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Construction Supply Chain Modeling: Issues and Perspectives

2.1 Introduction

Over the last two decades, most manufacturing firms have recognized supply chain management (SCM) as a new way of doing business. The implementation of this new approach was a consequence of various changes in manufacturing environments, such as development of information technology (Internet), globalization, and sophisticated customers who demand increasing product variety, lower cost, better quality, and faster response. Competition is shifting from firm versus firm to supply chain (SC) versus SC [Vonderembse et al. 2006; Min and Zhou 2002]. Successful firms such as Wal-Mart and Dell Computer have survived and achieved a high level of performance through organizing, planning, and controlling a SC as a whole.

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Construction Supply Chain Management Handbook

SCs are very complex systems for which final performance depends upon a combination of hundreds of decisions made by multiple independent firms. Because there are so many decision variables to assess, models and tools have been developed to support decision making and help practitioners realize the effect of their local decisions on the whole SC performance. Different modeling approaches used in the manufacturing context include, for example, spreadsheet-based inventory and mathematical programming models (e.g. linear and integer programming), discrete event simulation models [Kleijnen 2005], game theory, and decision support systems that utilize the Internet, data mining, and geographical information systems [see Min and Zhou 2002 for a complete review of SC modeling perspectives]. An early case application of a modeling tool for SC decision support is described by Davis (1993). In his paper, Davis shows a successful implementation of SC modeling at Hewlett-Packard, where risk and variability modeling help to optimize inventory levels and locations in a global SC.

In recent years, especially during the last decade, the construction industry has also recognized the importance of SCM to improve the performance of projects [O’Brien 1998; Vrijhoef and Koskela 2000]. As in the manufacturing context, construction companies are facing increasing competition and customers are requiring lower costs, higher quality, shorter execution durations and more reliable schedules.

Initial research has shown how complex and ineffective construction SCs are. To reach these conclusions, researchers had to develop SC models using tools developed for the manufacturing context to guide their assessment. These models, usually studied in an ad hoc manner, generated useful knowledge about modeling production in construction. However, this knowledge is not yet structured in a manner that helps researchers and practitioners interpret and utilize a wide body of existing tools and techniques.

This chapter aims to provide a structured approach to SC modeling in construction. The authors review key concepts and perspectives in modeling SC production, including the definition of manufacturing SC capabilities, decisions, and technologies in Section 2.2. Section 2.3 focuses on the characterization of construction SCs and provides an overview of existing tools and techniques for construction SC modeling. A detailed description and analysis of extant models enable us to identify modeling types, variables, and metrics that support the identification of gaps. Section 2.4 presents a structured approach to modeling construction SCs based on the gaps identified in Section 2.3. First, a conceptual framework is presented to link SC models’ purposes with models’ attributes. Building from the conceptual framework, a structured approach to defining construction SC models is detailed.

2.2 Perspectives and Concepts of SC Production Modeling

2.2.1 SC Capabilities and Decisions

The literature on SCM presents many similar definitions for SCs [see Bechtel and Jayaram 1997]. In this chapter we use the definition provided by the Committee on Supply Chain
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Integration [National Research Council 2000], which describes a SC as “an association of customers and suppliers who, working together yet in their own best interests, buy, convert, distribute, and sell goods and services among themselves resulting in the creation of a specific end product.”

A typical SC may involve a variety of stages including raw material (RM) and component suppliers, manufacturers, distributors, and customers [Chopra and Meindl 2004]. One or more companies, geographically dispersed, may be involved at each stage, for example, a manufacturer—in general the focal company—may receive material from several suppliers and then supply several distributors. Figure 2.1 shows the structure of a typical manufacturing SC.

A SC is complex, dynamic and involves the constant flow of information (forecast, orders, schedules, etc.), material (components, end products, etc.), and funds between different and independent stages. The appropriate management of these flows is required in order to respond to customers’ expectations and keep SC costs at an adequate level.

Understanding of customers’ expectations and SC uncertainty (demand and supply) that a company faces is essential for developing the right capabilities or abilities to serve its markets. A SC may need to emphasize either its responsiveness or efficiency capabilities, depending on a set of final product characteristics and expected performance.

A responsive SC is able to deal with a wide range of quantities demanded, meet short lead times, handle a large variety of products, meet a very high service level and handle supply uncertainty. However, there are many costs associated with responsiveness. This

FIGURE 2.1 Structure of a typical SC. (Adapted from Lambert et al. 1998)

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increase in cost leads to the second capability, which is efficiency. SC efficiency is the cost of making and delivering a product to the customer. The higher the costs, the lower the SC efficiency. Chopra and Meindl (2004) and Hugos (2006) presented a list of questions that support the identification of SC characteristics and consequently its required capabilities:

- Do customers want small or large quantities of products?
- Do customers expect quick service or is a longer lead time (time from order to the delivery of the product) acceptable?
- Do customers look for a narrow and well-defined bundle of products or a wide selection of different products?
- Do customers expect all products to be available for immediate delivery or are partial deliveries acceptable?
- Do customers pay more for convenience or do they buy based on the lowest price?

SC capabilities of responsiveness and efficiency are results of decisions made about five SC drivers [Hugos 2006; Chopra and Meindl 2004]. The right combination of these decisions determines the capabilities of a SC:

- Production: what products does the market want? How much of which products should be produced and by when?
- Inventory: what inventory should be stocked at each stage in a SC? How much inventory should be held as RMs, work in process, or finished goods (FG)?
- Location: where should facilities for production and inventory storage be located? Where are the most cost efficient locations for production and for storage of inventory? Should existing facilities be used or new ones built?
- Transportation: how should inventory be moved from one SC location to another? When is it better to use which mode of transportation?
- Information: how much data should be collected and how much information should be shared? Timely and accurate information holds the promise of better coordination and decision making.

Table 2.1 summarizes the characteristics of responsive and efficient SCs based upon these decision drivers.

Such decisions are made at different time periods and frequencies. The next section discusses a SC decision framework that provides a perspective on how these decisions can be categorized.

