Principles for the design and operation of engineer-to-order supply chains in the construction sector

Jonathan Gosling[1], Denis Towill[1], Mohamed Naim[1] and Andrew Dainty[2]

[1]*Logistics Systems Dynamics Group, Logistics and Operations Management Section, Cardiff University, Cardiff, UK.*

[2]*School of Civil and Building Engineering, Loughborough University, Leicestershire, UK*

By integrating the approaches of Jay Forrester (1961) and Burbidge (1961), a set of 5 design principles have emerged which provide a foundation for sound supply chain design. The 'FORRIDGE' principles have since been shown to be a powerful guide for effective design of make-to-stock supply chains. However, some have questioned the applicability of generic supply chain thinking, arguing for a tailored approach. Hence, the goal here is to investigate how these principles should be adapted for engineer-to-order industries (ETO), such as construction, capital goods and shipbuilding. The empirical elements draw on an extensive study of 12 suppliers and 2 large contractors in the construction industry. Supply chain tactics are identified for this range of companies, which are matched with real world problems, and linked with the FORRIDGE principles. This results in an additional 'Design for X' principle being proposed. The contributions made are the adaptation of established principles for the ETO sector, and the framework behind these principles.

Keywords: Supply chain; engineer-to-order; construction; design-for-X

1. Introduction

Supply chain management is a critical issue for engineer-to-order (ETO) companies, such as those found in the construction, capital goods, and shipbuilding sectors (Hicks *et al.* 2000, Gosling and Naim 2009). The complexity of such products often requires the bringing together of a diverse range of specialist companies to work together to meet individual customer needs. The problems faced when managing such supply chains are widely acknowledged (Wortmann *et al.* 1997, Dubois and Gadde 2002a, Gosling *et al.* 2013a). Agreement on a set of guiding principles for such supply chains is far from established though. Therefore, the purpose of this paper is to investigate principles to support the design and operation of supply chains in ETO supply chains through empirical research in the construction sector.

It has been argued that many modern supply chain principles may be traced back to the classic production distribution systems simulations by Jay Forrester (1961). By integrating the methodologies of industrial dynamics (Forrester 1961), feedback theory (Towill 1982), and material flow control (Burbidge 1961, Burbidge 1983), a set of system operation principles have been developed (Towill 1997). The latter looked to provide a foundation for sound supply chain design, and in doing so established a set of fundamental rules for enabling smooth and seamless material flow. The 'FORRIDGE' principles, a phrase derived from combining the key intellectual influences of Forrester and Burbidge, were originally defined as *control system principle, time compression principle, information transparency principle* and *echelon elimination principle*. A previously implied fifth *'synchronization' principle* was later made explicit by Geary et al. (2006). Since publication in 1997, the principles have been shown to offer a powerful guide for engineering effective make-to-stock supply chains.

Disseminating a widely agreed upon set of principles relevant to discrete parts manufacture value streams still remains a difficult and challenging prospect. Some researchers have, for example, questioned the applicability of generic thinking, and argued for a more tailored approach, taking into account market sector and/or product characteristics (Naylor *et al.* 1999, Briscoe and Dainty 2005). This raises the issue of how the above principles may be applied in a non make-to-stock (MTS) environment. As has been highlighted by researchers in the strategy field, ‘similarity mapping’ from one scenario to another can lead to a ‘candidate solution’ for the particular problem at hand. The danger is that this is undertaken on the basis of superficial similarity, not deep causal traits, and following inadequate investigation (Gavetti and Rivkin 2005). While it is easy to apply principles such as those outlined above, without careful thought to translation and adaptation to specific scenarios they may lead to unintended consequences for the organizations attempting to enact them.

One way of considering these specific scenarios is via the decoupling point concept (Hoekstra and Romme 1992). This can be defined as the point at which strategic stock is held as a buffer between fluctuating customer orders and smooth production output. It provides a useful classification system for supply chains, and helps to distinguish between stock driven and order driven systems. Using this concept, a range of structures can be defined ranging from very repetitive make-to-stock supply chains to very customized ETO industries (Hoekstra and Romme 1992, Olhager 2003, Gosling *et al.* 2007). In the latter, each item, or project, is to a degree unique, and the client will often engage extensively with the design process. Production dimensions are customised for each order, and they operate in project specific environments. The ETO supply chain is the particular structure that is of interest in this paper. To our knowledge, this is the first time the FORRIDGE principles have been investigated in a non-make-to-stock sector. Hence, the research question addressed in this paper is ‘which supply chain management principles and tactics should be adopted, or adapted, for ETO supply chains in the construction industry?’.The paper begins by outlining the research objectives and methodological approach, which outlines then scope and general research orientation. This is followed by a literature review that traces the origins of a specific set of supply chain management principles and discusses their application in ETO situations. Section 4 describes the methodology, including the multiple case studies that form the empirical elements of the study. Sections 5 and 6 present the findings, giving an analysis of problems, tactics and their relationship with supply chain management principles. The conclusions are given in section 7.

2. Research Objectives and Methodological Approach

Many of the difficulties in ETO supply chains arise from managing the new product development process (Rahman *et al.* 2003). Project based organisations undertaking engineering and construction works are constantly challenged by the complexity and innovation management required in a way that differs from those in some other sectors (Gann and Salter 2000). Ireland (2004) concluded that demand regularity is a key variable that differentiates project supply chains. The arena for the empirical work in this paper is the construction industry, where projects often require a complex mix of activities, relationships, organisations, knowledge and skills to come together to complete a 'one-of-a-kind' assignment. It is widely perceived to have structural problems inhibiting the adoption of some supply chain best practice (Briscoe and Dainty 2005), but the same has been noted in other ETO industries (Anderson *et al.* 2000, Hicks *et al.* 2000)

The sector has been the subject of many UK and Australian government reports which probe how the sector may improve performance and prescribe reform agendas. Murray and Langford (2003) analyse all UK construction reports published between 1944 and 2002, and conclude they all encourage a set of changing relationships between different parties to the construction process. Furthermore, most of these reports have largely highlighted the same persistent weaknesses around structural fragmentation and an apparent inability to innovate. This lack of progress is also noted in a more recent supply chain management handbook for the sector (O'Brian *et al.* 2009) This reflects the view that construction operations are the epitome of a ‘loosely coupled’ system (Dubois and Gadde 2002a), whereby interactions are optimised around productivity concerns at the expense of innovation and learning opportunities. Given the lack of ‘regularity’ in the project environment, some authors question the extent to which full supply chain integration through partnering can be achieved in such supply chains (Ireland 2004). This might also explain why the uptake of supply chain management practices within construction appears to be very slow (Akintoye *et al.* 2000, Saad *et al.* 2002). Hence, many of the problems identified in the empirical aspects of the paper are typical ‘structural’ challenges facing ETO construction supply chains. As yet, a succinct set of principles linked to well-established theory, and a framework for deriving these principles, has not emerged for this challenging sector.

