Integrating Inventory Planning with Project Management in Project-Driven Supply Chains *

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Abstract

Most real-world projects require material supplies at various stages. Project-driven supply chains (PDSCs) are the combinations of project activities and their supporting material supply chains where the demand for the latter is driven by the material requirement of the former. Material supply decisions (e.g., inventory positioning) and project decisions (e.g., resource planning, project scheduling) are intertwined in PDSCs. In this paper, we present a modeling paradigm to help firms make material supply decisions and project decisions jointly.

We model a PDSC by a combined network of material supply chain where inventory can be held and a set of activities initiated upon random demand for projects. The material availability constrains the starting times of project activities. We develop a joint optimization model to determine the optimal inventory levels, activity durations and project schedule simultaneously, so as to strike the balance between inventory cost and project costs. For tree structure networks, we develop an optimization algorithm based on dynamic programming. Using examples, we demonstrate that the joint optimization can lead to significant cost savings as compared to the common practice which optimizes material supply and project decisions sequentially. Even if activity durations cannot be modified, coordinating the project schedule with inventory decisions alone can result in sizable savings. We also discuss material customization issues and develop insights on how the savings are generated by the joint optimization, and when they are significant.

Keywords: Project-driven supply chain, project management, inventory positioning.

*Research supported in part by the CAREER Award no. 0747779 from the National Science Foundation.

1 Introduction

Project-driven supply chains (PDSCs) can often be found in practice, such as make-to-order/build-to-order (MTO/BTO) manufacturing, engineering and construction industries. For capital intensive projects, material supply often constrains the project schedules and affects the system-wide costs. Hence, it is clear that supply chain decisions and project decisions are intertwined. The objective of this paper is to define and characterize this class of practical applications and to establish a modeling framework to make supply chain decisions and project decisions jointly.

In practice, material supplies and project activities are often managed separately. Often, companies make project related decisions such as resource planning and project scheduling assuming that materials are always available; and then make material supply decisions accordingly. For examples of this practice in construction industry, we refer the reader to Walsh, et al. (2004) and reference therein. This practice is reasonable when the firm enjoys the luxury of extended project due dates, and relatively short and reliable lead times for material supplies.

However, today's business environment has changed due to globalization, heightened customer expectations and an increasingly technology-driven economy. Many firms now face more unpredictable demand for projects with tighter due dates. Heavy delay penalties force the firms to expedite project activities and/or better secure material supply, which naturally gives rise to the joint planning of material supply and project activities.

MTO/BTO manufacturers are a case in point. Many of them utilize a massive network of materials, facilities and vendors to make expensive and complex products. For instance, the Boeing 767 has 3.1 million parts and 1,300 vendors (Simpson, et al. 1991). While these firms build the products (i.e., projects) upon demand, many parts and subsystems can be held in inventory. Material supply and project management in such systems pose substantial challenges. For instance, Boeing Aircraft was forced to announce write downs of $2.6 billion in October 1997. The reasons are "raw material shortages, internal and supplier parts shortages" (Wall Street Journal, Oct. 23, 1997). The loss includes "late delivery payments, higher vendor costs, extensive overtime and expedited delivery costs" (October 26, 1997 *Seattle Times* entitled "Boeing Risk Backfired Last Week").

This crisis clearly illustrates the following trade-off: if materials are in short supply and the project schedule cannot accommodate the delays, activities of the project will have to be expedited which can be very costly, and the entire project is likely to be delayed. On the other hand, holding

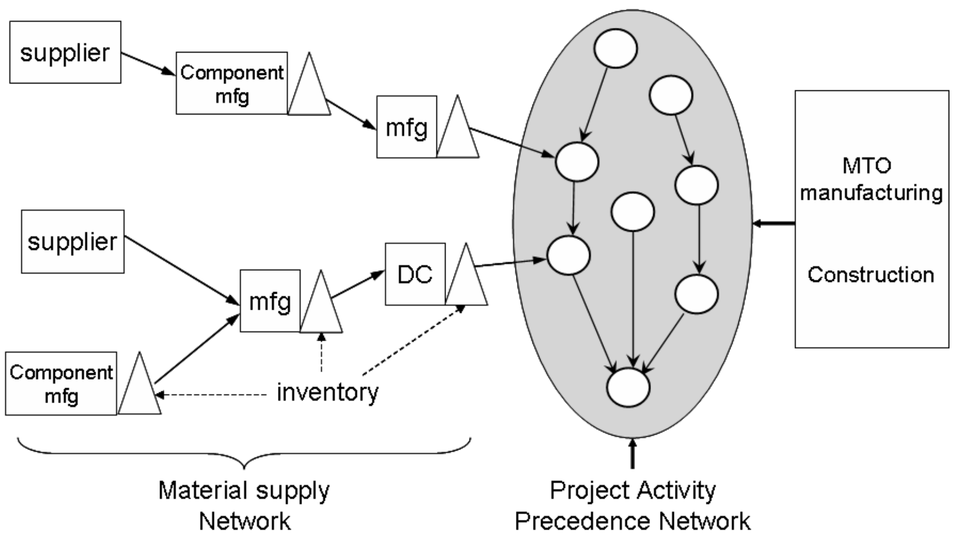

Figure 1: A project-driven supply chain (PDSC) that combines material supply and project activities.

inventory to guarantee immediate availability of all materials may not be wise. While one can maximize the project scheduling/planning flexibility, the inventory costs can be prohibitively high. Because the material availability and project decisions serve as mutual constraints, models should be developed to make the decisions on inventory, activity duration and project schedule jointly so as to strike a balance between supply chain costs and project costs.