### 2.2.2 Categories of SC Decisions: A Hierarchical View Decision Framework

Chopra and Meindl (2004) presented three SC decision categories based on the frequency with which they are made and the time frame over which a decision has an impact. The categories are the following: SC strategy, SC tactical planning, and SC operation. Strategic decisions are typically made for the long term, such as SC configuration, location
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and capacities of production and warehousing facilities, and modes of transportation to be made available along different shipping legs.

The SC tactical planning involves a set of operating policies within which a SC will function over a period of time. Tactical decisions include inventory control, production and distribution coordination, material handling, and order and freight consolidation.

At the operational level, the SC configuration is considered fixed and planning policies are already defined. The time horizon is weekly or daily and decisions deal with operational routines such as workforce scheduling, vehicle routing and scheduling, material replenishment, and packaging. The goal of SCM at the operational level is to reduce uncertainty and optimize SC performance given the constraints established by the configuration and planning policies.

The following scenario provides an example of these three categories [adapted from Mathur and Solow 1994]. A steel manufacturer produces two types of steel (high- and low-grade) at its two plants in the United States. One plant can process up to 1200 tons per year and the other, more modern and with lower processing costs, can produce at most 600 tons. These plants receive orders from the United States, Mexico, Korea, and Brazil. The RM (iron ores) are supplied by two American mines. The managers have collected data on purchase costs, ore shipping costs, processing costs at plants, demand per customer, and steel shipping costs. They face strategic, tactical, and operational decisions.

In the above scenario, these are examples of strategic decisions: Is it necessary to build another plant to fulfill the global demand? Should that plant be located in Asia or South America? How much high-grade and low-grade steel should be produced in each plant per year? Will it be necessary to build any warehouses in Brazil? Should steel be transported overseas by air or by ship?

Managers of the steel manufacturer are also supposed to make tactical decisions such as: deciding how much ore to order from the mines each quarter, adjusting the manufacturing capacity of each plant based on short-term demands from each market, finding

| TABLE 2.1 Characteristics of Responsiveness and Efficient Supply Chains (from Hugos 2006) |
|-----------------------------------------------|-----------------------------------------------|
| Decision Drivers                             | Responsive SCs                                 | Efficient SCs                                  |
| Production                                   | Excess capacity                               | Little excess capacity                         |
|                                               | Flexible manufacturing                        | Narrow focus                                  |
|                                               | Many smaller factories                        | Few central plants                             |
| Inventory                                    | High inventory levels                         | Low inventory levels                           |
|                                               | Wide range of items                           | Fewer items                                   |
| Location                                     | Many locations close to customers             | A few central locations serve wide areas      |
| Transportation                               | Frequent shipments                            | Few, large shipments                          |
|                                               | Fast and flexible mode                        | Slow, cheaper modes                           |
| Information                                  | Collect and share timely, accurate data       | Cost of information drops while other costs rise |

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alternatives to consolidating orders from Mexico and Brazil to reduce shipping costs, and coordinating shipping schedules with customers’ needs.

Finally, these are examples of operational decisions: Determining how many days or shifts per week each plant will produce, determining which routes are faster to ship to each customer, and determining how many tons of steel can be shipped in each delivery.

Mathematical optimization models based on linear and integer programming have been widely used to solve such complex decisions. However, while mathematical modeling is important, a qualitative understanding of SC configuration and concepts is needed because the complexity of these decisions cannot be fully represented mathematically. Knowledge of issues regarding SC configuration can facilitate, for example, the identification of potential supply risks that optimization programs might not handle, and also support the decisions to achieve the required SC capabilities. In the following section, some of these basic concepts and issues are described.

### 2.2.3 Issues in SC Configuration

Knowledge of a SC configuration—each individual firm, processes and products, as well as interfaces among different firms—can provide preliminary qualitative insights about overall SC performance and risks.

Manufacturing environments vary greatly with respect to their process structure, that is, the manner in which material moves through the plant [Hopp and Spearman 2000]. Hayes and Wheelwright (1979) classified manufacturing environments by process structure into four categories: job shops, batch, assembly line, and continuous flow.

- **A job shop environment typically produces low-volume and highly customized products.** Each product is usually of an individual nature and requires interpretation of the customer’s design and specifications. In a job shop, small batches are produced with a high variety of routings through the plant. The batch size refers to the number of units of a particular product type that will be produced before beginning production of another product type. Thus, the outputs differ significantly in form, structure, materials, and processing required.

- In the batch environment, firms provide similar items on a repeated basis, usually in low volumes. For this reason, many processes are repeated, creating a smoother flow of work-in-process (WIP) throughout the shop, although many of the characteristics of job shop production are retained.

- **Assembly line is the appropriate process for products with high demand.** The same operations are executed for each production run in a standard and usually automated flow and all products are very similar. Automobile production is a classic example of line flow processes.

- Finally, the continuous flow process encompasses a continuous product flow automatically down a fixed routing. This process is used to produce highly standardized products in extremely large volumes (e.g., refinery products). They are often characterized as a commodity.

A product–process matrix summarizes this description, presenting the associations between manufacturing processes and product types (Figure 2.2). SCs are usually
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<table>
<thead>
<tr>
<th>Process structure vs. product type</th>
<th>Low volume (one of a kind)</th>
<th>Low volume (multiple products)</th>
<th>Higher volume (standardized product)</th>
<th>Very high volume (commodity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job shop</td>
<td>Job shop</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Batch</td>
<td>Batch</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assembly line</td>
<td></td>
<td>Assembly line</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous flow</td>
<td></td>
<td>Continuous</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 2.2** Product–process matrix. (After Hayes and Wheelwright 1979)

Comprised of firms located in all different quadrants of this matrix. Therefore, this matrix can be used as a tool to provide an initial evaluation of SC capability.

In our example of the steel manufacturer, the RM suppliers provide iron ores (commodity), which will be transformed into steel by two plants (assembly-line process structure). Once the two types of steel are produced, they are shipped to their final destination. The capacity of each plant is 1200 and 600 tons of steel per year. Capacity or maximum throughput rate is defined as the maximum quantity of output (tons) that can be processed per unit of time (year). These plants produce the two types of steel in long production runs, and one of them has capacity limitations, thus any rush order has a high probability of delivery delay. This is due to the lack of flexibility of these types of plants to include an additional order in the long production run cycles and also the lack of capacity. Such brief descriptions of products and process characteristics—based on the configuration of the steel SC and the matrix evaluation—has provided an initial qualitative insight into SC risks.