This paper is concerned with the development of principles, which, in this context, can be defined as ‘a professed rule of action or conduct’ and ‘guiding theory or rule’ (Dictionary 1989). Furthermore, we make a distinction between principles and lower level tactics. This differentiation has been made elsewhere, whereby principles are regarded as guiding rules and tactics relate to practices and techniques (Anderson *et al.* 1994, Dean and Bowen 1994, Towill and Childerhouse 2006) . The original FORRIDGE principles are derived from theory, and then through empirical investigation, with subsequent iterations between theory and practice, the principles are refined and extended. This approach is informed by Dubois and Gadde’s (2002b) systematic combining logic, where concepts and frameworks evolve during ‘confrontation’ with case context and relevant literature throughout the research process. This approach is visualised in figure 1. We begin by showing the lineage of the FORRIDGE supply chain management principles, tracing their origins to systems thinking (Kramer and de Smit 1977, Parnaby 1979). Supply chain principles specifically for ETO supply chains are then addressed. The empirical elements of this paper highlight their usage by a range of construction companies. They are matched with real world problems identified through a set of case studies. We argue that sector specific studies feedback to the generic ETO principles to further inform theory. Adaptation for the specific context of ETO supply chains results in six proposed principles, rather than the original five, and two 'enablers' are added.

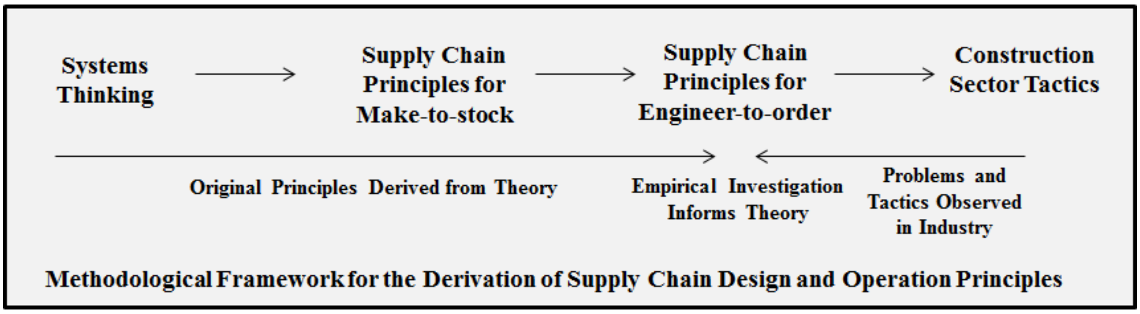


Figure 1: Methodological approach adopted

The research question articulated in the introduction is further developed to include three objectives, which are as follows:

- To develop a framework to consider the derivation of supply chain management principles for the ETO sector
- Building on relevant MTS research, to adapt and extend a set of principles for the design and operation of engineer-to-order supply chains
- To empirically investigate the application of these principles, and the tactics employed to enable them, within the specific setting of the construction industry.

3. Deriving principles for engineer-to-order supply chains from established knowledge

3.1 The Origins of the FORRIDGE Principles

The FORRIDGE principles find their intellectual roots in systems theory. The first attempt at a general systems theory was proposed by von Bertalanffy (1950). In this work, key principles such as wholeness, sum, closed and open systems, and equifinality were set out. 'Systems thinking' was later coined as a term to describe the common language for this theory (Kramer and de Smit 1977). Reality is regarded in terms of wholes, which consist of interdependent elements. In a system, the elements are arranged meaningfully in relation to the whole, so that the totality is more than the sum of its parts. Systems 'state' is an important element to the current discussion. This refers to the behaviour of the system, or more explicitly, a set of relevant properties at a particular time (Ackoff *et al.* 1972). Systems engineers often strive towards the design of a system that is able to return to its initial condition after a disturbance.

Control of production processes using systems thinking in supply chains has a long history. This dates back to early approaches to control theory in production systems (Simon 1952), and the servomechanism approach started with Tustin (1952). The evolution of integrated controls together with the wider exploration of process flow system design concepts established an intellectually sound methodology for taking a total view of strategically guided complex systems made up of many linked and related specialized functional elements (Parnaby and Towill 2009). Forrester (1961) emphasized the role of connectance, feedback and disturbances in manufacturing systems. Through simulation, he established that the more extended the chain, the worse the dynamic response. Hence, global operations can be particularly at risk from poor systems design. At around the same time Burbidge was developing ideas relating to material flow control (Burbidge 1961). These were explained in his work on production flow analysis (Burbidge 1989), as well as being made succinct in his made succinct in the 5 rules for avoiding bankruptcy (Burbidge 1983), which state: only make products which you can quickly despatch and invoice to customers, only make in one period those components you need for assembly in the next period, minimise the material throughput time, use the shortest planning period that can be managed efficiently, and only take deliveries from suppliers in small batches when needed for processing or assembly.

Throughout a distinguished career dating back to Spitfire production in World War 2, Burbidge clearly established the need for exploiting cycle time compression, synchronization of orders throughout the supply chain, simplified product structures and streamlined component flows within the factory (Burbidge 1982, Burbidge 1995). Forrester's (1961) major contribution was to emphasize the importance of the whole system structure, showing the importance of integrating information and material flows in feedback systems. The FORRIDGE principles united these different intellectual threads into a succinct set of principles (Towill 1997, Geary *et al.* 2006, Towill and Childerhouse 2006). They appeared in embryonic form in an early detailed study of the Forrester (1961) simulations, where a range of different approaches for improving supply chain dynamics were analyzed (Wikner *et al.* 1991). Table 1 gives definitions for the 5 FORRIDGE principles, along with details of the linkages to Forrester and Burbidge.

