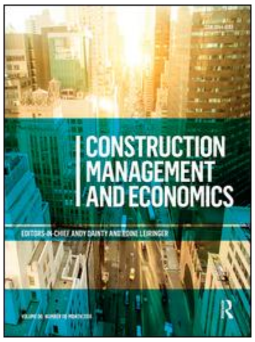

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Simulating the impact of supply chain management practice on the performance of medium-sized building projects

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Construction supply chains encompass the flows of materials, labour, information, plant, equipment and temporary works that originate from a variety of different parties. The impact of various supply chain management practices on project performance has been measured, through a combination of a survey and the development of simulation models. Preliminary investigations were carried out by visiting two medium-sized building projects regularly over a period of six months to gain an understanding of the ways in which delays on supply chains impact on project performance. This was followed by the main survey which was designed to collect data required for developing the simulation models. These models were developed using Pertmaster Risk Expert^{TM} software and incorporated supply chain delays applied to a CPM network of a typical medium-sized building project of 300 days' duration. The results of the simulation showed that the project's median delay was 67 days (22% of the project duration). The use of subcontractors in the project reduced this delay by approximately 45%. It was also learned that delays in material flow caused the biggest impact on the project, followed by labour flow, information flow and 'plant, equipment and temporary work' flow. These findings are an important measure of how much supply chain delays impact on project performance.

Keywords: Supply chain management, supply chain delays, project performance, simulation, risk.

Background

While supply chain management (SCM) in the manufacturing industry has developed and been widely understood for a number of decades, in the construction industry this approach is a much more recent area of interest. People in construction, i.e. clients, contractors, suppliers and subcontractors, are still exploring what SCM is, how it works to increase competitive advantage and what are its dynamics (Arbulu and Ballard, 2004).

Supply chains in the construction industry can be very complex. Large numbers of subcontractors and suppliers may be involved, especially in a large-scale project. In a construction project, any delay of the materials delivery may have knock-on effects on delaying the works and, if they are critical, the project will likely be delayed as a consequence. The same situation will also happen for the late completion of the subcontractors' works. At a corporate level, the number of parties involved in the supply chain may increase to thousands for the whole year.

Current research related to SCM in a construction context is looking at the issues of: relationships between contractor, subcontractor and supplier (Kadeforsi, 1999; Greenwood, 2001; Kale and Arditi, 2001), subcontractor and supplier selection (Kumaraswamy and Matthews, 2000), organizational perspectives/network alliances in SCM (London, 2001; Love *et al.*, 2002), just-in-time (JIT) practice (Akintoye, 1995; Tommelein and Li, 1999; Tommelein and Weissenberger, 1999), construction processes (Nicolini *et al.*, 2001; Roy *et al.*, 2003), industrial/economic perspective of SCM (London and Kenley, 2001), communication and information technology in SCM (Marsh and Finch, 1999; Edum-Fotwe *et al.*, 2001; O'Brien, 2001), risks in SCM (Tah and Carr, 2001), partnering (Larson,

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1995; Bresnen and Marshall, 1999; Briscoe *et al.*, 2001; Packham *et al.*, 2003; Greenwood, 2005), costs (O'Brien, 1997) and the roles of clients in SCM (Briscoe *et al.*, 2004), etc. There has, however, been little research to date on the impact of SCM practice on construction site performance, and this opens up an opportunity and provides justification to conduct research on this topic.

The impact of various supply chain management delays on project performance and the scope are defined as follows:

(1) This study focuses on supply chain management practice and project performance at the construction project site level, and not at the organization level or industry level.
(2) Project performance is considered as it relates to time only, and not to cost or quality.
(3) The data used for the simulation models were obtained from the main survey within the context of a typical medium-sized building project in the United Kingdom.

The key objectives are:

(1) To conduct an in-depth analysis of SCM practice on construction sites.
(2) To understand how supply chain management practice impacts on project performance.
(3) To produce models with various scenarios that simulate the impact of SCM practice on project performance.
(4) To use the model to test the sensitivity of the project performance to alternative SCM practice.

A most straightforward definition from O'Brien and Fischer (1993) is adopted for this research with some refinement as follows: supply chain management is the system where suppliers, contractors and clients/architects work together under the coordination of the main contractor to produce, deliver, install and utilize information, materials, plant, temporary works, equipment and labour and other resources for construction projects.

The main contractor, as the key coordinator of the project, has a strategic position to manage all the project stakeholders and resources along the supply chains. To be able to deliver the project in time, within budget, and with a defined level of quality, the main contractor has to manage delays or disruptions along the flows in the supply chains properly.

Flows and delays in construction supply chains

A typical construction supply chain involves the flow of information and the flow of materials (Vrijhoef and Koskela, 2000). Cox and Ireland (2002) widen this concept by including material supply chains, labour supply chains and equipment supply chains as additional components of construction supply chains. This view is in line with Muya *et al.* (1999) who categorize construction supply chains into three types: the primary supply chain, the support chain and the human resource supply chain. The primary supply chain delivers the materials that are incorporated into the final construction product, for example, raw materials, components, sub assemblies and mechanical and electrical equipment. The support chain provides equipment, expertise and materials that facilitate construction, for example falsework and framework, excavation supports, scaffolding, temporary works related to operation of equipment, site access. The human resource supply chain involves the supply of labour and the supervisory staff as inputs to the construction process. For the purposes of this research, these flows were summed up and simplified into four, i.e. the flows of materials, labour, information, 'plant, equipment and temporary work'. They will now be discussed individually.

Information flow

In construction, information is communicated between parties along the supply chains and exists in the form of documentation such as drawings, specifications, conditions, explanations and clarifications, which become the basis of activities in the project (Edum-Fotwe *et al.*, 2001).

