffs are depicted to the left and right respectively of the customer support.

The second step involves positioning the eight processes, derived from the eight steps described in scenario, within the depicted swim-lanes. These processes are derived as follows: 'request service', 'check services', 'check orders', 'update orders', 'place order', 'support feedback', 'customer feedback' and 'update services'. Apart from the process in which the technician orders a service and the service team gives feedback to the support staff, the rest of the processes are positioned within the swim-lane of the customer support. Each process is part of a 'service delivery' task, which in turn is part of a 'delivery' function. Processes are labelled using the scheme introduced in §4.2.2.2, starting from 1.1.1 and ending at 1.1.8. In Durugbo *et al*. (2009), no indication is given as to process timing, consequently, in this scenario, times for processes are estimated and used for illustration purposes.

For the third step, links for enabling information flow are introduced (and labelled) to connect processes and to show exchanges for data retrieval/ storage (information sharing). In the example, two records held by the customer support for data retrieval/ storage of orders and services are captured. The order records are accessed by the process to 'check orders' and modified by the 'update orders' process. Similarly, the service records are accessed by the 'check service' process and modified by the 'update services' process.

The fourth step entails representing the communication channels used in the scenario, mainly telephone conversations, e-mails, spreadsheets and company meetings as shown in Figure 4-3. Since, the communication channels used by process 1.1.1 are the same for succeeding processes 1.1.2 to 1.1.4, these communication channels are not replicated for processes 1.1.2 to 1.1.4. Similarly, the communication channels for 1.1.6 are not replicated since they are the same as those for 1.1.5.

4.3. An intra-organisational collaboration model

In this section, the intra-organisational collaboration (IOC) model is proposed as: (i) information structures in terms of organisational topologies, vertices and edges and (ii) quantitative indicators for characterising collaboration in organisations.

4.3.1. Information structure

Intra-organisational collaboration (IOC) is modelled as a connected, partitioned, non-overlapping hypergraph $G = (V, E)$ containing a graph for characterising the collaborative social network of individuals/groups $G_s = (V_s, E_s)$ and a digraph for characterising the collaborative activity network of processes/tasks $G_p = (V_p, E_p)$, as shown in Figure 4-4. V_s represents *social vertices* of collaborating individuals, teams or organisations, and V_p represents *activity vertices* for processes that are required to achieve a common goal that could not be achieved by the collaborating individuals. E_s and E_p correspond to edges between teams (or individuals) and processes.

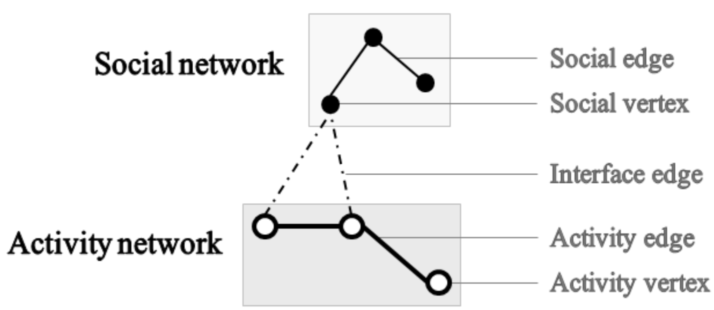


Figure 4-4: An intra-organisational collaboration model as a hypergraph

For the proposed model, processes become part of a collaboration based on the set of interface edges T created by vertices within collaborators i.e. T associates V_s with V_p.
Interface edges are connections between individuals/groups and tasks/processes for the exchange of resources. For instance, a machine operator may work on a problem and exchange information with a piece of equipment as part of a process in an intra-organisational collaboration. This interaction, related to formal work practise, can be

enabled by edges (defined here as interface edges) for human-machine relationships. Each social vertex can be linked to as many as V_p activity vertices. Consequently G is defined by $V = V_s \cup V_p$ and $V_s \cap V_p = \emptyset$. Similarly, $E = E_s \cup E_p \cup T$ and $E_s \cap E_p \cap T = \emptyset$.

4.3.1.1. Collaboration social network

For f groups (each containing g social vertices) within the **social network** G_s, three different (Types 1 to 3) topologies for characterising IOC are proposed as shown in Figure 4-5.

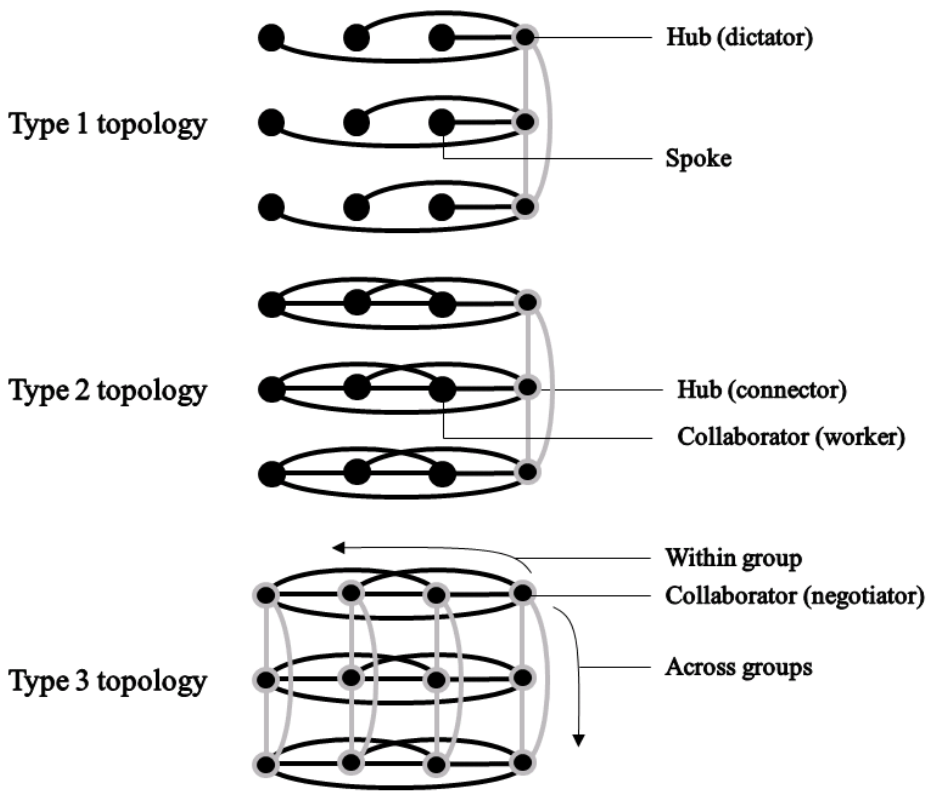


Figure 4-5: Topologies for social networks in the intra-organisational collaboration model[6]

In **Type 1 topologies**, based on dictatorship, collaboration between groups and individuals is realised by means of a leading hub in each group that is appointed to dictate

[6] based on three groups each containing four social vertices

or dominate interactions for collaborations between individuals and groups. In the proposed configuration, collaborating spokes within an organisation are connected to the group hubs (i.e. as a star or hub-and-spokes arrangement[7] in which several vertices (spokes) are connected to a central vertex (hub)). For a group containing a single hub, the social network contains $g - 1$ spokes that are connected to the hub. The total number of hubs that enable collaboration in multiple groups is given as f while the total number of spokes within f groups is given as $f(g - 1)$ i.e. $fg - f$.

Type 2 topologies, motivated by mutual collaboration, enable edges between connected social vertices who occupy themselves working with other social vertex in a group to achieve a specific goal that is posed. Also, groups are connected by a 'connector hub' that maintains collaboration across groups. Within a type 2 topology containing f groups, $fg - f$ social vertices (or spokes) can link with f hubs with connector roles. Each vertex within a group can also connect to other vertices within its group (i.e. $g - 1$ vertices) to work on a separate part of a problem that contributes to a common goal.

Type 3 topologies involve exclusive collaboration and enable edges between connected social vertices (that act as hubs) with similar or dissimilar specialties. Each social vertex works on achieving a collaborative goal and occasionally connects and negotiates with other vertices across collaborating groups for advice and updates on the status of factors such task prerequisites and dependencies, and to solve by uni-, inter- or multi-disciplinary problems. In the type 3 topology, collaboration is based on exclusive roles and the number of collaborating teams across organisations is equal to f whereas collaboration is enabled by maximum of V_s collaborating vertices.

In all the forms of social network topologies proposed in the IOC model, the number of vertices within the social network (G_s) can be calculated as the sum of social vertices from each group i.e.:

$$|V_s| = \sum_{i=1}^{f} g_i \qquad \textbf{(4)}$$

Where $|V_s|$ is the cardinality of V_s, f is the number of groups involved in collaboration and g_i is the number of social vertices that form a group i.

[7] This arrangement is widely used in configuring networks for transport and telecommunication

Within the **social network** G_s, as shown in Figure 4-5, two forms of edges facilitate connections: collaborative- and network- edges.

Collaborative-edges (E'_s), shown in Figure 4-5 as gray coloured lines between vertices, are a subset of edges that form a sub-graph of the social network (G_s') for enabling collaboration between groups. Within the type 1 and 2 topologies, f social vertices across teams (inter-team) acting as hubs can form $f(f-1)/2$ collaborative edges with each other. In the type 3 topology, each social vertex exclusively collaborates (i.e. creates edges) across groups by establishing $g \times f(f-1)/2$ edges based on factors such as common disciplines or pre-defined problems.

Network-edges (E_s) on the other hand, are the sum of possible edges for the topologies shown in Figure 4-5, and their cardinality $|E_s|$ is computed as follows:

Type 1 topology: $$\frac{\overbrace{f(f-1)}^{hubs}}{2} + \overbrace{f(g-1)}^{spokes}$$

Type 2 topology: $$\frac{\overbrace{f(f-1)}^{hubs}}{2} + \frac{\overbrace{fg(g-1)}^{chains}}{2}$$

Type 3 topology: $$\frac{\overbrace{fg(g-1)}^{within-groups}}{2} + \frac{\overbrace{gf(f-1)}^{across-groups}}{2} = \frac{1}{2}\left[g^2 f - 2fg + f^2 g\right] \quad \textbf{(5)}$$

4.3.1.2. Collaboration activity network

The **activity network** G_p within the IOC model is derived from: *serial topologies* that impose precedence in dependencies for creating an additive chain of processes, and *parallel topologies* that enforce multiple dependencies for concurrent processes. The parallel topology may involve multiple processes that are dependent on a single process (burst) or a single process that is dependent on multiple processes (merge) as shown in Figure 4-6.

For an activity network (G_p) containing I and J number of serial and parallel configurations for vertices, the number of vertices within G_p i.e. $|V_p|$ can be computed as:

$$|V_p| = \overbrace{\sum_{i \in I}^{I} s_i}^{serial} + \overbrace{\sum_{j \in J}^{J} p_j}^{parallel} \quad \textbf{(6)}$$

Where, s_i and p_j are the number of processes in each serial and parallel configuration respectively and $|V_p|$ is the cardinality of V_p. Suppose an intra-organisational collaboration is set up to carry out 4, 3, 5 and 2 processes with parallel dependencies and 9 serially dependent processes, and if the IOC makes use of 5 collaborating teams each containing 6 team members, then the number of vertices within the IOC will be 53, broken down as 5 × 6 = 30 social vertices for G_s and (4 + 3 + 5 + 2) + 9 = 23 activity vertices for G_p

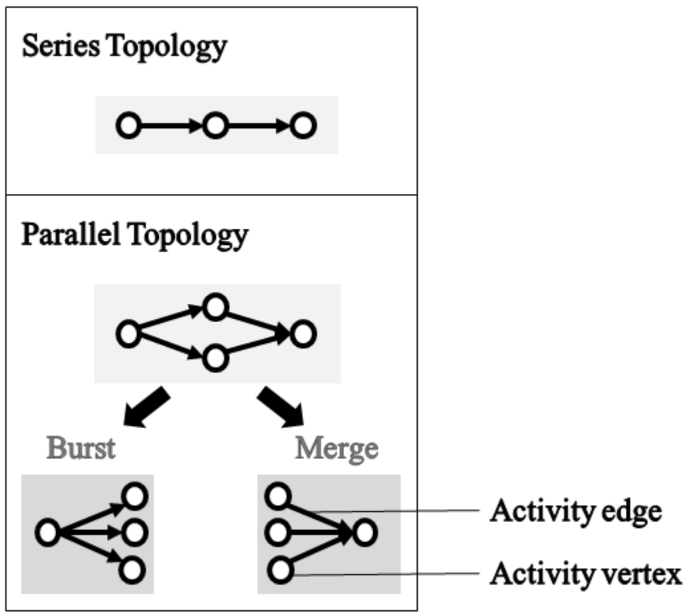


Figure 4-6: Topologies for the activity network in the intra-organisational collaboration model

If the activity network is made up of I serial, L parallel (burst) and M parallel (merge) then processes within G_p of the IOC are associated by E_p input and output edges in the formulation:

$$|E_p| = \overbrace{\sum_{i=1}^{I} a'_i}^{serial} + \overbrace{\sum_{l=1}^{L} b'_l + \sum_{m=1}^{M} c_m}^{parallel} \quad (7)$$

$|E_p|$ is the cardinality of E_p, a'_i and b'_l are inputs to I serial and L parallel (burst) sets of configured vertices and c_m is the output edge from M parallel (merge) sets of configured vertices where $E_p = a'_i \cup b'_l \cup c_m$ and $a'_i \cap b'_l \cap c_m = \emptyset$. The maximum number of edges within G_p can be computed as $|V_p|\,(|V_p| - 1)/2$. However, when $L = 0$ then the maximum number of edges within G_p can be simplified to $2|V_p| - 2$ activity edges. Two edges are subtracted from the total number for terminal vertices– the *start vertex* that has no preceding vertices and the *end vertex* that has no following vertices. The maximum number of possible interface edges in the model is given as $|V_s| \times |V_p|$ in which every social vertex is linked to every activity vertex.

4.3.2. Collaboration indicators

Within the IOC network (i.e. G_s and G_p), three collaboration indicators with values greater than or equal to zero and less than or equal to two are proposed.

The first indicator termed the **'teamwork scale'** (τ_i) is introduced to assess the activity of a social vertex *i* and interconnectedness within a cluster for teamwork. To do this, the degree centrality and clustering coefficient of *i* are multiplied by a teamwork constant (γ_i) that is based on the availability and capability of *i* (i.e. the participant) to pool resources. The teamwork scale τ_i for each social vertex *i*, can be calculated as:

For a social vertex *i*
$$\tau_i = \left[\overbrace{\frac{2|E_s|}{|V_s'|(|V_s'|-1)}}^{clust\_coefficient} + \overbrace{\frac{[\deg]_i}{|V_s'|-1}}^{\deg\_centrality} \right] \cdot \gamma_i \qquad \textbf{(8)}$$

Where, $[\deg]_i$ is the number of social vertices that are directly linked to *i*. For the overall IOC network, the *average teamwork scale* (τ) can be calculated as:

$$\tau = \frac{1}{|V_s'|} \sum_{i=1}^{V_s'} \tau_i \qquad \textbf{(9)}$$

Where, $|V_s'|$ is the cardinality of a sub-graph consisting of social vertices at group, inter-group or organisational level.

The 'decision-making scale' (δ_i) is the second collaboration indicator introduced to assess the ease with which a social vertex *i* within the intra-organisational network can make decisions based on the interconnectedness and connections for relationships. To do this, the clustering coefficient and closeness of *i* in a defined sub-graph (group or overall organisation) of the collaboration social network are multiplied by a decision constant (β_i) that is dependent on the availability and capability of *i* to make choices. It is calculated as:

For a social vertex i $\quad \delta_i = \left[\overbrace{\frac{1}{\sum_{i \neq j \in V_s'} d_{ij}}}^{closeness} + \overbrace{\frac{2|E_i|}{|V_s'|(|V'|_s - 1)}}^{clust\_coefficient} \right] \cdot \beta_i$ **(10)**

Where, d_{ij} is the distance between two vertices i and j, $|E_i|$ is the number of edges created with directly connected vertices. The *average decision-making scale* (δ) for social vertices in the IOC network can then be computed as:

$$\delta = \frac{1}{|V_s'|} \sum_{i \in V_s'}^{V_s'} \delta_i \quad \textbf{(11)}$$

The third indicator, the 'coordination scale' (χ_i) assesses the connections and activity associated with which a social vertex i through which interactions can be harmonised. To do this, a coordination constant (α_i) that is dependent on the availability and capability of i for harmonising interactions, is multiplied by the sum of the closeness and degree centrality of i towards the social and activity network. The activity network is included to take into account coordination theory that depicts dependencies as emerging from tasks (Albino *et al*., 2002). The coordination scale χ_i can be calculated as:

For a social vertex i $\quad \chi_i = \left[\overbrace{\frac{1}{\frac{1}{2}\left(\sum_{i \neq j \in V_s'} d_{ij} + \sum_{i \neq k \in V_p'} d_{ik} \right)}}^{closeness} + \overbrace{\frac{1}{2}\left(\frac{[\deg]_i}{|V_s'| - 1} + \frac{[\deg]_{i(T)}}{|V_p'| - 1} \right)}^{\deg\_centrality} \right] \cdot \alpha_i$ **(12)**

Where, $|V_p'|$ is the cardinality of a sub-graph consisting of activity vertices and $[\deg^s]_{i(T)}$ is the number of activity vertices that are directly linked to i through interface edges that constitute T. The *average coordination scale* (χ) for social vertices in the IOC network can then be computed as:

$$\chi = \frac{1}{|V_s'|} \sum_{i \in V_s'}^{V_s'} \chi_i \quad \textbf{(13)}$$

4.3.3. An example: intra-organisational collaboration for product development

Eppinger (2001), adapted to exemplify the application of the proposed model, is based on the management of the development of power trains at General Motors. No indication is given as to the social network for collaborating teams or the number of members in each team, rather the focus of Eppinger (2001),was to make use of the design structure matrix approach to analyse the sequence and configuration of processes based on the frequency of information flow feed-forwards and feed-backs.

The frequency of communications involving information flow, centred on daily, weekly and monthly interactions and the main design challenge was to improve communications for systems integration. This challenge was dealt with by reorganising the information flow through the introduction of a systems integration team and four new 'overlapping' teams. Teams were overlapped based on the sequence of processes and regular team interactions.

4.3.3.1. Pre-existing information flow

Prior to reorganisation, as shown in Figure 4-7(a) and Table 4-3, the intra-organisational collaboration for product development (IOC-PD) was made up of four teams that deliver short block systems (SBS), valve train systems (VTS), induction systems (IS), and emissions and electrical systems (EES).

