Simulation-Based Decision Support System for Economical Supply Chain Management of Rebar

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Abstract: The economics of a materials management system is defined by the size of the shipments, the scheduling strategy that allows contractors to handle uncertainty and variability in the supply chain, and the timing of the shipments, which in turn depend on the environment in which the project is taking place. This study presents a simulation-based decision support system to assist contractors in selecting the most economical rebar management system prior to the start of construction by recommending lot sizes (large, small), a scheduling strategy (optimistic, neutral, pessimistic), and buffer sizes (large, medium, small) given the conditions of the project. This model is of benefit to contractors and researchers because it generates the probable cost of inventory of 18 alternative rebar management systems ranging from just in case (JIC) to just in time (JIT) and including different variations in between. It allows contractors to select the alternative with least cost of inventory at the planning stages of a project. The simulation model was tested by using actual data obtained from a trade center project in Istanbul, Turkey. As expected, the test indicated that JIC was the most economical rebar management system in a case study conducted in a developing country, as it generated a savings of 4.8% over JIT.

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Introduction

Materials constitute a large proportion of the total cost of construction. Proper management of the material flow may play a significant role in enhancing the effectiveness of a contractor. The generally acknowledged rules of materials management are small orders, frequent deliveries, and reduced inventories (Sobotka 2000; Shmanske 2003). The main objective of these efforts is to lower the amount of capital tied up in inventory (Shmanske 2003) while making sure that production never stops due to shortage of materials.

One of the concepts in the manufacturing industry that addresses these issues is just in time (JIT), also known as zero inventory policy and Toyota production system that flourished in Japan in the early 1950s (Ohno 1987). JIT is a production and material delivery program with the primary goals of continuously reducing and ultimately eliminating all forms of waste, and adding value to raw materials as they proceed through various processing steps to end up as a finished product (Tommelein 1998).

Implementing the JIT materials management system requires eliminating all forms of buffer. Hopp and Spearman (2000) define three types of buffer that need to be considered:

1. Inventory buffers: Material stockpiles (raw materials, work-in-process, and finished goods) may be categorized according to their position and purpose in a supply chain.
2. Capacity buffers: In construction, consideration of the environment (i.e., site access and conditions) plays a major role in defining how much capacity should be allocated to a certain project. A capacity buffer is created by scheduling less than all the time available by allocating additional manpower and equipment to an activity beyond the need anticipated for completion. If production falls behind schedule, there is capacity available for catching up (Lean Enterprise Institute 2003).
3. Time buffers: Time buffers are used to manage schedules. They provide flexibility to define the start dates for activities, without delaying project completion. Floats may be seen as some sort of time buffers.

The successful implementation of JIT in the manufacturing industry improved productivity, reduced cost, and enhanced the competitive advantage of firms (Akintoye 1995; Pheng and Chan 1997; Pheng and Tan 1998; Pheng and Hui 1999). The implementation of JIT resulted in productivity increases in the construction industry too (Pheng and Chuan 2001).

Even though JIT practices provide several benefits, they also have a number of disadvantages. Elimination of inventory results in removal of costs related to inventory, but it also hinders the potential benefits associated with inventory (Shmanske 2003). A recent study by Polat and Arditi (2005) found that the total cost of inventory of rebar in the JIT system is higher than the total cost of inventory in the just in case (JIC) system in circumstances marked by uncertainty and variability in the supply chain, high inflation rates, high shipping costs, high material and time waste, bulk discounts, and price cuts for early purchases. These conditions are likely to be encountered in developing countries. Since

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the environment in which a construction project takes place directly influences the economics of the materials management system used, contractors should first recognize the circumstances of their project before they decide on the materials management system to be used in their projects.

The economics of the JIT and JIC materials management systems is defined in this study by buffer size, scheduling strategy, and lot size. These factors correspond to Hopp and Spearman's (2000) time, capacity, and inventory buffers, respectively. Buffer size refers to the time the material is stored on the construction site before it is used in production. Scheduling strategy involves making the appropriate assumptions in estimating the durations of the activities involved in production. Lot size is directly related to the gap between the quantity of material delivered and the quantity of material required.

Although there are numerous materials used in the construction process, this study focuses on the supply chain of a single material, namely reinforcing steel bars (rebar) used in the construction of reinforced concrete structures. Cut and bent rebar is used in this study because (1) if rebar is not supplied to site on time, the many succeeding activities are delayed and serious budget overruns may occur (Polat and Ballard 2003); (2) the activities related to rebar, namely procurement, unloading, fabrication, and assembly can be considered as a manufacturing process because of the fact that rebar is delivered from one workstation to another throughout the supply chain; (3) approximately 16–26% (by weight) of the total purchased amount of rebar is wasted during the construction process (Bossink and Brouwers 1996; Formoso et al. 2002); and (4) rebar constitutes a significant portion of the cost of reinforced concrete structures and can be subject to wildly variable prices (Polat and Arditi 2005).

The objective of this study is to provide contractors with an objective and dynamic tool, namely a discrete event simulation model to assist them in selecting the most economical rebar management system prior to starting construction by recommending lot sizes, a scheduling strategy, and buffer sizes given the conditions of the project. The discrete event simulation model presented in this study attempts to mimic all managerial and operational activities performed throughout the supply chain of rebar. The cost of inventory is considered to be the key factor in selecting the rebar management system. The model is used in a case study in Istanbul, Turkey in order to compare the cost of inventory of alternative rebar management systems.

JIT versus JIC

JIT, in simplest terms, means that no one upstream (predecessor workstation on the process line) should produce and/or deliver a good or service until the customer downstream (successor workstation) asks for it (Powell and Pierce 1999). This endeavor is achieved by JIT scheduling, which simply means that each activity on the process line should be completed at the very same time the successor activity starts (Anwar and Nagi 1997; Powell and Pierce 1999). For successful implementation of the JIT materials management system, all buffers need to be eliminated. In other words, in the JIT materials management system, the materials (raw materials or work-in-progress) are delivered from one workstation to another in small lot sizes with frequent deliveries with no buffer between the activities.

In JIC materials management systems, materials are pushed from one workstation to the next regardless of whether they are needed by the next workstation. The objective is to ensure a smooth production flow and to be able to cope with rejected materials and uncertainty and variability inherent in the supply chain (Pheng and Hui 1999). In the JIC materials management system, early start scheduling is used where each activity starts on its earliest start date (Powell and Pierce 1999; Yang 2002). In other words, in the JIC materials management system, the materials (raw materials or work-in-progress) are delivered from one workstation to another in large lot sizes with infrequent deliveries before the earliest start date of the successor activity.

Clearly, there are three major differences between the JIT and JIC materials management systems, which are: (1) buffer size; (2) scheduling strategy; and (3) lot size.

1. Buffer size: Buffer is the time span between the completion of an activity in the preceding workstation and the start of an activity in the succeeding workstation. In the JIC system, an activity on the process line starts on its early start date, while in the JIT system, an activity should be completed as late as the start of the succeeding activity (Anwar and Nagi 1997; Powell and Pierce 1999; Yang 2002). While large buffers are used in the JIC system, no buffer is allowed in the JIT system. In this study, the rebar production line can also be planned to operate with buffers halfway between no buffer and large buffer; this is termed medium buffer.