FORRIDGE Principles	**FORRIDGE Definitions** (Towill 1997, Geary *et al.* 2006)	**Forrester Inputs** (Forrester 1961, Forrester 1975)	**Burbidge Inputs** (Burbidge 1961, Burbidge 1983, Burbidge 1989)
Time Compression Principle	Every activity in the chain should be undertaken in the minimum time needed	-Faster order handling to improve stability and reduction of system time	-Minimize the material throughput time

	to achieve task goals	delays	
Control System Principle	There is a need to select the most appropriate control system best suited to achieving user targets and taking unnecessary guesswork out of the system.	-Change inventory policy to adjust the level of inventories and in-process orders	-Only make those product which you can quickly dispatch and invoice to customers -Only make in one period those components you need for assembly in the next period
Synchronization Principle	All events are synchronised so that orders and deliveries are visible at discrete points in time, and there is continuous ordering synchronised throughout the chain.	- Events should be synchronized, so that orders and deliveries are visible at discrete points in time.	-Use the shortest planning period -Only take deliveries from suppliers in small batches as and when needed for processing or assembly -Demand amplification can be reduced by continuous ordering synchronised throughout the chain
Information Transparency Principle	Up-to-the minute data free of 'noise' and bias should be accessed by all members in the system	-Ensure correct behavior of information-feedback systems	-Don't rely on long term forecasts and promote 'connectance'
Echelon Elimination Principle	There should be the minimum number of echelons appropriate to the goals of the supply chain.	-Eliminate distributor level to reduce demand amplification	-Efficiency is inversely proportional to the complexity of its material flow system

Table 1. Definitions and influences for the FORRIDGE Principles

Individual principles have been substantiated by many researchers, including time compression (Treville *et al.* 2004), information transparency (Smaros *et al.* 2003) and control (Dejonckheere *et al.* 2003a). McCullen and Towill (2001) have comprehensively shown that the application of the principles as core features within a business process re-engineering (BPR) programme have substantially reduced bullwhip in a real world supply chain. Furthermore, there was proven simultaneous reduction in both inventory levels and order variability. These principles have since been incorporated into a vision-principles toolbox model, and subjected to statistical testing across a range of real world supply chains (Towill and Childerhouse 2006). These studies provide convincing evidence for the effectiveness of the five principles in a discrete parts make-to-stock (MTS) context, where they were envisioned and exploited, but there is as yet no investigation of how these principles may apply in an ETO environment.

3.2 Deriving principles for engineer-to-order supply chains

As previously noted, a useful concept for categorising different types of supply is the material flow decoupling point (Hoekstra and Romme 1992), and the particular structure that is of interest in this paper is the ETO supply chain. A comprehensive review of research in this area is set out in Gosling and Naim (2009), which finds that many authors agree that all production dimensions in the ETO supply chain are customised for each order, that the decoupling point is located at the design stage, and that they operate in project specific environments. By decoupling the engineering and production related activities of the supply chain, it is also possible to show that engineering designs may also be 'in stock' or 'to order' (Wikner and Rudberg 2005).

Supply chains in complex ETO environments typically operate under different constraints and conditions than those in high volume make-to-stock structures. Project supply chains may be part of existing, longer lived supply chains, or they may be established specifically to meet a single project (Tommelein *et al.* 2009). The uncertainties faced in ETO projects, such as civil engineering, are markedly different from those in more stable environments (Gosling *et al.* 2013b) . In particular, procurement and the competitive bidding, as well as the design stage have been highlighted as being time bottlenecks for ETO supply chains (Elfving *et al.* 2005). Hicks et al. (2000), researching the capital goods sector, found that modular configurations and standard items can reduce costs and lead times. They also emphasized that some lessons can be learnt from the high volume sector, such as reduction of the supplier base and long term relationships, but that the characteristics of ETO markets significantly constrain the application of established supply chain management methods.

Some guidelines for ETO supply chain management are available in the literature, but it is far from conclusive. The importance of time compression is also highlighted in Towill's (2003) conclusion that a 40% reduction in project time can lead to a 25% reduction in total work undertaken and costs. Gosling et al. (2012) synthesize a range of supply chain management concepts to develop a four stage approach to improving ETO supply chains, suggesting that approaches to managing uncertainty are important for businesses thriving in the sector. They also note the lack of integration of well established concepts and theories for the ETO supply chain type. In addition, Cameron and Braiden (2004) found that when applying BPR techniques to four different ETO companies, a range of difficulties emerge. The benefits of RFID technologies for visibility throughout an ETO supply chain are well illustrated by Pero and Rossi (2013) However, a succinct set of principles linked to well-established theory is so far missing from the existing literature..

A number of studies have linked construction with the characteristics of the ETO structure (Winch 2003, Segerstedt and Olofsson 2010, Gosling *et al.* 2012). There are some guidelines on best practice in managing construction supply chains, but the issue of how to adapt mainstream thinking is far from clear and the sector typically suffers from lack of integration, lack of trust and zero-sum performative logics (Dainty *et al.* 2001) . Vrijhoef and Koskela (2000) defined four roles for supply chain management in construction including a focus on the interface between the supply chain and the construction site, focus on the supply chain, focus on transferring activities from the construction site to the supply chain and focus on the integrated management of the supply chain and the construction site. They concluded that many of the problems in construction are caused by 'myopic control of the supply chain'. Love et al. (2004) propose a seamless supply chain management model for construction, based on the integration of design and production processes of construction projects. Briscoe and Dainty (2005) found that the large number of supply chain partners and the significant level of fragmentation in the construction environment place constraints on the level of supply chain integration that is achievable. Further studies in the construction sector have highlighted the potential of mass customised approaches to balance the amount of bespoke design with mass production principles (Barlow *et al.* 2003). However, this has the potential to 'shift' companies away from a pure ETO marketplace.

3.3 Extending the principles and framework for the paper

Previous research in relation to the FORRIDGE principles has focused on the supply chain design and management domain, and has largely been concerned with the Product Delivery Process (Parnaby *et al.* 2003). We argue that in addition to the 5 principles documented in the existing FORRIDGE literature, a sixth, which is dependent on the type of supply chain, is required. When considering the ETO sector, the Product Introduction Process becomes an increasingly important part of the supply chain management domain, as each project is in some way unique. In this sense, as will be explained throughout the paper, by 'systematic combining' of the empirical study in the construction industry and existing literature, a sixth 'Design for X' (DfX) principle is proposed for the ETO context. Design issues emerge from the empirical elements of this research, and support our case for the inclusion of such a principle. DFX has become an umbrella term used to imply effective design principles (Kuo *et al.* 2001). Approaches such as design for assembly, design for manufacturing, design for buildability, and design for life cycle are all included in this umbrella (Asiedu and Gu 1998). This also includes the design of product configurations and platforms to help meet customization requirements in a manageable way (Salvador and Forza 2004, Jansson *et al.* 2013) An integrated design process should enable all elements of the design to be 'fit for purpose' and 'right first time'. Design goals and constraints should be considered early with input from key stakeholders.

A further consideration that is not explicit in the FORRDGE principles is that of learning. Organisational theorists have emphasised the importance of learning for some time. Early work by Argyris (1992) emphasized modes of learning and single and double loop learning, and Peter Senge (1990) proposed a range of core disciplines for building the learning organisation. However, a more recent seminal analysis by Ortenblad (2007) showed that Learning Organisation citations were taking quite different, and often conflicting, interpretations of its meaning. Garvin (1993) offers a clear and concise definition to exploit: "creating, acquiring, transferring knowledge and exploiting this to modify behaviour". The importance of learning does not stop at the boundaries of a single organisation. It is heavily dependent on inter-organisational learning and development. Bessant et al. (2003) coined the phrase 'supply chain learning' to refer to this. Such learning often requires collaborative working across organisational boundaries. This is consistent with Stephens (1991) conception of integration.

