Integrating Safety-Stock and Crashing Decisions for Recurrent Projects Subject to Random Material Delays

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Abstract

We identify a new class of problems and their common features – the recurrent projects with random material delays. Recurrent projects are those similar in schedule and material requirements. We present the model of project-driven supply chain (PDSC) to jointly optimize safety-stock decisions in the material supply chain and the crashing decisions in the projects. We exemplify the problem, the model and its impact by a real-world case study.

Keywords: Recurrent projects, random material delays, crashing, safety-stock.

1 Introduction

This paper focuses on recurrent capital projects with random material delays and the role of safety-stock in optimizing the total project and supply chain cost. This paper is motivated by a
case study on Intercontinental Construction Management (ICM) Inc., a construction management firm specialized in construction and renovation of military buildings (the name is fictionalized to protect proprietary information). Most construction projects of this firm are similar in schedule and material requirements. Indeed, all building projects follow a standard construction process with a total duration of about 25 weeks. Structural steel is the most expensive material which is used in all projects. The structural steel is manufactured by a producer and customized by a fabricator, all government authorized, in a make-to-order fashion. Materials cannot be delivered to construction sites before they are needed as inventory cannot be held on-site. The processing times at the producer and fabricator are random and thus structural steel may be delayed beyond its due date, in which case, the projects will be delayed if no action is taken (see §3 for more details).

As many companies in the construction industry, ICM passively reacts to random material delays by expediting (i.e., crashing) projects as needed to meet the due date. ICM has never looked at the safety-stock of structural steel as an option because it manages each project as a separate and unique entity and ignores the similarity among projects. However, projects are not unique in the construction process and material requirement for this firm.

In practice, while some projects are once-off and thus unique, many others are repeatable and thus do not have to be unique. In this paper, we define recurrent projects to be repeating projects that share similarity in schedule and material requirements. Recurrent projects are not rare in practice. In addition to ICM, other examples of recurrent projects in the construction industry can be found in Walsh, et al. (2004) and Brown, et al. (2004). Walsh, et al. (2004) presents a case study of a food company that is frequently engaged in projects of expanding an existing or adding a new facility. The key concern of the company is the critical material of stainless steel pipe and fittings that are used in all projects and are subject to the longest and most variable lead time. Brown, et al. (2004) presents the case study of Quadrant Homes Inc. which follows a standard
procedure in construction of residential houses with a fixed duration. Schmitt and Faaland (2004) shows that in addition to houses, projects of constructing airplanes and ships can be recurrent.

The industry reports of Kerwin (2005) and Xu and Zhao (2010) further confirm the wide existence of recurrent projects in the construction industry. Kerwin (2005) shows that home-builders like Pulte Homes Inc. offer only the most popular floor plans to boost efficiency in fulfilling tens of thousand of new orders in a year. Xu and Zhao (2010) surveys an important trend in construction industry – prefabricated housing, where houses have limited variety and are assembled by prefabricated materials. All these cases are characterized by repeating projects with limited variety and their supply chains of standardized materials (see Figure 1 for an illustration).

As materials have become a significant portion of the total project budget (e.g., 65% for residential houses – Somerville 1999), matching material delivery to on-site construction process becomes critical. This is especially imperative as random material delays are common in practice, as illustrated by the examples of ICM and Walsh, et al. (2004), and confirmed by an investigation of time waste in construction which reveals that the site work-force spends a considerable amount of time
<table>
<thead>
<tr>
<th><strong>Project-based Approach</strong></th>
<th><strong>Supply-based Approach</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniquely Engineered Facilities and Components</td>
<td>Assembly of Unique Facilities from Standardized Modules and Components</td>
</tr>
<tr>
<td>Competitive Bidding</td>
<td>Emphasis on Long-term Working Relationships</td>
</tr>
<tr>
<td>Information Hoarding</td>
<td>Create Information Visibility so that the Value Chain Supports the Supply Chain</td>
</tr>
<tr>
<td>Liquidated Damages</td>
<td>Problem Solving through Strategic Alliances for Key Products and Components</td>
</tr>
<tr>
<td>Long and Uncertain Lead Times with Extensive Use of Expediting</td>
<td>Short and Reliable Cycle Times from Raw Materials to Site Installation</td>
</tr>
<tr>
<td>Early Delivery of All Materials to the Site</td>
<td>Phased Delivery of Materials to the Site to Match Installation Rates</td>
</tr>
</tbody>
</table>

Table 1: Project-based approach vs. supply-based approach.

waiting for approval or for materials to arrive on site (Yeo and Ning 2002). Mohamed (1996) shows that the amount of work on non-value-adding activities can be as high as 40% of the total project duration.