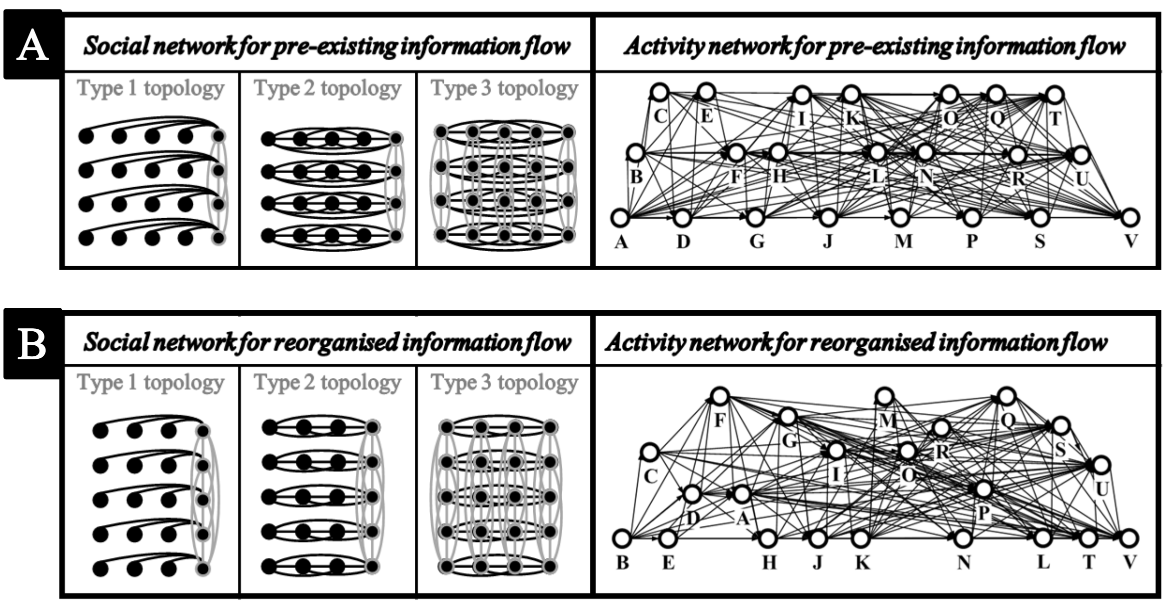


Figure 4-7: Topologies for the example of intra-organisational collaboration model for product development: (a) information structures for pre-existing information flow (b) information structures for reorganised information flow.

The IOC-PD is also made up of 22 processes i.e. *an activity network made up of 22 activity vertices* (A to V), assigned as follows: the SBS team was responsible for developing engine blocks (A), crankshafts (B), flywheels (C), pistons (D), connecting rods (E) and lubrication (F), the VTS team was responsible for cylinder heads (G), camshaft/valve trains (H), and water pump/cooling (I), the IS team was responsible for intake manifold (J), fuel system (K), accessory drive (L), air cleaner (M), AIR (N) and throttle body (O), the EES team was responsible for exhaust (P), EGR (Q), EVAP (R), ignition (S), ECM (T), and electrical system (U), while all collaborating teams were responsible for engine assembly (V). This demonstration assumes that each team in the initial IOC-PD is made up of five members corresponding to 20 human collaborators i.e. *a social network made up of 20 social vertices*. Five is chosen for this demonstration because it is the minimal value of the magic number for group sizes that is widely accepted as seven plus or minus seven (Cain, 1996).

Table 4-3: Assigned tasks in pre-existing information flow

Pre-existing teams in example	Number of interface edges	Assigned tasks
Short block team	7	A, B, C, D, E, F, V
Valve train system team	4	G, H, I, V
Induction system team	7	J, K, L, M, N, O, V
Emissions and electrical system team	7	P, Q, R, S, T, U, V

Table 4-4 presents the main results of the IOC-PD demonstration. The table provides data on the number of nodes, groups, participants, hubs and spokes (where appropriate) derived from the description of the scenario. Using these values and topologies from Figure 4-7(a), the values for SNA measures (clustering coefficient, degree centrality and closeness) were then computed. The last nine rows of Table 4-4 present the collaboration indications (individual and average) based on the calculated SNA measures. The first step in determining the collaboration indicators involves calculating the clustering coefficient, closeness and degree centrality of the network.

Table 4-4: Comparison of collaboration indicators for pre-existing and reorganised information flow

	Pre-existing Information Flow			**Reorganised Information Flow**		
	Type 1	*Type 2*	*Type 3*	*Type 1*	*Type 2*	*Type 3*
Overall vertices ($\|V'\|$)	42	42	42	42	42	42
Overall activity vertices ($\|V_p\|$)	22	22	22	22	22	22
Overall social vertices ($\|V_s\|$)	20	20	20	20	20	20
Number of groups (f)	4	4	4	5	5	5
Participants from each group (g)	5	5	5	4	4	4
Hubs	4	4	20	5	5	20
Spokes	16	16	–	15	15	–
Cc_i *of i (Hub) towards vertices in* V_s	0.0526	0.0842	0.0842	0.0684	0.0842	0.0842
Cc_i *of i (Spoke) towards vertices in* V_s	0.0211	0.0526	–	0.0158	0.0316	–
Dc_i *of i (Hub) towards vertices in* V_s	0.3684	0.3684	0.3684	0.3684	0.3684	0.3684
Dc_i *of i (Spoke) towards vertices in* V_s	0.0526	0.2105	0.0526	0.0526	0.1579	0.0526
c_{ij} *of i (Hub) towards vertices in* V_s	0.0323	0.0323	0.0323	0.0323	0.0323	0.0323
c_{ij} *of i (Spoke) towards vertices in* V_s	0.0204	0.0217	–	0.0204	0.0213	–
Teamwork scale (Hubs)	0.4211	0.4526	0.4526	0.4368	0.4526	0.4526
Teamwork scale (Spokes)	0.0737	0.2632	–	0.0684	0.1895	–
Average teamwork scale	**0.1432**	**0.3011**	**0.4526**	**0.1605**	**0.2553**	**0.4526**
Decision-making scale (Hubs)	0.0849	0.1165	0.1165	0.1007	0.1165	0.1165
Decision-making scale (Spokes)	0.0415	0.0744	–	0.0362	0.0529	–
Average decision-making scale	**0.0501**	**0.0828**	**0.1165**	**0.0523**	**0.0688**	**0.1165**
Coordination scale (Hubs)	0.3513	0.3513	0.3513	0.3510	0.3510	0.3510
Coordination scale (Spokes)	0.1993	0.2732	–	0.1993	0.2487	–
Average coordination scale	**0.2297**	**0.2888**	**0.3513**	**0.2372**	**0.2743**	**0.3510**

(i – social vertex, Dc_i – degree centrality, Cc_i – clustering coefficient, and c_{ij} – closeness). Bold fonts signify average values for collaboration indicators.

4.3.3.1.1. Clustering coefficient

Whereas the maximum number of vertices in a fully connected social network for the IOC-PD can be computed as $fg(fg - 1)/2$ i.e. 190, the hubs and spokes in Type 1 topologies can form $((f(f - 1)/2) + (g - 1))$ and $(g - 1)$ actual edges respectively as shown in Figure 4-7(a). The clustering coefficient (Cc_i) for each hub and spoke in the Type 1 topology can then be computed as $((4(4 - 1)/2) + (5 - 1))/190 = 0.0526$ and $(5 - 1)/190 = 0.0211$ respectively. For Type 2 and 3 topologies, each hub and spoke can have $((f(f - 1)/2) + (g(g - 1)/2))$ and $g(g - 1)/2$ actual edges corresponding to Cc_i values of 0.0842 and 0.0526 respectively.

4.3.3.1.2. Degree centrality

Within the social network of the IOC-PD, each hub would have (f – 1) + (g – 1) i.e. 7 neighbours whereas the spokes would have 1 neighbour (the dictator hub) in the Type 1 topology and g – 1 i.e. 4 neighbours in the Type 2 topology. From eqn. (1) and Figure 4-7(a), the degree centrality (Dc_i) for hubs can then be computed as 7/(20 – 1) = 0.3684. Dc_i for spokes can be calculated as 1/(20 – 1) = 0.0526 and 4/(20 – 1) = 0.2105 for Type 1 and Type 2/3 topologies respectively. Within the Type 1 topology, Dc_i for social vertices within the entire network of social and activity vertices can be calculated, using the interface edges shown in Table 4-3, as follows:

For SBS, IS and EES teams	*(Hubs)*	(7+7)/((20 – 1) + 22) = 0.3415
	(Spokes)	(1+7)/((20 – 1) + 22) = 0.1951
For VTS team	*(Hubs)*	(7+4)/((20 – 1) + 22) = 0.2683
	(Spokes)	(1+4)/((20 – 1) + 22) = 0.1220

Values for Dc_i in Type 2 and 3 topologies have been computed using similar approaches and are shown in Table 4-4.

4.3.3.1.3. Closeness

Within the social network of the IOC-PD, the geodesic distance (d_{ij}): between two hubs is 1, between a hub and a spoke in the hub's team is 1, between a hub and a spoke in a different groups is 2, between two spokes in a different group is 3, and between two spokes in the same group is 2 for Type 1 and 1 for Type 2 topologies. The geodesic distance for social vertices within the social network can therefore be computed as follows:

For each hub:	$\overbrace{\left(1\times(f-1)\right)}^{hub-hub(across\_groups)} + \overbrace{\left(1\times(g-1)\right)}^{hub-spoke(same\_group)} + \overbrace{\left(2\times((f\times g)-f-g+1)\right)}^{hub-spoke(different\_group)}$
For each spoke in Type 1 topology:	$\overbrace{\left(1\times 1\right)}^{spoke-hub(same\_team)} + \overbrace{\left(2\times(f-1)\right)}^{spoke-hub(different\_team)} + \overbrace{\left(2\times(g-2)\right)}^{spoke-spoke(same\_team)} + \overbrace{\left(3\times(f\times g)-f-g+1\right)}^{spoke-spoke(different\_team)}$
For each spoke in Type 2 topology:	$\overbrace{\left(1\times 1\right)}^{spoke-hub(same\_team)} + \overbrace{\left(2\times(f-1)\right)}^{spoke-hub(different\_team)} + \overbrace{\left(1\times(g-2)\right)}^{spoke-spoke(same\_team)} + \overbrace{\left(3\times(f\times g)-f-g+1\right)}^{spoke-spoke(different\_team)}$

Similarly, d_{ik} for social vertices to an activity vertices k via interface edges T can be calculated from the edges of topology of the activity network, shown in Figure 4-7(a), as follows:

Short block team (SBS)	$\overbrace{(1\times 7)}^{SBS\_assigned\_tasks} + \overbrace{(2\times 3)}^{VTS\_assigned\_tasks} + \overbrace{(2+3+2+3+2+3)}^{IS\_assigned\_tasks} + \overbrace{(2+2+3+2+2+2)}^{EES\_assigned\_tasks}$
Valve train system team (VTS)	$\overbrace{(2\times 6)}^{SBS\_assigned\_tasks} + \overbrace{(1\times 4)}^{VTS\_assigned\_tasks} + \overbrace{(2\times 6)}^{IS\_assigned\_tasks} + \overbrace{(2+2+2+3+2+2)}^{EES\_assigned\_tasks}$
Induction system team(IS)	$\overbrace{(2+3+2+3+2+3)}^{SBS\_assigned\_tasks} + \overbrace{(2\times 3)}^{VTS\_assigned\_tasks} + \overbrace{(1\times 7)}^{IS\_assigned\_tasks} + \overbrace{(2\times 6)}^{EES\_assigned\_tasks}$
Emissions and electrical system team (EES)	$\overbrace{(2+2+3+2+2+2)}^{SBS\_assigned\_tasks} + \overbrace{(2\times 3)}^{VTS\_assigned\_tasks} + \overbrace{(2\times 6)}^{IS\_assigned\_tasks} + \overbrace{(1\times 7)}^{EES\_assigned\_tasks}$

Values for Dc_i in Type 2 and 3 topologies have been computed using similar approaches and are shown in Table 4-4. Using the d_{ij} and d_{ik} of social vertex *i* the closeness of *i* within the social network and the entire IOC-PD network can be computed as shown in Table 4-4.

4.3.3.1.4. Collaboration Indicators

The next step in deriving the collaboration indicators involves multiplying the different SNA quantities with the various constants proposed in the model.

Assuming each vertex is always available and capable to harmonise interactions, pool resources and make choices, i.e. γ_i, α_i and β_i, are all 1, then the various collaboration indicators can be calculated, using Figure 4-7(a) and eqn. (8-13), as shown in Table 4-4. The table shows that the most effective means for collaboration was the Type 3 topology with 0.4526 (22.6%), 0.1165(5.8%) and 0.3513 (17.6%) out of a possible value of 2 for teamwork, decision-making and coordination.

4.3.3.2. Reorganised information flow

Following the reorganisation, the old IOC-PD configuration is replaced with four new teams (numbered 1 to 4) and an integration team, as shown in Figure 4-7(b). In the new IOC-PD, the teams are assigned to 6, 7, 8 and 5 tasks respectively with multiple teams working on the few overlapping processes as shown in Table 4-5. The integration team is exclusively assigned to five processes L-V.

In Eppinger (2001), the reorganisation involved the restructuring of available personnel which in this example corresponds to five groups made up of four personnel giving a total of 20 collaborating social vertices as in §4.3.3.1. Using the IOC model, the updated values for collaboration indicators can be derived as shown in Table 4-4.

Table 4-5: Assigned tasks in reorganised information flow

New teams in example	Number of interface edges	Assigned tasks
Team 1	6	A, B, C, D, E, F
Team 2	7	A, D, F, G, H, I, J,
Team 3	8	G, I, J, K, M, N, O, R
Team 4	5	G, J, N, P, Q
Integration Team	5	L, S, T, U, V

For the Type 1 topology, an additional hub and more edges between hubs due to increased number of group causes an improvement to the clustering coefficient of the social network, whereas degree centrality and closeness values remain constant. The overall effect of the reorganisation is that collaboration improves for the Type 1 topology.

For the Type 2 topology, the additional connector hub causes a decrease in the Cc_i, Dc_i and c_{ij} values for connected social vertices. This results in an overall decrease in the collaboration indicators although these values remain higher than those of the Type 1 topology.

Within the Type 3 topology, each social vertex acts as a hub meaning Cc_i and Dc_i values remain the same. However, the closeness decreases and counteracts gains due to increased coupling of processes. Consequently, teamwork and decision-making scales remain constant whereas coordination decreases slightly. Nonetheless, the Type 3 topology based on exclusive collaboration offers the highest values for collaboration indicators in both the pre-existing and re-organised information flow, correlating with previous empirical studies such as Maher *et al.* (1998) which suggest that exclusive collaborations are the most effective and productive.

4.4. SUMMARY

This chapter introduced a technique for modelling information flow in organisations delivering microsystems technology (MST) through a diagrammatical tool - the 'information channel diagram (ICD)' tool and a mathematical analysis approach – the 'intra-organisational collaboration (IOC)' model.

The 'information flow channel' (ICD) is a diagrammatical tool for modelling information flow with a view to analysing delivery information exchanges. The ICD tool contains a set of primitives for representing information flows during delivery exchanges that involve customers and manufacturers and a prescribed set of steps for using the tool. A case scenario of the delivery of integrated products and services within the health care sector was used to demonstrate how the prescribed set of steps can be used to model information flow during the delivery phase of organisations.

The 'intra-organisational collaboration' model is introduced as an amalgamation of *social networks* of human actors and *activity networks* of processes, and indicators for *teamwork* - to tally the manner in which participants and groups pool resources to achieve a goal, purposely, or inadvertently, *decision-making* - to score the manner in which choices are made during collaborations through dictated decisions by a dictating entity, participatory decisions made by participating entities and democratic decisions based on collaborators who are individually responsible for decision making, and *coordination* - to measure the ability of collaborators to harmonise interactions for maintaining and updating the flow of resources such as materials, funds and information. A case scenario of the management of the development of power trains was used to demonstrate how the mathematical model can be used to analyse collaborations within an organisation.

Chapter

5

CASE STUDIES

This chapter describes the findings of case studies involving three real-life organisation delivering microsystems technology (MST): ‘a software division in an MST firm’, ‘a micro-integrated device manufacturer’, and ‘a MST design house/ small-scale production company’. The information channel diagram (ICD) tool, proposed in §4.2, is validated by comparing the tool with existing tools used within organisations delivering MST. And applying the case studies, the intra-organisational collaboration (IOC) model, proposed in §4.3, is evaluated through its use for analysing the current state of information flow.

5.1. VALIDATION OF THE INFORMATION CHANNEL DIAGRAM

In this section, the findings of the cases studies to validate the ICD are presented as follows: firstly for the questionnaire comparing the ICD approach with the data flow diagram (DFD) and design structure matrix (DSM) techniques, and secondly for the comments made by participants during the empirical inquiry.

5.1.1. Generated scenarios for case studies

For uniformity, the cases used in the comparison of the ICDs, DFDs and DSMs were the flow of delivery information for work products that require the setting up of a project.

At **Company A** and **Company C**, managers of information flow described two main delivery scenarios involving the flow of off-the-shelf or custom-made work products in the forms of physical products (MST chips, devices and instruments), support services (field services, training, instrument installation and demonstration), and designs/software. In both companies delivery is triggered by an electronic customer purchase order that stipulates the type, quantity, and agreed price for MST deliverables. This process is usually preceded by a response to an initial customer request for work product quote. However, the delivery at **Company C** of project-based work products is guided by an initial service contract with a view to enabling tie-ins and avoiding fluidity that may result in customers taking designs away and making products elsewhere. In delivery cases involving off-the-shelf chips and devices, a customer request is the information used to guide personnel in retrieving and packaging standard parts from stock. Final work products are checked out through material requirements planning systems and dispatched with a delivery note via an outsourced local or international courier service depending on the location of the customer.

Company A makes use of a unique material in the development of products and as a result, typical deliveries involve setting up projects to deliver drawings, devices/instruments, and after-care services such as offering help in assembling devices and providing extra fittings. **Company C**, on the other hand, stocks a wide range of products such as pumps, chips and functional systems that are delivered as-is or customised (for instance attaching a connector or a header), inspected and tested. The delivery of larger or more complex systems is overseen through a project and deliverables include a final system, supported by after-care services, and customer training to carry out tasks such as changing contact angles.

Delivery information flow for project based work products in **Company A** and **Company C** follows a similar path involving: the receipt and acknowledgement of an electronic customer purchase order, the aggregation of delivery data through subsequent processes for design clarification/product preparation via emails and telephone conversations, the updating of delivery information during product dispatch and service delivery via a dispatch note and customer invoices.

Company A however maintains and manages these flows through a customer support personnel who draws upon work experiences from administration and customer service whereas **Company C** supports delivery information flow through a proprietary system that tracks delivery costs, timescales and risks.

According to **Company B**'s commercial director, the division at **Company B** delivers mainly software and tools to other divisions for integration in customer releases that are eventually included in semi-conductor based products (including microsystems technology (MST) chips and devices). Delivery by the division is triggered by an update or a new release for Windows / Linux users, and is overseen through a software project. Additional services are also delivered based on a formal request by the customer for training on the use of tools and technical support.