2. Scheduling strategy: Each activity is subject to uncertainty and variability in the supply chain. For example, the rebar fabrication process is governed by the extent of delays in promised lead times resulting from a contractor's defective ordering procedure (e.g., delay in the decision-making process, quantifying error, late ordering), a supplier's failure in delivering materials at the right time, sequence, quantity, and quality due to either the supplier's defective production process or shortage of steel received from steel mills, fluctuations in the productivity of rebar fabrication workers, and the accuracy of duration estimates. Activity durations are commonly estimated based on the contractor's past experiences. Each duration estimate has an implicit confidence level in it. The person who makes a duration estimate has a minimum and a maximum value in mind (McCabe 2003). A contractor may adopt one of the following scheduling strategies in handling uncertainty and variability in the supply chain of rebar when estimating the activity durations at the beginning of a construction project:

- *Optimistic strategy*: The contractor expects the best scenario to come true. In the best scenario, it is expected that worker productivity is highest, and lead times and delays are lowest, leading to minimum activity durations.
- *Neutral strategy*: The contractor expects the average scenario to come true. In the average scenario, it is expected that each activity is completed in the average duration, as worker productivity, lead times, and delays are halfway between their highest and lowest values.
- *Pessimistic strategy*: The contractor expects the worst scenario to come true. In the pessimist scenario, it is expected that worker productivity is lowest, and lead times and delays are highest, leading to maximum activity durations.

Clearly, the scheduling strategy used to handle the uncertainty and variability inherent in the supply chain of rebar directly affects activity durations, and consequently the start and completion times of the activities. The activity duration is estimated at the beginning of the project to account for uncertainties. But the actual duration of an activity is a result of various random factors and turns out to be either shorter or longer than or equal to the estimated duration. If the actual duration of the activity is shorter than its estimated duration, an unintended buffer will occur whose consequences (financing cost, handling cost, storage cost) should be calculated and included in the final decision. If the actual duration of the activity is longer than its estimated duration, a delay will occur whose consequences (waiting cost, shortage cost) should also be calculated and included in the final decision.

3. Lot size: While the JIT system advocates providing the materials in small lot sizes with frequent deliveries, in the JIC system, the materials are delivered in large lot sizes with infrequent deliveries in order to take advantage of lower shipping economics and to be able to cope with rejected materials. Since in the JIC system, extra rebar is delivered to the site earlier than needed in order to make use of the full capacity of the trucks, the lot size is referred to as "large lots." On the other hand, JIT requires frequent delivery of small lot sizes (exact amount that is required); the lot size equals the quantity of rebar needed on site including extra rebar to offset possible waste. In these instances, the trucks are utilized below capacity. Consequently, shipping costs increase. The lot size in the JIT system is referred to as "small lots."

It should be noted that all types of buffers are under the control of the contractor since the rebar management system is run by the contractor.

Although elimination of buffers is key to the JIT materials management system, researchers continue to investigate the applicability of this issue in the typical conditions prevailing in construction projects. Studies concerning buffers in construction address either how different types of buffers should be used in handling uncertainty and variability in different types of construction projects in order to reduce waste and improve project performance (e.g., Howell and Ballard 1995, 1996; Horman and Kenley 1998; Horman 2000; Al-Sudairi 2000; Horman 2001; Horman et al. 2003; Park and Peňa-Mora 2004; Horman and Thomas 2005) or how buffers are generated in production systems (e.g., Tommelein 1998; Tommelein et al. 1999; Tommelein and Li 1999; Tommelein and Weissenberger 1999). Several studies confirmed that buffers need to be located, sized, and managed carefully, otherwise, they are wasteful, they interrupt workflow, and they harm project performance (Howell and Ballard 1996; Al-Sudairi 2000; Alves and Tommelein 2004; Park and Peňa-Mora 2004; Horman and Thomas 2005). Guidelines on buffer sizing and positioning are often addressed in the literature (e.g., Ballard and Howell 1997; Ballard 2000; Yang and Photios 2001).

Some contractors may be familiar with buffer sizing and positioning techniques and be capable of managing buffers properly (Horman et al. 2003). On the other hand, most contractors continue to employ traditional project planning tools, and in many projects, buffers are still used to mask the problems resulting from unreliable planning (Howell and Ballard 1996) rather than being deliberately used as an alternate to better planning or a project management and control tool so as to complete the project within the schedule and budget (Horman et al. 2003; Horman and Thomas 2005).

If one considers buffer size, scheduling strategy, and lot size as factors that differentiate between the JIT and JIC management systems, contractors are faced with 18 alternative rebar management systems (see Table 1) from which they could pick the most economical one for use throughout the project. Since Polat and Arditi's (2005) recent study concluded that the indiscriminate use of the JIT materials management system is neither effective nor economical, it is important for a contractor to recognize the effects of the project environment on the economics of alternative rebar management systems. The simulation model presented in this paper provides typical contractors with a decision support system that allows them to see the economic impact of buffer size, scheduling strategy, and lot size on rebar management alternatives given the specific project environment at the start of construction.

Table 1. Eighteen Alternative Rebar Management Systems

Buffer size	Scheduling strategy	Lost size
Large	Optimistic	Large
		Small
	Neutral	Large
		Small
	Pessimistic	Large
		Small
Medium	Optimistic	Large
		Small
	Neutral	Large
		Small
	Pessimistic	Large
		Small
Small	Optimistic	Large
		Small
	Neutral	Large
		Small
	Pessimistic	Large
		Small

Methodology

Simulation is defined as the art and science of designing a model that acts in the same way as a real system does (Law and Kelton 2000). In other words, simulation accurately represents actual processes of a real system by means of computer realization. The basic advantages of simulation are its generality, flexibility, and power of simulating almost any behavior of the real system (Kant 1992; Schelasin and Mauer 1995; Martinez and Ioannou 1997). Discrete event simulation modeling was found to be appropriate for this research because a materials management system cannot be highly generalized (Sobotka 2000). The simulation package " Extend+BPR" was used in this study because of its powerful features including high flexibility, great capacity, animation capability, and sophisticated graphical user interface. Abdulhadi (1997), Al-Sudairi (2000), and Polat and Arditi (2005) have used "Extend+BPR" in similar studies with great success.

The information used to design the flow diagram used in the simulation model was obtained from two studies conducted previously on rebar management systems in the Turkish construction industry (Polat and Ballard 2003; Polat 2003). The logical connections between the main activities associated with the rebar supply chain consist of procurement, unloading, fabrication, and assembly and are illustrated in Fig. 1. Since the same crews, workstations, and technical personnel are utilized in the same activities performed repeatedly for each floor, an activity associated with a floor cannot start unless the same activity associated with the lower floor is finished.