Similar challenges appear in real estate and construction industry where material costs typically account for a significant portion of the project total cost, see Yeo and Ning (2002) and Walsh, et al. (2004). Construction projects suffer from constant overrun in time and costs. Indeed, an investigation of time waste indicates that site workforce spends a considerable amount of time waiting for materials to be delivered (Yeo and Ning 2002). In a case study, Walsh, et al. (2004) shows that the long and variable lead times for certain components and tight due dates force the builders to procure inventory in advance of specific projects.

The aforementioned PDSCs, although coming from different industries, share some common features. First, they are combinations of material supply chains where inventory can be held, and a set of project activities that are initiated upon demand, see Figure 1. The project activities are connected by a general precedence relationship. The material supply chains can be separated from the project network by customization points. Second, although projects are often highly customized by the materials and/or activities required, some core activities and components/subsystems are shared among most projects. Finally, projects are recurring but the exact arrival time of each project is random. For example, Boeing may receive several hundreds of aircraft orders each year which arrive randomly. It is thus reasonable to plan for the "recurrent projects" (or "multi-project") over a relatively long time horizon.

In this paper, we consider PDSCs for the "recurrent projects." We model such a PDSC by a combined network of material supply and project activities facing random demand for the projects. The material network interacts with the project network in the following ways: (1) the demand for the material supply chains is generated by the material requirements of the projects; (2) the material availability constrains the starting times of the project activities. We call such a network a material and project network, briefly, an **M&P network**. In an M&P network, material lead times and project durations are competing for the due date. To optimally balance the inventory holding costs (in material supply chains) and the activity expediting (or resource) costs/project delay penalties (in project networks), we formulate a joint optimization model to determine the optimal stock levels, activity durations and project schedule simultaneously so as to minimize system-wide cost per unit of time.

For tree structure M&P networks, we develop an optimization algorithm based on dynamic programming (DP). The DP algorithm generalizes that of Graves and Willems (2000, 2003a) from a pure material network to an M&P network. The complexity of the algorithm is polynomial in the maximum service time and the maximum latest finishing time. Given the solution of the DP algorithm, i.e., the committed service times from the supply network, one can determine the critical path and slacks for the project network by the critical path method (CPM, see Nahmias 2005) with additional material availability constraints on activity starting times.

Using representative examples, we demonstrate that the joint optimization can result in significant savings as compared to the common practice that makes material supply and project decisions sequentially. Intuitively, this is true because the joint optimization picks the right activity to expedite/delay so as to minimize the increase in project costs while maximizing savings in inventory costs. Even if the activity durations cannot be expedited, coordinating the project schedule with inventory decisions alone can result in sizable savings. We further extend the model to include material customization, and provide insights on how the savings are generated by the joint optimization, and when they are significant.

The rest of the paper is organized as follows: We review related literature in §2. In §3, we present the modeling paradigm, the notation and mathematical formulation. In §4, we outline the optimization algorithm. In §5, we study various examples and develop managerial insights. We extend the modeling paradigm to include material customization in §6. Finally, we conclude the paper and point out future research in §7.

2 Literature Review

There is extensive literature for both supply chain inventory management and project management. We refer to Zipkin (2000), Porteus (2002) and Axsater (2006) for comprehensive reviews on the former, and to Ozdamar and Ulusoy (1995), Pinedo (2005), Nahmias (2005) and Jozefowska and Weglarz (2006) for indepth surveys on the latter. Material supply chains often require different sets of decisions from project management, which lead to different cost functions. Specifically, inventory decisions are central to material supply chains, while expediting (or resource planning) and scheduling decisions are critical to project management. So far, little work has been done to integrate the supply chain and project decisions under uncertainty.

This paper is built on recent literature on inventory placement/positioning in general structured supply chains. The objective of these models is to determine the stock levels in a supply chain so as to optimize system-wide inventory costs. Recent reviews are provided by Axsater (2006), Graves and Willems (2003b) and Simchi-Levi and Zhao (2007).

Inventory placement models can be classified into the guaranteed service-time models and the stochastic service-time models. In the former, it is assumed that in case of stockout, each stage has resources other than the on-hand inventory to satisfy demand so that the committed service times can always be guaranteed. In the latter, it is assumed that in case of stockout, each stage fully backorders the unsatisfied demand and fills the demand until on-hand inventory becomes available. Thus, the delay due to stockout is random. We refer to Graves and Willems (2003b) and Simchi-Levi and Zhao (2007) for a review of these models and related literature. All of these works focus on the material supply network without considering the project network and their interactions.

More recently, Graves and Willems (2005) generalizes the guaranteed service-time models to optimize stock decisions and supply chain configurations simultaneously for new product introductions. In contrast, we apply the guaranteed service-time model to a new class of practical problems that involve coordination of material supply decisions and project decisions. We develop a modeling paradigm for this class of problems and provide new insights on the benefits of the coordination.