Delivery information flow for **Company B** begins with a press release that instructs internal customers (i.e. field application engineers) to access and download releases via a webpage. Information on access and downloads are also tracked, and a support database captures enquiries from webpage visitors for use in enhancing delivery through improving access to releases, planning future updates and providing services. Initial feedback is provided via email by field application engineers to customers and engineers to field application engineers within 2 days. And enquires are resolved also via email within 10 days by engineers involved in the project. In non-trivial cases, conference calls are organised with customers for improved flow of information in scenarios that are not effectively handled by emails.

Figures 5-1 to 5-3, Figures 5-4 to 5-6 and Figures 5-7 to 5-9 show the design structure matrices, data flow diagrams and information channel diagrams created from the case studies.

	Request product	Acknowledge order	Notify team	Notify director	Update record	Agree material	Agree consumables	Order material	Order consumables	Produce design	Deliver design	Request clarification	Clarify design	Update records	Update design	Approve order	Prepare product	Dispatch product	Confirm dispatch	Request feedback	Confirm receipt	Request service	Agree service	Provide service
Request product		X																						
Acknowledge order	X																							
Notify team		X																X	X			X		
Notify director		X			X													X	X			X		
Update record			X								X	X	X		X			X	X	X	X	X		X
Agree material				X				X		X	X	X	X									X		
Agree consumables				X	X	X			X	X	X	X	X									X		
Order material						X			X							X								
Order consumables							X									X								
Produce design				X				X	X		X	X	X	X								X		X
Deliver design										X			X	X			X					X		
Request clarification			X		X								X											
Clarify design								X	X	X		X			X	X				X		X		X
Update records			X	X		X	X				X	X	X		X	X	X	X	X		X	X	X	X
Update design										X	X	X	X				X				X	X	X	
Approve order								X	X		X		X										X	
Prepare product											X		X	X	X	X						X		
Dispatch product																	X							
Confirm dispatch																	X	X		X				
Request feedback																	X	X	X			X		
Confirm receipt																			X	X				
Request service																				X	X		X	
Agree service																				X		X		X
Provide service																							X	

Figure 5-1: Design structure matrix for delivery information flow at Company A

	Upload int_release	Promote int_release	Assess page	Identify int_release	Download int_release	Develop ext_release	Upload ext_release	Notify customer	Assess page	Identify ext_release	Download ext_release	Request training	Forward request	Plan training	Deliver training	Request support	Filter request (1st line)	Resolve issue	Update customer	Forward request (2nd line)	Provide feedback	Resolve issue	Update customer
Upload int_release		X	X		X																		
Promote int_release	X			X		X								X									
Assess page		X		X																			
Identify int_release			X																		X		
Download int_release			X	X																			
Develop ext_release		X			X		X									X		X					X
Upload ext_release						X		X	X														
Notify customer	X					X	X												X				X
Assess page								X		X	X												
Identify ext_release								X	X		X								X		X		
Download ext_release								X	X	X													
Request training										X	X												
Forward request												X											
Plan training													X		X							X	
Deliver training		X											X	X									
Request support								X	X	X	X												
Filter request (1st line)												X				X		X	X	X			X
Resolve issue																	X		X				
Update customer																		X					
Forward request (2nd line)																X	X						
Provide feedback												X			X					X			
Resolve issue																					X		X
Update customer																					X	X	

Figure 5-2: Design structure matrix for delivery information flow at Company B

	Plan project	Produce design	Deliver design	Request clarification	Clarify design	Confirm design	Prepare product	Notify customer	Prepare Delivery_note	Dispatch product	Send confirmation	Send user_guide	Confirm receipt	Plan training	Deliver training	Request feedback	Request service	Plan service	Deliver service
Plan project																			X
Produce design	X			X														X	
Deliver design		X		X															
Request clarification		X	X		X														
Clarify design		X		X		X	X												
Confirm design			X		X			X											
Prepare product		X							X										
Notify customer						X				X	X								
Prepare Delivery_note							X												
Dispatch product								X	X		X								
Send confirmation									X	X		X	X			X			
Send user_guide										X			X						
Confirm receipt											X	X				X			
Plan training	X														X	X		X	
Deliver training														X			X		
Request feedback											X	X	X		X				
Request service																X		X	X
Plan service	X														X		X		X
Deliver service																	X	X	

Figure 5-3: Design structure matrix for delivery information flow at Company C

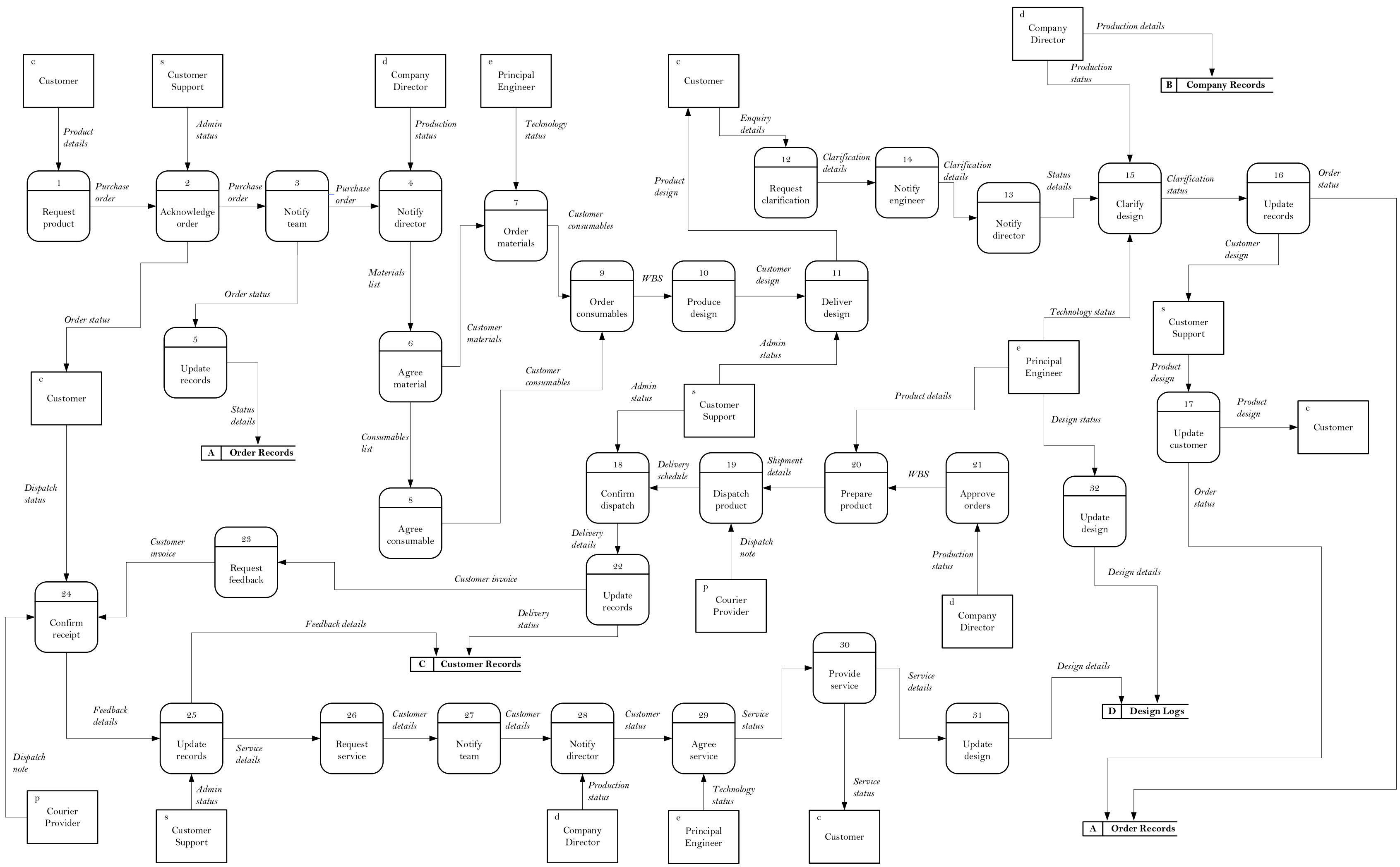


Figure 5-4: Data flow diagram for delivery information flow at Company A

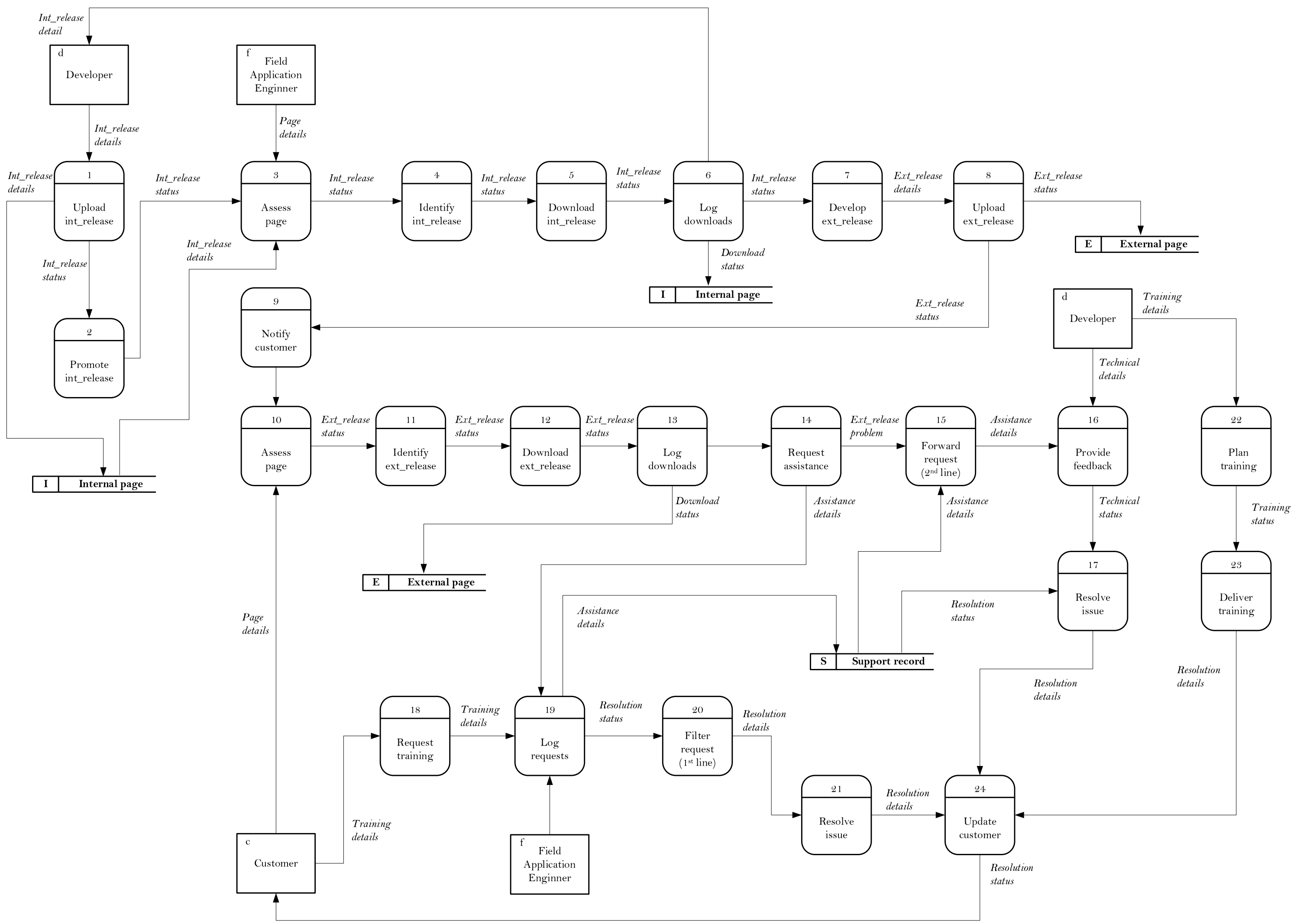


Figure 5-5: Data flow diagram for delivery information flow at Company B

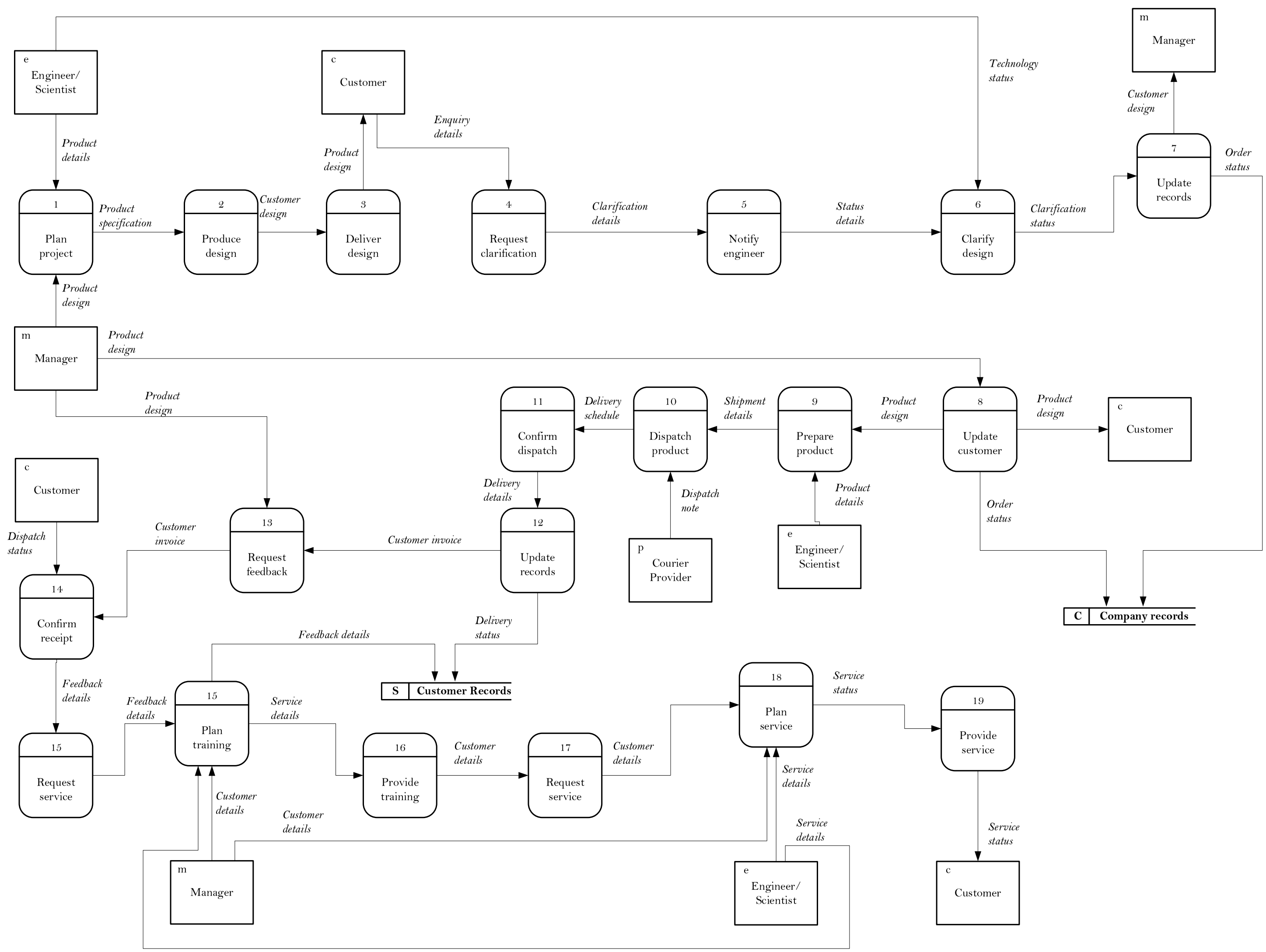


Figure 5-6: Data flow diagram for delivery information flow at Company C

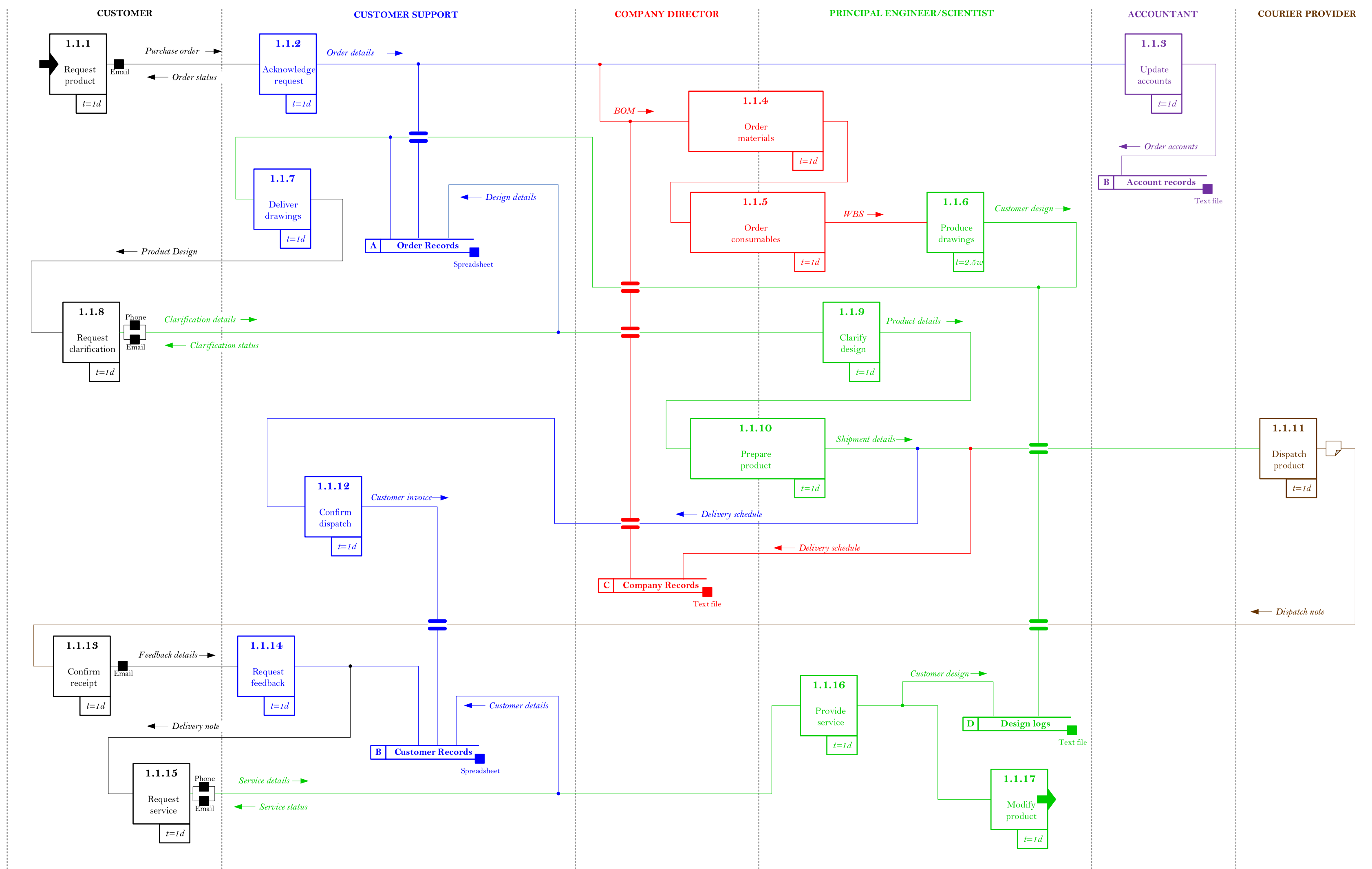


Figure 5-7: Information channel diagram for delivery information flow at Company A