"Procurement" involves filing purchase requisitions, sending out requests for quotations, selecting the appropriate supplier or fabricator, sending purchase orders to the supplier, and receiving the requested goods at the site after the standard lead time agreed upon by contractor and supplier. "Unloading" involves the process in which the required rebar is unloaded from trucks and

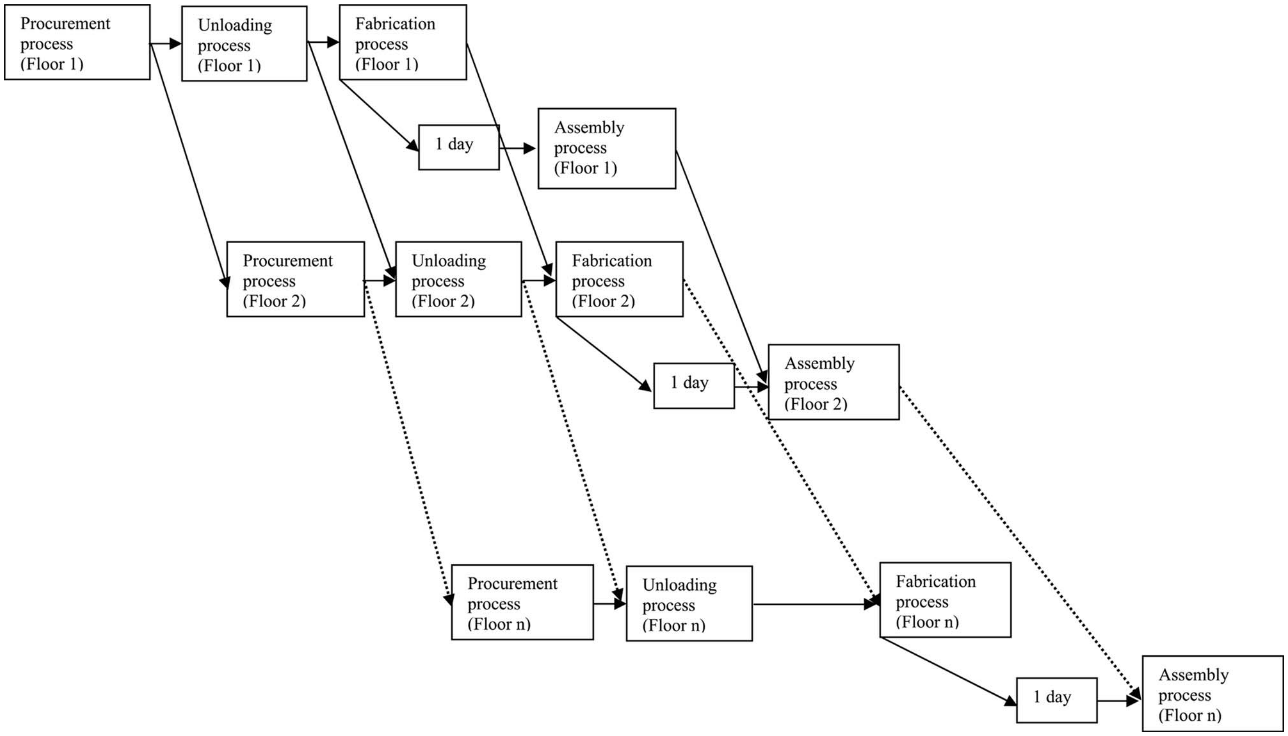

Fig. 1. Logic diagram of supply chain of rebar

stored on site. "Fabrication" involves the process in which the rebar is cut to measure and bent in accordance with specifications. "Assembly" involves the process in which the cut and bent rebar are tied together and are installed in formwork. It is customary to start the assembly process one day after the fabrication process starts on that floor.

In this study, the effects of buffer sizes, scheduling strategy, and lot sizes were observed on the total cost of inventory (TCI) of rebar given the circumstances in which the project is taking place. A contractor can select the most economical rebar management system out of the 18 alternatives generated by the model (see Table 1) prior to starting construction. The framework of the simulation model is presented in Fig. 2. The inputs, the transitional outputs, and the final outputs of this model are described in the following sections.

Inputs of the Simulation Model

The parameters in the relationships presented in the following sections are listed in alphabetical order in Table 2 along with their descriptions and units. The input variables are described in detail in the following for each of the main activities associated with a rebar management system.

- *Procurement process*: The procurement inputs include quantity of rebar, and efficiency, durations, and delays associated with administrative processes involved in rebar purchases. One of these input parameters deserves special attention. The day of the project on which the procurement process needs to start (T_{pij}) depends on lot size and the company's scheduling strategy. In T_{pij}, i denotes whether the optimistic (o), neutral (n), or pessimistic (p) scheduling strategy is adopted, whereas j denotes whether the lot size is small (s), medium (m), or large (l). T_{pij} is set by plugging actual data into the scheduling program "Primavera Project Planner" (P3). When $i=o$, P3 is run with minimum activity durations obtained by using maximum values for worker productivity, and minimum values for lead times and delays; when $i=n$, P3 receives the average activity durations obtained by using middle values for worker productivity, lead times, and delays; and when $i=p$, maximum activity durations obtained by using minimum values for worker productivity, and maximum values for lead times and delays are plugged into P3. When $j=s$, the start dates of each activity are calculated in P3 by setting all floats equal to zero (JIT scheduling); when $j=l$, the early start dates of each process (traditional scheduling) are calculated by P3; and when $j=m$, the midpoint between the start dates set by JIT scheduling and traditional scheduling are used.
- *Unloading process*: The unloading inputs consist of the capacity of trucks, and the number and productivity of workers in charge of unloading. The day of the project on which the unloading of the delivered rebar process needs to start is denoted by T_{uij}, where i represents the company's scheduling strategy and j the lot size. The same reasoning is used here to set i and j as was used for T_{pij} in the preceding process.
- *Fabrication process*: The fabrication inputs include the number and productivity of workers in charge of fabrication, and waste-related issues. The day of the project on which the fabrication process needs to start is denoted by T_{fij} where i and j are set in the same way they were set for T_{pij} and T_{uij}.
- *Assembly process*: The assembly inputs include the number and productivity of workers in charge of assembly. The values of i and j in the day of the project on which the assembly process needs to start (T_{aij}) are set in the same way they were set for T_{pij}, T_{uij}, and T_{fij}.
- *Cost inputs*: The cost inputs include costs associated with rebar, interest rates, workers, rental costs, delivery costs, and penalties for delay.