For recurrent projects with random material lead times, substantial efficiency can be gained by actively managing the material supply chains, as witnessed by recent case studies (Walsh, et al 2004, Brown, et al. 2004), and advocated by the conceptual frameworks of Tommelein, et al (2003), Tommelein, Ballard and Kaminsky (2009) in the area of construction supply chain management. Specifically, Tommelein, et al. (2003) proposes the *supply-based* approach (as opposite to the *project-based* approach) to manage construction projects, where the latter plans each project independently, the former plans projects on a continuing basis (see Table 1). While the options of supply-based
approach remain vast – from product design, to supplier relationships, and to inventory control, we focus on inventory control in this paper.

The inventory decisions (for material supply chains) shouldn’t be made in isolation from the project decisions because abundant safety-stock reduces material delays and thus project crashing costs but results in higher inventory cost. To optimally balance the project and supply chain costs, one must make the safety-stock decisions in the supply chain and the crashing decisions in projects jointly.

In this paper, we present a modeling framework, called project-driven supply chain (PDSC), to integrate the supply chain safety-stock and project crashing decisions for recurrent projects with random material delays. Specifically, we consider one critical material which is used in all projects and supplied by a supply chain with random processing times. Projects follow a standard schedule with known task durations and crashing costs. For each project, the critical material is needed at a certain time and if the material is delayed, the project will be delayed if no action is taken.

In the nutshell, the PDSC model is a two-stage dynamic optimization model: For a certain inventory position in the material supply chain, we can characterize material delays; and for each delay scenario, we can calculate the optimal crashing strategy - which task to crash and by how much to minimize project costs. We then optimize on the inventory position to minimize the total annual safety-stock and project crashing costs. We shall apply the PDSC model back to the motivating example of ICM and demonstrate its potential by comparing to the current practice.

The paper is organized as follows: In §2, we review the related literature. In §3, we provide operational details for the motivating example – ICM. In §4, we present the mathematic model and analysis. §5 applies the model back to ICM and quantifies its impact. Finally, §6 concludes the paper.
2 Literature Review

The project-driven supply chain (PDSC) model in particular and the integration of supply chain and project management in general are related to the literature of project management, supply chain management, and their interfaces such as project scheduling and material ordering (PSMO) and construction supply chain management. We shall review related literature in each area.

**Project Management Literature.** The project management literature focuses primarily on the planning and execution of a single project, which includes the classic results of critical path method (CPM), time-costing analysis (TCA), project evaluation and review techniques (PERT) and resource constrained project scheduling (RCPS). We refer to Ozdamar and Ulusoy (1995), Pinedo (2005) and Jozefowska and Weglarz (2006) for recent surveys. The time-cost analysis (TCA) or crashing analysis is a well developed technique in the project management literature to balance the duration and budget of a project. Most work on RCPS focuses on non-consumable and reusable resources such as machine and labor. For consumable resources (e.g., materials), one standard approach is to assume fixed lead times and then model material procurement processes as activities.

**Supply Chain Management Literature.** There is a vast literature of supply chain inventory management mainly grown out of applications in the manufacturing industry. We refer to Zipkin (2000), Porteus (2002) and Axsater (2006) for comprehensive reviews. For inventory placement/positioning models in general structure supply chains, we refer to Axsater (2006), Graves and Willems (2003) and Simchi-Levi and Zhao (2007) for recent reviews. Graves and Willems (2005) presents a general model to optimize stock decisions and supply chain configurations simultaneously for new product introductions. All of these works focus on material supply chains without considering the project decisions and their interactions.
Our work is related to three models of stochastic inventory systems. The first model, see Hadley and Whitin (1963), assumes full backorder and that the system fulfills demand as soon as on-hand inventory becomes available. The second model, see Harihana and Zipkin (1995), assumes also full backorder but that the system fulfills demand only on or after it is due. Clearly, it is possible to hold inventory and demand (not due) simultaneously in the second model. The third model, see Graves and Willems (2000), assumes guaranteed service-time (unsatisfied demand is filled by extraordinary measures other than on-hand inventory) and that the system fulfills demand only on or after it is due. Graves and Willems (2003) calls the first two models “stochastic service-time” models, and the third one the “guaranteed service-time” model.