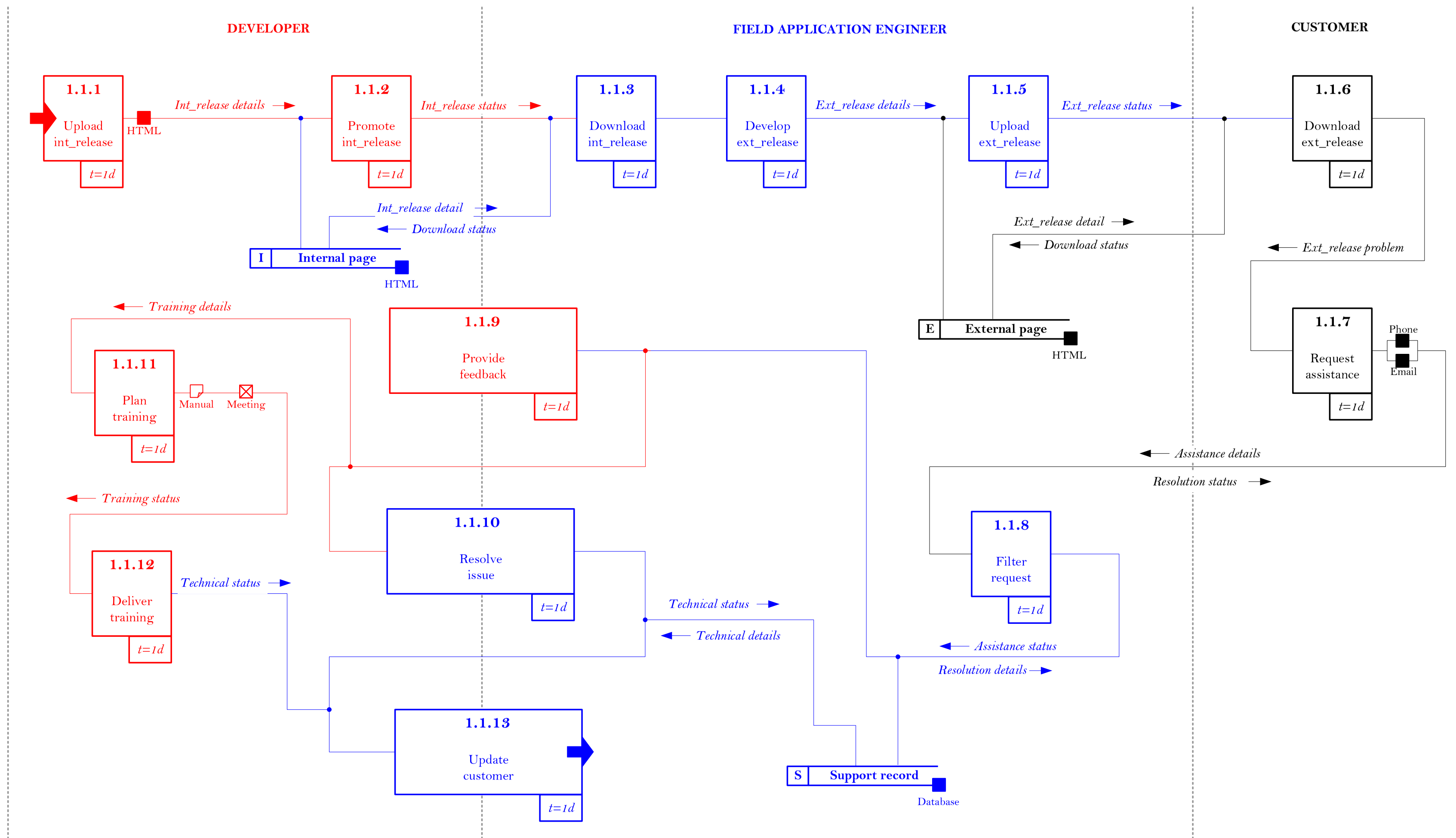


Figure 5-8: Information channel diagram for delivery information flow at Company B

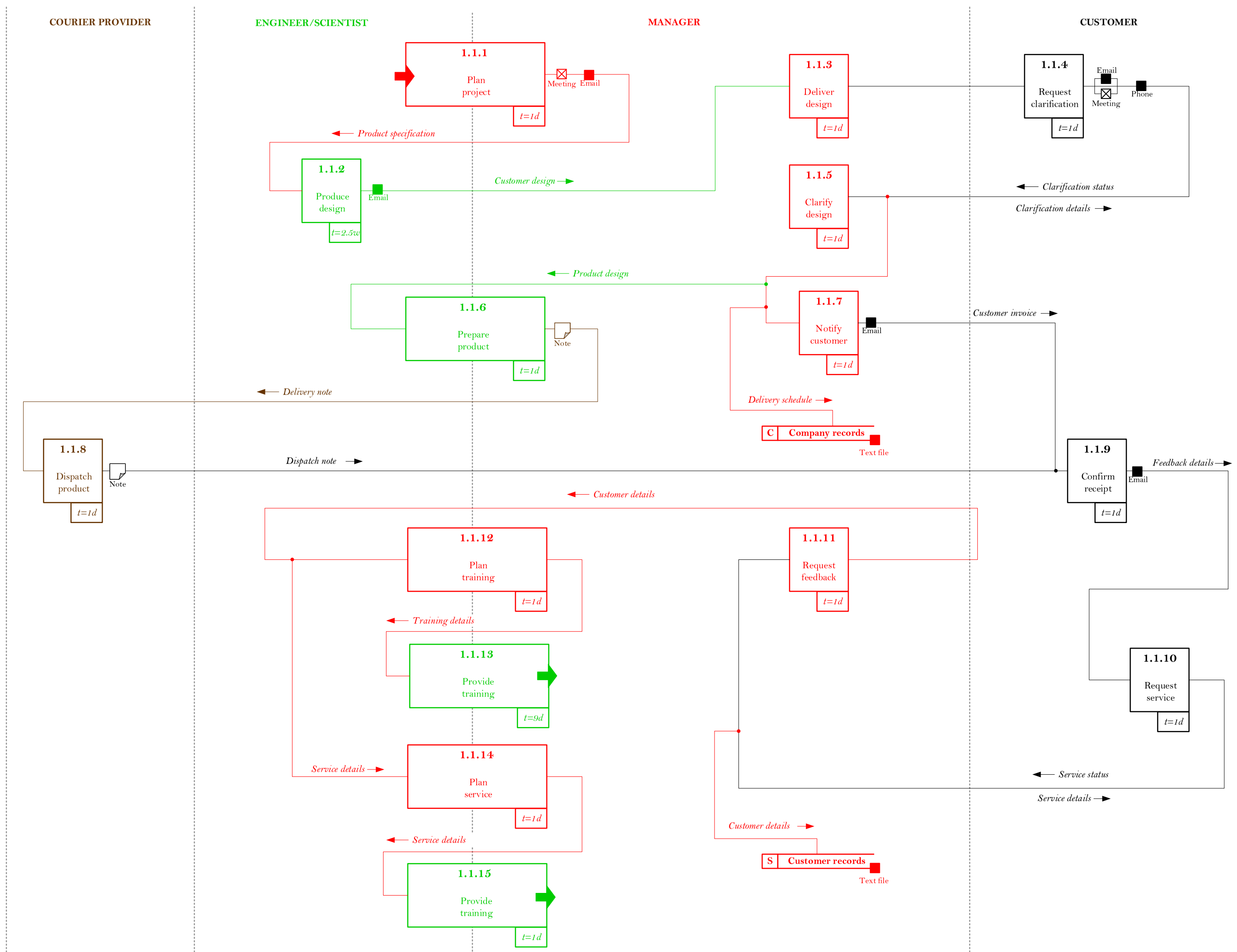


Figure 5-9: Information channel diagram for delivery information flow at Company C

5.1.2. Comparison of approaches to modelling delivery information flow

In all cases (the companies where the interviews were conducted - **Company A**, the software division at **Company B** and **Company C**), the study revealed that the ICD scored highest in participant responses to questions regarding the ability of tools to represent MST delivery information flow, as shown in Figure 5-10a. The scoring system at each company, calculated as a fraction of 54, is based on responses to 9 questions by six participants from each company i.e. 6 participants × 9 questions = 54. This number represents the total number of possible responses from each company for each compared tool. For instance, in 'Responses from Company A' in Figure 5-10a, the blue bars represent the number of times the participants at **Company A** selected the ICD in response to the questions posed in §3.3.4.2, numbered 1 to 9. As shown in the figure, 6 participants selected the ICD for 6 questions (1 to 6), 5 participants chose the ICD for 2 questions (7 and 9), and 4 participants chose the ICD for 1 question (8) i.e. (6×6) + (5×2) + (4×1) giving a score of 50/54 for the ICD at **Company A**.

At **Company A**, where designers and engineers are allowed to make use of intuitive and individual approaches, ICD scored 50/54, DFD scored 16/54, and DSM scored 4/54.

For **Company B** where the DFD is used in software design, ICD was selected for each of the 9 questions posed to each of the 6 participants from **Company B** – giving the ICD a score of 54 out of a possible 54 times. DFD scored 18/54 whereas DSM scored 3/54. **Company C** had previously used DFD and DSM approaches and the responses of participants revealed that ICD scored 42/54, DFD scored 20/54, and DSM scored 4/54.

The study showed that for questions 3 (can multiple communication channels during delivery be identified?), 4 (can the timing of delivery processes be identified?) and 6 (can the synchronisation of communication channels during delivery be identified?) only the ICD was selected by participants as capable of representing what was required.

For the two additional questions posed to participants regarding the ability of the tools to capture delivery information flows and which tools participants would consider using, the study also revealed that the ICD scored highest in two (**Company A** and **Company B**) out of the three participating companies, as shown in Figure 5-10b. In the third company (i.e. **Company C**), the ICD tied with the DFD approach.

(a) Questions on ability of tools to represent MST delivery information flow

(b) Additional questions on ability of tools to capture delivery information flow and user preference

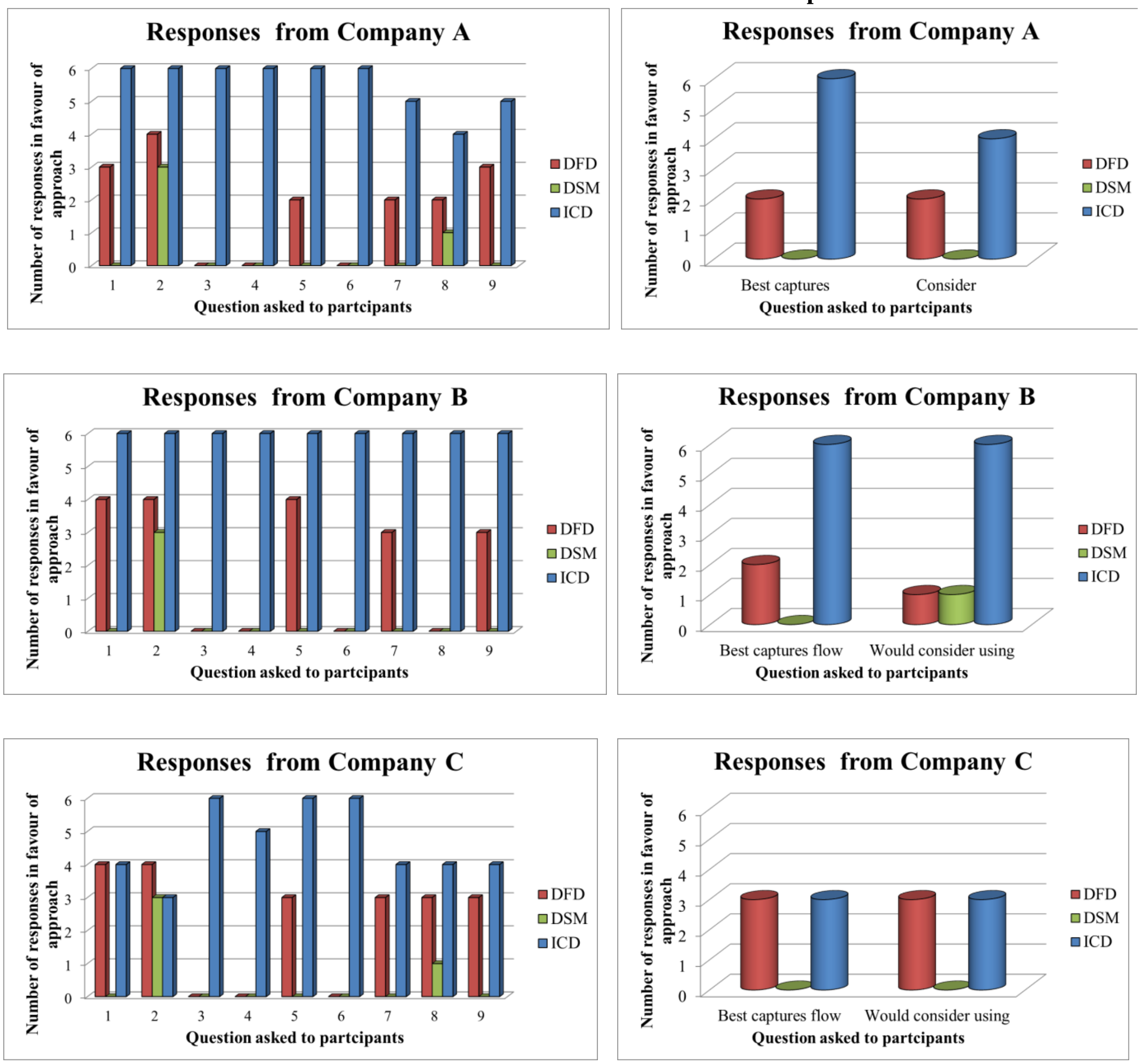


Figure 5-10: Findings from comparison of approaches to modelling delivery information flow

5.1.3. Comments during the empirical inquiry

During the empirical inquiry, participants made comments on attributes (positive and negative) of the approaches being compared. These comments are presented in Table 5-1.

Table 5-1: Comments by participants on attributes of data flow diagram (DFD), design structure matrix (DSM) and information channel diagram (ICD).

Participant	*Attributes of DFD*	*Attributes of DSM*	*Attributes of ICD*
Aa	Describes flow (+)	Describes flow (+) Complex to use (-)	Describes flow (+) Unsuitable for manufacturing process flow (-)
Ab	-	-	The use of colour improved representation (+)
Ac	-	Unsuitable for delivering presentations (-)	Clear demarcation of roles (+) Represents media forms (+)
Ad	Serial representation (+)	Complex representation (-)	Distinction between roles (+) Colour improved clarity (+)
Ae	Duplication of entities can be confusing (-)	Difficult to follow (-) Not enough detail (-)	Clarifies roles (+) Not suitable for backend process modelling (-)
Af	Depicts flow (+)	Depicts flow (+) Absence of roles (-)	Depicts flow (+) Colours enhance depiction (+)
Ba	Easy to follow flow (+)	Difficulty in understanding information flow path (-)	Easy to follow flow (+) Colour improved clarity (+)
Bb	Presents flow as a sequence (+)	Easy to program (+) Difficult to establish context (-)	Clear demarcation of roles (+)
Bc	-	-	Easy to establish staff responsibility (+)
Bd	-	Difficult to follow (-)	-
Be	-	-	Colours proved attractive for improving representation (+)
Bf	Serial representation (+)	Compact representation (+) Complicated to use (-)	Captures business flow (+)
Ca	Depicts flow as a sequence (+)	Compact representation (+)	Separation of roles (+)
Cb	Absence of process time (-)	Complicated to follow (-)	Useful role distinction (+)
Cc	Serial representation (+)	-	-
Cd	Easy to follow flow (+)	Compact representation (+)	Colour improved clarity (+)
Ce	-	No entities (-)	Colours enhance depiction (+)
Cf	-	-	Depicts process times (+) Clarifies roles (+)

(+) denotes positive attribute (-) denotes negative attribute

For the DFD, the main positive attribute was serial representation that made the flow of information easy to follow. Negative attributes of the DFD noted by participants included the absence of process times for establishing the duration of tasks and the duplication of entities in produced diagrams.

In the case of the DSM, participants responded negatively towards the tool with major difficulties in establishing the path for information flow and context for feed forwards and feedbacks of information. An absence of entities or roles and insufficient level of detail was also a negative attribute of the DSM noted by participants.

However, participant commented positively on the ease with which the flow captured by the DSM can be converted into a software code (i.e. programmability) and the compact representation of the DSM.

For the ICD, the main positive attribute was the ability of the tool to clarify flow depiction through the use of colour and the distinction/demarcation of roles and jobs through the use of swim-lanes. Other positive attributes of the tool commented on by participants included the depiction of process times for capturing task durations and the depiction/description of media forms for capturing the types of information content. Participants also commented on the unsuitability of the ICD to model backend tasks and interactions such as manufacturing and assembly.

Participants also made comments on the presentation of diagrams and considerations for modelling information flow. These comments are presented in Table 5-2 and are described in more detail in the following subsections.

Table 5-2: Comments by participants on the presentation of diagrams and considerations for modelling information flow.

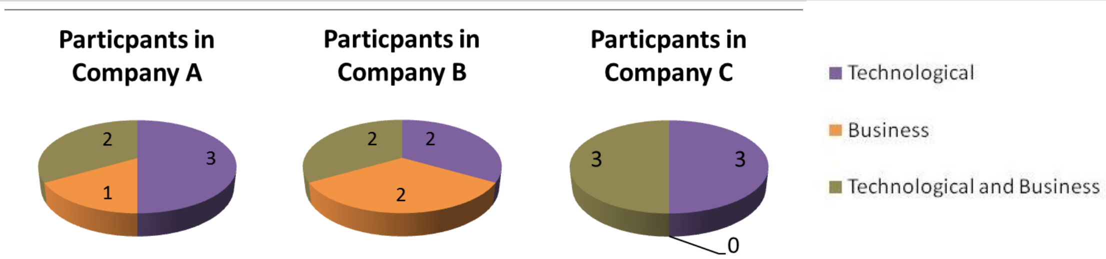
Participant	*Diagram presentation*	*Modelling considerations*
Aa	Minimise clutter	-
Ab	Simplicity in representation.	-
Ac	-	-
Ad	Distinction between business and technological content	-
Ae	-	-
Af	-	Establish if staff will use model
Ba	Strive for minimal clutter	Level of complexity of concepts
Bb	Ensure they are reflective of the actual flows within the organisation	Level of system implementation
Bc	-	Adopt tools on a case-by-case basis
Bd	-	-
Be		Assess significance of colours
Bf	-	Distinction between front- and back-end processes
Ca	Simplify as much as possible	Strive a balance in the use of primitives

Cb	Avoid clutter	Categorisation of information
Cc	-	Differentiate front- and back-end interactions
Cd	-	Responsibility for creating models
Ce	-	-
Cf	-	-

5.1.3.1. Information classification dichotomies

As shown in Table 5-2, participant Cc and Bf noted that interactions involving information flow with customers and staff can be modelled according to *frontend flows* for administrative, accounting, distribution and sales functions and *backend flows* for design, manufacturing and technical service functions. Similarly the technological /business distinction of content, as noted by participant Bd, is important in maintaining the day-to-day operations of MST companies. Business content relate to data from frontend interactions whereas business content is associated with backend interactions. In addition, an analysis of the roles of participants, as shown in Figure 5-11, suggests a split according to dichotomies of frontend vs. backend interactions, and technological vs. business data content.