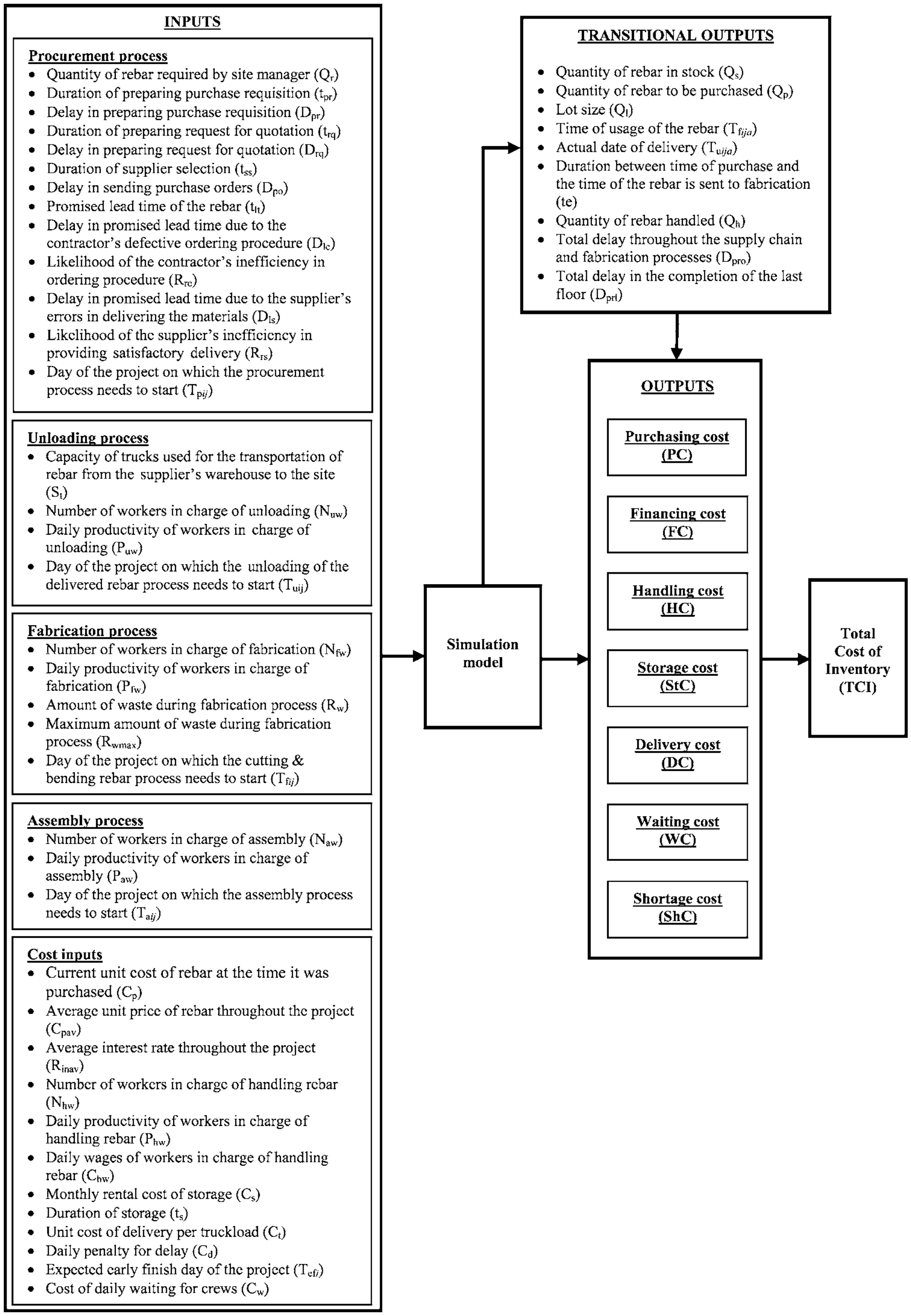

Fig. 2. Framework of the simulation model

Transitional Outputs of the Simulation Model

Transitional outputs are generated by the simulation model based on the inputs presented in the preceding section and the logical relationships between the various activities involved in rebar management systems. The transitional outputs and some of the inputs are later used by the simulation model to calculate the outputs of the model.

- *Quantity of rebar in stock* (Q_{sk}): This transitional output indicates the quantity of rebar in inventory at any time during the project. The quantity of rebar in stock (Q_{sk}) is the amount accumulated in the preceding deliveries [the first set of brackets in Eq. (9)], the difference between the quantity delivered and the quantity sent to fabrication (the second set of brackets), and the difference between the actual and estimated quantities used (the third and final set of brackets). $Q_{sk}=0$ when $k=1$. In this relationship, k accounts for the different deliveries of rebar for each floor throughout the project.
- *Quantity of rebar to be purchased* (Q_{pk}): Once a purchase requisition is sent to the purchasing department, the inventory is checked. If the amount of rebar in inventory is not sufficient to meet the required amount, a purchase order is issued. The quantity of rebar to be purchased (Q_{pk}) is calculated as the difference between the required quantity of rebar including probable maximum waste and the quantity of rebar in stock

Table 2. Input Variables Used in the Simulation Model, in Alphabetical Order

Symbol	Unit	Description	Values in the trade center project
C_d	\$/day	Cost of daily delay	344 \$/day
C_{hw}	\$/day	Daily wage of workers in charge of handling	11–18 \$/day (uniform distribution)
C_p	\$/ton	Current unit cost of rebar at the time it was purchased	obtained from unit price records
C_{pav}	\$/ton	Average unit price of rebar	343 \$/t
C_s	\$/month	Monthly rental cost of storage	—
C_t	\$/truckload	Unit cost of delivery per truckload	172 \$/truckload
C_w	\$/day	Daily cost of idle crews	—
D_{tc}	days	Delay in promised lead time resulting from the contractor's defective ordering procedure	0.5–1 days (triangular distribution)
D_{ls}	day	Delay in promised lead time resulting from the supplier's defective delivery procedure	0.5–2 day (triangular distribution)
D_{po}	days	Delay in sending purchase orders	0–2 days (triangular distribution)
D_{pr}	days	Delay in preparing purchase requisition	0–2 days (triangular distribution)
D_{rq}	days	Delay in preparing request for quotation	0–1 days (triangular distribution)
N_{aw}	—	Number of workers in charge of assembly	10
N_{fw}	—	Number of workers in charge of fabrication	4
N_{hw}	—	Number of workers in charge of handling	2
N_{uw}	—	Number of workers in charge of unloading	4–6
P_{aw}	tons/day/worker	Daily productivity of workers in charge of assembly	0.48–0.56 t/day/worker for the first floor; 0.3–0.35 t/day/worker for the other floors (triangular dist.)
P_{fw}	ton/day/worker	Daily productivity of workers in charge of fabrication	1.44–1.76 t/day/worker for the first floor; 0.9–1.1 t/day/worker for the other floors (triangular dist.)
P_{hw}	tons/day/worker	Daily productivity of workers in charge of handling	20–24 t (triangular distribution)
P_{uw}	tons/day/worker	Daily productivity of workers in charge of unloading	26–35 t (triangular distribution)
Q_r	tons	Quantity of rebar required specified by site manager	See Table 3
R_{inav}	%	Interest rate (average overnight reverse rate)	0.11%
R_{rc}	%	Likelihood of contractor's inefficiency in ordering procedure	5%
R_{rs}	%	Likelihood of supplier's inefficiency in providing satisfactory delivery	10%
R_w	%	Waste during fabrication	5–11% (triangular distribution)
$R_{w\,max}$	%	Probable maximum waste during fabrication	11%
S_t	tons	Capacity of the trucks	20–26 t (triangular distribution)
T_{ajj}	—	Day of the project on which assembly process needs to start	Obtained from P3
T_{efi}	—	Date on which the project is expected to be completed	T_{efo}=392, T_{efn}=432, T_{efp}=472
T_{fjj}	—	Day of the project on which fabrication process needs to start	Obtained from P3
t_{lt}	days	Promised lead time for rebar	1–3 days (triangular distribution)
T_{pjj}	—	Day of the project on which the procurement process needs to start	Obtained from P3
t_{pr}	days	Duration of preparing purchase requisition	0.5–1 day (triangular distribution)
t_{rq}	days	Duration of preparing request for quotation	0.5–1 day (triangular distribution)
t_s	months	Duration of storage	—
t_{ss}	days	Time for the supplier selection process	1–2 days (triangular distribution)
T_{uij}	—	Day of the project on which unloading process needs to start	Obtained from P3

[see Eq. (10)]. In this relationship, k accounts for the different deliveries of rebar for each floor throughout the project.