For applications considered in this paper, we cannot use the guaranteed service-time model because the random material delay (due to stock-out and/or random processing times) is a necessary part of the problem. We shall use the stochastic service-time models – both the first and the second models for different stages of the material supply chain.

**Interface – Project Scheduling and Material Ordering (PSMO).** One approach to incorporate consumable resources in project management is the PSMO model which jointly plans for project schedule and material order quantities. This approach is based on the following observation: A project may repetitively require the same material over time. Given the project schedule, the timing and size of material requirement are known, which serve as input to optimize material order quantities so as to balance the fixed ordering cost and inventory holding cost. Clearly, the project scheduling and material ordering decisions are coupled, and the question is how to jointly optimize both sets of decisions for a project. Aquilano and Smith (1980) initiates this approach by considering joint CPM and MRP planning with constant activity durations. Smith-Daniels and Aquilano (1984) and Smith-Daniels and Smith-Daniels (1987) present various extensions. More
recently, Dodin and Elimam (2001) includes varying activity duration, early reward/late penalty and quantity discount into the model.

The PDSC model complements the PSMO model by controlling material lead times. While the PSMO model focuses on the cycle stock issues for a single project facing economies of scale in ordering, and jointly optimizes project schedule and material order quantities, the PDSC model focuses on the safety-stock issues for recurrent projects subject to random material delays, and jointly optimizes project crashing decisions and material safety-stock levels.

**Interface – Construction Supply Chain Management.** The literature of construction management has traditionally focused on the management of individual projects (Tommelein, et al. 2003). Since middle 1990s, the supply chain management concepts and methodologies have been introduced into this literature and gained substantial attention. However, supply chain management is still relatively new in construction industry (O’Brien, et al. 2002, Tommelein, et al. 2003), and most published results focus on qualitative and conceptual frameworks (Vrijhoef and Koskela 2000, Vaidyanathan and Howell 2007) or on case studies (Walsh, et al. 2004, Brown, et al. 2004). There is a lack of rigorous mathematical treatments that integrate the issues of material supply chains and projects, and resolve them jointly. We refer to O’Brien, et al. (2002) for a survey on construction supply chain management.

In this literature, two papers are mostly related to our work. Walsh, et al. (2004) presents a case study where a large food manufacturer is frequently engaged in capital projects to increase its capacity. The supply chain of stainless steel components (used in all projects) is subject to the longest and most variable lead time. Both the occurrences and material requirements of future projects are unpredictable. In order to complete the projects on time, the company used to expedite the supply chain upon early signs of material delays. The authors proposed an alternative solution
– holding a certain amount of safety-stock in the supply chain, independently of any specific project order, to reduce and stabilize the random lead time. The supply chain is simulated to determine the proper inventory positions. The paper focuses on stainless steel supply chain without considering the project scheduling issues. Brown, et al. (2004) describes the practice of Quadrant Homes Inc. which applies lean manufacturing principles to construction projects by using standardized construction process, limit number of variations, and long-term suppliers of prefabricated and standardized parts. The paper emphasizes on matching material delivery to construction schedule, and provides empirical evidence to support the supply-based management approach and the concept of recurrent projects.

3 The Motivating Example

In this section, we provide a detailed description on ICM’s operations which serves as a basis for the mathematic model in §4. We refer the reader to Shah and Zhao (2009) for a complete case study.
ICM is a New Jersey based construction management firm that keeps internally only design, engineering, bidding, project planning and management functions and outsources all materials to suppliers and construction labor to subcontractors. The company follows a standard business process for each project as illustrated in Figure 2. After a project is awarded, ICM assigns it to a project manager who puts the plan into action by securing subcontractors and negotiating price with material suppliers. Each project of ICM is managed by an individual project manager at the construction site. The procurement is usually done by the project manager as per the requirement of the project. The project manager oversees the entire project execution and is not connected in any formal way to other project managers.