(a) Information handled by participants according to technological versus business data content



(b) Information flows involving participants according to backend versus frontend interactions

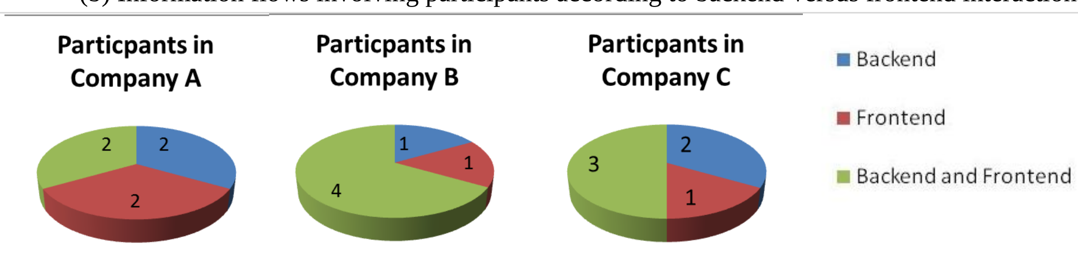


Figure 5-11: Information classification dichotomies for case study participants

5.1.3.2. Colour coding effectiveness

The use of colour in modelling was favoured by participants Ba, Be, Ab, Ad, Af, Cd and Ce of the study, as shown in Table 5-1. Colours improve visual perception and within the ICD use of colours also reinforces the role of personnel. Participants however cautioned on the use of colour because individual colours could symbolise different properties and may have different roles in other tools used by engineers and scientists. For instance, the colour red as noted by participant Be could be perceived as important roles or associated with critical tasks such as in the project evaluation and review technique.

5.1.3.3. Simplification of information

Within the study, participants identified simplification as an important factor in the presentation of information content and means for communication. Participants Ba, Be, Aa, Ad, Ac, Ca, and Cb emphasised that models must be free of clutter and simplified as much as possible if they are to be useful. However, this conflicts with the findings of the comparison in §5.1.2 where the DSM, a tool that was conceived to minimise clutter (Michael and Massey, 1997), scored lowest among the compared tools. Comments by participants offered clues to this contradictory finding. Firstly, participants noted that although the compactness of the DSM makes it simple, the tool lacks enough primitives to characterise 'what was going on'. Secondly, the DSM according to participant Ba, Bd, Ae and Cb, is difficult to understand and follow.

5.1.3.4. Case-by-case tool use

As shown in Table 5-2, participants Ba, Bb, and Bc also noted that in day-to-day operations, the choice and use of models must be based on a case-by-case basis depending on the level of complexity of concepts and system implementation. This is because the compared tools (DFD, DSM and ICD) all depict the flow of information in different ways. Furthermore, in practice, groups (such as manufacturers) or users (such as customers) are typically only concerned with some aspects of the information model. This supports the idea that an all-encompassing information model is unnecessary and impractical for designers (Scheller, 1990).

5.2. Evaluation of the intra-organisational collaboration model

An aggregation of the social networks made up of 14 staff and the activity network consisting of 19 (.01-.19) processes described by the customer support manager at **Company A** (that was validated by the participants of the face-to-face interviews) resulted in the information structure for **Company A**, as shown in Figure 5-12. Activity vertices .01 (request product), .10 (request clarification), .15 (confirm receipt) and .17 (request service) are carried out by the customer whereas .13 (dispatch product) is the responsibility of the courier provider. For collaboration within **Company A**, the 14 available staff i.e. the social vertices A1-A14, are connected to the remaining 14 processes through 57 internal interface links.

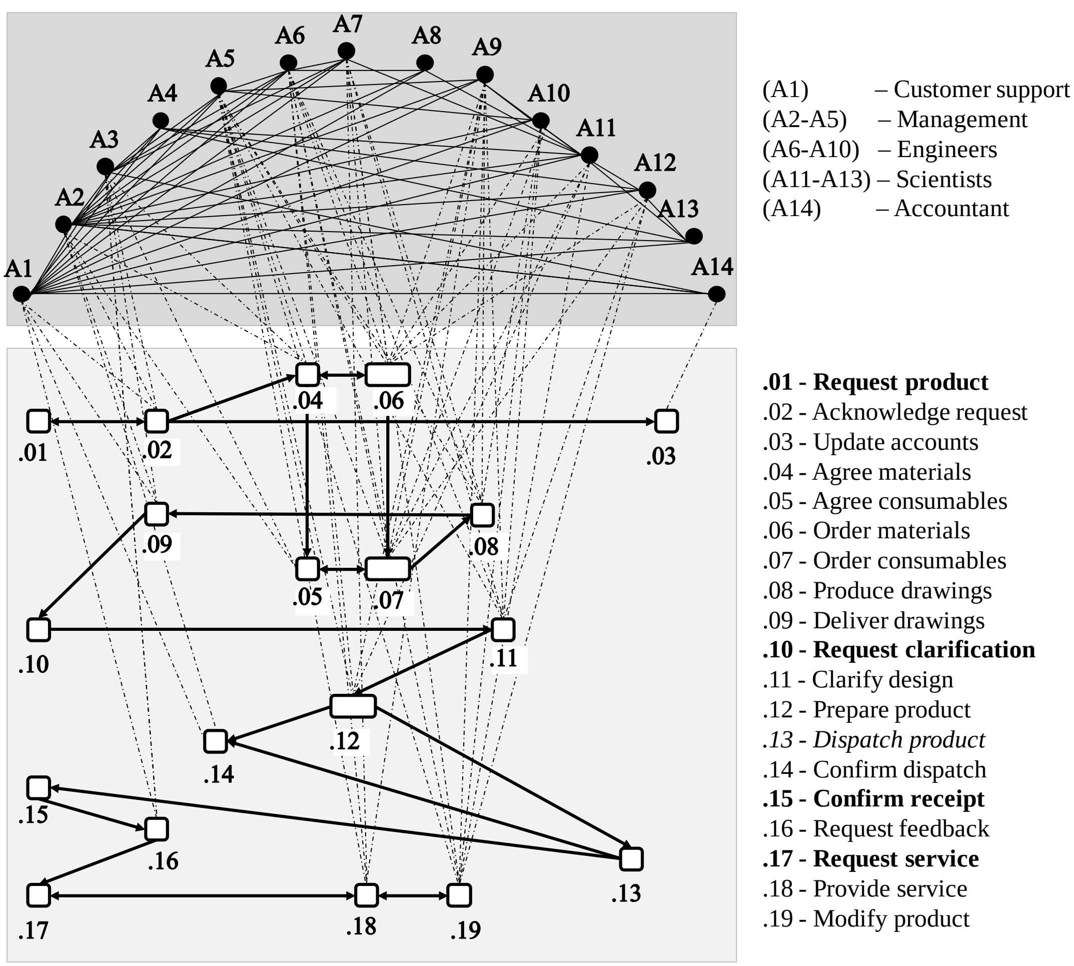


Figure 5-12: Information structure for Company A

Management processes, associated with social vertices A1 and A2-A5, form a subset of V_p consisting of vertices .02 (acknowledge request), .09 (deliver drawings), .14 (confirm dispatch) and .16 (request feedback). Similarly, engineering and science processes, associated with social vertices A6-A10 and A11-A13, form a subset of V_p involving activity vertices .04 (agree materials), .05 (agree consumables), .06 (order materials), .07 (order consumables), .08 (produce drawings), .11 (clarify design), .12 (prepare product), .18 (provide service) and .19 (modify product). The accounting process associated with A14 is activity vertex .03 (update account).

Within **Company B**, the IOC information structure was evaluated using members of a group working on a project, as shown in Figure 5-13. The social network of **Company B** is made up of 11 staff: 7 developers (B1-B7) and 4 field application engineers (B8-B11. The activity network is made up of 13 processes (.01-.19).

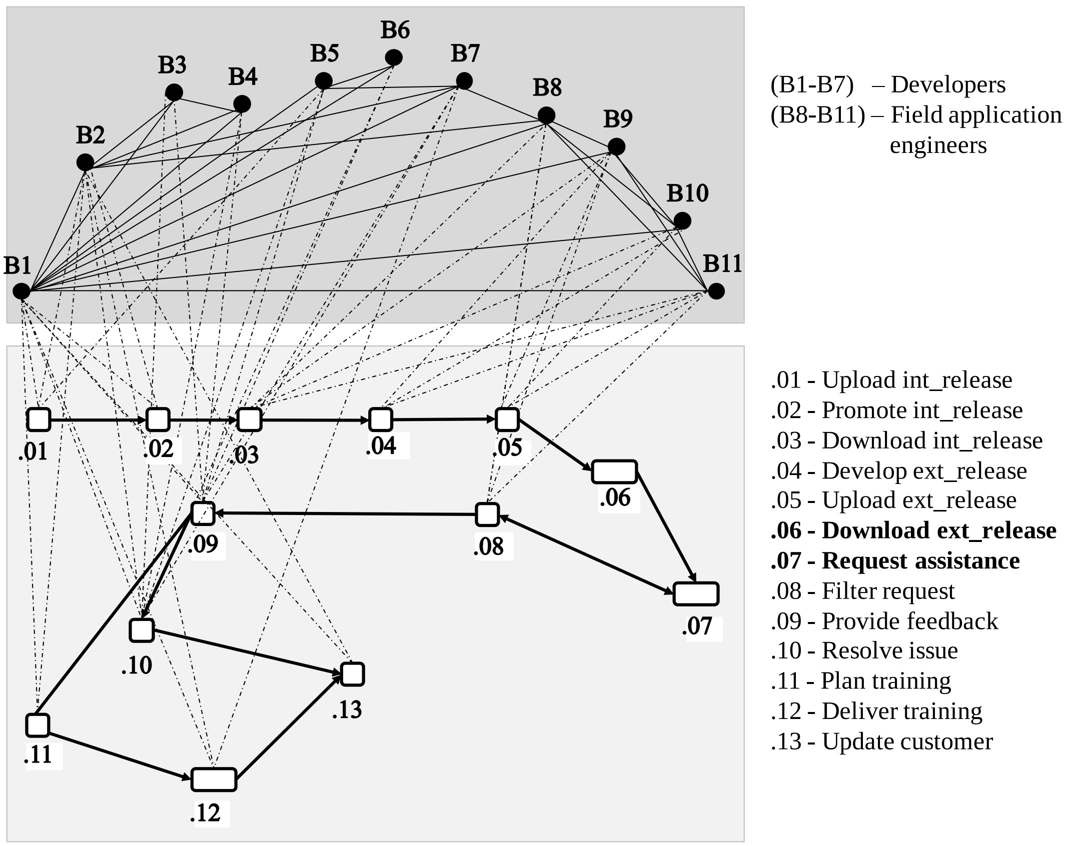


Figure 5-13: Information structure for Company B

For **Company C**, the IOC information structure was evaluated using the group within the business that delivers microfluidic solutions. This group was made up of 5 staff: 1 manager (C1), 2 engineers (C2-C3) and 2 scientists (C4-C5), as shown in Figure 5-14. The IOC information structure of is characterised by 15 processes (.01-.15).

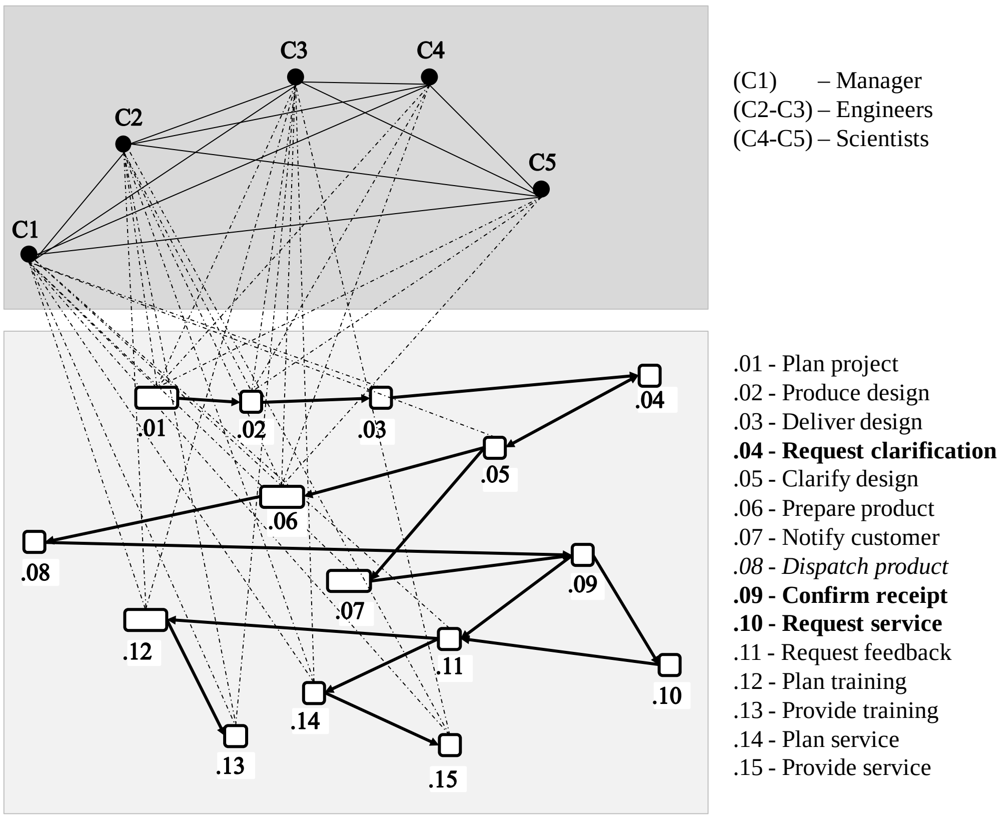


Figure 5-14: Information structure for Company C

Collaborative indicators for the social vertices in **Company A**, **Company B**, and **Company C** have been computed using the approach outlined in §4.3.3 and are shown in Table 5-3, 5-4 and 5-5 respectively.

Table 5-3: Collaboration indicators for Company A

Social vertices	Teamwork scale	Decision-making scale	Coordination scale
A1	1.593	0.670	0.651
A2	1.593	0.670	0.688

A3	1.593	0.670	0.688
A4	0.692	0.281	0.239
A5	0.824	0.338	0.613
A6	0.813	0.327	0.538
A7	0.549	0.212	0.426
A8	0.549	0.212	0.202
A9	0.692	0.281	0.501
A10	0.692	0.281	0.426
A11	1.505	0.654	0.613
A12	0.692	0.281	0.388
A13	0.692	0.281	0.239
A14	0.264	0.076	0.163

Table 5-4: Collaboration indicators for Company B

Social vertices	Teamwork scale	Decision-making scale	Coordination scale
B1	1.603	1.436	1.418
B2	0.746	0.902	1.029
B3	0.569	0.796	0.726
B4	0.569	0.796	0.726
B5	0.556	0.783	0.786
B6	0.405	0.705	0.668
B7	0.759	0.915	0.846
B8	0.997	1.022	0.906
B9	0.759	0.915	0.906
B10	0.759	0.915	0.846
B11	0.759	0.915	0.906

Table 5-5: Collaboration indicators for Company C

Social vertices	Teamwork scale	Decision-making scale	Coordination scale
C1	2.000	2.000	1.500
C2	2.000	2.000	1.194
C3	2.000	2.000	1.194
C4	2.000	2.000	0.900
C5	2.000	2.000	0.900

In Table 5-6 the average values for collaboration indicators of **Company A**, **Company B**, and **Company C** are summarised and compared.

Table 5-6: Comparison of collaboration indicators for case studies

	Case study companies		
	Company A	**Company B**	**Company C**
Overall vertices ($\|V'\|$)	22	27	16
Overall activity vertices ($\|V_p\|$)	11	13	11
Overall social vertices ($\|V_s\|$)	11	14	5
Average teamwork scale	**0.771**	**0.911**	**2.000**
Average decision-making scale	**0.918**	**1.056**	**2.000**
Average coordination scale	**0.887**	**0.900**	**1.138**

The average values of the studied companies suggest significant levels of collaboration within the companies correlating with existing studies in which it is suggested that small and medium enterprises (SMEs) within high-tech firms, such as organisations delivering MST, are effective at working together for innovation (Trumbach *et al*., 2006).

5.3. Summary

In this chapter, case studies involving three United Kingdom based microsystems technology (MST) companies to evaluate and validate the proposed technique of Chapter 4 were described. The evaluation of the intra-organisational collaboration (IOC) model involved an assessment of social vertices (i.e. participants in collaborations) using the proposed information structure and collaboration indicators. The validation of the information channel diagram (ICD) tool involved comparing it with data flow diagrams and design structure matrices created in an empirical study of delivery information flow in the three MST companies. The study also suggested that the ICD was the tool identified by participants as suitable for depicting communication channels and delivery timing of delivery processes. Insights from the case studies supported suggestions that high-tech small and medium enterprises (SMEs) can be effective at collaborating for delivery. Participants also made four main recommendations for improving information flow modelling: identifying dichotomies for information classification, effectiveness of colour coding within diagrams, simplification of information content and communication, and case-by-case use of tool during modelling.

Chapter

6

DISCUSSION

The following sections present a general discussion of the key observations from the four main phases of the research, i.e. literature review, industry scope, proposed technique and case studies, as identified in §1.5. Each phase is discussed in terms of the main findings and specific insights offered by this research. The chapter also describes the applications and limitations of the technique proposed in Chapter 4.

6.1. KEY OBSERVATIONS

In this section, key observations from the research are highlighted in terms of the literature review, industry scope, proposed technique and case studies.

6.1.1. Literature review

The literature review covered in Chapter 2 concentrated on identifying existing techniques and tools for modelling information flow in organisations. It outlined the purpose, approaches and applications of diagrammatical and mathematical information flow modelling for organisations. Key diagrammatical tools for modelling information flow were compared and contrasted based on their origin, concept and applications. The main tools investigated were data flow diagrams (DFDs), Integrated DEFinition method of modelling functionality and information modelling (IDEFØ and IDEF1), Graphes à

Résultats et Activités Interreliés (GRAI) grids and nets, Petri nets, Input-Process-Output diagrams and design structure matrices (DSMs). Key mathematical techniques for modelling information flow through the use of flow and organisational analysis were also identified. The chapter also identified probability theory and more recently, network theory, as research areas currently exploring mathematical analysis particularly for modelling information flow for 'organisations as networks'. The chapter also identified research gaps based on the review of literature with regards to the need for an analysis of delivery information flow characteristics and the need to explore the suitability and selection of models for information flow.