Other SC risks are the consequence of the occurrence of variations that appear to be out of one’s control—variability. According to Davis (1993), the three sources of variability that may affect SCs are supplier performance, the manufacturing process itself (e.g., process type as well as machines reliability), and customer demand. In the steel manufacturer scenario, customer demand is fairly stable, the older plant presents higher variability due to old machinery, and delivery performance to Brazil and Korea are much more variable than deliveries to the United States and Mexico due to overseas shipments.

To mitigate these risks, derived from the firms’ characteristics and SC overall variability, managers can locate buffers at strategic locations of the chain. Buffers are resource cushions used to protect the production system against variability or resource starvation. There are three different types of buffers: inventory, capacity and time [Hopp and Spearman 2000]. Inventory buffers are material stockpiles of RM, WIP, or FG. Capacity buffers are extra available capacity that may be used in case production falls behind schedule. Time buffers are extra time embedded in schedules to deal with potential variations. In our scenario, customers in Brazil and Korea need to store much more steel (inventory buffer) than customers in the United States and Mexico. Otherwise, these customers are highly exposed to the risks of delay caused by overseas transportation. Another strategy...
that could be adopted by these customers is the inclusion of time buffers in the procurement schedule—ordering the steel well in advance. As for the capacity buffer, the plant that has the higher capacity to produce steel can be utilized to fulfill unexpected demands of the plant that has limited capacity in certain months of the year.

Another concept related to buffering is the decoupling point, which is a strategic stock that buffers the SC from changes in customer demand, in terms of both volume and variety [Naim, Naylor, and Barlow 1999]. The decoupling point differs between product groups (Figure 2.3). Starting with the most upstream location of a decoupling point we have engineered-to-order (ETO), followed by made-to-order (MTO), assembled-to-order (ATO), and then made-to-stock (MTS) products. In the steel SC, the steel plants can mass produce the two types of steel and keep them stored to better respond to variations in local and global demand. However, inventory is a source of cost and the manufacturer needs to judge how much to hold. Another example of such a concept is presented by Walsh et al. (2004). These authors discuss the strategic positioning of inventory in the SC for stainless steel pipes.

This section of the chapter has covered fundamental concepts, different decisions, and phases involved in the configuration of manufacturing SCs. The modeling of production in this context is supported by a structured framework that comprises a set of SC capabilities, categories of decisions to achieve them, and the different phases during which these decisions should be made. The following section addresses these issues in the construction industry scenario.

### 2.3 Review of Modeling Approaches for Construction SCs

The modeling of construction SCs is a subject that has been mainly investigated since the early 1990s. The goal is to explore how manufacturing concepts can be transferred
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to the construction context in order to improve production efficiency and reduce project costs. Initial case study descriptions and partial implementation have been reported by many researchers, especially those associated with the International Group for Lean Construction (IGLC). Their findings have shown insightful solutions or suggestions for improvement which demonstrate the usefulness of modeling production beyond the boundaries of construction sites.

However, construction industry characteristics differ substantially from the manufacturing SCs presented in the previous section of this chapter. Recent publications [see Vaidyanathan and O’Brien 2003; Green, Fernie, and Weller 2005; London and Kenley 2001] have investigated the application of manufacturing SC concepts in construction and have highlighted differences and opportunities. We summarize some of the key differences in Table 2.2. These are useful for understanding the difficulties in applying SCM concepts in construction as well as illustrating how some SC practices, such as buffering and capacity planning, are distinct between these contexts.

### TABLE 2.2 Manufacturing vs. Construction SCs

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Manufacturing SCs</th>
<th>Construction SCs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>Highly consolidated</td>
<td>Highly fragmented</td>
</tr>
<tr>
<td></td>
<td>High barriers to entry</td>
<td>Low barriers to entry</td>
</tr>
<tr>
<td></td>
<td>Fixed locations</td>
<td>Transient locations</td>
</tr>
<tr>
<td></td>
<td>High interdependency</td>
<td>Low interdependency</td>
</tr>
<tr>
<td></td>
<td>Predominantly global markets</td>
<td>Predominantly local markets</td>
</tr>
<tr>
<td>Information flow</td>
<td>Highly integrated</td>
<td>Recreated several times between trades</td>
</tr>
<tr>
<td></td>
<td>Highly shared</td>
<td>Lack of sharing across firms</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td>Slow</td>
</tr>
<tr>
<td></td>
<td>SCM tools (factory planning and scheduling, procurement, SC planning)</td>
<td>Lack of IT tools to support SC (no real data and workflow integration)</td>
</tr>
<tr>
<td>Collaboration</td>
<td>Long-term relationships</td>
<td>Adversarial practices</td>
</tr>
<tr>
<td></td>
<td>Shared benefits, incentives</td>
<td></td>
</tr>
<tr>
<td>Product demand</td>
<td>Very uncertain (seasonality, competition, innovation, etc.)</td>
<td>Less uncertain (the amount of material is known somewhat in advance)</td>
</tr>
<tr>
<td></td>
<td>Advanced forecasting methods</td>
<td></td>
</tr>
<tr>
<td>Production variability</td>
<td>Highly automated environment (machines, robots), standardization, production routes are defined—lower variability</td>
<td>Labor availability and productivity, tools, open environment (weather), lack of standardization and tolerance management, space availability, material and trade flows are complex—higher variability</td>
</tr>
<tr>
<td>Buffering</td>
<td>Inventory models (EOQ, safety inventory, etc.)</td>
<td>No models</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inventory on site to reduce risks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Use of floats (scheduling)</td>
</tr>
<tr>
<td>Capacity planning</td>
<td>Aggregate planning</td>
<td>Independent planning</td>
</tr>
<tr>
<td></td>
<td>Optimization models</td>
<td>Infinite capacity assumptions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reactive approach (respond to unexpected situations, for example, overtime)</td>
</tr>
</tbody>
</table>
Modern construction production modeling is somewhat broader than traditional site operations analysis. Terms like buffer, variability, and uncertainty are not yet common among experienced construction managers. However, on-site production inefficiency is often caused by poor production planning (which includes decisions on buffers) and limited planning concerning the impact of off-site production and delivery variability. It is a common practice to keep large amounts of inventory on job sites to reduce risk of delays on site production (decoupling strategy). However this material requires site space, resources to manage it, and represents, in most cases, an unnecessary investment. Another traditional practice is the development of optimistic schedules that do not include time buffers to protect against uncertainties (e.g. manufacturing and delivery of materials). Moreover, scheduling tools consider infinite capacity assumptions that are not real and need further investigation. We believe that SC modeling can guide managers to better allocate different types of buffers and include uncertainty issues in their production planning.