Bringing together the different threads of research from the literature review, a framework has been developed to show the origin of the supply chain management principles, and how they have been adapted for different operating environments. The framework is shown in figure 2. It highlights that supply chain management principles for the make-to-stock sector can trace their origins to systems thinking (Kramer and de Smit 1977, Parnaby 1979). These principles are then adapted for the specific context of ETO supply chains. At the tactical level, these principles may be interpreted differently across the range of ETO industries. In this paper we are interested in construction sector issues. Such sector specific studies feedback to the generic ETO principles, through specific examples of best and ineffective practice, thus helping to further inform theory.

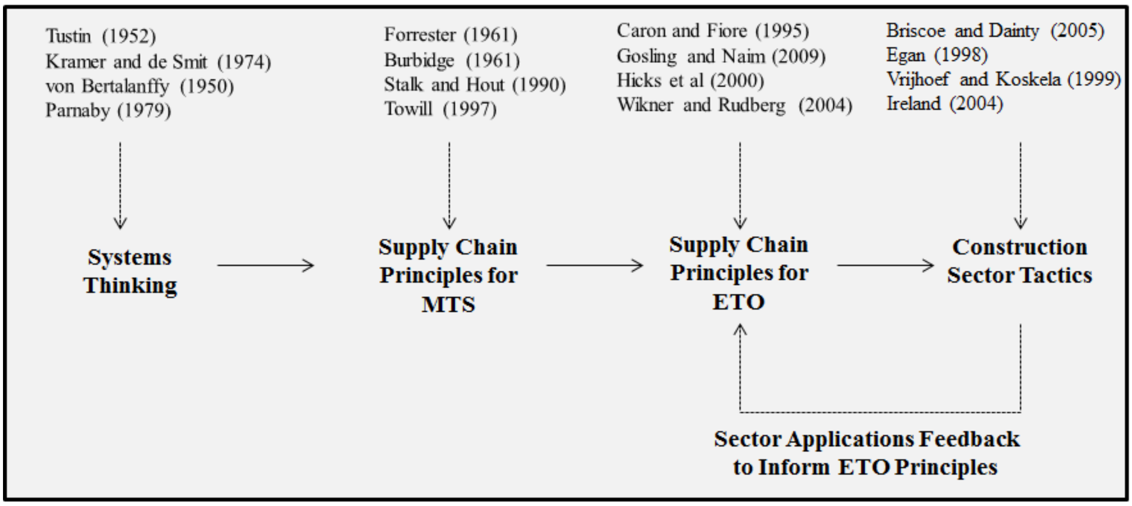


Figure 2: Deriving the principles for the design and operation of engineer-to-order supply chains

4. Methodology

4.1 Overview

To develop the initial framework development, literature was categorised into streams resulting in the 4 levels for deriving principles for ETO supply chains. This was highlighted in Figures 1 and 2 , which act as a guiding framework for the paper. As described in section 2, the study combines deductive and inductive elements. The ETO principles are derived from theory relating to systems thinking and MTS principles, but are informed and 'confronted' by empirical elements (Dubois and Gadde 2002b). The latter relates to the investigation of real world supply chain problems and tactics. A system thinking perspective provides a foundation for conceptualization of ETO supply chains. Consideration of system boundaries and elements contributes significantly to the 'carving up' and definition of the objects of study.

According to Stake (1994), while case study research does not aim to sample in the same way as survey research, careful thought given to case selection can help to maximise what one can learn about the phenomena under study. Yin (2003) suggested defining a set of operational criteria whereby candidates will be deemed qualified to serve as cases. Main contractors were chosen on the basis of likelihood of fit with ETO characteristics, willingness to engage in research, and demonstration and commitment to innovation and best practice. Both main contractors involved in the study have won various industry and national awards for their improvement initiatives. Once the main contractors were selected, the next step was to identify suitable supplier pipelines to study. The criteria for selection was the supplier must supply into one or more current projects, represent a range of supply chain structures, and have a relationship agreement in place with the main contractor.

The structure of the research design described above is made explicit in a systems diagram shown in figure 3. Each system comprises of a ‘systems integrator’ (the main contractor). Both of these companies are responsible for managing a range of projects (labelled P1, P2, P3, P4 and P5). These projects are engineered-to-order, in the sense that each project is co-developed for an individual customer with unique requirements. The figure also shows the suppliers in the study (labelled cases A through to L). Each system has a design subsystem, a regulatory subsystem, and a client or customer. The arrows in the diagram indicate where specific suppliers are linked with particular projects. System 1 comprises 1 focal company, 3 projects and 9 suppliers. The lead company in this network specialises in delivering housing projects on a ‘design and build’ basis. System 2 comprises 1 systems integrator, 2 projects and 3 suppliers. For each of the projects the systems integrator has to liaise with clients, design consultants, such as architects and structural engineers, and regulatory bodies, such as local councils, in order to complete the project. The lead company in this network specialises in managing large commercial tower buildings delivered on a construction management basis. The empirical elements are based on an extensive research programme in the construction sector. For this particular paper the elements of interest are ‘supplier pipelines’, which will be explained further in the following section.

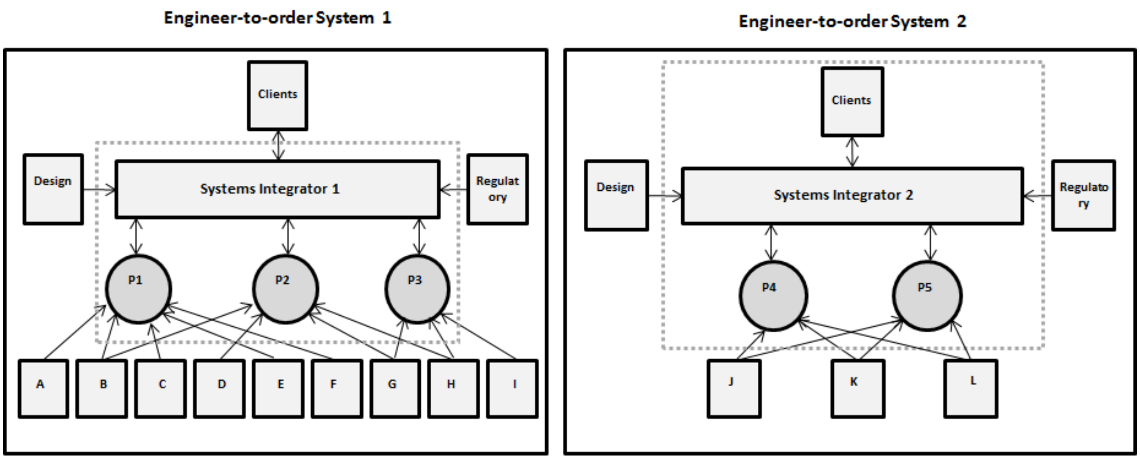


Figure 3: A systems view of the two engineer-to-order construction supply chains in the study