6.1.2. Industry scope

Concentrating on the research gap to analyse characteristics of delivery information flow requirements, an industry scope was established based on two empirical studies: an industry survey of 100 companies and an exploratory study involving 3 MST companies, as presented in §3.2.

The industry survey (§3.2.1) was carried out to capture industry practice in the use of modelling tools by organisations delivering MST. The study was based on a sample of 100 MST foundries, manufacturers, computer-aided design (CAD) developer, intellectual property (IP) companies, consulting firms and distributors within Europe, North America and Asia. The findings from 40 respondents to the survey revealed that of the tools reviewed in Chapter 3 only DFDs and DSMs have been used by organisations delivering MST. The study also showed that collaboration was the most important characteristics for MST firms as suggested by 90.0% of the survey respondents.

The exploratory study (§3.2.2) investigated information flow during the delivery phase of 3 real-life MST companies through a model that captured the various dimensions of information flow namely information access, information exchange and documentation. The industry scope established by the studies showed that modelling information flow, a challenge for delivery performance, requires an understanding of nine characteristics: the roles of company personnel, information flow path, availability of multiple channels of communication, timing of processes, collaborative processes, ability to synchronise communication channels, harmonisation of internal and external flows, contextualising information and information sharing.

6.1.3. Proposed technique

Centred on the need to explore the suitability and selection of models for information flow during the delivery phase, a technique for modelling information flows during the delivery phase of MST organisations was proposed, in Chapter 4.

As a first step towards the proposed technique, a diagrammatical tool, the information channel diagram (ICD), was proposed as a set of diagrammatic primitives and modeling methodology, as presented in §4.2. The section evaluates the tools reviewed in Chapter 3 (DFDs, IDEFØ and IDEF1, GRAI grids and nets, PNs, IPO diagrams and DSMs) against the delivery phase information flow characteristics outlined in §3.2.3. Motivated by the inability of individual existing tools to fully represent these characteristics, the ICD approach was proposed as a set of primitives as follows: *swim-lanes* to represent roles during interactions, *lines* to depict process links, *arrows* to show information flow, *rectangles* to show (individual and collaborative) processes and process times, *varied squares* to illustrate communication channels (face-to-face interactions, paper documentation and, information and communication technologies), and *open ended rectangles* tagged with squares to depict information sharing. Coloured links and arrows are also used to depict how information flow can be contextualised. A prescribed set of steps based on diagrammatic composition is also proposed. In this methodology diagrammatic primitives are increasingly added to populate the information flow model in four main steps that depict roles, position processes, introduce flow links and represent communication channels.

Next, a mathematical analysis technique, based on complex networks (a key and current area of research for modelling information flow) was proposed in terms of topologies, vertices and edges, as described in §4.3. The section adapted current approaches to analysing the complex networks of social interactions (i.e. social network analysis (SNA)) for the development of an intra-organisational collaboration (IOC) model of organisational networks. The IOC model that was developed through: (i) combining social and activity networks for defining an organisation's information structure and (ii) proposing indicators that assess the information behaviour of social vertices in terms of coordination, decision-making and teamwork. Social networks consist of human actors (defined by swim-lane roles of the ICD) within the IOC and are based on topologies that foster dictator, mutual and exclusive collaboration. The activity network consists of processes (represented as rectangles in the ICD) and is based on the activity-on-node (AON) of the widely used Project Evaluation and Review Technique (PERT) and critical path method (CPM). Coordination, decision-making and teamwork scales are indicators within the IOC model that are realised as sums of clustering coefficient, closeness and degree centrality values. These values are derived from SNA and reflect interconnectedness within groups, individual connections for relationships and activity of individuals

6.1.4. Case studies

The case studies outlined in Chapters 5 concentrate on evaluating/validating the use of the proposed technique within the 3 MST companies used to establish the industry scope.

In §5.2, the ICD was used to model real life-scenarios for delivery within 3 MST companies. DFDs and DSM (existing tools used by MST firms as revealed by the industry survey in §3.2.1) were also created from the scenarios and compared against the ICD through a questionnaire that assessed the ability of the tools to model delivery phase information flow characteristics outlined in §3.2.3. In §5.3, instances of the IOC model was created and evaluated with a view to analysing the level of collaboration. The validation revealed that in all 3 companies the ICD was favoured by 18 participants as a suitable tool for representing MST delivery information flow. Furthermore, 83.3% (15 out of 18) selected the ICD as the tool that best captures delivery information flow against the DFD chosen by 38.9% (7 out of 18). None of the participants chose the DSM.

6.2. Applications of the proposed technique

This section highlights and discusses some applications of the proposed model in terms of the: (i) ICD tool for delivery information flow management and role definition, and (ii)

IOC model for enhancing the quality and sharing of information within organisations and for analysing roles for communication during collaboration.

6.2.1. Delivery information flow management and role definition

Within an ICD, where possible, the manager of delivery information flow (for which the ICD is proposed) must be positioned centrally to distinguish external and internal information flows. It is for this reason that the creation of an ICD begins with the depiction of the role of the 'information flow manager' such as information professionals (Hibberd and Evatt, 2004), web masters (Van Der Walt and Van Brakel, 2000) and chief information officers (Gottschalk, 2002).

Flow management for information exchanges with customers located to the right of the information flow manager, as shown in §4.2.3, could then be analysed for managing and improving customer service. Internal information exchanges with staff to the left of the information flow manager could also be analysed for defining control policies such as delivery data storage/ privacy and information sharing.

Using the ICD approach, the roles of staff could be defined for delivery tasks that are allocated in relation to organisational structures such as: management information systems, communication channels, delivery networks, business processes, databases and decision support system. These structures could be particularly useful for defining the physical layout in modern organisations by illustrating roles that require interactions and access to common delivery information. The illustration of roles could then be used as a guide in the positioning of organisational departments

6.2.2. Enhancing information quality and sharing

Information quality describes the free flow of information within an organisation whereas information sharing is a factor of information flow that describes the joint use of critical and proprietary information that could be generic (inventory control policies) or specific (weekly manufacturing schedule) in nature (Durugbo *et al.*, 2010b).

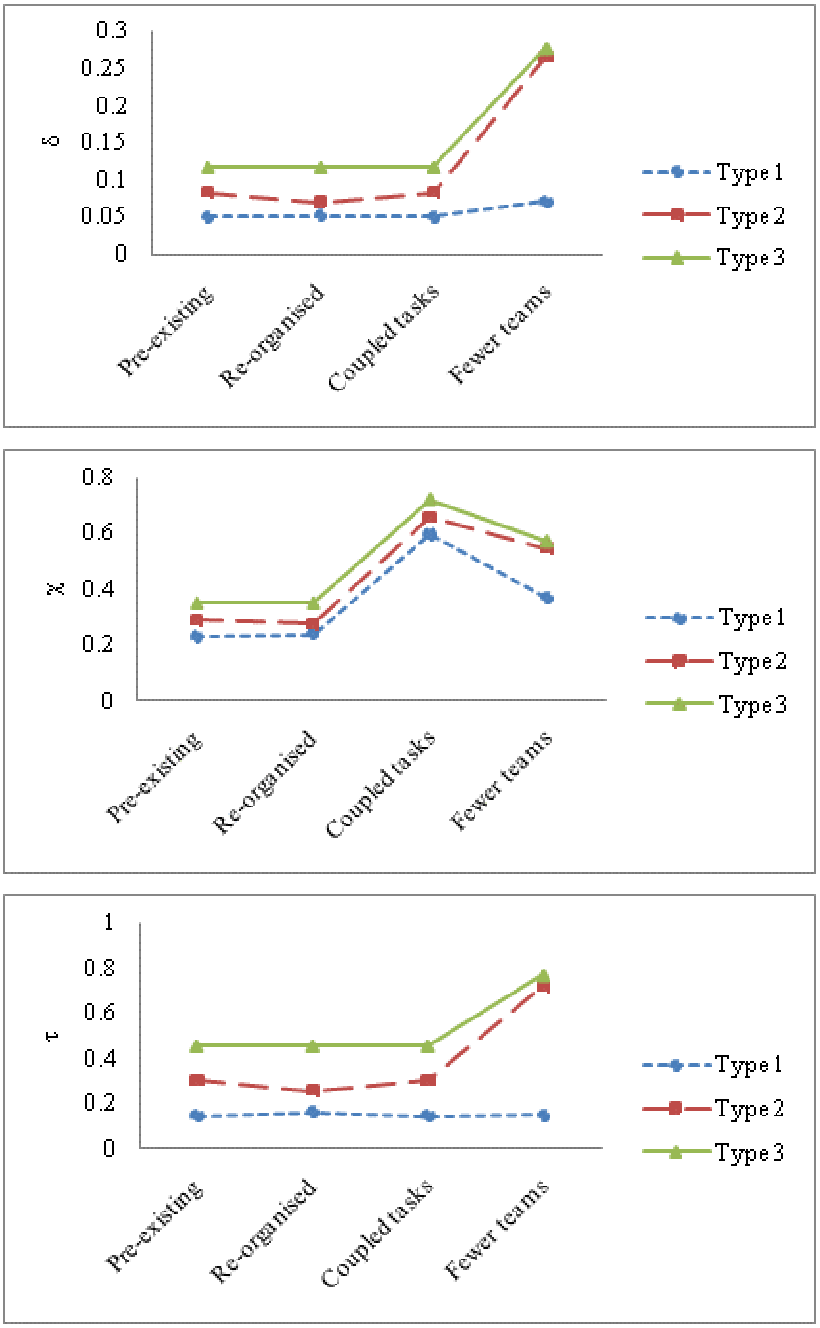
In terms of enhancing information quality and sharing, the proposed model can be used to plan the configuration of organisations through the identification and selection of suitable collaboration topologies. Possible configurations such as those identified in §4.3.1 could be generated and collaboration indicators such as those proposed in §4.3.2 may then be used to analyse potentials for collaboration. This is typical of network analysis techniques that explore the paradox of peripherality versus centrality of actors in an organisation (White, 2008).

For the case scenario of the intra-organisational collaboration for product development (IOC-PD) presented in §4.3.3, the type 3 configuration scored highest in terms of potentials for teamwork, decision-making and coordination with τ, δ, and χ values of 0.4526, 0.1165 and 0.3513 respectively, as shown in Table 4-4. However, the reorganised information flow for the type 3 configuration failed to improve the collaboration indicators. Rather, the coordination degree decreased by a value of 0.0003 (-0.85%). In contrast, the generated values for τ, δ, and χ in the type 2 configuration decreased by 0.0458 (-15.21%), 0.014 (-16.91%) and 0.0145 (-5.02%) respectively.

For the type 2 configuration in §4.3.3, the results of comparing the pre-existing and re-organised information flow showed that generated τ, δ, and χ values increased by 0.0173 (+12.08%), 0.0022 (+4.39%) and 0.0075 (+3.27%) respectively.

The managerial implication of the results is that enhancements to information flow must be driven by an analysis of the initial configuration of organisations. In practice, the configuration of an organisation may involve a combination of all the topologies identified in §4.3.2. An initial analysis of the organisation's topology is therefore required prior to reorganisation. For instance, managers could decide to change an organisation's topology from a type 1 to a type 3 configuration. Alternatively, strategies for improving information flow could be investigated and analysed. Using the proposed model for instance, alternative structures for social and activity vertices can be applied to improve intra-organisation collaboration as shown by the plots[8] in Figure 6-1. Figure 6-1a depicts a chart of the average decision-making scales, Figure 6-1b shows the average coordination scales, and Figure 6-1c presents the average teamwork scale chart.

[8] Calculations for deriving these plots are presented in Appendix D



(a) Decision-making scales

(b) Coordination scales

(c) Teamwork scales

(δ = average decision-making scale, χ = average coordination scale, τ = average teamwork scale).

Figure 6-1: Graph plots of collaboration indicators for alternative structures for demonstrated example

In the plots, four different configurations are applied to generate collaboration indicators for the IOC-PD. The first two markers in each chart from left to right represent the collaboration indicators for the pre-existing and reorganised information flow respectively. The third markers (that offer highest values for coordination as shown in Figure 6-1b) represent changes to the pre-existing information flow achieved through highly coupled processes in which each of the original four teams are assigned to 21 overlapping tasks each. The fourth markers (that offer highest values for decision-making and teamwork as shown in Figure 6-1a and Figure 6-1c) indicate modification to the pre-existing information flow by means of restructuring personnel to two groups made up of ten members each. In Figure 6-1, γ_i, α_i and β_i are all 1 (i.e. vertex is always available and capable to harmonise interactions, pool resources and make choices).

In practice, the proposed collaboration indicators can vary depending on factors such as skill levels, staff knowledge and experience, working hours, study/sick leaves and involvement in multiple projects. High values of collaboration indicators for social vertices therefore suggest high potentials for working together whereas low collaboration indicators could imply high independent work/ research. Consequently, collaboration indicators could offer a useful avenue for planning staff availability, implementing staff covers and backup, and establishing multiple information access points.

6.2.3. Analysing communication roles

Within the proposed IOC model, human participants can take up key roles as hubs or spokes according to the nature of the collaboration – dictatorship, mutual or exclusive. For the case scenario of the IOC-PD, type 1 topology hubs share similar pre-existing Dc_i (individual connections) and c_{ij} (activity) scores of 0.3684 and 0.0323 respectively, with type 2 and 3 topology hubs. However, in terms of interconnectedness, type 1 topology hubs have lower Cc_i scores of 0.0526 in comparison to the Cc_i scores of 0.0842 for the type 2 and 3 topology hubs. Similarly, as shown in Table 4-4, the Dc_i, c_{ij} and Cc_i scores for the type 1 topology spokes are lower than the type 2 topology spokes.

For organisational managers, periodical assessments of Dc_i, c_{ij} and Cc_i scores could offer a useful avenue for evaluating the performance of an organisation's agent- and web-based systems. In the analysis of agent based systems multiple agents may assume the role of a single vertex and a vertex may assume multiple roles, an occurrence known as ‘interlocking’ that has been the focus of studies in which individuals, usually directors affiliated to one organisation, sit on the board of other organisations (Mizruchi, 1996). Similar interlocking ideas have been applied in industrial practice for design processes with a view to promoting coupled designs (Sonnenwald, 1996). Also, in web-based systems social vertices acting as servers may be included in the social network to serve as hubs for clients. Special considerations for server-to-server links could then be made for enhancing collaboration through the timely synchronisation of servers across groups with minimal disruption to the availability of information. Furthermore, as shown in Figure 6-1, a combination of fewer groups and coupled tasks could be combined or traded-off for improved collaboration. Consequently, layers of groups resembling hierarchical structures could be created for effective collaborative work that requires high numbers of social vertices. Where this is the case, groups of ‘collaborative actors’ may then become the unit for analysis for social vertices in the IOC model.

6.3. LIMITATIONS OF THE PROPOSED TECHNIQUE

As mentioned earlier, the ICD approach was developed based on ‘what managers of information flow during the delivery of MST would like to better understand and represent’. Consequently, there is a need to explore other delivery phase requirements of organizations from different domains. This could lead to a more comprehensive model that fulfils delivery requirements across industry sectors promoting interoperability within and across sectors. Furthermore, the ICD approach is a tool for modelling information flow in individual and collaborative processes at a high-level of abstraction but is limited to point-to-point links between processes. The approach considers the dynamics associated with organisational roles and processes but aspects such as integrity, privacy and confidentiality associated with information flow are not prescribed.

Although the IOC model identifies a single indicator for each collaboration characteristic, it is however important to note that users of the proposed model still require some training or experience in the use of SNA. This is because terms such as closeness and clustering coefficient are fundamental quantities from the SNA technique. The simplicity of the proposed model has also meant that basic quantities and collaboration forms have been adopted. For instance, the degree is a measure used in the model that can be broken down further into indegree and outdegree that characterise the direction of edges between two vertices. If the degree is based on directed edges towards a vertex *i* then it is known as the *indegree* whereas if it is based on directed vertices from *i* then the measure is known as the *outdegree* (White, 2008). Furthermore, in the model the presence as opposed to the strength of edges is employed. This strength of relationships accounts for why individuals with similar characteristics usually associate with one another, a trend known as *homophily* (Wu *et al.*, 2004).

Also, in the IOC model, collaboration indicators are analysed from the perspective of social vertices within the network in accordance with the SNA technique from which the model in this research was proposed. Furthermore, in the case scenario of the IOC-PD, it is assumed that vertices are always available and capable of establishing edges for harmonising interactions, pooling resources and making choices. However in real-world scenarios, activities may be automated or semi-automated for activity vertices to take over some collaborative work resulting in 'indirect influences' and improvements on the level of collaboration in organisations.

6.4. SUMMARY

This chapter has discussed the main limitations and applications of the information channel diagram (ICD) tool and intra-organisational collaboration (IOC) model. The main applications of the proposed technique described in §6.2 were discussed within the context of delivery by organisations. However, due to the focus of the ICD tool on primitives for organisational characteristics and the IOC model on formulations for collaboration, the use of the technique could be extended for modelling other areas of an organisation and could potentially support the ability of firms to leverage ICT, i.e. competitive networking.

The ICD supports competitive networking by enabling organisational designers and analysts to visualise/analyse links and communication channels within which ICT are used.

In addition to visualising ICT as electronic communication channels, the ICD approach also illustrates verbal (face-to-face interactions) and written (paper documentation) communication channels. Based on these communication channels, competitive networking within organisations could then be enhanced through the use of features captured by the ICD approach such as: number of organisational roles, level of individual and collaborative tasks, data storage required, and concentration of information flow.

The application of the IOC model suggested that merely discovering and concentrating on working in a group may not be adequate for collaboration, there is a need to factor the number and levels of collaboration much like hierarchies in traditional organisations as well as the overlapping of tasks that may be automated or semi-automated. Within the proposed IOC model, communication is enabled by social, activity and interface edges. For researchers and industrial practitioners, the presence of these different edges presents a wide range of communication roles for enabling human-to-human, human-to-process and process-to-process communications. Furthermore, within the proposed IOC model, initial or regular analysis of the information structure and behaviour for collaboration can be conducted to determine and review information flow factors such as group sizes, data storage roles, and flow control policies. Also, the proposed IOC model can serve as a benchmarking approach for improving the free flow and exchange of information within organisations.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

The following sections summarises the main outcome of the research carried out for this thesis and identifies some possible future research directions. A section on concluding remarks for this thesis is also included.

7.1. MAIN RESEARCH OUTCOME

The main outcome of this research is a technique consisting of a diagrammatical tool and a mathematical analysis approach for modelling information flow. At the heart of this proposed technique is the need to assist microsystems technology (MST) companies to map the current (logical or physical) state of information flow for organisations during delivery.

This research has sought to provide an opportunity to understanding and improving information flow during delivery phases of companies. Through academic literature and industry practice studies within the MST domain, a technique has been proposed and demonstrated in real-life MST companies.