Projects. All construction projects follow a template of schedule (see Figure 3) where the tasks in darker color are on the critical path. The total duration of a standard project is 25 weeks.

The structural steel is needed for Task 5 (Framing) at the beginning of the 7th week. If this material is delayed, the tasks that can be expedited to bring the schedule back on track are 5 (Framing), 6 (Roofing), 16 (Painting), 18 (Bathroom, Kitchen and Cabinets) because the minimum...
duration of a task is one week, and thus tasks with only one week duration cannot be expedited.

Expediting a task reduces its duration but must maintain the total workload – labor hours. Expediting cost comes from over-time wage which is 50% higher than regular labor hours. The expediting cost of each task is known and linear in the weeks expedited. The delay penalty per week for a project is constant – 1% of the project revenue (less materials).

**Structural steel supply chain.** For a typical project, 65% of the cost comes from materials, while the share of equipment and construction labor is 20% and 15% respectively. Structural steel is the most expensive material that is used in all construction projects. The structural steel supply chain consists of three stages: producer, service center and fabricator (see Figure 4 for an illustration). The producer manufactures standardized hot-rolled shapes which are customized according to construction drawings by the fabricator. These companies are the only government authorized suppliers in proximity and thus cannot be switched. Currently the entire structural steel supply chain makes to order and the total lead time ranges from 5 to 8 weeks.

ICM’s weekly material requirements are highly sporadic and possibly zero if no projects require
framing at a certain week. Occurrences and material requirements of future projects are unknown until the bid is won. According to convention, all needed structural steel at one building must be delivered in one set; while materials move immediately downstream once the work on them is done at any stage of the supply chain, materials can not be delivered earlier than due date to sites because inventory cannot be stored on-site.

4 The Mathematic Model

In this section, we present the mathematical model of PDSC based on the practice of ICM. The model can be extended to handle more general cases (see discussion in §6). We make the following assumptions:

- Safety-stock can only be held at the service center and cannot be held at fabricator due to customization (ICM can purchase some inventory in advance of any specific project and hold it at service center).

- Inventory management assumptions: (1) all stages in the supply chain operates a periodic-review base-stock policy. (2) We assume standard sequence of events (receiving, reviewing, ordering, demand, accounting), see Hadley and Whitin (1963). Deliveries are made only at the end of a period. (2) Processing times at all stages of the supply chain are random but sequential. (3) Unsatisfied demand is fully backordered at each stage. (4) All needed structural steel at one building must be delivered in one set. (5) Orders are fulfilled on a first-come-first-serve basis (FCFS) at each stage. (6) Delivery is made as soon as inventory becomes available in all stages of the supply chain except the fabricator where no early delivery can be made to project on-site. (7) The fabricator holds any structural steel which is ready before needed in a project. (8) Material orders are placed immediately upon start of the
project.

- Project management assumptions: (1) each task has known duration and linear crashing cost per period. (2) The project delay penalty per period is known and constant.

We define the following notation:

- $D_t$: the demand for structural steel at the $t^{th}$ week. For convenience, we define $D[t, t + k] = \sum_{i=0}^{k} D_{t+i}$ for $k \geq 0$. If $k < 0$, then $D[t, t + k] = 0$. We also define $D(l)$ be demand during $l$ periods of time.

- $L$: the total lead time of the service center that includes the processing times at the producer and the service center.

- $S$: the base-stock level at the service center.

- $X$: the service time provided by the service center.

- $Y$: the processing time at the fabricator.

- $h_s, h_f$: The annual inventory holding cost per unit at the service center and fabricator respectively.

- $T$: the due date of structural steel for a project since the inception of the project.

- $\Delta$: the delay of structural steel.

- $\pi$: the delay penalty cost per project per period.

- $\lambda$: the average number of projects completed in one year.