4.2 Data Collection and Analysis

Investigation of companies was undertaken via a pipeline investigation protocol. A ‘pipeline’ is defined herein as the delay between generating an order and the receipt of that order into stock. This relates to a specific product or ‘work package’. Berry et al. (1998) refer to operational mechanisms and procedures that are employed to service a specific product. The pipelines of interest in this study are shown in Table 2. It shows that the paper is based on the investigation of 12 pipelines. The positions of the people interviewed are shown in the final column. An interview template was followed, which included structured and semi-structured questions that probed market and product details, the external environment (suppliers and customers), internal environment, strategy, procurement and design. This also included a template to investigate different elements of the lead-time for important processes. Each interview was accompanied by a site or factory visit, usually a guided tour enabling the researcher to probe issues as they arose. The approach is adopted from Berry et al. (1998) and Naim et al. (2002).

Case	Sector	Employees	Turnover	Network	Interviewees
A	Elevators and Escalators	44000	£3.83bn	1	Sales Manager, Operations Manager
B	Windows	30	£4.5m	1	Account Manager
C	Pre-cast Concrete	350	£230m	1	Account Manager, Operations Manager,
D	Roof Trusses	150	£8m	1	Operations Manager
E	Metalwork	20	£1.25m	1	Managing Director
F	Brickwork	234	£15.7m	1	Sales Executive, Divisional Director
G	Timber Frame Systems	1400	£420m	1	Sales Manager, Project Manager, CAD engineer
H	Doors	205	£22.5m	1	Operations Manager
I	Builders Merchant	10600	£2bn	1	Account Manager
J	Paint	67	£11.5m	2	Managing Director
K	Modular Bathrooms	425	£53.8m	2	Managing Director, Business Development Manager
L	Safety Systems	100	£14m	2	Chief Estimator

Table 2: Summary of the pipeline suppliers

Process maps were drawn up for each company visited with the help of company representatives. Input-Output diagrams were developed, showing key processes and enablers for these processes. The approach adopted was to investigate the perception of the top few problems. This provides focus on a limited number of key issues, and gives a valuable starting point for supply chain re-engineering. This was discussed in terms of ‘hot spots’ facing companies within the study, and offers some insight into difficulties experienced by organisations. When probing hot spots the focus was on ‘the pipeline’. Complete freedom was given to company executives on highlighting their pains. Interviewees were shown a generic process map of pipeline activities and asked to describe their top 3 problems across the pipeline. Once this was complete the research probed causes and potential solutions to these problems. Interview transcripts from the pipeline protocol were coded to identify the problems that most frequently occurred. All data from the study was then amassed and the hot spots were consolidated by the research team. The hot spots provided a useful means for developing themes fom the responses. The research team then used the emergent themes to develop a fishbone diagram to give richer insight. The tactics were identified via triangulation of interviews, process maps and observations during site visits. Once a list of tactics had been developed, the research team assigned linkages to principles.

5. Characterising typical pipeline problems

Based on the data collected, Figure 4 shows the eight most frequently cited pipeline ‘hot spots’ identified during the empirical work, along with an analysis of the root causes for these problems. Some of the causes, such as lack of collaboration and poor site management, are common across hot spots. Building upon this, Figure 5 shows the same problems in relation to generic pipeline activities with the different players that are involved at different points. It also shows which of the particular cases experienced this problem. It is worth noting that pipelines in project environments may operate under different constraints and conditions than those in high volume make-to-stock structures. Sanderson and Cox (2008), for example, argue that complex project environments introduce radical unpredictability into functional pipelines that should demonstrate stable demand patterns. Elfving et al. (2005) also found that project based pipelines have characteristics, such as competitive bidding, which pose significant challenges. Therefore, while pipelines been classified according to their structure using the decoupling point concept, we argue that the problems experienced in part flow from the project environment in which they operate within. Hence, the ETO project influences pipelines of various structures that supply into the project.

Problem 1 relates to *incorrect specification*. This can be the result of a combination of late changes made by the client, design errors, initial designs that are too vague, and suppliers receiving designs too late in the project to make any realistic contributions or react to any problems. Design changes that are made late in the pipeline can be particularly costly. Problem 2 is the suppliers' *inability to establish site readiness*. Due dates and delivery times are generally agreed upon early in the tender process. When suppliers are ready to deliver, the initial due date agreed is typically either too early or too late. If the supplier has poor visibility of site progress, or if the communication between the site management and supplier are poor, changes to the due date will not be registered.

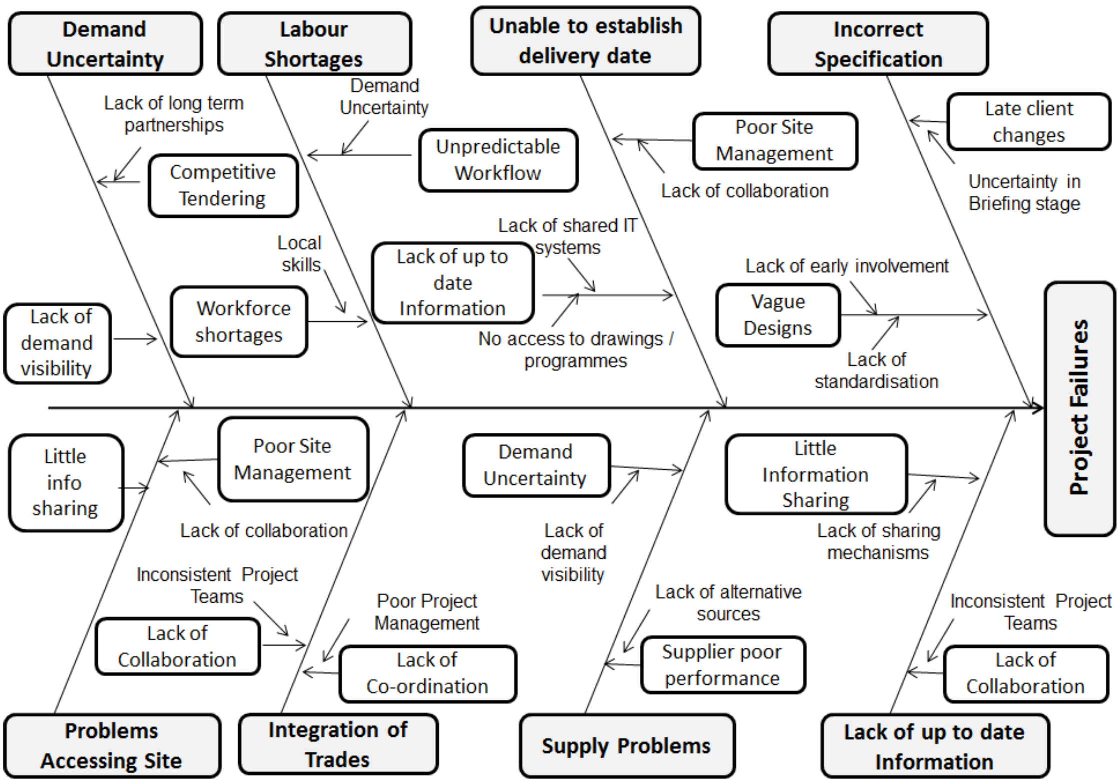
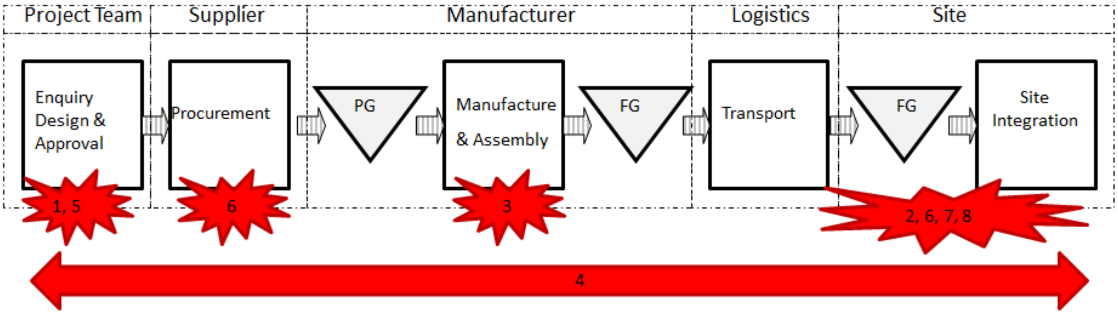