- *Lot size* (Q_{lk}): For large lot size, the calculation of Q_{lk} reflects the fact that extra rebar is delivered to the site earlier than needed in order to make use of the full capacity of the trucks. Large lot size is calculated using Eq. (11). In this relationship, k accounts for the different deliveries of rebar for each floor throughout the project.

  On the other hand, small lot size is nothing but the quantity of rebar to be purchased. In this case, the trucks are utilized below capacity. Consequently, shipping costs increase [see Eq. (12)].
- *Duration between the time of purchase and the time the rebar is sent to fabrication* (t_{ek}): Early purchasing of rebar increases financing cost. Financing cost depends on the duration between the actual date of delivery (or the actual date on which the unloading process starts) and the actual time the rebar is sent to fabrication. This duration is calculated using Eqs. (13)–(17).
- *Quantity of rebar handled* (Q_{hk}): The handling activity in-

cludes moving the straight rebar delivered to the construction site from the trucks to the storage area, moving the required amount of straight rebar augmented by the maximum quantity of waste $(1+R_{w\,\max})$ from the storage area to the fabrication area, moving the cut and bent rebar to the work area (actual floor of construction), and delivering the remaining quantity of rebar from the work area back to the storage area (to get the unused pieces back). When the purchased rebar is delivered to the site earlier than needed, it stays in storage until it is needed. If the delivery date of the rebar occurs earlier than the date on which the fabrication process should start, the delivered rebar is directly sent to storage. In this case, the rebar is moved four times: from trucks to storage, from storage to fabrication, from fabrication to work area, and from work area to storage. On the other hand, if the delivery date of the rebar is equal to or occurs later than the date on which the fabrication process should start, the quantity of rebar handled depends on the quantity of the delivered rebar and the required quantity of rebar augmented by the maximum quantity of waste $(1+R_{w\,\max})$. In this case, if the quantity of the delivered rebar is larger than the required quantity of rebar augmented by the maximum quantity of waste $(1+R_{w\,\max})$, then the required quantity of rebar augmented by the maximum quantity of waste $(1+R_{w\,\max})$ is sent to the fabrication area while the remaining rebar is sent to storage; at the end of the fabrication process the unused rebar is sent back from the fabrication area to inventory and the required quantity of rebar is sent to work area. If the quantity of the delivered rebar is smaller than the required rebar augmented by the maximum quantity of waste $(1+R_{w\,\max})$, then the quantity of delivered rebar is sent to the fabrication area, and the remaining amount to add up to the required rebar augmented by $(1+R_w)$ is delivered from the storage area and at the end of the fabrication process the required quantity of rebar is sent to work area. The quantity of the rebar to be handled is calculated using Eqs. (18)–(20).

- *Total delay throughout the supply chain* (D_{pro}): Total delay throughout the supply chain is the sum of the time gaps between the actual and scheduled start dates of each activity associated with rebar. Total delay throughout the supply chain (D_{pro}) is calculated using Eq. (21). The summation sign in this relationship accounts for the different deliveries.
- *Total delay in the completion of the last floor* (D_{prl}): Contractors may be subject to pay a penalty in case the delivery of the superstructure is delayed. This is measured by considering the completion of the last floor compared to the scheduled finish date. Total delay in the completion of the last floor (D_{prl}) is equal to the difference between the actual and scheduled finish dates of the assembly process of the last floor. Total delay in the completion of the last floor is calculated using Eqs. (22)–(24).

Outputs of the Simulation Model

The output of the materials management system is the TCI. The components of TCI include the costs of purchasing, financing, handling, storage, delivery, shortage, and waiting. The input parameters in the relationships presented in the following sections are listed in alphabetical order in Table 2 along with their descriptions and units.

- Purchasing cost (PC): The purchasing cost represents the direct cost of rebar to the contractor.

$$\text{PC} = \sum C_p Q_{lk} \tag{1}$$

where Q_{lk}=lot size and is obtained from Eqs. (11) and (12). The summation sign accounts for the different acquisitions.
- Financing cost (FC): When a material is purchased before it is needed, the inventory is carried in storage with a financing cost. This cost depends on the length of time the material is kept on inventory and the value of money. If the contractor borrows money to purchase the material, the financing rate is equal to the actual interest rate. If the contractor pays cash for the material, then the financing rate is equal to the opportunity cost of capital to the contractor

$$\text{FC} = \sum \left[(C_{\text{pav}} Q_{sk})((1+R_{\text{inav}})^{t_{ek}} - 1)\right] \tag{2}$$

The values for Q_{sk}, i.e., the quantity of rebar in stock and t_{ek}, i.e., the duration between the time of purchase and the time the rebar is sent to fabrication, are obtained from Eqs. (9) and (13), respectively. The summation sign accounts for the changes in the values of Q_{sk} and t_{ek} throughout the project.
- Handling cost (HC): This is the cost of moving the rebar from the trucks to the storage area, moving the required amount of rebar augmented by the maximum quantity of waste $(1+R_{w\,\max})$ from the storage area to the fabrication area, moving the cut and bent rebar to the work area (actual floor of construction), and delivering the remaining quantity of rebar from the work area back to the storage area (to get the unused pieces back)

$$\text{HC} = \sum \left[\left(\frac{Q_{hk}}{(N_{\text{hw}} P_{\text{hw}})}\right)(N_{\text{hw}} C_{\text{hw}})\right] \tag{3}$$

In this relationship, the value of Q_{hk}, i.e., the quantity of rebar handled is obtained from Eqs. (18)–(20). The summation sign accounts for the changes in the values of Q_{hk}.
- Storage cost (StC): Storage cost consists of the rental cost of the storage area, management cost, and maintenance and upkeep cost, which includes the cost of rebar movement within the storage area

$$\text{StC} = C_s t_s \tag{4}$$

- Delivery cost (DC): This is the cost of moving the rebar from the supplier's warehouse to the construction site

$$\text{DC} = \sum \left[C_t \,\text{roundup}\left(\frac{Q_{lk}}{S_t}\right)\right] \tag{5}$$

The value of Q_{lk}, i.e., the lot size is obtained from Eqs. (11) and (12). The summation sign accounts for the different deliveries.
- Waiting cost of idle crews (WC): This is the cost of idle workers waiting for the rebar to arrive in case rebar is not available on site when it is needed

$$\text{WC} = C_w D_{\text{pro}} \tag{6}$$

where D_{pro} represents the total delay throughout the supply chain and comes from Eq. (21).
- Shortage cost (ShC): This is the cost of delay caused by shortage of rebar. This delay causes a delay in the pouring of concrete in the last floor, resulting in penalties to the contractor

$$\text{ShC} = C_d D_{\text{prl}} \tag{7}$$

where D_{prl} represents the total delay in the completion of the last floor and is obtained from Eq. (22).

The total cost of inventory is therefore

$$TCI = \sum [C_p Q_{lk}] + \sum [(C_{pav} Q_{sk})((1+R_{inav})^{t_{ek}} - 1)] + \sum \left[\left(\frac{Q_{hk}}{(N_{hw} P_{hw})} \right) (N_{hw} C_{hw}) \right] + [C_s t_s] + \sum \left[C_t \, \mathrm{roundup} \left(\frac{Q_{lk}}{S_t} \right) \right] + [C_w D_{pro}] + [C_d D_{prl}] \quad (8)$$

Case Study

The simulation model was applied to a case study. The purpose was to compare the TCI of each of the 18 alternative rebar management systems characterized by varying buffer sizes, scheduling strategies, and lot sizes (Table 1).