The need for change in construction practices is clear. First, owners and general contractors (GCs) have to understand the increasing importance of suppliers for achieving project goals. The identification of key suppliers can lead to the adoption of partnerships or long-term relationships that may facilitate the implementation of modern SC practices. Second, there is still much room for the development and implementation of SC modeling tools in construction. For example, a more systematic and formal method to model SCs for construction planning or even during the preproject planning to support strategic analysis and identification of major risks seems necessary.

The following sections advance the discussion on construction projects’ characteristics, key production decisions that should be taken into account along any project life cycle, and current efforts on production modeling in construction.

2.3.1 Projects as Composed of Multiple SCs

O’Brien, London, and Vrijhoef (2002) presented a conceptual view of the construction project SC, which is shown in Figure 2.4. Figure 2.4 gives an indication of the complexity of SC production operations, depicting part of the large number of firms that compose a construction project SC. Owners, designers, GCs, subcontractors, and multiple types of suppliers that supply distinct technologies at different project phases are organized to form a unique SC configuration. Thus, the scope of analysis includes production both on-site and off-site. When extended to multiple subcontractors, each with their own supply structure, Figure 2.4 indicates that the scale of a construction SC is extensive even for small projects. As such, we take the perspective that construction projects are composed of multiple SCs, each with specific behaviors. Their behavior is strongly determined by the type of product that is delivered to a project site.

Elfving (2003) and Arbulu, Koerckel, and Espana (2005) described the characteristics of four general types of construction products: ETO, MTO, ATO, and MTS. ETO products are specially made for the customer following detailed specifications (e.g., power distribution equipment, preassembled rebar components), commonly characterized by long lead times and complex engineering processes for product specifications. MTO products are usually products manufactured once customer orders have been placed (e.g., cast-in-place concrete, prefabricated panels). Usually, MTO manufacturers don’t hold stock and lead times can be either long or short, depending on the manufacturing...
complexity. ATO products are also assembled (manufactured) after customer orders, however these products are usually standard or made of standard components (e.g., doors, windows). Lead times are usually short (or shorter than MTO lead times) and some stock is held by manufacturers, who need to manage an uncertain mix of orders. Finally, MTS products are commodities (e.g. consumables such as bricks, bolts) characterized by short lead times. MTS manufacturers usually hold stock, however managing the physical distribution of such products may be complex.

In construction, all material flows converge to on-site production. However, the focal point (job site) usually has no power to coordinate the SC in the same way as large manufacturing companies. Job sites constitute the demand that needs to be fulfilled by all SCs. This demand—typically when something is needed as opposed to how much—is often unstable due to the lack of reliability of site production systems. In cases of changes in demand, information should flow quickly to suppliers so that they can respond. However, access to demand information (which includes material orders, construction schedules, and site conditions) is somewhat limited to a few suppliers and subcontractors. As a consequence, the coordination of material flows is not efficient and much waste is spread through SCs [see Naim and Barlow 2003 for a case study on housing SC].

Another source of complexity in construction is the involvement of subcontractors with multiple projects at the same time [O’Brien and Fischer 2000]. Therefore, subcontractor resource availability has become a critical performance factor for any project. Also, some subcontractors are responsible for coordinating upstream material flows with their own suppliers. Then, the subcontractor’s capability to coordinate this flow effectively is fundamental to reducing risks of material delays on construction job sites.

As for the suppliers, many variables influence their performances. Most risk resides either in those suppliers that provide long lead time products or those that have limited capacity to handle market demand. In general, these types of suppliers prioritize orders based on preferred customers or to gain internal efficiency. Thus, strategies to mitigate risks associated with the supply of materials provided by them should always be addressed by construction managers.
Finally, owners and designers may also influence SC performance. When owners are directly involved in the construction phase, they may delay approval processes, require design changes, and so on. The designers, on the other hand, may delay the procurement process of certain products (delay of detailing design conclusion) and also may affect on-site production, either in the form of change orders or lack of details interrupting production (bad quality design). The involvement of suppliers in the design process for ETO products also complicates SC coordination and increases risk.

### 2.3.2 Issues in Construction Project Configuration

The way construction projects’ SCs are configured may determine their final success or failure. The configuration of any construction project describes how materials and information flow between companies. Usually, this configuration is detailed over the project life cycle, as a result of various decisions made from preproject planning to the end of construction phases.

Major decisions regarding projects’ SC configuration are made in early phases, even before the start of conceptual design. Major decisions such as site location and selection of complex and long lead time technologies are mostly made during the preproject planning phase. For example, will the structure be cast-in-place or prefabricated? What are the dominant process technologies (for industrial plants)? In this phase, it is expected that most client requirements will be captured and further guide the design process. The output of the preproject planning phase provides a good idea of the final product complexity and the design effort coordination needed (e.g., number of different system designers), and a fair idea which subsystems are going to be outsourced or going to be executed by the GC (make or buy decision).

The design phase is fundamental for project SC performance. During this phase designers recommend systems’ specifications, develop the detailed drawings that indicate the bill of materials, and assess constructability issues that might cause problems throughout project construction. Decisions regarding standardization and modularization of systems’ components may make a substantial difference in the project’s total cost and schedule. These differences may be reflected in the increased installation productivity of modular components, economy of scale during the manufacturing of modules, or possible price discounts when negotiating with manufacturers. These design decisions are increasingly influenced by input from GCs and key subcontractors and suppliers (particularly those supplying ETO systems). When designers make independent decisions without considering SC capabilities, costs can be higher and performance reduced. As an example of potential SC collaboration during design, Azambuja and Formoso (2003) provide an example of how different elevator shaft sizes may affect the prices among different elevator suppliers and then affect the project’s total cost.