Figure 4: Root cause analysis for pipeline problems identified in study

The third problem identified is that of *labour shortages*. Many suppliers found labour shortages a major constraint for timely completion of tasks. For example, the elevator manufacturer found finding sufficient levels of labour for site installations very difficult, and the roof truss manufacturer found it difficult to recruit drivers for its in-house fleet and in finding local labour for the factory. Problem 4 relates to *information exchange*. Getting the correct information at the right time was perceived as a significant problem for pipeline activities. The paint subcontractor in the Pipeline J required 3 types of information to complete a project: programme details which include a start date, a schedule of works and a finishing specification. Typically, at least 1 of these pieces of information was not received early enough.

Two sources of uncertainty are covered by problem 5, *demand uncertainty*. Suppliers deliver to projects that vary in scope, scale and design requirements. Architects do not always have incentives to standardize elements of their designs, and product variations proliferate as a result. Further demand uncertainty is caused by the competitive tendering process. A network co-ordinator, typically, will send an enquiry out to a number of potential subcontractors for work packages and material supplies, selecting each project through a competitive tendering mechanism. Problem 6 is *supply problems* in relation to raw materials. The door manufacturer suffered from problems in global supply networks, as there were only a few specialist suppliers of specialist parts. Case L, the dry-lining supplier, was dominated by terms and conditions of the three big suppliers of dry-lining timber.



Key	Pipeline Hot Spot	Pipelines Experiencing Hot Spot					Example(s)
		BTO	MTO	ATO	MTS	Total	
1	Incorrect Specification	H, E	D, C	K	I	6	Pre cast supplier received incorrect specification for hole penetration points
2	Unable to Establish Site Readiness		B, C, D	A	F	5	Lift supplier unable to establish if the site is ready for delivery
3	Labour Shortages	L	D	A, K		4	Roof truss manufacturer shortage of drivers and factory workers.
4	Lack of up to date information		B, C, G		J	4	Paint subcontractor not given up to date schedule and specification information
5	Demand Uncertainty	E	D	A	I	4	Metalwork supplier unable to forecast workload accurately
6	Supply Problems	H, L	D			3	Drylining subcontractor subject to price and delivery changes by large suppliers.
7	Integration of trades		G	A, K		3	Timber frame manufacturer did not liaise with roof truss manufacturer
8	Access Issues		C	K		2	Pre cast supplier unable to get access to site every 4 hours for JIT deliveries.

Figure 5: Pipeline activities and main ‘hot spots’ identified in case studies

The seventh problem is *integration with other trades.* This is connected with the problem of establishing site progress, as frequently the activities of other trades are not completed on time and this delay is not communicated effectively. Fragmentation of the supply chain, inconsistent project teams and trades being ignorant of each others’ requirements is typical. Problem 8 relates to *Access Issues.* The challenge here is to plan access points and ensure clear access and an uninterrupted work area on site. If site work areas and access points are not managed to ensure materials can flow to required areas then access will become an issue for suppliers. These problems set out the foundations for a more thorough discussion of the FORRIDGE principles.

6. Supply chain principles, tactics and problems

During the empirical phases of the research, we have observed a range of tactics employed to help improve performance. These have been categorised using the FORRIDGE principles, helping to establish some of the lower level tactics that relate to each principle. Figure 6 shows the clustering. The linkages indicate the interconnectedness of the principles and enablers. The tactics are derived from the empirical investigation, but draws on existing theory to cluster and categorise. The principles are interrelated, and are underpinned by two key factors: training / learning, and supply chain integration. A 'vision' for each of the principles has also been included for each of the principles, thereby helping to conceptualise the ideal state to be achieved.