The project management literature includes classic results on critical path method (CPM), time-costing analysis (TCA), project evaluation and review techniques (PERT) and resource constrained project scheduling (RCPS). Most work on RCPS focuses on non-consumable and reusable resources such as machine and labor. This paper differs from the literature because it focuses on consumable resources and material supply constraints. It aims at establishing a modeling framework that integrates supply chain inventory planning with project time-costing analysis for recurrent projects.

No attempt was made to combine project management and material supply until the 1980s. Aquilano and Smith (1980) considers joint CPM and MRP planning with lead times. Smith-Daniels and Aquilano (1984) and Smith-Daniels and Smith-Daniels (1987) present various extensions. The most related work in this literature is perhaps Dodin and Eliman (2001), which considers the joint planning of project duration/schedule and material supply for a "one-time project" which repetitively requires the same materials. In their setting, the demand for materials is known, and the supply chain is approximated by single-stage systems under the economic lot-sizing models. In contrast, our paper assumes that the demand for materials is driven by the material requirements of "recurrent projects" which arrive randomly.

This paper is also related to the available-to-promise (ATP) models, which address questions such as, when to accept or reject a production order? And how to utilize the available resources to fulfill the order? We refer the reader to Ball, et al. (2004) for a recent survey. While ATP models focus on short-term order fulfillment issues, we consider long-term inventory/resource planning decisions.

Finally, in construction management literature, supply chain management concepts have received substantial attention since middle 1990s. Most of the research in construction supply chains focuses on establishing qualitative and conceptual frameworks (Yeo and Ning 2002, Vaidyanathan and Howell 2007) or on case studies (Walsh, et al. 2004) where simulation models are developed to handle uncertainties. We refer to O'Brien, et al. (2002) for a survey.

3 The Modeling Paradigm

We first introduce the modeling assumptions and notation in §3.1, then we present the joint optimization model in §3.2.

3.1 Assumptions and Notation

Consider a project-driven supply chain (PDSC) exemplified in Figure 1 with a material supply network and a set of project activities. We make the following assumptions.

- **The Material Network**. Following convention, a node is defined as a unique combination of product and facility, and an arc is defined as a pair of nodes with direct supply-demand relationship. We consider the guaranteed service-time model (see, e.g., Graves and Willems 2000) for the material network. The transit times are constant. The supply chain has convergent tree structure, where each stage utilizes a periodic-review base-stock policy to control inventory.

- **The Project Network**. We consider the activity-on-node project network. The activity durations are deterministic. The expediting/resource cost for each activity is linear in the activity duration. The penalty cost is also linear in the project delay. The project network has a tree structure where activities do not share common materials and there are no non-consumable resource constraints.

- **The Interface**. Upon arrival of a project, the material network is notified of the project and its material requirement. On one hand, the starting time of an activity depends on the finishing times of the preceding activities as well as its material lead times. On the other hand, given a project schedule, the maximum allowable lead-time for a material is effectively the time between the project arrival and the time when the material is needed (i.e., the starting time of the activity that requires the material). Clearly, the actual lead-time, which must be smaller than the maximum, depends on the inventory levels of the material network; while the starting time of the activity also depends on the activity durations and the schedule of the project network.

Consistent with practice, we assume that if a node in the M&P network belongs to the material network, then all its upstream nodes belong to the material network. We further assume that the external demand (for projects) follows a Poisson process. For the ease of exposition, we focus on the core activities and materials required by all projects. Material customization is discussed in §6, and activity customization is discussed in §7.

Notation For the material network, we have a set of nodes and arcs denoted as $(\mathcal{N}_m, \mathcal{A}_m)$, where m indicates the material network. We define the following notation. For $k \in \mathcal{N}_m$,

- X_k: committed service time of node k, $k \in \mathcal{N}_m$.
- $\widetilde{L}_k$: the replenishment lead time at node k.
- $L_{j,k}$: transportation lead time, $(j,k) \in \mathcal{A}_m$.
- L_k: processing time at node k.
- h_k: inventory holding cost at node k.
- s_k: base-stock level at node k.

For simplicity, we assume that one unit of a product requires one unit of each component.

For the project network, we have a set of nodes and arcs denoted as $(\mathcal{N}_p, \mathcal{A}_p)$, where p indicates the project network. A node here stands for an activity, while an arc here denotes an immediate precedence relationship between nodes. The precedence relationship can be general and is not limited to the bill of materials. Let J be the ending node of the project network. If there are multiple ending activities, one can always create a pseudo activity with zero duration as the unique ending node. We define the following notation.

- F_i: finishing time of node i relative to the arrival time of the project, $i \in \mathcal{N}_p$.
- u_i: activity duration of node i, $i \in \mathcal{N}_p$.
- π: penalty cost per unit of time if the project is delayed.
- T: due date of the project relative to the arrival time of a project.

Finally, we define $\mathcal{A}_I$ to be the set of arcs that connects the material network and the project network. These arcs represent the material requirements of the activities.

3.2 Mathematical Formulation

Given an M&P network, our objective is to minimize the system-wide cost per unit of time, which includes the inventory holding costs, resource/expediting costs and project delay penalty cost. The decision variables are the committed service times (or base-stock levels) for all stages in the material network, and the durations and finishing times for all activities in the project network. The constraints are defined by the supply-demand relationship in the material network, the precedence relationship in the project network, and the material requirements of the project network. It is also natural to assume upper and lower bounds for the activity durations and committed service times.