For a project to be successful, the information flow across the supply chain must be timely and well organized. Delays in information flow may cause slow decision-making for all project teams, which was identified as one of the main delays in construction projects by Chan and Kumaraswamy (1997). Sharing information between the supply chain members is seen as the key for effective supply chain management, although it is admitted that this is not easily done due to project complexity and the large number of participants in the construction supply chain (Titus, 2005).

Material flow

On receiving orders from the contractor, suppliers begin to deliver materials to the project site at agreed times. The materials could be delivered all at once or when the site needs them. Based on the types of material, the delivery process of materials can further be classified into three types, i.e. delivery chains of customized materials, standard materials and small purchases (Wegelius-Lehtonen and Pahkala, 1998).

Causes of delay in material flow are closely associated with the quality of the material management. Thomas and Sanvido (2000) concluded from a case study of three projects that poor material management has a significant impact on labour efficiency and schedule delays, and found that labour productivity was reduced by more than 50% and the activities took 50% to 130% longer than expected.

Labour flow

As most construction projects are labour intensive, managing labour flow is vital to success. From empirical research on three projects, Thomas *et al.* (2003) concluded that ineffective labour flow is responsible for 58% of the total inefficient work hours. Delays in the construction project related to labour factors include: labour shortages, low skill levels, weak motivation and low productivity (Chan and Kumaraswamy, 1997).

Plant, equipment and temporary work flow

Plant, equipment and temporary works are another important determinant of the efficiency and cost effectiveness of delivery of construction products (King and Hudson, 1985). The provision of temporary works, which is the responsibility of the contractor, facilitates plant and labour to perform their duties efficiently and safely (Illingworth, 2000). Plant and equipment are often used in a harsh construction environment, and sometimes can be undersized or oversized, as the proper-sized plant or equipment may not be available, which in turn can affect the frequency of maintenance (Thomas *et al.*, 2003). Some factors which are identified to cause delay in this flow, include: shortages, low efficiency, breakdowns and wrong selection (Chan and Kumaraswamy, 1997).

Roles of subcontractors in construction supply chains

Subcontractors play an important role in achieving a reliable flow of work in a project, as they help the main contractor by carrying out specialist works. It is not uncommon for as much as 90% of a construction project to be subcontracted (Matthews *et al.*, 2000) and consequently subcontractors may contribute as much as 90% of a main contractor's turnover (Ndekuri, 1998).

Subcontractors' early involvement in a project allows them to gain a better understanding of the project itself and helps the overall relationship with the main contractor, which promotes trust and team working between parties (Matthews *et al.*, 1996). It should be noted that a good relationship between main contractors and subcontractors has been considered to be a great strategic asset for both of them (Kale and Arditi, 2001). These factors show the important position and contribution of subcontractors to the main contractor and to the success of the project.

Research methods

The research methods adopted comprised preliminary investigations, a main survey and the development of simulation models, as will be explained below.

The preliminary investigations

The preliminary investigations were carried out by having regular visits to two medium-sized building projects over a period of six months to understand supply chain management practice in construction in a real life situation and its impact on the project. These were one-floor school building projects with budgets of £2.5–£3 million. Through the regular visits, much was learnt by adopting a process of immersion in the supply chain activities on the projects. Useful lessons were obtained through direct observations, interviews, examination of project documents, attending project meetings, etc. It was found from one of the projects visited that approximately 70% of the delays were related to supply chain issues and the remaining 30% arose from natural causes. It was also found on one site that there were 30 delays out of 39 (77%) information requests from the contractor to the client, which ranged from two days to 20 weeks. From these visits, particular types of problems and delays on sites related to supply chain management practice were identified. For example, there was late information regarding the design and specifications of the roof lights and windows from the architect, which caused delays in placing an order for the materials and hence delayed the work. Delays also occurred when a window glass was damaged on arrival on site due to careless handling by a worker, and it took several days to get a replacement. Another delay occurred when plasterers took several days off to finish work on another project, which could indicate that this particular skill was in high demand. These were useful examples from real life situations, and helped to reinforce the understanding of how problems with the supply chain can impact on project performance. A specific CPM network with a 300-day duration was obtained from one of the projects visited (Figure 1 and Table 1) and this became the basis of the generic CPM network later used in the simulation model.

The main survey

The main survey was intended to collect data required for developing simulation models. Questionnaires were used for this survey to obtain a wide response from practitioners in the construction industry and were developed using the inputs obtained from the literature review and the preliminary investigations, where many examples of supply chain delays were obtained. In

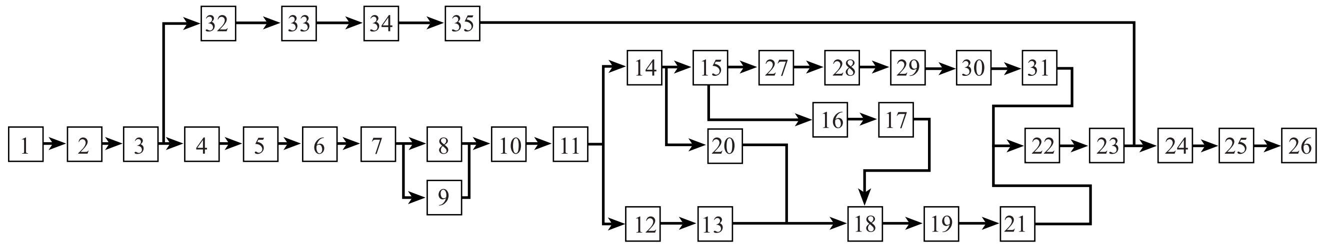


Figure 1 CPM network of a typical medium-sized building with 300-day duration

Table 1 Activities in the CPM network and their durations (days)