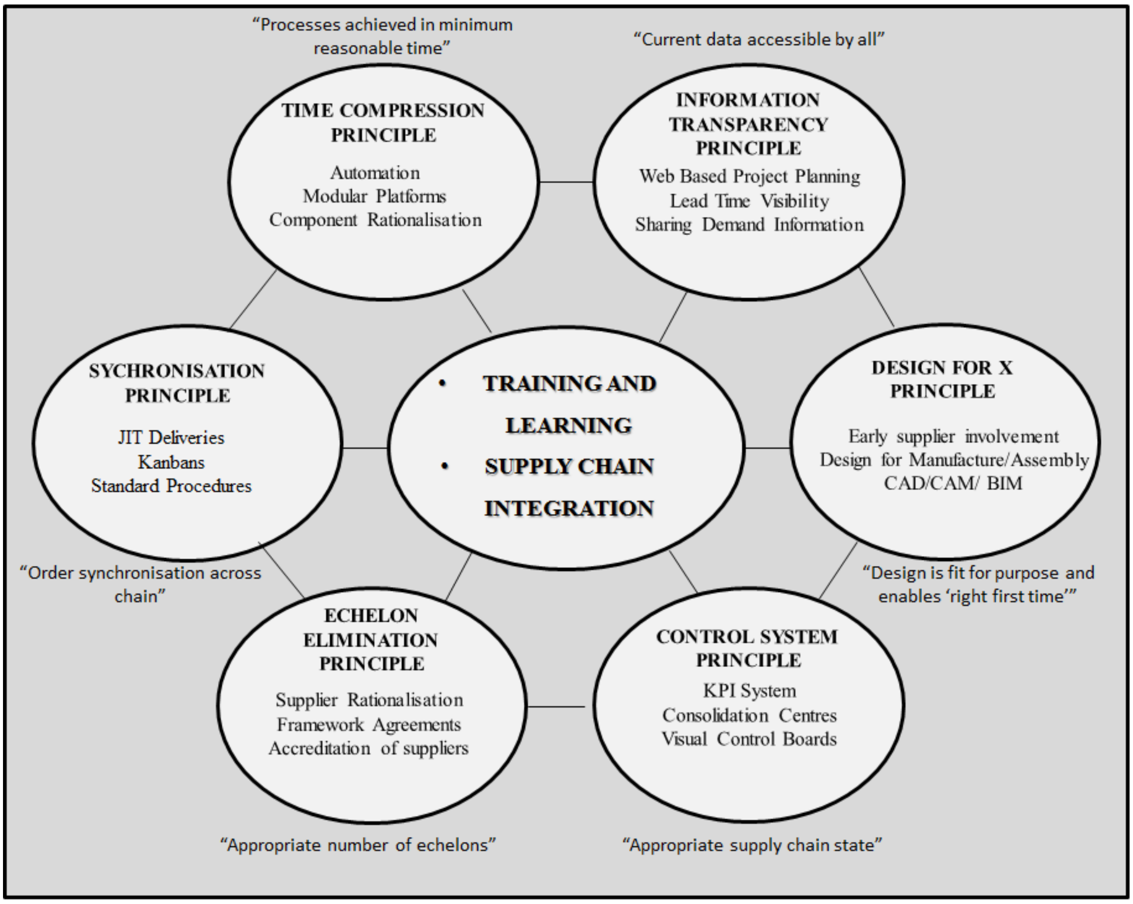


Figure 6: The six principles with observed construction sector tactics from case studies

The first group of tactics relate to *time compression*, where the focus is on reducing total cycle times and minimising the time needed to achieve task goals. The target here is ‘minimum reasonable time’. In practice, this means removing non-value added time or ‘muda’ from the system. It also means delivering on time what is actually required, and covers process capability. Component rationalisation and modular platforms are two techniques that were employed to compress cycle times. Modularity involves product configurations that are obtained by mixing and matching sets of standard components (Salvador *et al.* 2002). Company K, the modular bathroom manufacturer, used a modular base as a core, made from steel frame and wood panelling, with careful thought given to how this interfaces with different components. High specification bespoke finishes were then added. This approach combines the cost savings of generic standardised components with the service level of a customised finish.

Company A, the lift manufacturer, also used modular design principles. Standard components and interfaces are used across and between product groups to enable cross product architectures. Assembly kits were delivered flat pack and the kits could be assembled with minimal labour and time on the construction site. Automation has also helped to compress cycle times. The timber frame manufacturer referred to automation of its factory and state of the art machinery as key to reducing cycle times. This allows precision and standardisation in manufacturing and design. The timber for a standard sized house can be manufactured in 45 minutes. In addition, the company has also invested in compressing factory set up times through SMED techniques.

The next cluster of tactics relate to *information transparency*. Information sharing practices such, as vendor-managed inventory (VMI), give manufacturers access to more accurate demand information. The value of this type of information sharing has been established in many studies (Smaros *et al.* 2003).We argue that up-to-the minute data, free of bias, should be accessible by all members in the system. This simultaneously removes information delays, distortions and double-guessing. Inventories, specifications, work-in-progress, flow rates, and orders should be visible throughout the supply chain, making holistic control possible. As highlighted in the previous section, a common problem in the ETO context is the poor visibility of updated drawings and programmes. Solutions include information technology (IT) systems that facilitate visibility of project progress and good proactive communication between supply chain members. Techniques employed here were web-based project planning software. There was also evidence of sharing of lead-times and long term demand information disseminated through executive briefing sessions. If all companies get visibility of designs and project progress, as implied by the information transparency principle, then incorrect specification will be much less likely. Network co-ordinator 2, for example, held executive briefing sessions for its strategic suppliers to give them full visibility for prospective work

In the Forrester (1961) simulations, all events are *synchronised* so that orders and deliveries are visible at discrete points in time. Tactics here include JIT deliveries from supplier onto the site. For example, the manufacturer of pre-cast concrete delivers products at 4 hour intervals ready for immediate installation into the site activities. Labour availability, a clear working area, and specialist equipment are all then needed to manoeuvre the pre-cast blocks into place. Kanbans are also used to signal production activities. . Standard operating procedures were occasionally observed in the case studies, but it was noted that they are very difficult to implement in such a dynamic environment, particularly at the system integrator level. The next steps here would be more sophisticated RFID and ‘track and trace’ systems to make material flow completely transparent.

Tactics also relate to *control systems* for the supply chain. There is a need to facilitate and select the most appropriate, integrated control system to achieve user targets (Burbidge 1959, Dejonckheere *et al.* 2003b). In turn this will necessitate accessing important supply chain states thus taking unnecessary guesswork out of the system. This includes putting in place robust decision support systems, and performance management systems, as well as work load control (Bertrand and Muntslag 1993). There was evidence that KPI systems are being implemented, with the larger contractors (Systems integrators) implementing project KPI measurement systems, and manufacturers adopting their own internal measures. In some cases these were displayed on visual control boards, both onsite and on the factory floor. A different approach is the use of consolidation centres or strategic stockholding points so that stock can be held and deliveries controlled to ensure that the site is ready to accept deliveries. Traditional forecasting systems using demand smoothing were not widely adopted, largely due to the perception that project demand is too complex to apply such algorithms.

The next cluster of tactics relate to the principle of *echelon elimination.* This original posit behind this principle was there should only be the minimum number of echelons appropriate to the goals of the supply chain (Towill 1997). The aim is not only to have the optimum resources and inventory, but to have these at the right time at the right place. This principle needs further clarification for ETO project industries, where very often the majority of suppliers are non-make-to-stock and are configured for the needs of a particular project. For ETO companies, the challenge is to reduce the number of handovers and interfacing issues. Therefore long and unwieldy chains of companies should be avoided. This is being done through supplier rationalisation, and framework agreements, whereby suppliers are categorised into those that are strategic, preferred and approved, each category having different collaborative opportunities and activities.