The case was a trade center project in Istanbul, Turkey. The contract value for the 27 story high reinforced concrete structure was \$15 million. The construction of the superstructure started in October 2002 and finished in February 2004. The research was conducted right after the completion of the superstructure. The contact person in the company was the project manager. The focus of this research was the rebar supply chain. The related input variables' values obtained from the project manager are presented in the last column of Table 2.

In this application, production productivity ($P_{uw}, P_{hw}, P_{fw}, P_{aw}$) in the JIT system was considered to be the same as in the JIC system. Successful implementation of JIT depends on workers' ability to eliminate waste, to multitask, to detect problems at the source, to be innovative when solving problems, to always seek better performance in terms of time, quality, and cost, and to participate in the traditional duties of top management (Pheng and Hui 1999). However, in Turkey, workers are not as qualified as their counterparts in industrialized countries regardless of the materials management system used (Polat and Arditi 2005). When implementing JIT in Turkey, it is normal practice to order $(1+R_{w\,max})$ times the quantity required by the site manager to prevent shortages caused by workers' mistakes and misuses, as it is the case in JIC.

Another input required by the simulation model is the unit price of rebar at the time of purchase (C_p). In Turkey, it is usual for rebar unit prices to fluctuate day by day considerably (Polat and Arditi 2005). The unit prices of rebar at the time of delivery were obtained from site records.

Most contractors manage their business with the monthly payments they receive from the owner (Polat 1999). They can invest their limited cash for only the short term. Therefore, in this study, the financing cost is calculated by considering repurchase transactions, which are accepted as the standard financial instrument for short-term loans of cash or securities (Morrow 1995). The overnight repo rates in Turkey varied between 0.09 and 0.13% in the period of October 2002 to February 2004 (Daily 2004). In this study, an average overnight repo rate of $R_{inav}=0.11\%$ was used. The average unit price of rebar (C_{pav}) in Istanbul, Turkey was calculated as \$343 in the period of October 2002 to February 2004.

Based on the records provided by the project manager of the trade center project, there was no monthly rental cost of storage (C_s). Since there was ample space on the construction site, the rebar was stocked on the construction site free of charge. Therefore, C_s was taken as zero.

If the rebar did not arrive to site on time, other tasks were assigned to the workers. The absence of strong unions in Istanbul allowed the contractor to reassign workers to different activities without problem. Since workers were never idle, the waiting cost (C_w) was taken as zero.

Table 3. Quantity of Rebar Required by Site Manager at the Trade Center Project

Floor	Required quantity of rebar, Q_r (tons)
1	170
2	91
3	91
4	91
5	91
6	91
7	43
8	33
9	59
10	54
11	54
12	52
13	44
14	43
15	42
16	42
17	41
18	40
19	39
20	37
21	37
22	37
23	17
24	14
25	14
26	14
27	14

In general, StC considerably increases the total cost of inventory in the JIC system due to high monthly rental cost of storage (C_s) and long duration of keeping materials in storage (t_s). On the other hand, WC is a significant cost component in the JIT system because of the high waiting cost of idle workers (C_w) and probable delays in promised lead times and in activity durations. However, in the actual environment of the studied project, both the monthly rental cost of storage (C_s) and the waiting cost of idle workers (C_w) were zero. Obviously, in a different project environment in which the values of these cost components are not zero, a different rebar management alternative would have had the lowest total cost of inventory.

A schedule was generated by P3 after plugging in the logical connections between the main activities associated with rebar illustrated in Fig. 1, and the input values presented in Tables 2 and 3. The scheduled times generated by P3 and the input values presented in the last column of Tables 2 and 3 were entered into the simulation model.

For good results, Chase and Brown (1992) recommend a coefficient of variance below 5% when conducting experiments. A coefficient of variance of 0.5% was targeted in this study and the simulation model was run several times (30–100 runs depending on the case) until the coefficient of variance went below 0.5% for each alternative.

AbouRizk and Halpin (1992) found that the beta distribution is appropriate for representing construction activity durations. The beta distribution can be approximated with a triangular distribution, which requires three parameters for its definition: the lower or optimistic limit, the mode or most likely value, and the upper or pessimist limit (McCabe 2003). Therefore, the triangular distribution was used to represent the random factors inherent in the durations of the activities associated with rebar.

Tests of normality and homogeneity of variances were conducted by using the statistical package SPSS Inc., Chicago, IL, in order to select the most appropriate statistical test to assess whether the means of the TCI of each rebar management system in the trade center project are statistically different from each other. Since the assumptions on normality and homogeneity of variances were not met, the Kruskal-Wallis test was conducted, again using SPSS Inc., Chicago. The significance was less than 0.05, so it can be inferred that there is a significant difference between the TCIs of the alternative rebar management systems.

While the lowest TCI was found to be \$517,717 in the rebar management system having large buffer size, optimistic scheduling strategy, and large lot size (i.e., typical JIC), the highest TCI was found to be \$542,712 in the alternative having small buffer size, optimistic scheduling strategy, and small lot size (i.e., typical JIT). Selecting the alternative bringing about the lowest TCI provided the contractor with a cost advantage of \$24,996, corresponding to a savings of 4.8%. It is not surprising to see that JIC is more economical than JIT in an environment marked by uncertainty and variability in the supply chain, high inflation rates, weak unions, low storage costs, high shipping costs, bulk discounts, price cuts for early purchases, and high material and time waste. These conditions are likely to be encountered in developing countries.

Obviously, in a different project environment, the rebar management system that brings about the lowest total cost of inventory would have been different. Any difference in any of the input parameters of the model would probably change the most economical rebar management system selected by the model. For instance, a recent study by Polat and Ballard (2005) revealed that a project environment where uncertainty and variability in activity durations are minimized and workers' productivity is improved brings about a decrease of 7% in the total cost of inventory.

Also, a model that optimizes the cash cycle rather than the cost of inventory could result in different outcomes. Optimizing the difference between the monies received from the client for work completed and the monies paid to suppliers for rebar received could constitute an alternative model to the one presented in this paper unless this dimension is added to the existing model in future work.

Conclusion

Materials constitute a large proportion of the total cost of construction. Proper management of the material flow may play a significant role in enhancing the effectiveness of a contractor. The generally acknowledged rules of materials management are small orders, frequent deliveries, and reduced inventories in raw material and work-in-progress. One of the concepts in the manufacturing industry that addresses these issues is JIT. Although several studies reveal that the implementation of the JIT materials management system in the construction industry lowers project cost and duration, a recent study by Polat and Arditi (2005) found that the total cost of inventory of rebar in the JIT system is higher than the total cost of inventory in the JIC system in developing countries.