Defining Cost Functions For the material network, we utilize the guaranteed service-time model to determine the base-stock levels and inventory holding costs. We refer readers to Graves and Willems (2000, 2003a) for a thorough discussion. Below, we outline the main results. At any node $k \in \mathcal{N}_m$, the base-stock level at node k can be obtained by,

$$s_k = \lambda_k(\widetilde{L}_k - X_k) + z_\alpha \cdot \sigma_k \cdot \sqrt{\widetilde{L}_k - X_k}, \quad \forall k \in \mathcal{N}_m, \tag{3.1}$$

where λ_k (σ_k) is the mean demand (demand standard deviation, respectively) per period at node k, and z_α is the safety factor. The demand statistics can be obtained by the bill of materials. The safety-stock holding cost at node k can be approximated by,

$$H_k(\widetilde{L}_k, X_k) \ = \ z_\alpha \cdot h_k \cdot \sigma_k \cdot \sqrt{\widetilde{L}_k - X_k}, \tag{3.2}$$

Clearly, $H_k(\widetilde{L}_k, X_k)$ is concave in X_k, and $H_k(\widetilde{L}_k, X_k)$ is increasing in $\widetilde{L}_k$ but decreasing in X_k.

For a project network, we consider two types of cost: expediting/resource cost and penalty cost. The expediting cost for an activity is a function of the activity duration. In general, the activity duration can be expedited by investing more resources, including workers, equipment, etc. We assume that the expediting cost increases linearly as the activity duration decreases (see Nahmias (2005) Chapter 9 for a justification). Thus the expediting cost of activity $i \in \mathcal{N}_p$ can be formulated as follows,

$$(a_i - b_i u_i), \tag{3.3}$$

where parameters a_i, b_i are constants obtained from the known expediting/normal costs and durations.

Penalty cost occurs when the last activity J in the project network fails to finish on time.

$$\pi \cdot (F_J - T)^+. \tag{3.4}$$

The Connections The connections between the material network and the project network are defined by the following constraints,

$$F_i \ \geq \ X_k + u_i, \quad \forall (k, i) \in \mathcal{A}_I, \ k \in \mathcal{N}_m, \ i \in \mathcal{N}_p, \tag{3.5}$$

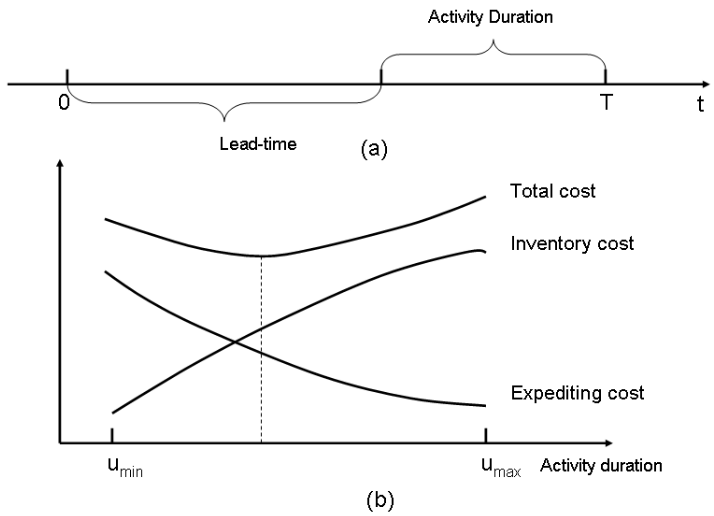

Figure 2: Trade-Off.

This inequality indicates that the finishing time of activity i should occur later than the committed service times of all of its material supplies plus its activity duration. This is true because an activity can only start after all the required materials become available.

The Basic Trade-Off To illustrate the basic trade-off between the inventory cost and the project cost, we consider an M&P network with one activity which requires one material. We assume that project penalty cost is high enough so that no delay is allowed. At time $t = 0$, an order of the project is confirmed with a due date $T > 0$. Clearly, the latest time for the material to be ready is T subtracting the activity duration (see Figure 2 (a)), which is the maximum allowable lead-time for the material because by assumption, one can only order the material after the project is confirmed.

It is easily seen that the activity duration and the material lead-time are competing for the total available time, T. If we reduce the activity duration, then we can save the inventory cost but lose on activity expediting cost. Figure 2 (b) illustrates the inventory cost, activity cost and total cost as functions of the activity duration.

For general M&P networks with many materials and activities, the basic trade-off stays the same, but additional issues arise. For instance, one needs to determine how many resources to plan for each activity and how much inventory to carry for each material. Before constructing a joint optimization model to address these issues, we develop some insights on the conditions under which joint optimization can generate positive benefits. For this purpose, we define the concept of the *extended project network*, which is the combination of the project network and the material network with zero base-stock level everywhere.

For a given due date, we now differentiate between a *critical material node* and a *non-critical material node* as follows: A material node is critical if there is a path of the extended project network that contains this node with the total path duration longer than the due date. Intuitively, zero inventory at all critical material nodes does not guarantee the due date. A material node is non-critical if all paths of the extended project network that contain this node have total path durations not longer than the due date. Clearly, if all material nodes are non-critical, no inventory should be carried in the material network, and the benefit of joint optimization is zero. Otherwise, the benefit may be positive.