The procurement phase (which increasingly overlaps with the design phase) greatly defines the final configuration of a construction project SC. In this phase, most of the suppliers and subcontractors are selected. Usual criteria to select those companies are price, safety, quality, and schedule performance. Once the negotiation and contracts with the selected suppliers are concluded, a good number of the project SCs’ constraints can be specifically recognized. The location of suppliers is already known, their capabilities (e.g., manufacturing and transportation, quality, safety, schedule reliability) were
evaluated based on the project-specific criteria, the lead times for delivery of products are established with critical suppliers, and they have declared resource availability (labor or equipment) for the project (although that availability may change due to commitments to other projects). At this moment, any construction project manager can potentially understand how efficient or responsive to possible changes their project SC is. However, they should plan and protect their projects from the negative impacts that variability and uncertainty may cause. Common causes of problems affecting construction schedule and cost performance are related to suppliers; some examples include: delay of fabrication or deliveries by material suppliers, damaged or wrong products arriving at the job site, subcontractors having low productivity, and so on.

The construction stage is when the detailed SC operation and coordination take place. It is also the stage where construction planning has to assure that all uncertainties are considered and actions are taken in order to protect the job site production from the off-site environment. In this phase, mitigation strategies such as the use of time, inventory, or capacity buffers are used to shield construction operations from the off-site uncertainties. Another general concern is job site space utilization and work packages sequencing. These decisions directly affect the manner in which the materials are delivered and stored on site. As a result, important questions that need to be constantly considered during construction are: (a) how often should different types of materials be ordered and in what batch size? (b) how much inventory should be kept? (c) where should the inventory be located? Another important issue is the job site capacity to accomplish the proposed schedule. Having excess labor, equipment, and overtime are common strategies used to mitigate uncertainty problems. However those strategies usually have a negative impact on construction costs and should be used only when there is no other alternative.

Figure 2.5 illustrates a spectrum of SC decisions that should be made in each project phase and relates them to the strategic, tactical, or operational purposes set in the manufacturing context. The figure shows these stages in the classic, sequential order of project phases; increasingly, however, project phases overlap, collapsing the time in which decisions must be made.

Unlike manufacturing, research in construction has not shown any structured framework to categorize SC decisions and suggest when they should be made along the project life cycle. In this section, we have suggested such categories in order to provide an initial point for further discussion on the subject.

2.3.3 Construction SC Modeling: Capability Review and Needs

The spectrum of SC decisions from strategic to operational listed in Figure 2.5 have been studied in part by construction researchers. Studies have focused on specific decisions, mostly at the tactical level. In addition, most studies have also focused on descriptive, rather than prescriptive, analysis. This leads to several gaps in current approaches to construction SC modeling. This section reviews the current studies to identify these gaps in the context of the modeling discussion above and in support of the framework presented in the next section.

Beyond the classification of SC questions described above, the further separation of models as descriptive and prescriptive is useful for examining the current state of construction SC modeling. Descriptive models are usually deterministic, meaning that
FIGURE 2.5 Construction project phases and associated SC decisions.
all model parameters are assumed to be known and certain. Descriptive models are also often static, illustrating a snapshot of an SC current state. Prescriptive models, by contrast, generally take into account uncertain and random model parameters. They are dynamic and aim to mimic SC behavior and performance, allowing prediction and discovery of emergent behavior in the SC for optimization.

Perhaps due to the complexity of the construction SC, most studies have focused on case descriptions of SCs for specific products (for example, rebar [Polat and Ballard 2003] and heating, ventilation, and air conditioning (HVAC) ductwork [Alves and Tommelein 2003]). These descriptions usually deploy visual process modeling tools to illustrate or “map” the respective SCs. Among the available mapping tools, construction researchers have predominantly adopted variants of Value Stream Mapping (VSM), a tool developed by the Lean Enterprise Institute. VSM is a process of representing the flows of information and materials, and other parameters such as inventory size and cycle time as they occur, summarizing them visually, and envisioning a future state with better performance [Jones and Womack 2003]. The objective is to identify inefficiencies or waste in the SC and remove them. This is usually measured comparing SC lead time and throughput time. VSM can be used to model current states of the SC as well as represent future states. In this sense the tool crosses between descriptive and prescriptive process analysis, although the tool lacks support for dynamic modeling or optimization. As such, it is employed primarily for descriptive analysis in construction.

Tommelein and Li (1999) and Tommelein and Weissenberger (1999) used the VSM to analyze the possibility of adopting a just-in-time production system through the strategic location of buffers (inventory and time) in the SC. Subsequent applications of VSM have mainly been used to support evaluation of different SC configurations [Arbulu and Tommelein 2002; Elfving, Tommelein, and Ballard 2002; Polat and Ballard 2003; Azambuja and Formoso 2003]. These models are simple diagrams or maps that typically include a partial sketch of engineering, procurement, fabrication, and installation processes specific to the SC problem addressed. Those authors used these visual maps to enrich their case descriptions and to provide insights for supporting strategic SC decisions, such as improvement of coordination and communication among companies, location of buffers to mitigate risks, and elimination of processes to reduce lead times.

VSM models have been used to guide tactical and operational SC decisions. Akel, Tommelein, and Boyser (2004), and Fontanini and Picchi (2004) presented more detailed models which included not only processes, but also material and information flow data. These models also dealt with lead time reduction, providing additional insights into transportation, batching, and material ordering issues. Supporting these studies, simulation-based models have also supported analysis of tactical and operational decisions. In particular, simulation models have predicted lead times and/or throughput performance of construction SCs. Several studies have assessed the effects of buffer and batch sizes [Al-Sudairi et al. 1999; Arbulu et al. 2002; Alves and Tommelein 2004; Walsh et al. 2004; Jeong, Hastak, and Syal 2006], variability in process durations [Alves, Tommelein, and Ballard 2006], and product standardization [Tommelein 2006] on the above-mentioned performance measures. While generally based on a descriptive study, the simulation models allow exploration of variation in parameters and hence support either optimization or broader generalization of, for example, the value of buffers or deleterious effects of variability.
Perhaps due to the nature of the modeling tools, VSM and simulation-based models tend to focus on SC configurations and processes that are well described in terms of production units (plants or work centers depending on the level of analysis), buffers, and materials flows. Measures such as throughput and time are standard in these models. As such, these models tend to focus on a subset of the SC decisions—in particular, strategic and tactical ones about specific and reasonably detailed SC configurations. The tools and models as deployed do not easily scale to earlier strategic decisions for a given project where details about specific process and materials flows have not been firmly identified. At the same time, the models have not supported wide-scale analysis of operational decisions, perhaps due to a lack of data and the challenges incumbent in modeling and calibrating such detailed models.