For the supply chain, we have two cost components – the inventory holding cost at the service center and the inventory holding cost at the fabricator. For the projects, we are concerned about
the crashing cost and project delay penalty cost. Specifically, we define $G_s(S)$ to be the annual inventory holding cost at the service center, and $G_f(S)$ to be the annual inventory holding cost at fabricator. Clearly they are functions of the base-stock level, $S$, at the service center. Let $C(z)$ be the minimum crashing cost if $z$ periods have to be crashed for a project. Let $\Pi(y)$ be the project delay penalty cost if it is delayed by $y$ periods. $\Pi(y) = \pi y$. Clearly $z + y = \Delta$, where the distribution of $\Delta$ depends on $S$ because the distribution of $X$ depends on $S$.

We are now ready to present the optimization model. Our objective is to minimize the sum of the annual supply chain safety-stock cost and project crashing/delay penalty costs. That is,

$$\min_S \{G_s(S) + G_f(S) + \lambda E_{\Delta}[\min_z \{C(z) + \Pi(\Delta - z)\}]\}, \quad (4.1)$$

where $E_{\Delta}$ is the expectation taken with respective to $\Delta$. This is a two-stage optimization problem where we first optimize the project crashing decisions for each scenario of material delay, $\Delta$, then we optimize over inventory decision $S$. For convenience, let $G(S) = G_s(S) + G_f(S) + \lambda E_{\Delta}[\min_z \{C(z) + \Pi(\Delta - z)\}]$ be total annual cost.

We now characterize how the base-stock level, $S$, determines the distribution of the service time ($X$) at the service center, the random material delay ($\Delta$) to projects, and the total cost of the supply chain. Define $R_k$ to be the probability that $D_t (> 0)$ is satisfied within the period $t + k$ at the service center. For a constant lead time $L$, $R_k = \Pr\{S - D[t - L + k, t] \geq 0|D_t > 0\}$ for $k \leq L$ (Hausman, et al. 1998). For stochastic and sequential lead time $L$ (see Zipkin (2000) Chapter 7), we let the probability of $L = L_i$ be $\Pr\{L = L_i\}$, then $R_k = \sum_i \Pr\{S - D[t - L_i + k, t] \geq 0|D_t > 0\} \Pr\{L = L_i\}$ for $0 \leq k \leq \max_i\{L_i\}$. Because $X$ is the service time of $D_t$ ($D_t > 0$), then $R_0 = \Pr\{X = 0\}$ and $R_k = \Pr\{X \leq k\}$ for $k > 0$. Consequently, $\Pr\{X = 0\} = R_0$ and $\Pr\{X = k\} = R_k - R_{k-1}$ for $k > 0$. 

14
With the distribution of $X$ (for $D_t > 0$), we can calculate the distribution of $\Delta$ by observing

$$\Delta = (X + Y - T)^+.$$  \hfill (4.2)

The annual inventory holding cost at the fabricator can be calculated by

$$G_f(S) = h_f E[D]E[(T - X - Y)^+]$$ \hfill (4.3)

where $E(D)$ is the expected demand in one period. The net inventory at the end of period $t$ at the service center is $N(t) = S - D[t - L, t]$, and the on-hand inventory at the service center is $I_s(t) = N(t)^+$. In steady state, the annual inventory holding cost at the service center is

$$G_s(S) = h_s E[I_s] = h_s E[(S - D(L + 1))^+]$$ \hfill (4.4)

Given a material delay $\Delta = \delta > 0$, one has to determine the least-cost project crashing plan. For any $0 \leq z \leq \delta$, we can obtain $C(z)$ by solving a linear programming problem for the project, see Nahmias (2005). Clearly, $C(z)$ is a convex function in $z$ while $\Pi(y)$ is linear in $y$.

5 Numerical Study

In this section, we apply the PDSC model back to ICM and demonstrate its impact. The review period for ICM and its structural steel supply chain is one week. Using historical data in 2008 (totally 53 weeks of data), we construct an empirical distribution for weekly requirement of structural steel, $D_t$, as shown in Table 2. Here we use the approximation of discrete demand by rounding up, for instance, all values in $[41, 50]$ to 50.