The Joint Optimization Problem Combining all cost terms in Eqs.(3.2)-(3.4), we have the following mathematical model where decision variables are the committed service times in the material network, the activity durations and the finishing times in the project network. Let λ be the arrival rate of projects, the problem (P) can be written as follows,

$$
\text{(P)} \quad \begin{array}{lrl}
\min & \sum_{k\in\mathcal{N}_m} H_k(\widetilde{L}_k, X_k) + \lambda[& \sum_{i\in\mathcal{N}_p}(a_i - b_i u_i) + \pi\cdot (F_J - T)^+ \;] \\
\text{s.t.} & \widetilde{L}_k \geq X_k, & k \in \mathcal{N}_m, \\
 & X_j + L_{j,k} + L_k \leq \widetilde{L}_k, & (j,k) \in \mathcal{A}_m, \\
 & F_i \geq X_k + u_i, & \forall (k,i) \in \mathcal{A}_I, \\
 & F_i - F_j \geq u_i, & \forall (j,i) \in \mathcal{A}_p, \\
 & LB_i \leq u_i \leq UB_i, & i \in \mathcal{N}_p, \\
 & X_k \geq 0 \text{ and integer}, & \forall k \in \mathcal{N}_m, \\
 & F_i \geq 0 \text{ and integer}, & \forall i \in \mathcal{N}_p.
\end{array} \tag{3.6}
$$

Note that for Problem (P), the objective function on inventory cost is concave, while the objective function on the project costs is convex.

In Problem (P), the first two constraints define the relationship between committed service times and replenishment lead times in the material network. The first constraint says that the committed service time of node k should be less than or equal to the replenishment lead time at node k. The second constraint specifies the relationship between the replenishment lead time at node k and upstream committed service times, transportation times and the processing time at node k. The third constraint connects the material and project networks (see Eq. 3.5). The fourth constraint is defined by the precedence relationship in the project network, which ensures that the finishing time of an activity i subtracting it duration is not sooner than the finishing times of all of its immediate predecessors. The fifth constraint provides upper and lower bounds for activity durations. UB_i is the normal activity duration under a so-called baseline specification (for example, the current project plan) and LB_i is the most expedited activity duration: the minimal feasible duration of the activity (presumably adding more resources will not further reduce the activity duration, see, e.g., Nahmias 2005). All decision variables are integer-valued.

The Case Without Expediting In practice, activity durations may not be expedited. Thus, an interesting and important special case of problem (P) is that the activity durations in the project network, u_i, are fixed for all $i \in \mathcal{A}_p$. The resulting problem, namely, problem (P1), can be formulated in the same way as problem (P) but without $\sum_{i \in \mathcal{N}_p}(a_i - b_i u_i)$ in the objective function and without u_i being the decision variables.

4 Dynamic Programming

To solve problem (P), we develop a dynamic programming (DP) algorithm which generalizes that of Graves and Willems (2000) to the combined network of material supply and project activities. We first label all the nodes in both networks in an order that is increasing from upstream to downstream. That is, each node in the resulting network has a larger label than any of its upstream nodes. We also define $\widetilde{EF}_i$ and $\widetilde{LF}_i$ as the earliest and latest possible finishing times for activity $i \in \mathcal{N}_p$. Let M_k be an upper bound on $\widetilde{L}_k$ for each $k \in \mathcal{N}_m$.

Functional Equations For the material network, we utilize the same DP algorithm as in Graves and Willems (2000, 2003a). The project network requires more work. Let $\overline{F}_i = \{F_j | \forall (j,i) \in \mathcal{A}_p\}$.

$$C_i(\overline{F}_i, u_i, F_i) \; = \; \lambda(a_i - b_i u_i) + \sum_{(k,i) \in \mathcal{A}_I} f_k(F_i - u_i) + \sum_{(j,i) \in \mathcal{A}_p} g_j(F_j), \tag{4.1}$$

where $f_k(X_k)$ is the minimum cost for the material subnetwork ending at node k (see Graves and Willems 2000), and $g_i(F_i)$ is given as follows,

$$g_i(F_i) \; = \; \min_{\overline{F}_i, u_i} \quad C_i(\overline{F}_i, u_i, F_i) \tag{4.2}$$

$$\text{s.t.} \quad LB_i \le u_i \le UB_i, \tag{4.3}$$

$$F_i - F_j \ge u_i, \quad \forall (j,i) \in \mathcal{A}_p, \tag{4.4}$$

$$\widetilde{EF}_j \le F_j \le \widetilde{LF}_j, \quad \forall (j,i) \in \mathcal{A}_p. \tag{4.5}$$

Clearly, in the optimal solution, $F_j = \min\{F_i - u_i, \widetilde{LF}_j\}$ if $F_i - u_i \geq \widetilde{EF}_j$; otherwise, F_i is not feasible. So for each possible F_i, one only needs to enumerate on u_i to determine $g_i(F_i)$.