Models that address different parameters are relatively rare. O’Brien (1998) proposed a qualitative model to predict SCs’ performance behavior. The model included a set of firms that were classified according to a typology of suppliers based on the suppliers’ production technology, as well as the impact of site demand (uncertainty) on their performance. The combination of different classes of suppliers resulted in a high-level view of SC performance capabilities and intrinsic risks. These high-level models support rapid analysis without the need for detailed models, and could be used to support a variety of strategic configuration decisions, but their use has not been further explored.

Not until recently have SC models reported results which include cost performance. For example, Vidalakis and Tookey (2006) simulated the flow of materials from building merchants to construction sites and assessed inventory and transportation costs. Additionally, Polat, Arditi, and Mungen (2007) built a model to assist contractors in selecting the most economical rebar management system prior to the start of construction by recommending batch sizes, scheduling strategy, and buffer sizes. The inclusion of cost analysis offers a promising next step in construction SC modeling. For example, many existing models address lead time reduction, but the costs associated with the reduction of time are not clear. Time-cost tradeoff type analyses can help managers make more informed decisions.

The early, existing construction SC models support a variety of decisions for specific decisions, but do not address the full scope of decisions as described in the preceding section. Construction lacks models that enable professionals to draw inferences about construction SC strategic decisions. Examples of such decisions include: (a) determining buffer sizes and locations based on companies’ geographic locations; (b) establishing the locations of projects to reduce overall logistics costs (especially transportation costs); and (c) identifying the demand per region to reduce the risk of delay of material delivery. These decisions are important as global materials sourcing is becoming common practice on a range of projects.

A broader view of various independent SCs converging to “multiple” construction projects is another perspective that deserves further modeling effort in the construction industry. Multiple construction projects means either different projects executed by one GC or projects executed by different GCs. Current models have largely focused on the analysis of individual SCs that convert to a single or multiple construction project executed by one GC. This focus of analysis is useful to identify problems in the interface between one supplier (or subcontractor) and one GC. However, it does not support the understanding of more complex issues, such as the capacity of suppliers to react to multiple projects’ demand spikes or change orders. In order to carry out the broader level of analyses, researchers and practitioners need to understand the typology of suppliers involved in their projects [e.g., O’Brien 1998].
Beyond increased scope for strategic decisions, SC modeling of tactical and operational decisions also needs to become more flexible and expressive to better capture project complexities and constraints. Existing models effectively support the identification of companies, processes, or deterministic lead times of SCs. However, new data have to be included or modified; for example, clarifying the location and type of buffers; including maximum, minimum, and most likely durations of SC processes (if possible, showing the probability distribution based on real data). Current models address lead time reduction. However, it is not clear how much time one can reduce in each process (e.g., is there a minimum duration?). Making models more capable, perhaps with some standard prespecified boundary conditions for classes of suppliers, would allow more rapid as well as prescriptive modeling for a range of tactical and operational decisions. The extension of these models to include cost will also spread the range of model applications.

Moreover, as noted by Azambuja and O’Brien (2007), a defined set of performance measures for the evaluation of construction models is needed to complement model development and evaluation. Ideally, modelers would select and monitor performance based on a proposed set of metrics that depend on specific model purpose and level of detail. As a result, different scenarios could be evaluated and compared, helping managers select the right SC configuration to achieve project goals.

### 2.4 Framework for Developing Construction SC Models

As noted above, construction modeling efforts are capable but need to be extended to better include a range of strategic as well as tactical and operational decisions. It is unclear to what extent the basic modeling constructs for SCs need fundamental extension to address various decisions or to what extent existing tools can address the decisions. A broader need, however, is discipline in applying the various approaches. In this section, we propose and describe a conceptual framework to model construction SCs. The framework, shown in Figure 2.6, consists of five sequential steps which support the modeling process. The steps are as follows: (a) define SC model purpose; (b) establish SC performance measures; (c) determine product type; (d) define SC configuration; and (e) characterize SC elements. It is expected that this framework will provide the necessary support for modelers to develop a comprehensive SC model that includes the model goal and metrics, as well as adequate boundaries, elements, and attributes.

![FIGURE 2.6 Framework for supply chain modeling.](image-url)
The first step of the framework is to define the SC model purpose or goal. SC models can serve various purposes, which vary from choosing the best SC configuration to reducing material supply risks, to those which assess how companies’ internal processes affect SC lead time and throughput performance. Table 2.3 presents a comprehensive list of purposes that have been modeled in construction and manufacturing over the last decade.

Once the modeler defines the purpose of the modeling exercise, a set of performance measures need to be associated to the model goal (step 2). For example, if the model goal is to support lead time reduction, metrics such as order processing time, engineering time, manufacturing/assembly time, and delivery time are fundamental. If a manager is interested in reducing the inventory buffer in a construction job site, the SC performance metrics to be monitored could be the number of items in stock, average waiting time in stock, average inventory turnover, installation demand rate, and