Assuming zero base-stock level at the service center, the structural steel supply chain makes to order and can deliver an order to project on-site at the beginning of $7^{th}$, $8^{th}$, $9^{th}$, and $10^{th}$ week due to the review period, and thus may cause a delay of 1, 2, or 3 weeks because it is needed at the beginning of $7^{th}$ week.
<table>
<thead>
<tr>
<th>Value</th>
<th>Frequency</th>
<th>Probability</th>
<th>Value</th>
<th>Frequency</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>32</td>
<td>0.604</td>
<td>60</td>
<td>4</td>
<td>0.075</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0</td>
<td>70</td>
<td>1</td>
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</tr>
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<td>20</td>
<td>0</td>
<td>0</td>
<td>80</td>
<td>2</td>
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</tr>
<tr>
<td>30</td>
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<tr>
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<td>7</td>
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<td>4</td>
<td>0.075</td>
<td>110</td>
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<td>0</td>
</tr>
</tbody>
</table>

Table 2: The empirical distribution of $D_t$.

We assume that the processing time at the producer has an equal chance to be 3, 4, and 5 weeks, and the processing time at the fabricator has an equal chance to be 1 and 2 weeks. Thus, the distribution of the total lead time of the structural steel supply chain (with $S = 0$) is 5 weeks (with probability 1/6), 6 weeks (probability 1/3), 7 weeks (1/3), and 8 weeks (1/6). The monthly inventory holding cost is $16.6 per ton, and thus the annual inventory holding cost $h_s = h_f = $199.2 per ton per year.

By historical data, the average number of construction projects conducted by ICM annually, $\lambda$, is 20. Clearly, $T = 6$. The regular wage of construction labor is $25/hour. The overtime wage is 50% more. To calculate ICM's crashing cost for one, two, and three weeks, we first calculate the crashing cost per week for each of four tasks that can be expedited, see Table 3. The project delay penalty per week is 1% of the project revenue (less materials), which is $13,700 (assuming 15% gross margin for ICM). Clearly the delay penalty is much more expensive than the crashing costs and thus should be avoid.

We now compare the result of the PDSC model to the current practice of ICM which passively crashes project durations upon delay of the structural steel. Figure 5 summarizes the numerical
<table>
<thead>
<tr>
<th>Task</th>
<th>Normal duration (in weeks)</th>
<th>Workload – total labor-hours required</th>
<th>Overtime labor-hours per week expedited</th>
<th>Crashing cost per week</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2</td>
<td>720</td>
<td>360</td>
<td>$4500 = 360 \times \frac{25}{2}$</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>1920</td>
<td>640</td>
<td>$8000 = 640 \times \frac{25}{2}$</td>
</tr>
<tr>
<td>16</td>
<td>3</td>
<td>1560</td>
<td>520</td>
<td>$6500 = 520 \times \frac{25}{2}$</td>
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<tr>
<td>18</td>
<td>3</td>
<td>1560</td>
<td>520</td>
<td>6500</td>
</tr>
</tbody>
</table>

Table 3: The crashing costs of tasks.

results, where the vertical axis stands for the annual safety-stock and project crashing cost, $G(S)$, while the horizontal axis presents the base-stock level at the service center, $S$. We make the following observations:

- The total cost function, $G(S)$, is not convex but seems quasi-convex in $S$. It decreases as $S$ increases from zero and it reaches the global minimum at $S = 140$. Then it slowly increases as $S$ further increases.

- Comparing to the current practice of passive crashing, the PDSC model brings the cost down from $161,667 to $24,879, with a 84.6% saving.

6 Conclusion

In this paper, we define the problem of recurrent projects with random material delays, provide the model of project-driven supply chains and demonstrate its impact by a real-world example. While we only consider one critical material in this paper, the modeling framework of PDSC can be readily extended to include multiple materials that are required by projects at different times and are subject to random delays. These problems, although much more complex, can be
modeled in a similar way by observing that material safety-stock, held at the right locations of the supply chain, can be a viable option, and the safety-stock decisions should be made jointly with project crashing decisions. The corresponding mathematic model shall sequentially optimize project crashing decisions for each material delay scenario and inventory positions to maximize the supply chain and project performance.

Another interesting variation arises when recurrent projects share certain common materials but with non-identical schedule. That is, the material may be required at different times upon start of different types of projects. While the general trade-off and idea of the PDSC model still apply here, we must modify the model to account for different types of projects. The development and application of the PDSC model in these areas remain as our future research directions.

Acknowledgments

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