No.	Activities and durations	No.	Activities and durations
1	Start = 0d	19	Joinery works = 20d
2	Site establishment/fencing (precast) = 15d	20	M & E installations = 50d
3	Form access road and reduce level = 10d	21	2nd fix electrical = 10d
4	Construct foundations = 15d	22	Decoration = 25d
5	Erect structural steel frame = 10d	23	Furnishing = 5d
6	Substructure brickwork = 15 d	24	Fixtures and fittings = 5d
7	Concrete floor slab = 15 d	25	Test and commission = 10d
8	Superstructure brickwork = 25d	26	Finish = 0d
9	Insulation = 20d	27	IPS framework/panelling/vanity units =18d
10	Roof joist/framework = 20d	28	Plumbing/sanitary ware = 20d
11	Roof coverings = 15d	29	Shower cubicles = 5d
12	Fascias and soffits = 9d	30	Wall tiling-shower/toilet AREAS = 20d
13	Windows and doors = 15d	31	Vinyl flooring = 5d
14	Floor screed = 10d	32	Drainage works = 35d
15	Suspended ceilings grid-tiles = 15d	33	Edge kerbing = 10d
16	Floor tiling = 20d	34	Stone up and bitmac footpaths = 10d
17	Partitions = 20d	35	Landscaping = 20d
18	Plasterwork = 10d		

general, the questionnaire asked the respondents to identify specific examples of delays in the construction supply chain that were likely to occur on a typical medium-sized building project site and to indicate, in percentage terms, how often these delays would occur, to represent the probability of occurrence, and to indicate the extent of the impact if they did occur. The extent of the impact was represented by three values, i.e. minimum, most likely and maximum, to define a distribution that could be used in the simulation. The following is a typical example of the questions in the questionnaire, 'Which materials would typically be delivered later than the scheduled date?', 'How often would this occur?', 'When these delays did occur, please estimate their duration (minimum, most likely and maximum)'. To give the respondents a context to help them respond, a picture of such a building project was shown in the questionnaire.

Table 2 gives examples of the typical questions included in the mail survey. The supply chain delays were classified based on the flows identified in the construction supply chains, i.e. information flow, material flow, labour flow and equipment/plant/temporary work flow.

Of the 105 questionnaires distributed to contractors specializing in building projects in the United Kingdom, a response rate of 22% was obtained. The respondents were site managers (53%), project managers (30%), quantity surveyors (13%) and building managers (4%), with an average of 22 years' experience in the industry. With such a profile of respondents, the information gathered was considered to be reliable, as the respondents had been involved in many projects and had a good understanding of the industry.

The simulation models

The simulation models consisted of a generic CPM network of a typical medium-sized building project, which was obtained from one of the projects visited, and supply chain delays, which were obtained from the main survey. This simulation allowed different supply

Table 2 Typical questions from the mailshot questionnaire survey

Construction supply chain flows	Questions to ask	Probability of occurrence	Extent of SC delays (days)		
			min	most	max
Information flow	Activity affected by delays of information flows?	…%	…	…	…
Material flow	Typical material to be delivered late?	…%	…	…	…
	Typical material delivered with the wrong specifications?	…%	…	…	…
	Typical material delivered with insufficient quantity?	…%	…	…	…
	Typical material delivered damage on arrival?	…%	…	…	…
	Typical material difficult to obtain in the market?	…%	…	…	…
Equipment/plant/ temporary work flow	Typical equipment/plant/temporary work in shortage?	…%	…	…	…
Labour flow	Typical skills in shortage during construction period?	…%	…	…	…
Workflow (subcontracted work)	Typical work to be subcontracted?	…%	…	…	…

chain management practices and their impact on project performance to be examined. Pertmaster Risk Expert^{TM} was used to produce and run the simulation models. This is Monte Carlo-based project risk management software, which allows probabilistic risks to be inserted into a CPM network and then simulates outcomes to learn their impact on the project.

Assumptions used in the model

In an attempt to reduce the complexity of the simulation model and to fulfil the aims of the simulation, some assumptions were made, as follows:

(1) The durations of activities in the CPM network are deterministic, meaning that each activity has only a single duration. The implication of this is that for each activity, it is assumed that a late start will cause a late finish. It is, of course, recognized that the durations of activities in a realistic simulation are subject to variation, but fixing activity duration in this way is very important, as it allows the model to show the impact of supply chain delays on the project which otherwise would not be clearly identified.

(2) Delays were assumed statistically independent, which means that the occurrence probabilities and the lengths of delays are independent of one another.

(3) The frequency of occurrence of the delays is as defined by the respondents and the extent of the delays follows a distribution defined by the three values of minimum, most likely and maximum, also as reported in the questionnaire results. A beta distribution was used, as this type of distribution is argued to be suitable for representing activity durations in construction (AbouRizk and Halpin, 1992).

(4) Resequencing of activities is not allowed. In practice, when delays occur causing an activity to be unable to start on time or to stop for a period, the site manager might decide to start other activities instead. To be able to clearly show the impact of supply chain delays on the project, however, the current version of the model has no opportunity for such rescheduling. The implication of applying this assumption is that the results of the simulation could be slightly inaccurate when compared to the real project. They could be overstated, as the assumption neglects the opportunity of avoiding delays by managing the sequence of activities in the network. On the other hand, they could also be understated, as in practice, the opportunity of resequencing of activities, if not handled properly, may result in out-of-sequence executions of activities and other collateral effects which in turn create an even longer delay.

(5) The main contractor is responsible for delays related to material flows and equipment/plant/temporary work and labour flows. For this reason, they may also be called the main contractor delays. Information delay is assumed to be the responsibility of the client.

(6) For all subcontracted work, it is assumed that there is only one delay, called the subcontractor delay. This delay, assumed to be the responsibility of the subcontractor, basically encompasses the main contractor delays, i.e. delays related to material flows and equipment/plant/temporary work and labour flows. For subcontracted work, the information delay remains as the responsibility of the client.

(7) The materials for an activity are needed on the first day the work commences. For example, it is assumed that the bricks are needed from the very first day of the brickwork activity. Hence, any delay with the bricks' delivery obviously will delay the start date of the brickwork.