**TABLE 2.3 SC model purposes**

| Evaluate the supply chain configuration   |
| Evaluate the best SC configuration to fulfill the demand (improve response time) |
| Assess SC complexity (# of members, information and material flows, coordination effort) |
| Assess location of facilities |
| Show which company is responsible for each process (ownership decisions) |
| Reduce product lead time (eliminating or combining activities) |
| Identify the number of processes performed to deliver the product |
| Identify the time spent in each process (conversion and flow) |
| Classify each process performed (value-added or non-value-added) |
| Simplify the SC (eliminating non-value added activities, relocating inventories, consolidating points for distribution) |
| Evaluate buffering decisions |
| Locate inventory buffers in the SC (decoupling points) |
| Identify the type and size of buffers |
| Influence of buffer location and size on the product lead time |
| Evaluate production decisions |
| Assess batch decisions and their influence in the final product throughput |
| Influence of set-up time on companies’ delivery performance |
| Evaluate the effect of capacity decisions on the SC (inventory behavior, lead time, throughput) |
| Evaluate transportation decisions |
| Assess how transportation (type and frequency) affects SC (lead time, delivery performance, costs) |
| Assess SC costs |
| Inventory costs, process costs, transportation costs, ordering costs, cost of resources |
| Understand the risk of materials delay (on the construction schedule) |
| Illustrate the SC information coordination (IT application) |
| Identify the frequency, content, and type of information exchanged (and how it is transferred) |
| Evaluate the risk of communication errors and delays on material flows and inventory buffers (Bullwhip Effect) |
| Assess the impact of product complexity (standardization, # of parts) on the SC response time |
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Supplier delivery time and frequency. Table 2.4 provides a list of metrics that may be associated with other SC model purposes.

The third step in the process is to determine which type of product is going to be modeled. The type of product can provide valuable insights about the model boundaries and level of detail. So far, researchers have not considered how different products might affect SC model boundaries. A model of an ETO product needs to include various processes executed by different actors such as designers, engineering firms, GCs, and suppliers. Several information flows need to be taken into account when modeling SC processes for this kind of product since these flows directly affect the manufacturing process and product delivery. By contrast, a model of an MTS product involves fewer actors, usually the GC or subcontractor, and the supplier. The flow of information is usually restricted to the transaction process, although processes directly or indirectly related to material flows often need to be modeled.

The understanding of general types of products may also support a qualitative assessment of SC capabilities and potential risks. For example, a supplier of an ETO product is certainly a job shop producer that manufactures very low volumes and has difficulties reacting to short-term changes in production. Table 2.5 shows potential manufacturing environments, actors, and processes that should be taken into account when modeling different products. The outcome of this step is an initial indication of the SC model boundaries and level of detail (i.e., which SC processes may be included in the model).

The fourth modeling step is the definition of SC configuration. In this step, the model elements—SC actors, processes, activities, material flow, information flow, inventory buffers, and resources—are arranged to build the SC model. The knowledge of previous framework steps is important for refining the model level of detail. The model

<table>
<thead>
<tr>
<th>SC Model Purposes</th>
<th>Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify material supply risks</td>
<td>SC average throughput; SC lead time variability; percent on-time deliveries; lateness of deliveries</td>
</tr>
<tr>
<td>Decrease transportation costs</td>
<td>Delivery frequency; minimum batch size; distance; cost per unit; handling cost</td>
</tr>
<tr>
<td>Decrease manufacturing costs</td>
<td>Labor and machine costs; labor and machine utilization; process cycle time; capacity utilization; total inventory costs</td>
</tr>
<tr>
<td>Increase SC throughput</td>
<td>SC throughput; buffer sizes; batch sizes; number of processes; process cycle time; manufacturing lead time; delivery lead time</td>
</tr>
<tr>
<td>Measure SC reliability</td>
<td>SC lead time variability; percent on-time deliveries; lateness of deliveries; supply quality (shipping errors, customer complaints); stockout probability</td>
</tr>
<tr>
<td>Evaluate supply flexibility</td>
<td>Production volume (capacity); production mix (variety of products); or delivery dates (change planned delivery dates)</td>
</tr>
<tr>
<td>Evaluate SC complexity</td>
<td>Number of processes; number of different companies; geographical locations; flows of materials (number of stages); flow of information (centralized vs. decentralized)</td>
</tr>
</tbody>
</table>
TABLE 2.5 Suggestion of Model Boundaries and Processes Based on Different Technologies

<table>
<thead>
<tr>
<th>Product Type</th>
<th>Manufacturing Environment</th>
<th>SC Boundaries</th>
<th>SC Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Made-to-stock</td>
<td>Assembly line or continuous flow</td>
<td>MTS supplier; warehouses; subcontractor or GC; job site</td>
<td>Subcontractor or GC places order; supplier checks product availability, picks and delivers; unloads on site; product installation</td>
</tr>
<tr>
<td>Assembled-to-order</td>
<td>Assembly line</td>
<td>ATO supplier; upstream supplier of critical RM component; subcontractor or GC; job site</td>
<td>Subcontractor or GC places order; supplier checks RM availability; either starts assembling the product if RM available or needs to wait for RM; temporary FG inventory; delivery; unload on job site; product installation</td>
</tr>
<tr>
<td>Made-to-order</td>
<td>Job shop or batch</td>
<td>MTO supplier; upstream suppliers of critical RM components; GC; designer; owner</td>
<td>GC receives detailed design and places order; supplier checks design and order; if information is complete and RM are available it starts manufacturing, otherwise waits for RM or GC, designers and owners to review and approve changes; product manufacturing; temporary FG inventory or immediate delivery; unload on construction site; installation</td>
</tr>
<tr>
<td>Engineered-to-order</td>
<td>Job shop</td>
<td>ETO supplier; upstream suppliers of critical RM components; architect; owners; engineering company</td>
<td>Supplier either fully designs or only details the design received from an engineering company; the owner checks the detailed design; if design is accepted, the supplier can start manufacturing the product, otherwise it waits for owner response; product manufacturing; temporary FG inventory or immediate delivery; unload on construction site and installation</td>
</tr>
</tbody>
</table>

boundaries and processes identified in step 3 support the SC configuration. In order to configure the SC, those processes are assigned to the actors who are responsible for their execution. Then, the relationships between actors and processes can be visualized, as well as their logical sequence in the process.