Buffer size (i.e., the time the material is stored on the construction site before it is used in production), scheduling strategy (i.e., making the appropriate assumptions in estimating the durations of the activities involved in production), and lot size (i.e., the quantity of material ordered) are the three major differences between the JIT and JIC materials management systems. The indiscriminate use of JIT is neither effective nor economical (Polat and Arditi 2005). The economics of rebar management system is dependent on the conditions prevailing in the project's environment. It is only by considering the special circumstances in which the project is operating that the decision-maker can pick the most economical alternative that specifies the right combination of buffer size, scheduling strategy, and lot size. The model presented in this study provides contractors with an objective and dynamic tool, namely a discrete event simulation model, to assist them in selecting the most economical rebar management system.

Actual data obtained from a trade center project in Istanbul, Turkey were input into the simulation model. The TCI was calculated for 18 different rebar management systems by running the simulation model several times until the coefficient of variance went below 0.5% for each alternative. It was found that selecting the alternative with the lowest TCI of rebar provided the contractor with a cost advantage of \$24,996, corresponding to a savings of 4.8%. This finding is to be expected in the special conditions prevailing in a developing country and agrees with previous research conducted by Polat and Arditi (2005).

Since contractors are profit-seeking organizations and profit margins are generally low, using the materials management system that minimizes the total cost of inventory is one of their major concerns. This model is of benefit to contractors and researchers because it generates the probable cost of inventory of 18 alternative rebar management systems ranging from JIC to JIT and including different variations in between. It allows contractors to select the alternative with least cost of inventory at the planning stages of a project. It allows researchers to see the potential use of simulation as a decision support tool to predict the probable outcomes of different implementation choices. Also, it provides an initial framework for future studies where a reliable planning tool can be developed that optimizes buffer sizes by integrating simulation techniques with network scheduling and by thoroughly mimicking all types of managerial and operational activities performed throughout the supply chain, hence improving overall project performance.

Appendix. Transitional Outputs of the Simulation Model

The parameters used in the relationships presented in the following are listed in alphabetical order in Table 2 along with their descriptions and units.

- *Quantity of rebar in stock* (Q_{sk})

$$Q_{sk} = \lfloor Q_{s(k-1)} \rfloor + \lfloor (Q_{l(k-1)}) - (Q_{r(k-1)}(1 + R_{w\,\max})) \rfloor + \lfloor Q_{r(k-1)}(R_{w\,\max} - R_w) \rfloor \quad (9)$$

- *Quantity of rebar to be purchased* (Q_{pk})

$$Q_{pk} = [Q_{rk}(1 + R_{w\,\max})] - Q_{sk} \quad (10)$$

- *Lot size* (Q_{lk})

Large lot size

$$Q_{lk}=\left[\text{roundup}\left(\frac{Q_{pk}}{S_t}\right)\right]S_t \tag{11}$$

Small lot size

$$Q_{lk}=Q_{pk} \tag{12}$$

- *Duration between the time of purchase and the time the rebar is sent to fabrication* (t_{ek})

$$t_{ck}=T_{fijka}-T_{uijka} \tag{13}$$

where T_{uijka} is calculated by summing up all actual durations and delays associated with procurement activities

$$T_{uijka}=T_{pijka}+t_{\text{pr}}+D_{\text{pr}}+t_{\text{rq}}+D_{\text{rq}}+t_{\text{ss}}+D_{\text{po}}+t_{\text{lt}}+D_{\text{lc}}+D_{\text{ls}}$$

when

$$T_{pijka}+t_{\text{pr}}+D_{\text{pr}}+t_{\text{rq}}+D_{\text{rq}}+t_{\text{ss}}+D_{\text{po}}+t_{\text{lt}}+D_{\text{lc}}+D_{\text{ls}}\geqslant T_{uijk} \tag{14}$$

or

$$T_{uijka}=T_{uijk}$$

when

$$T_{pijka}+t_{\text{pr}}+D_{\text{pr}}+t_{\text{rq}}+D_{\text{rq}}+t_{\text{ss}}+D_{\text{po}}+t_{\text{lt}}+D_{\text{lc}}+D_{\text{ls}}< T_{uijk} \tag{15}$$

D_{lc} and D_{ls} depend on the contractor's efficiency in the ordering procedure (R_{rc}) and the supplier's efficiency in providing satisfactory delivery (R_{rs}).

T_{fijka} is calculated by summing up all actual durations and delays associated with procurement and unloading activities

$$T_{fijka}=T_{uijka}+\left[\frac{Q_{lk}}{N_{\text{uw}}P_{\text{uw}}}\right]$$

when

$$\left[T_{uijka}+\left[\frac{Q_{lk}}{N_{\text{uw}}P_{\text{uw}}}\right]\right]\geqslant T_{fijk} \tag{16}$$

or

$$T_{fijka}=T_{fijk}$$

when

$$\left[T_{uijka}+\left[\frac{Q_{lk}}{N_{\text{uw}}P_{\text{uw}}}\right]\right]< T_{fijk} \tag{17}$$

- *Quantity of rebar handled* (Q_{hk})

$$Q_{hk}=Q_{lk}+[Q_{rk}(1+R_{w\,\max})]+Q_{rk}+[Q_{rk}(R_{w\,\max}-R_w)]$$

when

$$T_{uijka}< T_{fijk} \tag{18}$$

$$Q_{hk}=Q_{lk}+Q_{rk}+[Q_{rk}(R_{w\,\max}-R_w)]$$

when

$$T_{uijka}\geqslant T_{fijk}\text{ and }Q_{lk}>Q_{rk}(1+R_{w\,\max}) \tag{19}$$

$$Q_{hk}=Q_{rk}+[Q_{rk}(1+R_w)]$$

when

$$T_{uijka}\geqslant T_{fijk}\text{ and }Q_{lk}<Q_{rk}(1+R_{w\,\max}) \tag{20}$$

- *Total delay throughout the supply chain* (D_{pro})

$$D_{\text{pro}}=\sum[(T_{uijka}-T_{uijk})+(T_{fijka}-T_{fijk})+(T_{aijka}-T_{aijk})] \tag{21}$$

- *Total delay in the completion of the last floor* ($D_{\text{pr}l}$)

$$D_{\text{pr}l}=\left[T_{aijka}+\left(\frac{Q_{rk}}{N_{\text{aw}}P_{\text{aw}}}\right)\right]-T_{efi} \tag{22}$$

for the last floor where T_{aijka} is calculated as

$$T_{aijka}=T_{fijka}+1$$

when

$$T_{fijka}+1\geqslant T_{aijk} \tag{23}$$

or

$$T_{aijka}=T_{aijk}$$

when

$$T_{fijka}+1<T_{aijk} \tag{24}$$

References

Abdulhadi, N. H. (1997). "Simulation as a tool for re-engineering construction processes." Ph.D. dissertation, Univ. of Colorado at Boulder, Boulder, Colo.

AbouRizk, S. M., and Halpin, D. W. (1992). "Statistical properties of construction duration data." *J. Constr. Eng. Manage.*, 118(3), 525–544.

Akintoye, A. (1995). "Just in time application and implementation for building materials management." *Constr. Manage. Econom.*, 13, 105–113.

Al-Sudairi, A. (2000). "Evaluation of construction processes: Traditional practices versus lean principles." Ph.D. dissertation, Univ. of Colorado at Boulder, Boulder, Colo.

Alves, T. C. L., and Tommelein, I. D. (2004). "Simulation of buffering and batching practices in the interface detailing-fabrication-installation of HVAC ductwork." *12th Annual Conf. on Lean Construction*, Denmark.