Connecting supply chain delays to relevant activities in the model

To build the simulation model, the data on supply chain delays obtained from the survey was synchronized with relevant activities in the CPM network. For this purpose, a matrix of the supply chain delays and activities was developed, as shown in Table 3. The supply chain delays (top rows) need to be connected to the relevant activities in the CPM network (first column on the left). For example, bricks were identified in the survey as one of the materials which could be a source of delay, as they were likely to be delivered late (ML4), delivered with wrong specifications (MW2), delivered with insufficient quantity (MI1), damaged on arrival (MD4) or difficult to obtain in the market (MO2). Bricklayers (L1) were also identified in the survey as one potential delay, as this skill was likely to be in short supply. Clearly, activities in the project which use these materials and skill could be affected as a consequence. In this case, *Substructure brickwork* (activity number 6) and *Superstructure brickwork* (activity number 8) are the two activities which use these materials and skill, hence they were connected with these delays.

Combining delays

On a real project, several delays can occur and impact on an activity consecutively or simultaneously, as the following examples illustrate. A package of material was delivered later than the scheduled date (delay A). When it arrived, it was damaged due to careless handling on site (delay B). Since it took several days to get the replacement material, the work using the material could not start on time. Another example to illustrate delays occurring simultaneously is as follows: The bricks were expected to be delivered on site at a particular time, which did not happen (delay A), while at the same time the bricklayers were not available on site to do the work (delay B). The brickwork could not start on time as a consequence.

Figure 2 below shows that the delays which occur consecutively can be modelled by positioning them in series, while those which occur simultaneously can be positioned in parallel. The implication is that for the delays positioned in series, the total delay is simply the sum of each delay, while for the delays positioned in parallel, the total delay is the longest of each separate delay. The supply chain delays were assumed to occur consecutively to represent the worst case scenario, hence they were positioned in series, as shown by Figure 3. Positioning delays in this way allows the maximum impact of the supply chain on the project to be examined, although it should be recognized that as the frequency of occurrence of most delays was quite low, most passes in the simulation would only have one delay effective, at most.

In general, more than 60% of these delays are connected with activities on the critical path. Clearly, delays on the critical path will be more likely to cause delay to the project than those on non-critical paths. Although it is possible that delays on non-critical paths may become critical during the simulation and may cause delay to the project, the percentage of time an activity appears on the critical path during the simulations (the criticality index), as shown in Figure 4, shows that the majority of the activities on the original critical path were critical for all of the simulations. This means that for the typical CPM network used for this simulation, delays on the original critical path are likely to determine whether or not the project will be delayed.

The scenarios

To understand the impact of supply chain delays on the project, two main scenarios were tested, as shown in Table 4 below. Scenario A is when all work is carried out by the main contractor and scenario B is when subcontractors are used in the project. In scenario A, the supply chain delays from the four flows were applied all together (model 1), or one at a time (models 2 to 5) to learn how the project is affected by them as a whole or partially. Scenario B was used to understand the impact of supply chain delays with the involvement of subcontractors in the project. This was done by incorporating the subcontractor delays into activities which normally are carried out by specialist contractors. In this way the effect of subcontractor delays on the project can be identified.

The results

The simulation models were run 20 000 times, and the results converged with less than 0.01% variation. This level of convergence is more than adequate, as with

Table 3 Connecting supply chain delays to activities in the CPM network

Activity	Information flow	Material flows					Plant/ equipment/ temp workflow	Labour flow	Workflow
	Activities affected by information delays (I)	Materials delivered later than scheduled delivery dates (ML)	Material delivered with wrong specifications (MW)	Insufficient quantity of materials delivered (MI)	Materials damaged on arrival (MD)	Difficulties in obtaining materials in the market (MO)	Plant/ temporary work in shortage (P)	Skills in shortage during construction (L)	Subcontractor delays (S)
1									
2		ML3 (10%,3,6,10)						L8 (11%,1,3,6)	
3	I1 (38%,4,11,22)								S1 (38%,4,11,22)
4	I2 (16%,3,8,12)		MW3 (15%,1,2,3)	MI2 (6%,1,1,2)				L9 (10%,2,4,7)	S2 (16%,3,8,12)
5	I4 (39%,5,9,14)	ML1 (9%,3,5,8)					P1 (11%,3,6,15)	L6 (16%,3,5,13)	S4 (39%,5,9,14)
6		ML4 (8%,2,5,11)	MW2 (9%,4,7,15)	MI1 (15%,3,6,11)	MD4 (6%,10,13,16)	MO2 (14%,7,12,18)		L1 (26%,5,9,16)	
7		ML2 (7%,2,4,7)	MW3 (15%,1,2,3)	MI2 (6%,1,1,2)				L9 (10%,2,4,7)	
8		ML4 (8%,2,5,11)	MW2 (9%,4,7,15)	MI1 (15%,3,6,11)	MD4 (6%,10,13,16)	MO2 (14%,7,12,18)	P2 (25%,3,7,11)	L1 (26%,5,9,16)	
9								L1 (26%,5,9,16)	
10		ML6 (10%,3,6,10)	MW4 (6%,4,10,12)				P1 (11%,3,6,15)		
11		ML6 (10%,3,6,10)	MW4 (6%,4,10,12)				P2 (25%,3,7,11)	L7 (16%,2,4,7)	
12			MW5 (12%,6,7,13)	MI3 (16%,2,5,8)			P2 (25%,3,7,11)	L7 (16%,2,4,7)	
13	I7 (31%,4,7,11)	ML5 (16%,4,7,13)	MW1 (6%,7,12,35)		MD1 (7%,9,15,27)				S7 (31%,4,7,11)
14									
15	I3 (11%,4,7,12)				MD3 (7%,3,6,10)				S3 (11%,4,7,12)
16	I3 (11%,4,7,12)					MO5 (20%,1,12,36)			S3 (11%,4,7,12)
17	I3 (11%,4,7,12)							L2 (28%,4,7,11)	S3 (11%,4,7,12)