For node J, we have

$$C_J(\overline{F}_J, u_J, F_J) \quad = \quad \lambda[(a_J - b_J u_J) + \pi(F_J - T)^+] + \sum_{(k,J)\in\mathcal{A}_I} f_k(F_J - u_J) + \sum_{(j,J)\in\mathcal{A}_p} g_j(F_j). \quad (4.6)$$

For each F_J, we first compute $g_J(F_J)$ as follows,

$$g_J(F_J) \quad = \quad \min_{\overline{F}_J, u_J} \quad C_J(\overline{F}_J, u_J, F_J) \quad (4.7)$$

$$\text{s.t.} \quad LB_J \leq u_J \leq UB_J, \quad (4.8)$$

$$F_J - F_j \geq u_J, \quad \forall (j, J) \in \mathcal{A}_p, \quad (4.9)$$

$$\widetilde{EF}_j \leq F_j \leq \widetilde{LF}_j, \quad \forall (j, J) \in \mathcal{A}_p. \quad (4.10)$$

Then we compute the minimum total cost by

$$\min_{F_J} \quad g_J(F_J) \quad (4.11)$$

$$\text{s.t.} \quad \widetilde{EF}_J \leq F_J \leq \widetilde{LF}_J. \quad (4.12)$$

The Joint Optimization Algorithm Based on the functional equations, the algorithm works as follows,

1. **Preprocessing on** $\widetilde{LF}_i$. Given zero base-stock levels at all nodes in the material network and also the normal activity durations for all activities in the project network, we apply the forward computation step of the critical path method (Nahmias 2005) to obtain the project duration, i.e., $\widetilde{LF}_J$. Then assuming the shortest activity durations for all activities in the project network, we use the backward computation step of the critical path method to determine $\widetilde{LF}_i$ for each $i \in \mathcal{N}_p, i \neq J$.

2. **Preprocessing on** $\widetilde{EF}_i$. Given zero committed service time from all material nodes and the shortest durations of all activities in the project network, we obtain $\widetilde{EF}_i$ for each activity in the project network by critical path method.

3. Following the sequence of the node labels, we compute $f_k(X_k)$ for all possible X_k at each $k \in \mathcal{N}_m$, or compute $g_i(F_i)$ for all possible F_i at each $i \in \mathcal{N}_p$.

4. For node J, we enumerate all possible F_J to find the one that minimizes $g_J(F_J)$.

The computational complexity of the DP algorithm is $O(|\mathcal{N}_m| \cdot M^2)$ for the material network where $|\mathcal{N}_m|$ is the cardinality of set $\mathcal{N}_m$ and M is the maximum service time; it is $O(|\mathcal{N}_p| \cdot \breve{M}^2)$ for the project network where $\breve{M} = \widetilde{LF}_J$, the latest possible finishing time at node J. We point out that the DP algorithm also works for project networks with general expediting cost functions and project delay.

Given the solution, the earliest and latest starting times of activities can be computed by standard critical path method with additional material availability constraints on the starting times of activities. Based on this information, one can determine the critical path of the project and slacks for non-critical activities.

The Sequential Heuristic For comparison, we consider a heuristic that optimizes project and material supply decisions sequentially. The heuristic works as follows:

1. Assuming immediate availability of all materials, we optimize the project network using time-costing analysis (see, e.g., Nahmias 2005).
2. Given the activity duration, we determine the latest starting time of all activities by CPM.
3. Finally, we optimize the committed service times for the material network such that no material delay occurs.

Clearly this heuristic is inferior to the joint optimal solution because it determines project decisions and supply chain inventory decisions sequentially rather than jointly.

The Case Without Expediting For systems with fixed activity durations, the mathematical formulation is given by problem (P1) in §3.2. For this special case, the DP algorithm still applies. To develop insights on how the joint optimization generates benefits, we design the following joint heuristic algorithm for this case.

Given each possible due date of the project, one can solve for the project schedule without considering the material network, then solve the material planning problem that guarantees the feasibility of the schedule. Specifically, it works as follows,

1. for each possible F_J, solve the project scheduling problem by the critical path method to find the latest starting times for all nodes.

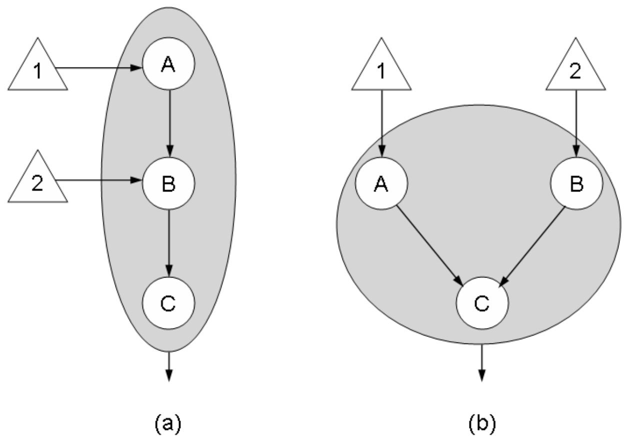

Figure 3: Special Cases.

2. Then, determine the required committed service time for each material.

3. Next, solve for the base-stock levels in the material network.

4. Finally, enumerate all possible F_I to determine the minimum system total cost.

The joint heuristic algorithm generates equally good solutions as the joint optimization algorithm. This is true because given a solution of the joint optimization algorithm, we can always compute the latest starting/finishing times for activities. Scheduling the activities according to these latest times does not change the total cost but does produce a feasible solution for the joint heuristic algorithm.