Anwar, M. F., and Nagi, R. (1997). "Integrated lot-sizing and scheduling for just-in-time production of complex assemblies with finite set-ups." *Int. J. Prod. Res.*, 35(5), 1447–1470.

Ballard, G. (2000). "The last planner system of production control." Ph.D. thesis, Univ. of Birmingham, Birmingham, U.K.

Ballard, G., and Howell, G. (1997). "Toward construction JIT." *Lean construction*, L. Alarcon, ed., Balkema, Rotterdam, The Netherlands.

Bossink, B. A. G., and Brouwers, H. J. H. (1996). "Construction waste: Quantification and source evaluation." *J. Constr. Eng. Manage.*, 122(1), 55–60.

Chase, W., and Brown, F. (1992). *General statistics*, 2nd Ed., Wiley, New York.

"Daily indicative value of government domestic debt instruments determined by Central Bank of The Republic of Turkey." (2004). ⟨www.tcmb.gov.tr⟩ (Dec. 3, 2004).

Formoso, C. T., Soibelman, L., De Cesare, C., and Isatto, E. L. (2002). "Material waste in building industry: Main causes and prevention." *J. Constr. Eng. Manage.*, 128(4), 316–325.

Hopp, W. J., and Spearman, M. L. (2000). *Factory physics*, 2nd Ed., McGraw-Hill Int. Edition, Boston.

Horman, M. J. (2000). "Process dynamics: Buffer management in building project operations." Ph.D. dissertation, Univ. of Melbourne, Melbourne, Australia.

Horman, M. J. (2001). "Modeling the effects of lean capacity strategies on project performance." *Proc., 9th Annual Conf. on Lean Construction*, Singapore.

Horman, M. J., and Kenley, R. (1998). "Process dynamics: Identifying a strategy for the deployment of buffers in building logistics." *International Journal of Logistics: Research and Applications*, 1(3), 221–237.

Horman, M. J., Messner, J. I., Riley, D. R., and Pulaski, M. H. (2003). "Using buffers to manage production: A case study of the Pentagon renovation project." *Proc. 11th Annual Conf. on Lean Construction*, Blacksburg, Va.

Horman, M. J., and Thomas, H. R. (2005). "Role of inventory buffers in construction labor performance." *J. Constr. Eng. Manage.*, 131(7), 834–843.

Howell, G. A., and Ballard, G. (1995). "Factors affecting project success in the piping function." *Proc., 3rd Annual Conf. on Lean Construction*, Albuquerque, N.M.

Howell, G. A., and Ballard, G. (1996). "Managing uncertainty in the piping process." *RR47-13*, Construction Industry Institute, Univ. of Texas at Austin, Austin, Tex.

Kant, K. (1992). *Introduction to computer system performance evaluation*, McGraw-Hill, New York.

Law, A., and Kelton, W. D. (2000). *Simulation modeling and analysis*, 3rd Ed., McGraw-Hill, Boston.

Lean Enterprise Institute. (2003). *Lean Lexicon: A graphical glossary for lean thinkers*, Version 1.0, The Lean Enterprise Institute, Brookline, Mass.

Martinez, J. C., and Ioannou, P. G. (1997). *State-based probabilistic scheduling using STROBOSCOPE's CPM add-on, Construction Congress V*, Minneapolis, ASCE, Va.

McCabe, B. (2003). "Monte Carlo simulation for schedule risks." *Proc., 2003 Winter Simulation Conf.*

Morrow, R. (1995). "Repo, reverse repo and securities lending markets in Canada." *Bank of Canada Review*, 75(14), 61–70.

Ohno, T. (1987). *Toyota production system*, Productivity, Portland, Ore.

Park, M., and Peňa-Mora, F. (2004). "Reliability buffering for construction projects." *J. Constr. Eng. Manage.*, 130(5), 626–637.

Pheng, L. S., and Chan, Y. M. (1997). *Managing productivity in construction: JIT operations and Measurements*, Ashgate, Brookfield, Vt.

Pheng, L. S., and Chuan, C. J. (2001). "Just-in-time management of precast concrete components." *J. Constr. Eng. Manage.*, 127(6), 494–501.

Pheng, L. S., and Hui, M. S. (1999). "The application of jit philosophy to construction: A case study in site layout." *Constr. Manage. Econom.*, 17(5), 657–668.

Pheng, L. S., and Tan, S. K. L. (1998). "How 'just-in-time' wastages can be quantified: Case study of a private condominium project." *Constr. Manage. Econom.*, 16(6), 621–635.

Polat, G. (1999). "Yuklenici insaat firmalarinda teklif hazirlama ve maliyet yonetimi surecinin incelenmesi." M.Sc. thesis, Istanbul Technical Univ. (in Turkish).

Polat, G. (2003). "Supply chain management in construction: Problem analysis of current supply chain configurations for engineered-to-order products." *Proc., ISEC'2003*, Orlando, Fla.

Polat, G., and Arditi, D. (2005). "The JIT materials management system in developing countries." *Constr. Manage. Econom.*, 23(7), 697–712.

Polat, G., and Ballard, G. (2003). "Construction supply chains: Turkish supply chain configurations for cut and bent rebar." *Proc., 11th Annual Conf. on Lean Construction*, Blacksburg, Va.

Polat, G., and Ballard, G. (2005). "Impacts of infrastructural changes on the economics of rebar supply chains in Turkey." *Proc., the 11th Joint Int. Conf. on Computing and Decision Making in Civil and Building Engineering*, Montreal.

Powell, R. A., and Pierce, K. R. (1999). "The project manager's role as defender of contingency time: A new strategy and methodology to minimize the effects of risk." *Proc., 30th Annual Project Management Institute Seminars and Symp*.

Schelasin, R., and Mauer, J. (1995). "Creating flexible simulation models." *IIE Solutions*, 1(1), 50–55.

Shmanske, S. (2003). "JIT and the complementarity of buffers and lot size." *American Business Review*, 21(1), 100–106.

Sobotka, A. (2000). "Simulation modeling for logistics re-engineering in the construction company." *Constr. Manage. Econom.*, 18(2), 183–195.

Tommelein, I., and Li, A. E. Y. (1999). "Just-in-time concrete delivery: Mapping alternatives for vertical supply chain integration." *Proc., 7th Annual Conf. on Lean Construction*, Berkeley, Calif.

Tommelein, I. D. (1998). "Pull-driven scheduling for pipe-spool installation: Simulation of lean construction technique." *J. Constr. Eng. Manage.*, 124(4), 279–288.

Tommelein, I. D., Riley, D. R., and Howell, G. A. (1999). "Parade game: Impact on work flow variability on trade performance." *J. Constr. Eng. Manage.*, 125(5), 304–310.

Tommelein, I. D., and Weissenberger, M. (1999). "More just-in-time: Location of buffers in structural steel supply and construction processes." *Proc., 7th Annual Conf. on Lean Construction*, Berkeley, Calif.

Yang, I. (2002). "Stochastic analysis on project duration under the requirement of continuous resource utilization." *Proc., 10th Annual Conf. on Lean Construction*, Gramado, Brazil.

Yang, I., and Photios, G. (2001). "Resource-driven scheduling for repetitive projects: A pull-system approach." *Proc., 9th Annual Conf. on Lean Construction*, Singapore.