Table 3 (*Continued*)

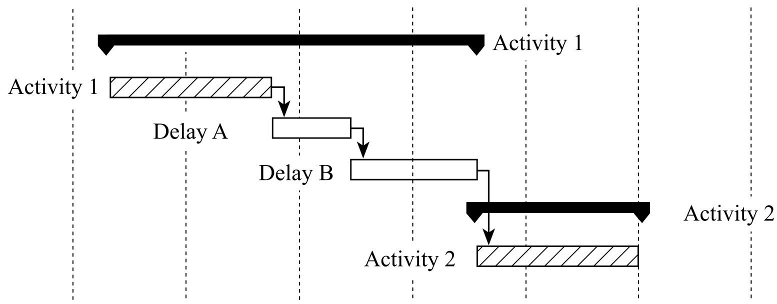
Activity	Information flow	Material flows					Plant/ equipment/ temp workflow	Labour flow	Workflow
	Activities affected by information delays (I)	Materials delivered later than scheduled delivery dates (ML)	Material delivered with wrong specifications (MW)	Insufficient quantity of materials delivered (MI)	Materials damaged on arrival (MD)	Difficulties in obtaining materials in the market (MO)	Plant/ temporary work in shortage (P)	Skills in shortage during construction (L)	Subcontractor delays (S)
18								L3 (27%,4,8,13)	
19	I6 (43%,4,8,18)					MO6 (10%,4,10,14)		L2 (28%,4,7,11)	S6 (43%,4,8,18)
20								L5 (28%,4,9,13)	
21								L5 (28%,4,9,13)	
22	I3 (11%,4,7,12)								S3 (11%,4,7,12)
23	I3 (11%,4,7,12)			MI4 (21%,6,9,15)		MO3 (32%,4,7,18)			S3 (11%,4,7,12)
24	I5 (55%,5,9,14)					MO1 (38%,9,15,46)		L2 (28%,4,7,11)	S5 (55%,5,9,14)
25									
26									
27								L4 (28%,4,8,13)	
28								L4 (28%,4,8,13)	
29					MD2 (5%,6,10,15)				
30	I3 (11%,4,7,12)					MO5 (20%,1,12,36)			S3 (11%,4,7,12)
31	I3 (11%,4,7,12)								S3 (11%,4,7,12)
32	I1 (38%,4,11,22)			MI5 (23%,4,5,8)	MD5 (6%,2,3,4)			L8 (11%,1,3,6)	S1 (38%,4,11,22)
33								L8 (11%,1,3,6)	
34	I1 (38%,4,11,22)							L8 (11%,1,3,6)	S1 (38%,4,11,22)

Table 3 (*Continued*)

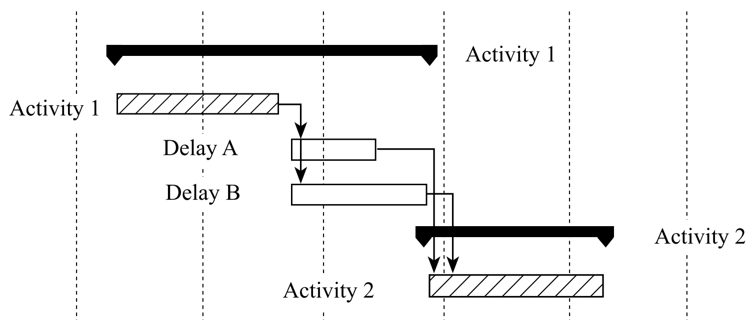
Activity	Information flow	Material flows					Plant/ equipment/ temp workflow	Labour flow	Workflow
	Activities affected by information delays (I)	Materials delivered later than scheduled delivery dates (ML)	Material delivered with wrong specifications (MW)	Insufficient quantity of materials delivered (MI)	Materials damaged on arrival (MD)	Difficulties in obtaining materials in the market (MO)	Plant/ temporary work in shortage (P)	Skills in shortage during construction (L)	Subcontractor delays (S)
35	I1 (38%,4,11,22)							L8 (11%,1,3,6)	S1 (38%,4,11,22)

Notes:
I1 = Ground works, I2 = Foundation, I3 = Finishes & decoration, I4 = Steelwork, I5 = Fixture & fittings, I6 = Joinery / Ironmongery, I7 = Windows & doors, ML1 = Steel frame, ML2 = Steel reinforcement, ML3 = Precast concrete element, ML4 = Bricks/blocks, ML5 = Windows & doors, ML6 = Roofing materials, MW1 = Windows & doors, MW2 = Bricks/blocks, MW3 = RM Concrete, MW4 = Roofing materials, MW5 = Timber, MI1 = Bricks/blocks, MI2 = RM Concrete, MI3 = Timber, MI4 = Furniture, MI5 = Drainage, MD1 = Windows & doors, MD2 = Shower cubicles, MD3 = Ceiling, MD4 = Bricks/Blocks, MD5 = Drainage, MO1 = Fixtures & fittings, MO2 = Bricks (special), MO3 = Furniture, MO4 = Claddings, MO5 = Tiles, MO6 = Joinery (special), P1 = Crane, P2 = Scaffolding, L1 = Bricklayers, L2 = Joiner, L3 = Plasterer, L4 = Plumbers, L5 = Electrician, L6 = Steel work erectors, L7 = Scaffolders, L8 = Labourer, L9 = Concrete gang, S1 = Ground works, S2 = Foundation, S3 = Finishes & decoration, S4 = Steelwork, S5 = Fixture & fittings, S6 = Joinery / Ironmongery, S7 = Windows & doors.

In the above example, ML4 (8%,2,5,11) means material 4 (bricks) has 8% of probability to be delivered late, with the extent of delays of 2 days minimum, 5 days most likely and 11 days maximum.