As shown in §4.2 and §5.1, supporting the mapping of the current state of information flow is an important output of this research. The proposed information channel diagram (ICD) technique offers primitives for depicting organisational characteristics of organisational interactions and processes as well as information coordination and streamlining. These characteristics reflect current needs of ‘managers of information flow’ and are useful in creating maps of information flow that an organisation could adopt as schemes to strategise the delivery process.

Also, as shown in §4.3 and §5.2, the analysis of complex networks for delivery is the goal of the proposed intra-organisational collaboration (IOC) model. The model characterises vertices, edges and topologies for working personnel and connected processes. In particular, two main types of edges involving personnel were defined by the IOC model. Firstly, communicational edges for people-to-people connections that enable social interactions and communicating work updates/progress. Secondly, computational edges for people-to-process connections that enables the monitoring and carrying out of tasks.

7.2. CONCLUDING REMARKS

This thesis has presented work in Chapter 4 to 5 aimed at addressing the research gap from a review of literature in Chapter 2 that was used to establish an industry scope in Chapter 3. The thesis has stressed that information flow models support organisations in three ways: offering common representations for communication, defining the roles of individuals and computing effectiveness and efficiencies of networks. However, human judgement is required to identify and map information exchanges due to difficulties associated with capturing requirements without jeopardising business objectives. This thesis concludes with the following remarks:

- *Analysing collaborations requires modelling for a combination of tasks and teams*. Merely considering or isolating the networks of tasks or teams fails to assess the level of collaboration. This is because key formal links and flows may be omitted in team networks involving social interactions and task networks involving process links.
- *Delivery information flow for firms is non-monolithic and dependent on companies' strategy for maintaining firm competitiveness*. Different starting points for delivery information flows were identified within the companies studied to establish an industry scope according to focus on customer requests, service contracts and work

product releases. However, the general purpose of each flow was to maintain the competitiveness of the company with a view to maintaining sustainable operations.

- *A demarcation of roles is vital to modelling information flow*. This is because a wide range of information flows to and from companies during day-to-day operations. These flows are managed by roles and systems that coordinate interactions between information sources and destinations. Consequently, depictions to analyse information flow for organisations must include the information source, destination and management roles.
- *The use of colour improves representations*. Colours offer opportunities for characterising the properties of concepts such as processes, objects and materials. Particularly, as shown by the case studies, the use of colour in representations for the ICD improved visual perception and reinforced the role of personnel.
- *Simplified communications is necessary for effective operations*. Modern day businesses, in an attempt to remain competitive, undertake processes and projects that may be complex and/or large in scale. Communication if complicated in these cases creates additional tasks, wastes company time and reduces overall productivity.
- *Information managers offer a useful avenue for improving delivery performance*. Unmanaged information flow results in repeated communications, misinterpreted information or erroneous interpretations of information. In high-tech firms, highly skilled engineers, scientists and designers may be expected to interact internally and externally to communicate and explain technological data. However, the communication of business data requires information managers with unique skills such as customer care, administration, book keeping and so on.
- *A review of the flow of information is important to maintaining firm competitiveness*. Modern day business is characterised by the use of computer technology. Also, computer technology continues to experience rapid growth fostered by the emergence of concepts such as ubiquitous computing and ambient intelligence. It is therefore important that firms continue to analyse and review

policies and strategies for managing information flow to keep up with new developments in communications and computer technology.

7.3. FUTURE RESEARCH DIRECTIONS

Discussions in Chapter 6 on the applications and limitations of the proposed technique highlight: (i) the need for possible improvements to the proposed technique and (ii) the need to explore possible research areas further. These areas are now highlighted in the subsections that follow.

7.3.1. Improving the intra-organisational collaboration model

Prior works such as López *et al.* (2002) and Ehsani *et al.* (2010) have proposed or demonstrated the use of mathematical models for analysing collaboration characteristics or relationships. Similarly, this research has proposed and demonstrated the use of a mathematical model, i.e. the IOC model, for analysing collaborations in organisations. The IOC model involves some key indicators of decision making, coordination and teamwork as characteristics of collaboration. However, there is a need to explore and model factors of interpersonal interactions (such as negotiations, competition and authorisation) and organisational behaviour (such as organisation culture, learning organisation and organisation learning) as they relate to collaboration. This is because such insights could offer more comprehensive and analytical information for use by practitioners in strategising interactions and operations within organisations. The use of eigenvector studied in current social network analysis (SNA) research for the spectral analysis of networks (Boccaletti *et al.*, 2006), could serve as a useful starting point for analysing these factors in relation to the characteristics of collaboration identified in this research. For instance, negotiations may be modelled as a function that modifies decision-making.

Consequently, challenges exist to explore the practicality and usability of the IOC model for analysing real-life organisations and processes. There is therefore a need to examine if the IOC model can be applied for specific or a wide range of companies and to define the performance of the model for effective collaborations. Some useful research areas that could be explored include the extent to which the IOC model could be applied for analysing collaborations, the performance of the IOC model against other tools, and the validation of the model across different organisations. Case studies of companies could be used to capture the topologies, vertices and edges of the IOC model and to outline lessons that could be learnt and used to improve collaborations.

7.3.2. Improving the information channel diagram technique

Previous studies such as Ellis (1989) and Stapel *et al.* (2007) have proposed and demonstrated the use of novel diagrammatical tools for fulfilling the requirements of specific sectors such as administrative processes of publishing firms and software development processes. Similarly, this research has proposed and demonstrated the use of a novel tool, i.e. the ICD approach, for fulfilling the requirements of delivery processes.

This research also presents an initial attempt to propose a diagrammatic approach for modelling information flow based on ‘what managers of information flow during the delivery of MST would like to better understand and represent’ through a sample of 100 MST companies. Consequently, there is a need to explore other delivery phase information flow characteristics of organisations from different domains other than the MST domain such as aerospace or wider sectors such as the hi-tech industry sector. Exploratory case studies across industry sectors could also offer a useful future research direction for thoroughly characterising information flow during the delivery phase in organisations.

7.3.3. Exploring possible research areas

Future research could focus on improving the modelling of delivery phases by investigating, defining and incorporating delivery requirements. This could lead to a more comprehensive model that fulfils delivery requirements across industry sectors promoting interoperability within and across sectors.

Consequently, an initial evaluation of the main delivery groups and users could be strategic in identifying models that are practical and useful. The ICD approach, as a starting point, may serve as a guide for the development of future approaches so as realise a comprehensive methodology in which diagrammatic primitives are reused much like existing modelling languages such as IDEF and GRAI. Key characteristics that such a ‘comprehensive model’ must capture include information flow as well as business processes, product and services, processes, work flow and company structure.

Future research could also explore and analyse communication channels that enable information flow during delivery. This could lead to more effective and efficient use of information and communication technologies for enabling delivery information flows. Studies are therefore required to model and propose functions for assessing attributes such as synchronisation in relation to maintaining the flow of up-to-date delivery information. Other communication channel attributes that could be analysed to enhance delivery information flow include harmonisation of internal and external flow of delivery information as well as the frequency of use and cost of communication channels for delivery information flow.

Exploring the space within which organisations are designed is an area of research that could aid in the development of unique and more effective structures for improving organisational functions and behaviour, and characteristics for analysing the performance of an organisation. Different idealisations and metaphors such as ‘organisations as organisms’ or ‘an organization as part of a jungle’ could assist analysts and managers to explore, refine and improve layers within an organisation viz. face-to-face interactions, paper documentation, and ICT.

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APPENDIX A – ONLINE SURVEY QUESTIONNAIRE EMAIL

Dear Sir/Madam,

My name is Christopher Durugbo and I am a PhD student at Cranfield University. As part of my research I am trying to understand information flow in microsystems. I would be grateful if you assist my research by offering your opinion on 8 questions. You can supply answers via 3 routes:

Firstly, online at http://www.kwiksurveys.com/online-survey.php?surveyID=HMIEJ_a393c1f4 (Please input this unique Survey ID when prompted)
Secondly, using the attached word document (please remember to save the file with your selections before attaching it).
Thirdly, by replying to this email with your answers (see questions below)

Yours sincerely,

Christopher Durugbo
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1. INFORMATION FLOWS

a. What media forms are used in the flow of information?
   a) Text (emails, letters etc.)
   b) Graphical
   c) Video
   d) Audio
   e) Other (Please specify)

b. When are these media forms applied?
   a) Communication
   b) Analysis
   c) Description
   d) Documentation
   e) Other (Please specify)

c. What are the major considerations in the choice of these media forms?
   a) The nature of the business
   b) Domain of application
   c) Available capital and resources
   d) Other (Please specify)

d. Who is responsible for information flow in your company?
   a) Company Management
   b) Information system
   c) Information support team
   d) Other (Please specify)

e. How are functions and processes carried out in the company?
   a) Collaborative
   b) Hierarchical
   c) Automated
   d) Networked
   e) Centralised
   f) Distributed
   g) Other (Please specify)

2. INFORMATION FLOW MODELS

f. What modelling techniques have you used as part of your duties?
   a) Data Flow Diagrams
   b) Design Structure Matrix
   c) Petri Nets
   d) GRAI
   e) IDEFØ
   f) HIPO
   g) Other (Please specify)

g. What are these tools used to model?
   a) Products
   b) Services
   c) Other (Please specify)

h. When are these tools used?
   a) Design of Products
   b) Design of Services
   c) Development of Products
   d) Development of Services
   e) Other (Please specify)

APPENDIX B – ADDITIONAL FINDINGS FROM INDUSTRY SURVEY

In terms of media forms, the industry survey revealed that 40 of the 40 respondents made use of text formats (electronic mail, facsimile and text files) while 34 of the 40 respondents applied graphical representations (diagrams and charts) for the flow of information. Audio and video formats, on the other hand, were used by 16 and 21 of the 40 respondents respectively as shown in Figure B-1.

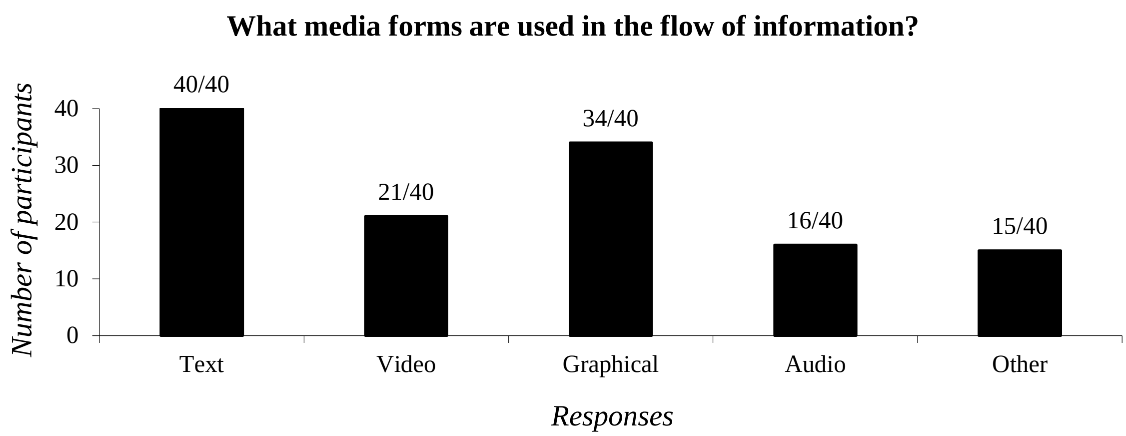

Figure B-1: Media forms for microsystems technology production

15 of the 40 respondent made use of other media forms as follows: (i) 5 of the 40 respondents noted the use of software based simulation and three dimensional (3D) simulation /animation by means of computer-aided design (CAD) tools as key to information flow during design and development, (ii) 5 of the 40 respondents noted that popular information technology formats especially slide presentations, video conferencing and internet/intranet websites were crucial to the flow of information for the design and development of microsystems technology (MST), (iii) 1 of the 40 respondents noted the use of physical prototypes as a means of information flow, and (iv) 4 of the 40 respondents also noted that information flow by face-to-face and word of mouth was applied to complement their companies' media forms because they were small and new companies to the MST industry.

In terms of the purpose for using media forms (the question posed was ‘When are these media forms used?’), 40 of the 40 respondents chose various media forms based on use for communication, 31 for description of functions and processes, 29 for analysis of systems and 34 for documentation (as shown in Figure B-2). Other uses of media forms captured by 9 of the 40 survey respondents included: for presenting results and for conversations to clarify concepts or rectify issues.

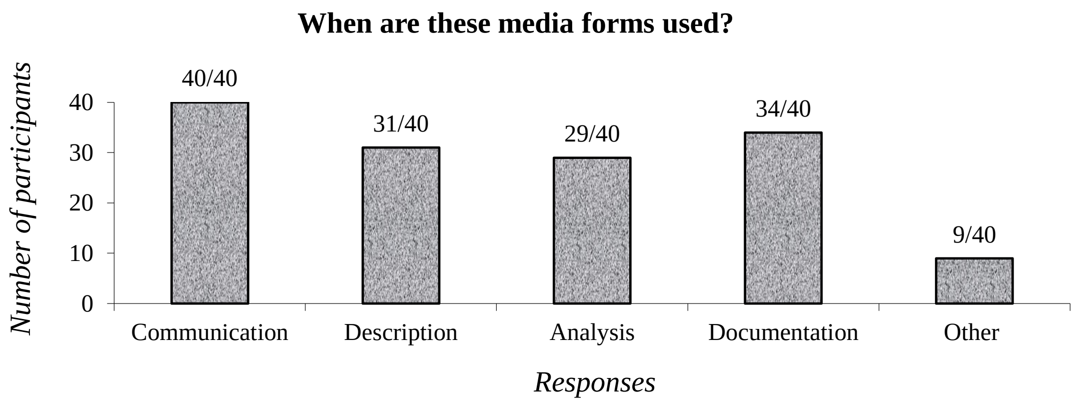

Figure B-2: Purpose of use for media forms during microsystems technology production

In relation to major considerations for selecting media forms, the study revealed that 30 of the 40 respondents chose various media forms because of the nature of their business, 15 because of the domain of application, and 13 because of available capital. Other considerations for the choice of media forms include: standard industry practice, ease of communication, effort required to generate the material vs. the communication value, ease of use and convenience. These other considerations were noted by 10 of the 40 survey respondents, as shown in Figure B-3.

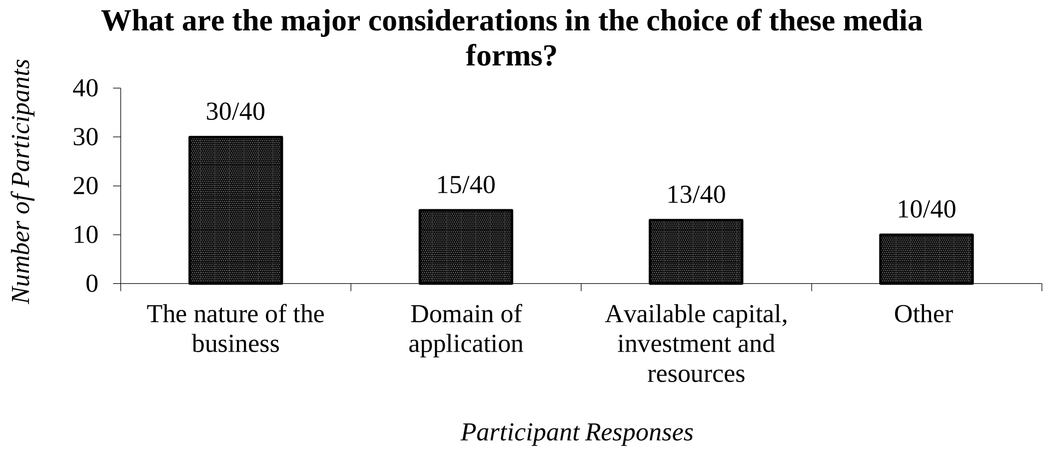

Figure B-3: Major considerations for selecting media forms during microsystems technology production

Also, when asked 'Who is responsible for information flow in the organisation?', 27 of the 40 respondents selected company management, 9 chose information systems, 7 chose information support team (as shown in Figure B-4). Other personnel responsible for information flow captured by 6 of the 40 survey respondents included: everyone in the organisation (based on level of trust, information tagging and participation in information generation), company policy, customer service, sales managers and company managers/directors.

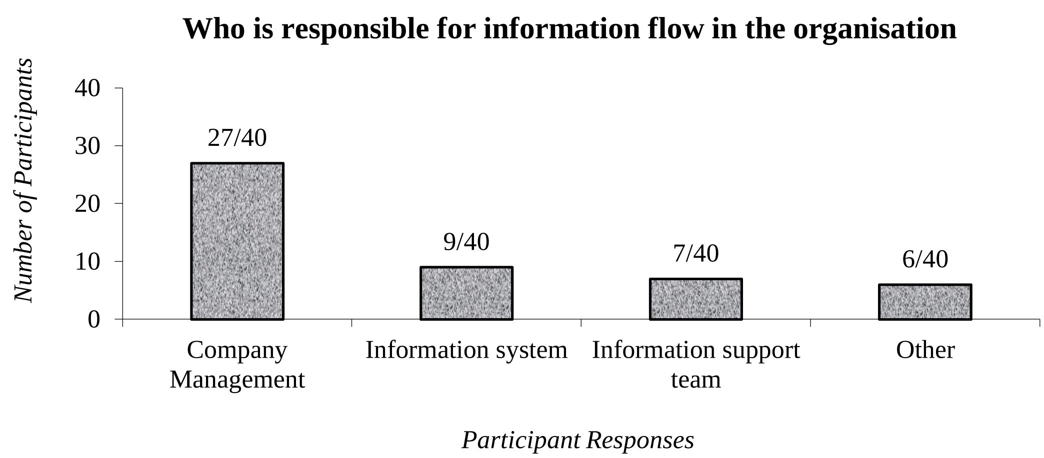

Figure B-4: Management of information flow for microsystems technology organisations

APPENDIX C – EVALUATION OF CURRENT MODELLING TOOLS

A star-based system was adopted to evaluate each modelling tool based on the representations required by managers of information. Each cell in Tables C1-C7 was inspected to ascertain if current tools offered diagrammatic primitives for representing delivery phase information flow. Corresponding cells of each of the tables were also inspected to identify 'gaps' in the evaluated tools with a view to summarising the design goal of the research.

Key:

A completely shaded star (★) implies that the modelling tool provides basic primitives to represent what is required.

A partially shaded star (⯪) indicates that the modelling tool provides primitives that are related to what is required.

A clear star (☆) shows that the modelling tool does not provide any primitives to represent what is required.

Table C1: Evaluation of data flow diagrams

Information flow path	**Harmonise flows**	**Roles of company personnel**
★ Linked *rounded boxes* that show how sequential processes are connected as a sequence	★ Simple approach that makes use of arrows to show flow of data (internal and external). Arrows are also labelled to indicate type of information.	⯪ Shows boxes that represent entities (representation for roles during information flow can be improved)
Multiple channels	**Information sharing**	**Timing of processes**
⯪ Requires the creation of multiple diagrams to illustrate multiple media forms for a single process	⯪ Provided data stores as open ended rectangles (no explicit representation to indicate if information is shared)	☆ No diagram primitives.
Contextualising information	**Synchronise channels**	**Collaborative processes**
☆ No diagram primitives.	☆ No diagram primitives.	☆ No diagram primitives.