In this special case, the sequential heuristic differs from the joint heuristic only by setting $F_J = T$ in the latter's first step and removing the latter's last step.

5 Examples and Managerial Insights

The objective of this section is to demonstrate the value of the joint optimization via examples. We also develop insights on the conditions under which the joint optimization results in substantial savings relative to the sequential heuristic with or without expediting.

5.1 Joint Optimization with Expediting

In this section, we assume that activity durations can be expedited. We first analyze a few special cases to develop insights, then we conduct a numerical study for an M&P network.

Special Cases We first consider a simple serial project network, see Figure 3(a). For simplicity, we assume that delaying the project is so expensive that no delay is allowed. So one can only expedite activity durations to save on inventory costs. We also assume that the due date is achievable if one expedites all activities.

Clearly, expediting activity A only delays the starting time of A and allows longer lead-time for material 1. Thus it saves inventory cost only for this item. In contrast, expediting activity B delays the starting times of both A and B, which allows longer lead-times for both material 1 and 2. Thus it saves inventory cost for both items. In addition, expediting B provides more flexibility for planning activity A's duration.

Consider then a parallel project network, see Figure 3(b). The same issue remains, but expediting activities saves inventory cost in a different way. In particular, expediting either activity A or B only delays its own starting time and saves the inventory cost for its corresponding item.

Intuitively, the joint optimization outperforms the sequential heuristic because it picks the right activities to expedite by considering the inventory cost and the project cost simultaneously, while the latter makes project decisions and inventory decisions sequentially. Obviously, the savings tend to be higher when the project network and the material network are comparable in cost and transit times, and when material nodes are on the critical path of the extended project network (see definition in §3.2).

A Numerical Example The example is illustrated in Figure 4. (a) represents the original network for a partial MTO manufacturing system, where M1 and M2 are two manufacturing steps which can hold inventory. All other manufacturing steps (3 and 5) react upon demand, and therefore, they are project activities. (b) represents its corresponding M&P network with node M1 and M2 as two material nodes and nodes 1-5 as project activity nodes. Node 1 (2,4) is created to denote the transportation activity between M1 (M2, node 3, respectively) and node 5.

We consider two cases of the example with varying project due dates and levels of demand uncertainty. In the first case, M1 is on the critical path of the extended project network (see definition in §3.2) without expediting any activity. Whenever the due date is shorter than the duration of the critical path, M1 becomes a critical material node. In the second case, M1 and M2 are not on the critical path of the extended project network.

We set the input parameters in a way such that the material network has transit times and costs

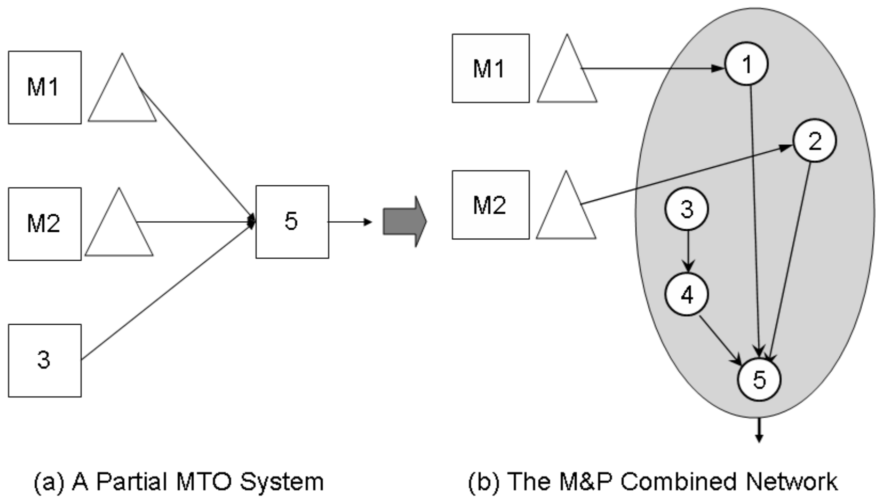

Figure 4: An M&P network.

λ	L_1	L_2	h_1	h_2
1	10	5	20	10

Table 1: Parameters for material networks in cases 1 & 2

comparable to those of the project network. Tables 1-2 summarize the input parameters for both cases. The lead-times of external suppliers at nodes M1 and M2 are set to zero. The project penalty cost, π, is set 40. Due date varies from 0 to an upper limit (set to be the latest finishing time of the project without expediting any activity and with zero base-stock level for each material).