(a) Delays affecting activity 1 which occur consecutively, modelled in series



(b) Delays affecting activity 1 which occur simultaneously, modelled in parallel

Figure 2 Combining delays

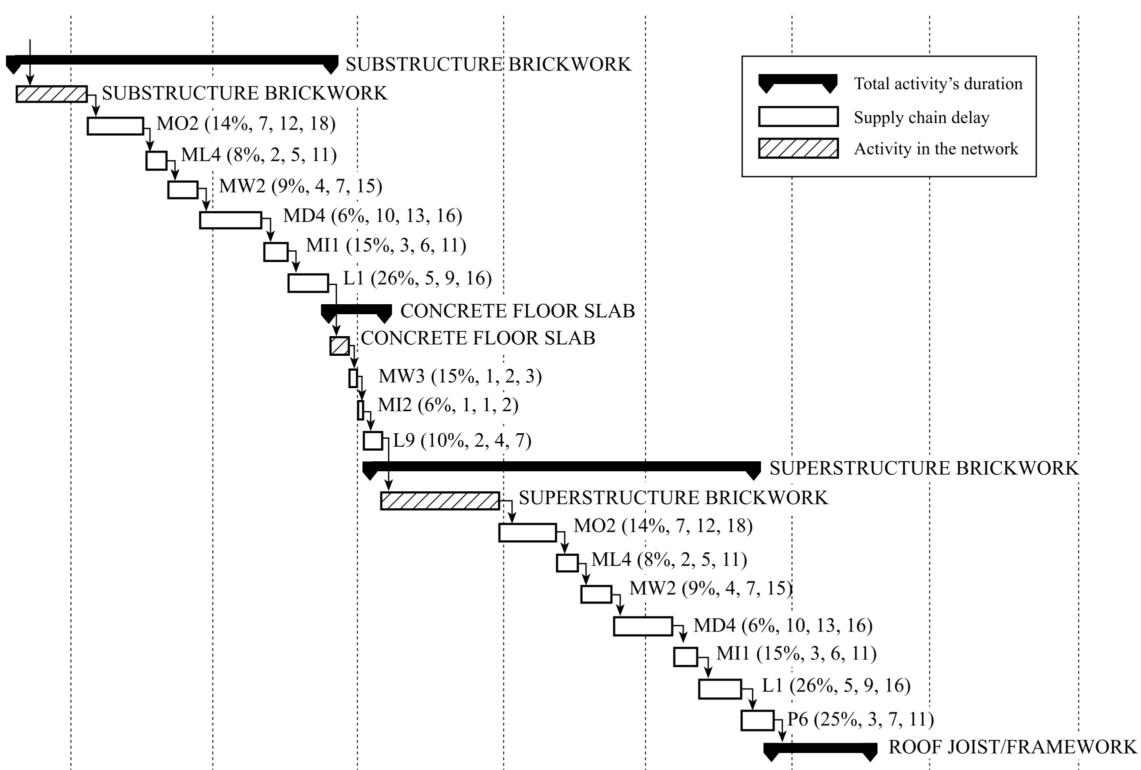


Figure 3 Example of the series positions of the supply chain delays on the network to represent the worst case scenario and to examine the maximum impact of the delays on the project