The next group can be described as *'Design for X'* (DFX) tactics, where careful account of manufacturing, logistics and assembly during the design phase (Boothroyd 1994). This is a new addition to the principles which we argue is crucial for the ETO context. Some of the companies in the study have been promoting the early involvement of suppliers in the design process. This allows active contribution and input before important design decisions are made. In the case of timber frame manufacturers, the company espoused the "partnership opportunity curve", which was articulated in company documents. This suggests that if the manufacturer is only involved in the construction phase of a project, or shortly before the start of construction, there is limited opportunity to add value. If the manufacturer is involved early on during planning approval, tender issue and project design stages, then it can advise on appropriate specification, cut costs, contribute to buildability, design out waste and minimise design risk and error. Design for manufacture principles can be embedded from an early stage. Computer Aided Design (CAD), and the more recent Building Information Modelling (BIM), software can help all stakeholder contribute early in the process.

We argue that two important factors are central to all these principles. The first is *supply chain integration* (Stevens 1989). Optimisation of the whole supply chain is considered to achieve better performance than a string of optimised sub-systems. Collaborative mechanisms should be put in place to facilitate this, which result in better interface management, decision making and management of trade-offs and disputes. For example, we have observed cluster workshops, whereby network co-ordinators host ‘supplier clubs’ to bring suppliers together to discuss problems, solutions and better ways of working.

The second underpinning factor is *Learning and Training* (Senge 1990). As previously mentioned, the ‘loose coupling’ of ETO systems often favour short term productivity while hampering education and learning (Dubois and Gadde 2002a). By getting the couplings right, it may be possible to form a situation whereby the right kinds of knowledge transfer and flows can be brought about to support the enactment of the principles. In this way integration and learning are interlinked. Possible solutions observed here include training schemes to develop local labour and flexible labour models through combinations of in-house and outsourced labour, and team working initiatives to encourage discussion between related trades.

A synthesis to bring together the different elements of the paper is shown in table 3. It maps the real world problems identified from the case studies against supply chain tactics and principles. We have indicated the potential links by adding darker blocks, which signify a strong linkage between problem and principles, and the lighter shaded blocks, which show moderate links between the two. The table illustrates the complex interaction between different tactics and principles required to solve real world problems. Information transparency and DfX tactics appear to have the most comprehensive applicability to real world problems identified in this paper. It is important to note that further empirical work would help to substantiate these relationships. We would also encourage researchers and practitioners not to be constrained by the tactical interpretation of the principles presented here. In particular, the principles of ‘design for X’ have much wider applicability beyond early supplier involvement and DFM suggested herein.

Real World Problems ↑ / Tactics →	*Automation*	*Modularity*	*Component Rationalisation*	*Web Systems*	*LT Visibility*	*Sharing Demand Information*	*Early Supplier Involvement*	*DFM*	*CAD/CAM/BIM*	*KPI Systems*	*Consolidation Centres*	*Visual Control Boards*	*Supplier Rationalisation*	*Framework Agreements*	*Supplier Accrediation*	*JIT Deliveries*	*Kanbans*	*SOPs*
Incorrect Specification			░	■		■	■	■	■	░		░			░			■
Establishing Site Readiness				■								░				░	░	
Labour Shortages	■				■	■	░									░		
Lack of up to date info				■	■	■			░			■						
Demand Uncertainty		░		░	░	■								░				
Supply Problems				░	░	░	■	■		■	■	░	■	■	■	░	░	
Integration of trades		░		■		■	■	░		░			░	░	░			■
Access Issues							░		░		■							
Principles	*Time Compression*			*Information Transparency*			*Design for X*			*Control System*			*Echelon Elimination*			*Sychronization*		
Summary for each Principle	■ = 1 ░ = 3			■ = 11 ░ = 5			■ = 6 ░ = 5			■ = 4 ░ = 5			■ = 3 ░ = 5			■ = 2 ░ = 5		

Key: ■ = *Strong Linkage*; ░ = *Moderate Linkage*; (blank) = *Weak/no Linkage*

Table 3: Applicability of principles and tactics to the problems identified

7. Discussion and Conclusion

Since the original FORRIDGE principles were published, they have been shown elsewhere to offer core contributions to bullwhip reduction, and to contribute towards achieving the seamless supply chain ideal. The goal of this paper was to investigate which supply chain management principles and tactics should be adopted, or adapted, for engineer-to-order industries, such as construction, capital goods, shipbuilding and complex components. We conclude that the FORRIDGE principles apply to a wide range of supply chain types, including the ETO situation, but the extent and criticality varies. In the cases included in this paper, information transparency and DfX principles were identified as the most widely applicable. Tactical interpretations of the principles may even require tailoring to the individual supply chain. A framework was proposed to consider the derivation of supply chain management principles as adapted for the ETO sector. It highlights that the FORRIDGE principles for the make-to-stock sector can trace their origins to systems thinking, but these principles can be adapted for the specific context of ETO supply chains. At the tactical level, these principles may be interpreted differently across the range of ETO industries, such as construction. Through extensive case study investigation, eight real world problems were highlighted, and later these were matched with the principles and tactics.

Investigation of the FORRIDGE principles results in an enriched framework. The paper adds detailed insight into how the original principles may be conceived in an ETO environment. A further 'design for X' principle was also added to original principles. This is crucial for the ETO supply chain, where companies have to engage in new designs for each customer. This integrates a well established concept in the design engineering literature with the FORRIDGE principles, thereby expanding and strengthening the principles for use in the ETO sector. In addition, the inclusion of the two central enablers contributes to the development of a comprehensive framework for a supply chain design and operation. Implementing the two enablers and the six principles effectively offers considerable opportunity for competitive advantage for those companies willing to invest. In this way, the paper provides guidance on how to address some of the structural problems outlined in the challenging setting of the ETO sector. While the principles and enablers are described in previous individual studies, this paper provides value for practitioners by integrating them in a holistic and easily understood way.

The important contributions made in the paper are the synthesis of established principles for the ETO sector, and the framework for deriving these principles. To our knowledge, this is the first time the FORRIDGE principles have been investigated in a non-make-to-stock sector.. This is of considerable interest to scholars interested in such supply chains, addressing a long standing debate of the extent to which generic supply chain management thinking should be adopted. We acknowledge that the empirical elements of this paper inevitably have limited claims to generalisability, but we do seek to generalise to a new theoretical position to address some of the failings and problems outlined in ETO industries. Care should also be taken in generalising these findings from the construction sector to other ETO situations. The empirical limitations could be addressed through further research using different research methods, and additional research in other ETO sectors. In particular, the linkages between problem, tactics and principles summarised in table 3 would benefit from wider empirical enquiry. While we believe the FORRIDGE principles described are a powerful guiding set of principles, we leave it to future researchers and research projects to evaluate the sufficiency of the six principles, as well as their application across different market sectors.

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