Table C2: Evaluation of integrated DEFinition method of modelling functionality

Information flow path	**Harmonise flows**	**Roles of company personnel**
★ Ordered sequence of *boxes* that show how sequential processes are connected	⯨ Provides various orientated arrows to show how input and output are enabled by controls and mechanisms. Arrows are also labelled to indicate type of information.	⯨ No diagram primitives to indicate roles during information flow (described in IDEF1). Mechanisms can however be used to suggest possible roles
Multiple channels	**Information sharing**	**Timing of processes**
⯨ Other media forms can be enabled by means of control and mechanism *arrows*	☆ No diagram primitives.	☆ No diagram primitives.
Contextualising information	**Synchronise channels**	**Collaborative processes**
☆ No diagram primitives.	☆ No diagram primitives.	⯨ Control arrows

Table C3: Evaluation of graphes à résultats et activités interreliés grids

Information flow path	**Harmonise flows**	**Roles of company personnel**
★ Compact *grid* showing the flow of information between processes that are marked as *cells*	★ Shows the flow of information as *arrows* that are transferred to internal sources in manufacturing processes	☆ No diagram primitives to indicate roles during information flow. (rather initial and final states for decision making in systems are described)
Multiple channels	**Information sharing**	**Timing of processes**
⯨ Requires the creation of multiple diagrams to illustrate multiple media forms for a single process	☆ No diagram primitives.	★ Labels grids with timescales to show estimated (or actual) process duration
Contextualising information	**Synchronise channels**	**Collaborative processes**
☆ No diagram primitives.	☆ No diagram primitives.	☆ No diagram primitives.

Table C4: Evaluation of Petri nets

Information flow path	**Harmonise flows**	**Roles of company personnel**
★ Order sequence of bubbles that show connection and various process relationships	⯨ Provides unlabelled *arrows* showing direction of flow.	☆ No diagram primitives.
Multiple channels	**Information sharing**	**Timing of processes**
⯨ Requires the creation of multiple diagrams to illustrate multiple media forms for a single process	☆ No diagram primitives.	☆ No diagram primitives.
Contextualising information	**Synchronise channels**	**Collaborative processes**
☆ No diagram primitives.	☆ No diagram primitives.	☆ No diagram primitives.

Table C5: Evaluation of input-process-output diagrams

Information flow path	**Harmonise flows**	**Roles of company personnel**
★ A set of ordered *boxes* that represents inputs, processes and outputs	⯪ Describes the inputs and outputs in *boxes* that flow in and out of processes	☆ No diagram primitives.
Multiple channels	**Information sharing**	**Timing of processes**
⯪ Can be textually described in the boxes provided for input, process and output	☆ No diagram primitives.	☆ No diagram primitives.
Contextualising information	**Synchronise channels**	**Collaborative processes**
☆ No diagram primitives.	☆ No diagram primitives.	☆ No diagram primitives.

Table C6: Evaluation of design structure matrices

Information flow path	**Harmonise flows**	**Roles of company personnel**
★ *Matrix* representing various relationships between processes	☆ Shows information flows as a *mark* but the type of information is not labelled.	☆ No diagram primitives.
Multiple channels	**Information sharing**	**Timing of processes**
⯪ Requires the creation of multiple diagrams to illustrate multiple media forms for a single process	☆ No diagram primitives.	☆ No diagram primitives.
Contextualising information	**Synchronise channels**	**Collaborative processes**
☆ No diagram primitives.	☆ No diagram primitives.	☆ No diagram primitives.

Table C7: Evaluation of the information channel diagram

Information flow path	**Harmonise flows**	**Roles of company personnel**
★ *Lines* indicating communication links for connecting processes shown as *rectangles* and *arrows* showing the flow of information	★ *Centralised* swim-lane for information flow managers so as to distinguish external and internal sources	★ *Swim lanes* containing processes to show responsibility in the organisation
Multiple channels	**Information sharing**	**Timing of processes**
★ *Varied boxes* to show the different verbal, written and electronic channels	★ *Open ended rectangles* labelled with varied boxes to show means for sharing information	★ *Processes* labelled with estimates of their duration
Contextualising information	**Synchronise channels**	**Collaborative processes**
★ Information streams represented by different *colours*. These colours are also used for the label ascribed to each swim-lane	★ Possible means for flows along an information flow path are show in *parallel* whereas multiple communications are shown in *series*	★ Rectangles can be *stretched* across several swim-lanes.

APPENDIX D – CALCULATED DATA FOR IMPROVING INTRA-ORGANISATIONAL COLLABORATION

This appendix presents formulations used for deriving collaboration indicators of the information structure for intra-organisational collaboration (IOC) model that is realised through task coupling and fewer groups. For improvements through *coupled tasks,* each of the original four teams of the intra-organisational collaboration for product development is assigned to 21 overlapping tasks as shown in Figure D-1.

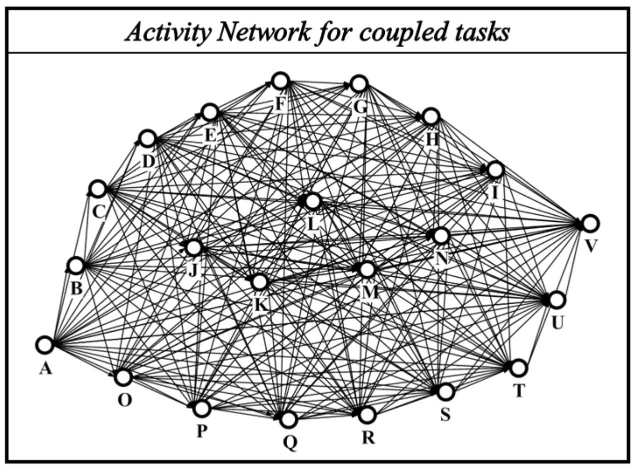

Figure D-1: Activity network for improvements through task coupling for intra-organisational collaboration model for product development in §4.3.3.

Consequently, the values for the degree centrality and closeness measures for social vertices towards activity vertices are different due to more direct access of activity vertices to each other. These new values are computed in Table D1.

Table D1: Degree centrality and closeness measures for social vertices towards activity vertices

Social Network Measure	*Type 1*	*Type 2*	*Type 3*
Dc_i of i (Hub) towards vertices in V_p'	0.6829	0.6829	0.6829
Dc_i of i (Spoke) towards vertices in V_p'	0.5366	0.6098	–
c_{ij} of i (Hub) towards vertices in V_p'	0.0370	0.0370	0.0370
c_{ij} of i (Spoke) towards vertices in V_p'	0.0290	0.0303	–

(*i* – social vertex, Dc_i – degree centrality and c_{ij} – closeness)

Using Table D1 and the values from existing values of degree centrality, clustering coefficient and closeness of social vertices towards activity vertices, computed in Chapter 4, the values for the IOC model can be computed and compared against the pre-existing information flow, as shown in Table D2.

Table D2: Comparison of collaboration indicators for improved information flow achieved through coupled tasks

	Pre-existing Information Flow			**Coupled tasks**		
	Type 1	*Type 2*	*Type 3*	*Type 1*	*Type 2*	*Type 3*
Overall vertices (|V'|)	42	42	42	42	42	42
Overall activity vertices (|V_p|)	22	22	22	22	22	22
Overall social vertices (|V_s|)	20	20	20	20	20	20
Number of groups (f)	4	4	4	4	4	4
Participants from each group (g)	5	5	5	5	5	5
Hubs	4	4	4	4	4	4
Spokes	16	16	16	16	16	16
Cc_i of i (Hub) towards vertices in V_s	0.0526	0.0842	0.0842	0.0526	0.0842	0.0842
Cc_i of i (Spoke) towards vertices in V_s	0.0211	0.0526	–	0.0211	0.0526	–
Dc_i of i (Hub) towards vertices in V_s	0.3684	0.3684	0.3684	0.3684	0.3684	0.3684
Dc_i of i (Spoke) towards vertices in V_s	0.0526	0.2105	–	0.0526	0.2105	–
c_{ij} of i (Hub) towards vertices in V_s	0.0323	0.0323	0.0323	0.0323	0.0323	0.0323
c_{ij} of i (Spoke) towards vertices in V_s	0.0204	0.0217	–	0.0204	0.0217	–
Teamwork scale (Hubs)	0.4211	0.4526	0.4526	0.4211	0.4526	0.4526
Teamwork scale (Spokes)	0.0737	0.2632	–	0.0737	0.2632	–
Average teamwork scale	**0.1432**	**0.3011**	**0.4526**	**0.1432**	**0.3011**	**0.4526**
Decision-making scale (Hubs)	0.0849	0.1165	0.1165	0.0849	0.1165	0.1165
Decision-making scale (Spokes)	0.0415	0.0744	–	0.0415	0.0744	–
Average decision-making scale	**0.0501**	**0.0828**	**0.1165**	**0.0501**	**0.0828**	**0.1165**
Coordination scale (Hubs)	1.4052	1.4052	1.4052	2.8799	2.8799	2.8799
Coordination scale (Spokes)	3.1884	4.3716	–	9.0443	10.2357	–
Average coordination scale	**0.2297**	**0.2888**	**0.3513**	**0.5962**	**0.6558**	**0.7200**

(*i* – social vertex, Dc_i – degree centrality, Cc_i – clustering coefficient, and c_{ij} – closeness)

For improvements through *fewer groups* the original four teams of the intra-organisational collaboration for product development were reconfigured into two teams (Team A and Team B) responsible for 15 and 9 tasks respectively. The topologies for this social network involving fewer groups are shown in Figure D-2.

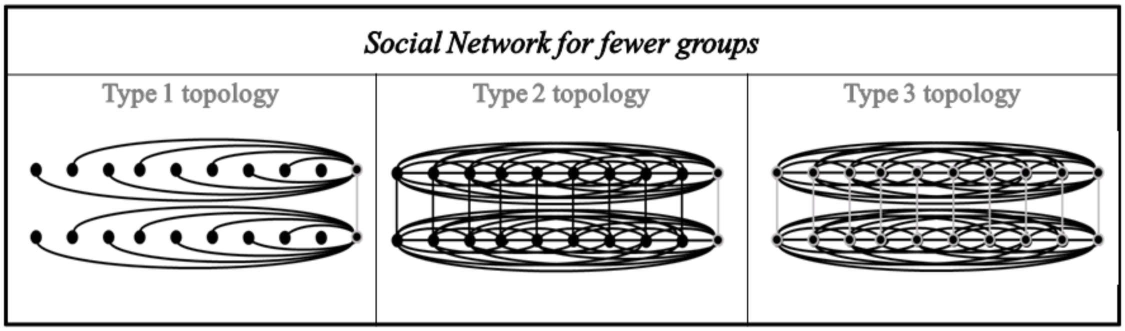

Figure D-2: Social network for improvements through fewer groups for intra-organisational collaboration model for product development in §4.3.3.

Also, the values for the degree centrality and closeness measures for social vertices towards activity vertices are different due to individuals in teams having more direct access to activity vertices. These new values are computed in Table D3.

Table D3: Degree centrality and closeness measures for social vertices towards activity vertices

Social Network Measure	*Type 1*	*Type 2*	*Type 3*
Dc_i *of i (Hub)in Team A towards vertices in* V_p'	0.6098	0.6098	0.6098
Dc_i *of i (Spoke) in Team A towards vertices in* V_p'	0.3902	0.5854	–
Dc_i *of i (Hub)in Team B towards vertices in* V_p'	0.4634	0.4634	0.4634
Dc_i *of i (Spoke) in Team B towards vertices in* V_p'	0.2439	0.4390	–
c_{ij} *of i (Hub) in Team A towards vertices in* V_p'	0.0368	0.0368	0.0368
c_{ij} *of i (Spoke) in Team A towards vertices in* V_p'	0.0276	0.0311	–
c_{ij} *of i (Hub) in Team B towards vertices in* V_p'	0.0329	0.0329	0.0329
c_{ij} *of i (Spoke) in Team B towards vertices in* V_p'	0.0254	0.0282	–

(*i* – social vertex, Dc_i – degree centrality and c_{ij} – closeness)

Similarly, using Table D3 and the values from existing values of degree centrality, clustering coefficient and closeness of social vertices towards activity vertices, computed in §4.3, the values for the IOC model can be computed and compared against the pre-existing information flow as shown in Table D4.

Table D4: Collaboration indicators for improved information flow achieved through fewer groups

	Pre-existing Information Flow			Fewer groups		
	Type 1	*Type 2*	*Type 3*	*Type 1*	*Type 2*	*Type 3*
Overall vertices (|V'|)	42	42	42	42	42	42
Overall activity vertices (|V_p|)	22	22	22	22	22	22
Overall social vertices (|V_s|)	20	20	20	20	20	20
Number of groups (f)	4	4	4	2	2	2
Participants from each group (g)	5	5	5	10	10	10
Hubs	4	4	4	2	2	2
Spokes	16	16	16	18	18	18
Cc_i of i (Hub) towards vertices in V_s	0.0526	0.0842	0.0842	0.0526	0.2421	0.2421
Cc_i of i (Spoke) towards vertices in V_s	0.0211	0.0526	–	0.0474	0.2368	–
Dc_i of i (Hub) towards vertices in V_s	0.3684	0.3684	0.3684	0.5263	0.5263	0.5263
Dc_i of i (Spoke) towards vertices in V_s	0.0526	0.2105	–	0.0526	0.4737	–
c_{ij} of i (Hub) towards vertices in V_s	0.0323	0.0323	0.0323	0.0357	0.0357	0.0357
c_{ij} of i (Spoke) towards vertices in V_s	0.0204	0.0217	–	0.0217	0.0263	–
Teamwork scale (Hubs)	0.4211	0.4526	0.4526	0.5789	0.7684	0.7684
Teamwork scale (Spokes)	0.0737	0.2632	–	0.1000	0.7105	–
Average teamwork scale	**0.1432**	**0.3011**	**0.4526**	**0.1479**	**0.7163**	**0.7684**
Decision-making scale (Hubs)	0.0849	0.1165	0.1165	0.0883	0.2778	0.2778
Decision-making scale (Spokes)	0.0415	0.0744	–	0.0691	0.2632	–
Average decision-making scale	**0.0501**	**0.0828**	**0.1165**	**0.0710**	**0.2646**	**0.2778**
Coordination scale (Hubs)	1.4052	1.4052	1.4052	1.1429	1.1429	1.1429
Coordination scale (Spokes)	3.1884	4.3716	–	6.1845	9.7534	–
Average coordination scale	**0.2297**	**0.2888**	**0.3513**	**0.3664**	**0.5448**	**0.5714**

(*i* – social vertex, Dc_i – degree centrality, Cc_i – clustering coefficient, and c_{ij} – closeness)

APPENDIX E - LIST OF PUBLICATIONS

Chapters of this thesis have been developed from edited versions of papers that have been published[9] or submitted[10] as follows:

Paper 1 Durugbo C., Tiwari A., Alcock J.R., 2011, Modelling Information Flows for Organisations: A Review of Approaches and Future Challenges. *International Journal of Information Management*

Paper 2 Durugbo C., Tiwari A., Alcock J.R., 2011, A Review of Information Flow Diagrammatic Models for Product-Service Systems. *International Journal of Advanced Manufacturing Technology,* 52 (9-12), 1193-1208 *(published)*

Paper 3 Durugbo C., Tiwari A., Alcock J.R., 2010, Survey of Media Forms and Information Flow Models in Microsystems Companies. Camarinha-Matos, L.M., Pereira, P., Ribeiro, L., (eds.) *Emerging Trends in Technological Innovation* (IFIP Advances in Information and Communication Technology Book Series) AICT 314, 62-69.

Paper 4 Durugbo C., Tiwari A., Alcock J.R., 2011, Information Flow for Enhancing Delivery: A Study of Microsystems Companies. *International Journal of Production Research.*

Paper 5 Durugbo C., Hutabarat W., Tiwari A., Alcock J.R., 2011, Information Channel Diagrams: An Approach for Modelling Information Flow. *Journal of Intelligent Manufacturing*, DOI : 10.1007/s10845-011-0523-7 *(available online)*

Paper 6 Durugbo C., Hutabarat W., Tiwari A., Alcock J.R., 2011, Modelling Collaboration using Complex Networks. *Information Sciences,* 181 (15), 3143-3161.

Paper 7 Durugbo C., Tiwari A., Alcock J.R., 2011, Modelling Information Flow for Delivery Reliability: A Case Study of Microsystems Companies. *International Journal of Production Research.*

Paper 8 Durugbo C., Tiwari A., Alcock J.R., 2011, Modelling Information Flow for Collaboration. Camarinha-Matos, L.M., (eds.) *Technological Innovation for Sustainability* (IFIP Advances in Information and Communication Technology Book Series) AICT 349, 3-10.

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9 Published papers are publications that have been published electronically and /or in paper form.

10 Submitted papers are publications that have been submitted and are currently under review.

Other papers developed during the course of the PhD include:

Paper 9 **Durugbo C., Tiwari A., Alcock J.R., 2009, An Info-dynamic Engine Approach to Improving the Efficiency of Information Flow in a Product-Service System. *Proceedings of the 1st CIRP IPS2 Conference*, Cranfield, 1-2 April 2009, 107-112.**

Paper 10 **Durugbo C., Bankole O., Tiwari A., Alcock J.R., Roy R., Shehab E., 2010, Product-Service Systems across Industry Sectors: Future Research Needs and Challenges. *Proceedings of the 2nd CIRP IPS2 Conference*, Linköping, 14-15 April 2010, 535-542.**

Paper 11 **Durugbo C., Tiwari A., Alcock J.R., 2010, Managing Information Flows for Product-Service Systems Delivery. *Proceedings of the 2nd CIRP IPS2 Conference*, Linköping, 14-15 April 2010, 365-370.**

Paper 12 **Durugbo C., Hutabarat W., Tiwari A., Alcock J.R., 2010, SysML for the Analysis of Product-Service Systems Requirements. *Proceedings of the 2nd CIRP IPS2 Conference*, Linköping, 14-15 April 2010, 125-132.**

Paper 13 **Durugbo C., Erkoyuncu J., Tiwari A., Alcock J.R., Roy R., Shehab E., 2010, Data Uncertainty Assessment and Information Flow Analysis for Product-Service Systems: A Library Case Study. *International Journal of Services Operations and Informatics*, 5 (4), 330-350.**

Paper 14 **Durugbo C., Tiwari A., Alcock J.R., 2011, Service Delivery for Microsystems Production: a Study. *CIRP Journal of Manufacturing Science and Technology, DOI: 10.1016/j.cirpj.2011.02.005*. *(available online)***

Paper 15 Durugbo C., Tiwari A., Alcock J.R., 2011, Collaborative Design for Microsystems: A Review. *International Journal of Design Engineering*.