Detailed SC models are generally complex and confusing; therefore a hierarchical approach is proposed to deal with this issue. The first level of the hierarchy depicts the SC actors, their respective product types, geographical location, and transportation flows (Figure 2.7).
Once the relevant SC actors are identified, classified and located, the model can be further detailed in order to describe each actor’s processes and boundaries (level 2 of the hierarchy). At this level, the main processes are listed and their interfaces can be linked. Figure 2.8 through Figure 2.13 depict SC actors’ common internal processes as well as those that define their external interfaces (arrows crossing the rectangle borders). The actors’ names (top left of boxes) are followed by a number, which identifies their horizontal tier in relation to the job site. This identification serves to locate each actor participating in the material flow. For example, an MTS supplier 1 sends material directly to the job site while an MTS supplier 2 sends its product to the other location (e.g., warehouse) before delivering to the job site. The MTS supplier shown in Figure 2.7 is an instance of MTS 2. As for subcontractors, they can always be identified as number 1 as long as they are responsible for buying and storing material in their own location before the final installation on the job site. If they are only responsible for the installation, the install process (Figure 2.8) characterization is enough to describe the subcontractor’s role.

Owners, designers, engineering firms, and GCs often are not part of off-site material physical flows. Instead, they are responsible for coordinating information flows and usually are the ones who exchange information with suppliers (e.g., orders, design approvals, detailing) to support the material flows. Thus, these types of actors do not require an identification number (SC horizontal tier). The responsibility for information coordination varies depending upon each project’s organizational structure. For example, who will order materials: owner, GC, or both? Who will provide a detail design: engineering firm or supplier? For this reason we decided not to represent those actors’ generic process models. However, they are part of the modeling effort. Their interfaces with product suppliers are represented by the arrows pointing in and out of processes, such as receiving orders, design detailing, and approvals (Figure 2.10 through 2.13). Consideration
and inclusion of designers or engineering firms is important in construction SC modeling because the design is required to execute tasks on-site. Often the design is pulled due to site and material needs, thus the modeling of designers/engineering activities may provide some indication of risks. This is particularly common in fast-track projects.

The outcome of this hierarchy level (level 2)—after linking all actors’ processes—is a representation very similar to the visual models presented by Arbulu and Tommelein (2002) and Polat and Ballard (2003), which were used to assess different SC configurations.

The third and last level of the hierarchy is depicted in Figure 2.14. This level details the processes presented in level 2. Level 3 serves to illustrate and describe which activities, buffers, and resources may be included in the model. Figure 2.14 shows all the activities required to manufacture an MTO product.
FIGURE 2.11   SC configuration level 2: ATO supplier processes.
FIGURE 2.12 SC configuration level 2: MTO supplier processes.
FIGURE 2.13 SC configuration level 2: ETO supplier processes.
FIGURE 2.14 SC configuration level 3: Manufacturing process of MTO supplier. (Adapted from Arbulu and Tommelein 2002)
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Note that the name of the process still includes the actor's identification. Hence, each actor's properties previously identified in level 2 can be transferred to this level. The hierarchical modeling approach used to configure SCs is useful to define and visualize any model elements. The selection of which level of detail (hierarchy levels) one needs to model depends on the model's purpose, boundaries, and processes required by each type of product.

The fifth and last step of the modeling approach is to characterize the SC model elements. This step encompasses the description of each model element in order to provide complete information on the current SC model and helps users understand the model behavior. Each model element will then have its own set of attributes. These attributes are necessary for the creation of prescriptive models such as simulation tools and for improving the descriptive power of construction SC models. Table 2.6 presents a list of SC elements and attributes.

Figure 2.15 provides one example of the attribute list applied for the pack activity. The standard list of attributes provides valuable information about the pack activity that is part of the manufacturing process of an MTO product located at the horizontal level \( n \) of a SC.

### TABLE 2.6 Attributes of SC Elements

<table>
<thead>
<tr>
<th>SC Elements</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC actors</td>
<td>Name, location, processes; interfaces (boundaries), product type (ETO, MTO, ATO, MTS), final product</td>
</tr>
<tr>
<td>Processes and/or activities</td>
<td>Name (verb+noun), type (material or information conversion), cycle time (deterministic or probability distribution), resources, production batch size, cost</td>
</tr>
<tr>
<td>Material flow (delivery)</td>
<td>Product (size, weight), batch size, time, frequency, transportation mode, cost</td>
</tr>
<tr>
<td>Information flow</td>
<td>Information type (order, design drawing, schedule), time, frequency</td>
</tr>
<tr>
<td>Inventory buffers</td>
<td>Type (FIFO, LIFO), product in stock, maximum # of parts, holding costs</td>
</tr>
<tr>
<td>Resources</td>
<td>Name, type (labor, equipment), quantity, capacity, costs, failure or maintenance (downtimes), schedule (fixed or variable capacity)</td>
</tr>
</tbody>
</table>

![Activity Diagram](image.png)

**FIGURE 2.15** Attributes of model elements: Pack activity.
2.5 Prospects for Construction SC Modeling

This chapter provides an overview of various concepts and issues regarding SC production modeling in manufacturing and construction contexts. We reviewed the literature on construction SC modeling and briefly described the extant modeling tools and their initial applications in case studies. The review allowed us to identify some modeling gaps that need to be addressed to make construction SC models more capable with respect to supporting a range of decisions. Finally, we proposed a conceptual modeling approach that consists of sequential steps and emphasizes issues that need to be considered when modeling construction SCs, such as a structured set of metrics, product characteristics and level of detail, and assignment of attributes to model elements.

Construction SC modeling is, in the authors' belief, very much the next generation of productivity modeling for construction. Much as construction benefited from traditional productivity studies (e.g., the application of time and motion to the job site) and their extension to constructability analysis (i.e., the application of construction knowledge in design to improve productivity), construction projects can benefit from SC models to improve tactical and operational decisions and apply that knowledge to generate wisdom for strategic decisions. At the same time, the history of productivity modeling poses challenges for the development of SC models. Productivity modeling suffered from a long period of limited development and a lack of widespread deployment for many years; only the relatively recent introduction of lean concepts has invigorated productivity modeling. SC models could suffer the same fate; the current models that are predominantly descriptive and specific to individual projects (and hence do not easily generate broad findings) do not yet represent a suite of analysis tools and associated understandings that will actively let managers make effective and informed SC decisions for their projects. It is the hope of the authors that the discussion and framework above will stimulate development of a wider and more capable range of construction SC models that can effectively enhance practice.

References


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