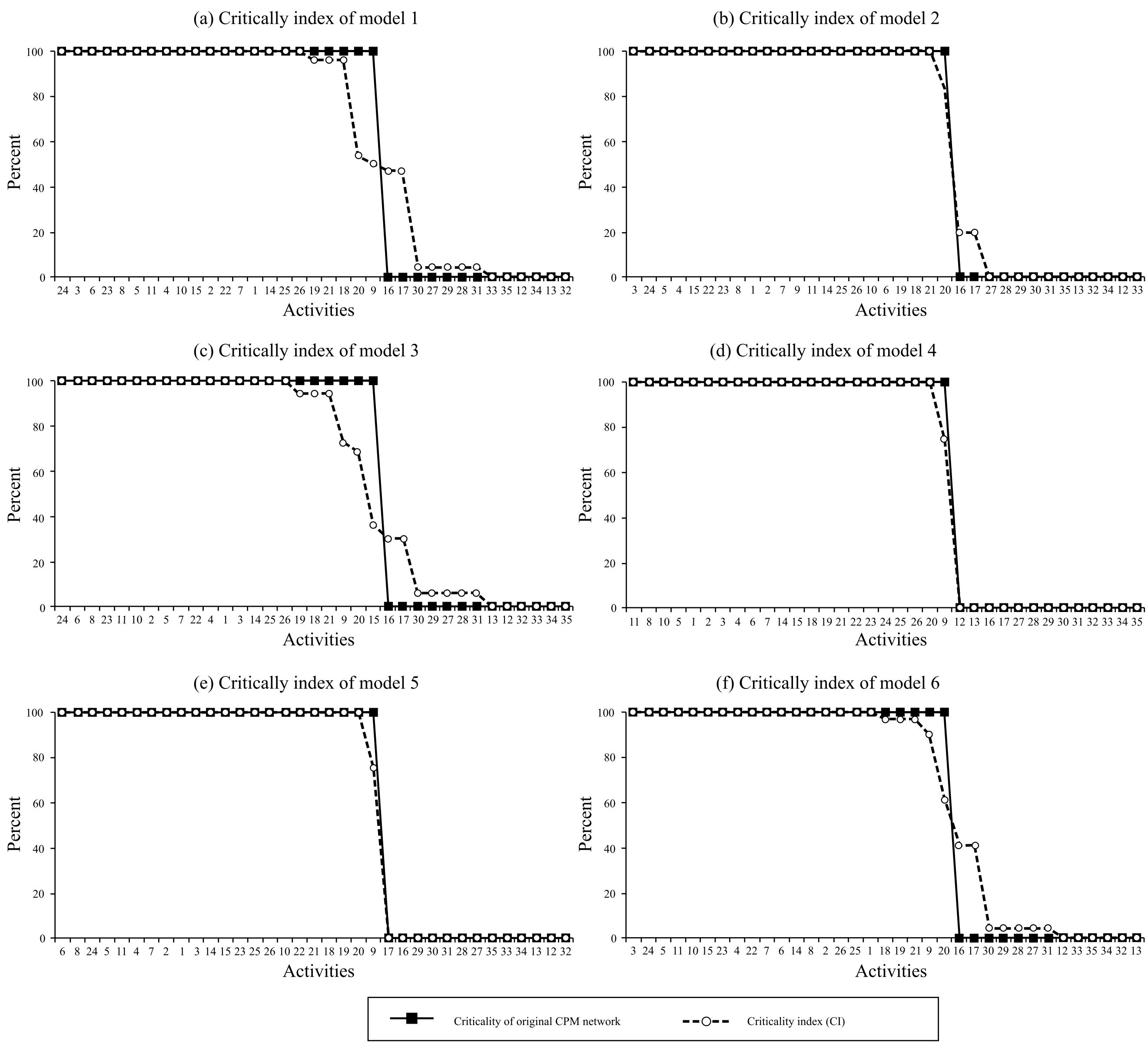


Figure 4 The criticality index of activities in the network

such low variation, it can be said that the mean project duration effectively remains constant for 20 000 consecutive iterations. Figure 5 shows the results of the simulation (rounded to integers), which use the median to represent the frequency distribution of the extent of delays on the project. To give an idea of how this single duration can actually vary, the duration with a 10% chance of being exceeded is also included. It can be seen that when all the work is carried out by the main contractor, with all possible supply chain delays related to information flow, material flow, ‘plant, equipment and temporary work’ flow and labour flow (model 1), the project’s median delay was 67 days (equivalent to 22% of the project duration), with a 10% chance of exceeding 96 days (equivalent to 32% of the project duration).

When the supply chain delays were applied one at a time (models 2 to 5), the extent of median delays ranges from 5 to 25 days (equivalent to 2% to 8% of the project duration). Material flow has the biggest impact on the project with median delays of 25 days and a 10% chance of delaying the project by 48 days (equivalent to 16% of the project duration). Delays due to the labour flow and the information flow were not significantly different, i.e. 19 and 17 days (both were equivalent to 6% of the project duration), with a 10% chance of exceeding 35 and 32 days (equivalent to 12% and 11% of the project duration). Finally, the lowest impact was due to

Table 4 Scenarios to be tested

	Models	How SC delays were applied in the model	What can be learnt
	(1) All	All SC delays were applied at once	The total impact of SC delays on the project
A	(2) Info	Only SC delays related to information flow was applied	The impact of individual SC delays on the project
	(3) Material	Only SC delays related to material flow was applied	
	(4) Plant	Only SC delays related to plant/equipment/ temporary work flow was applied	
	(5) Labour	Only SC delays related to labour flow was applied	
B	(6) All+S/C	All SC delays together and all subcontractor delays	The impact of SC delays with the involvement of subcontractors

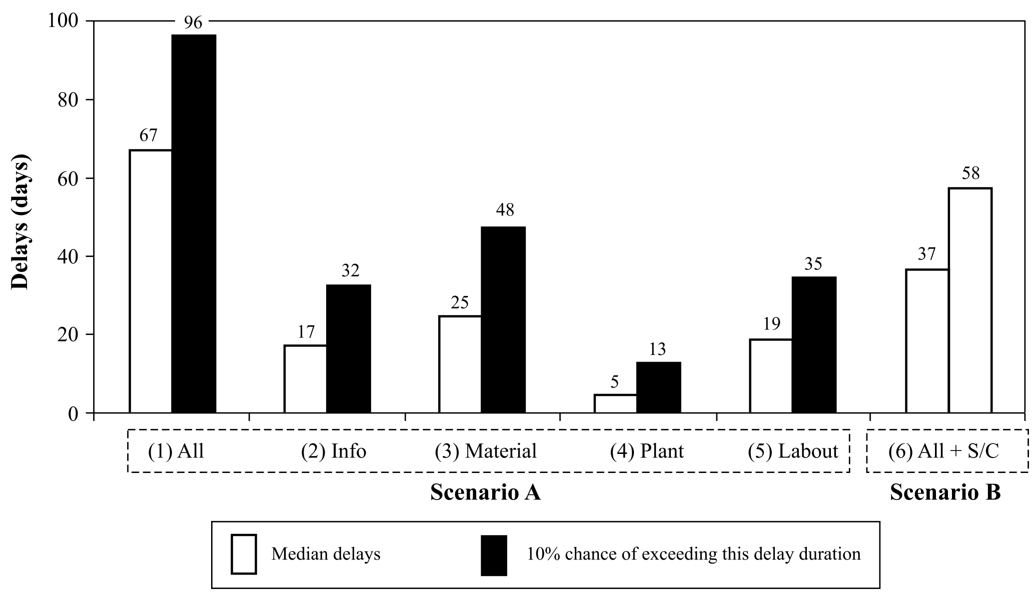


Figure 5 Results of the simulation: the extent of supply chain delays on project duration

problems related to 'plant, equipment and temporary work' flow of 5 days (equivalent to 2% of the project duration), with a 10% chance of delaying the project by 13 days (equivalent to 4% of the project duration).

When subcontractors were used as much as possible and the rest of the activities were carried out by the main contractor (model 6), the project's median delay was 37 days, (equivalent to 12% of the project duration), with a 10% chance of exceeding 58 days (equivalent to 19% of the project duration).

Discussion and analysis

In general, the findings provide important measures of how much various supply chain management practices may impact on project performance. It is believed that this is the first time that the impact of supply chain delays on project performance has been quantified and the results clearly show that problems related to the supply chain in construction are likely to generate significant disruption to the project. The implication of these findings is that the main contractor needs to be aware of how to identify and cope with these problems, which in most contracts would be categorized as the main contractor's responsibility, apart from delays in information flow, which are likely to be the responsibility of the client. If the delays are not properly managed, the main contractor may have to pay liquidated damages should the project not finish on time. To manage these supply chain delays better, the main contractor has to focus particularly on those supply chain delays with the biggest impact on the project, either by making allowances in the programme, by monitoring their durations and acting when necessary, or more likely both.

The results of the simulations suggest that the biggest impact on the project was due to delays in material flow, followed by labour flow, information flow and 'plant, equipment and temporary work' flow. Of course, this ranking is true for the selected project and might be assumed to be similarly true for other such projects (medium-sized low-rise buildings). For other types of project, the contribution of these flows to the performance of the project may have to be revisited.

The project's median delay due to supply chain delays in the material flow is 25 days, with a 10% chance of delaying the project by 48 days. This finding is consistent with the fact that in a typical building project, there are likely to be hundreds of different kinds of materials to be used in the project. The kinds of materials in this type of project can be very complicated, especially when compared to typical civil engineering projects (e.g. roads, bridges, dams) where only a few different types of materials are needed, but in large quantities. All in all, the complexity of the material flow can clearly become a large problem in such a typical building project.

As with material flow, labour flow also poses a significant problem to the project with a median delay of 19 days and 10% chance of exceeding 35 days. In this typical building project, there are many work items with various types of materials which require specific skills from the workforce, e.g. bricklayers, plasterers, joiners, plumbers, etc. Referring back to the survey results, it can be seen that joiners, plumbers and electricians are among the top skills with a high probability of shortages during the construction period (28%), while concrete gangs and labourers are among the skills with the least probability of a shortage (10% and 11%). It should be borne in mind that for other types of projects, where a smaller variety of skills is needed, (e.g. civil engineering projects), the results might be different.

At the time this data were obtained in the UK, January to April 2006, it was reported that there had been a lack of skills in construction in the UK (CIOB, 2006). It was also reported that many foreign workers from eastern Europe had filled this demand which could not be filled by local labour. All in all, the simulation results represent this situation and show that labour flow is one of the significant factors that can impact on project performance. Hence, it should become the main contractor's prime concern after material flow.

Delays in the information flow rank third in terms of the extent of impact on the project, with the project's median delay of 17 days (equivalent to 6% of the project duration), and a 10% chance of exceeding 32 days (equivalent to 11% of the project duration). These figures are just slightly lower than the extent of impact due to delays in the labour flow. Problems in information flow include obtaining information, approvals and drawings, from a client or architect. This can be a very critical problem, since an activity often cannot start without them. Quite often, these problems are beyond the main contractor's capability to control, unlike the problems in material flow, where the main contractor can use his superior position over suppliers when they do not perform well. With information flow, the main contractor is dependent on others to provide the information needed. It should be recognized, however, that in contractual terms, a contractor is likely to be able to claim for extra costs and time for this type of delay, whereas all the other supply chain delays in the model are typically at the contractor's risk.

Among the four flows, 'plant, equipment and temporary work' flow seems to have the least impact on project performance. These low results can be understood as this study was carried out for a typical school building project, which in nature do not require a lot of heavy plant, temporary work nor large-scale earthmoving. These results may also suggest that there are no significant problems regarding the supply of plant, equipment and temporary work in the industry for such typical projects. It should be noted that for larger scale building projects or for other types of projects, such as civil engineering work, where a lot more plant, equipment and temporary work are needed, the impact could be much higher.

The models show that subcontracting as much as possible of the work that is normally subcontracted resulted in a 45% reduction of delays to the project when compared with the scenario where all work is carried out solely by the main contractor. These findings suggest that subcontracting work which is normally subcontracted can benefit the main contractor. They may also justify the general practice of subcontracting large amounts of work in building projects as a way of reducing the risks of project delays. In such projects, there is a lot of specific work which needs special equipment and expertise. Subcontractors are the ones who usually have the resources and expertise to carry out such specific work most efficiently. Their experience of undertaking the same work over the years makes them more specialized, efficient and cost-effective and gives them greater control of possible delays. For this reason, although a main contractor may have the resources to carry out the work itself, it may not be the best option to do so. Once work is subcontracted, a subcontractor is responsible for finishing it. From the risk management perspective, it can also be seen as a way of transferring as well as sharing risks between the main contractor and its subcontractors. In addition, while the temporary nature of the project may cause the main contractor difficulties in finding the right local suppliers for its project, the local subcontractors may already have their own suppliers who have worked with them for years. All these, in turn, may reduce the risks of experiencing delays on the project.

While this study suggests that subcontracting works offers many benefits, there are factors related to subcontracting which need attention from the main contractor, such as: unclear responsibility of work, lack of control over schedule and quality, possible legal disputes and loss of know-how. It is also understood that main contractors in some countries are limited by rules, which set the limits on the portion of subcontracting costs and prevent core activities from being subcontracted. These factors may cause the potential benefits of subcontracting works in projects to be difficult to achieve.

Conclusions

A model to quantify the impact of supply chain delays on the performance of a building project has been produced. This model provides an important measure of how much supply chain delays may impact on project performance, suggesting that problems related to the supply chain in construction are likely to generate significant disruption to the project. The findings also reinforce the view that using subcontractors can improve the performance of projects and gives some quantification of the benefits. As the research design made it essential that a specific project type be adopted, the results are true for the selected project and might be assumed to be similarly true for other such medium-sized building projects. It should be recognized that factors such as complexity of construction, types of materials, use of plant, and extent of subcontracting will mean that other types of project will be affected differently by supply chain delays. Nevertheless, a platform is provided for future investigations of the impact of supply chain delays on projects that are different in their nature and characteristics.

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