Figure 5 summarizes the numerical results, where the vertical axis stands for the percentage saving of the joint optimization relative to the sequential heuristic, and V stands for the variance of demand per unit of time. The numerical results reveal the following insights:

- As the due date decreases to the lower limit (i.e., $\widetilde{EF}_J$), the savings from joint optimization

	Case 1					Case 2				
Critical Path	1-5					3-4-5				
Project node	1	2	3	4	5	1	2	3	4	5
a	79	70	76	63	82	44	46	109	93	82
b	5	6	11	10	8	5	6	11	10	8
LB(Expedited Time)	4	2	4	2	3	4	2	4	2	3
UB(Normal Time)	12	10	6	5	8	5	6	9	8	8

Table 2: Parameters for project networks in cases 1 & 2

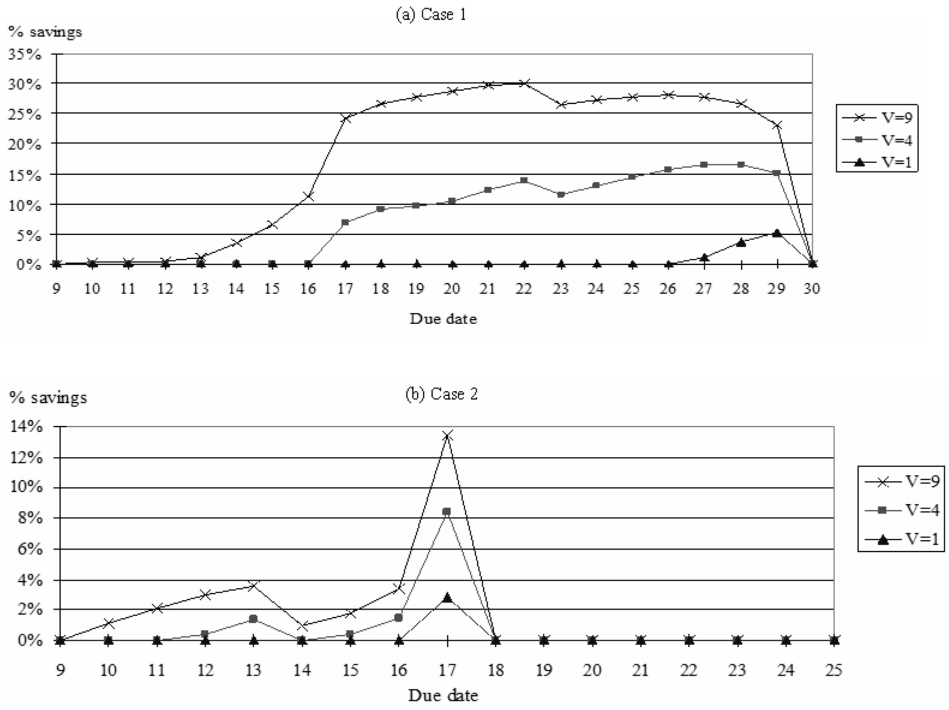

Figure 5: % savings of the joint optimization relative to the sequential heuristic.

diminish. This is true because the high penalty cost and the tight due date forces activity durations to crash to their minimum in both the joint optimization and sequential heuristic. Joint optimization cannot improve system performance because there is no flexibility in choosing different material lead-times.

- As the due date increases to the upper limit (i.e., $\widetilde{LF}_J$), the savings from the joint optimization also diminish. This is true because there is enough time to secure all material supplies, thus it is not necessary to consider material supply while planning for the project network.

- When the due date is in between the lower and upper limits, the savings can be quite significant because one has the flexibility to adjust activity durations and material lead-times so as to balance the inventory cost and project cost.

- Case 1 demonstrates greater % savings than case 2. This is true because in case 1, material supply nodes (e.g., node 1) are more often critical material nodes than in case 2. Thus coordinating the material lead-times and activity durations directly affects the project duration.

- Higher demand uncertainty (which increases the proportion of inventory costs in the total cost) results in greater savings from the joint optimization.

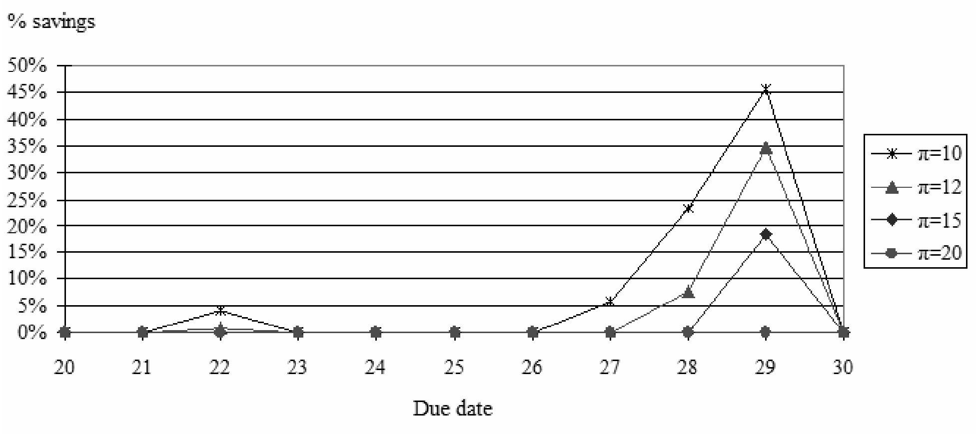

Figure 6: % savings of the joint optimization in case 1 without expediting.

In summary, we show that the joint optimization can lead to significant cost benefits relative to the sequential heuristic. The savings are particularly substantial when the due date is in between the lower and upper limits, when material nodes are on the critical path of the extended project network, and when inventory costs are high.

5.2 Joint Optimization without Expediting

To examine the effectiveness of joint optimization in cases without expediting, we utilize the same numerical example in the previous section, except that here we assume fixed activity durations which are equal to the normal times. Please see Tables 1-2 for input parameters. The variance of demand per unit of time, V, is set to be 4 for all instances. Note that in this case, delaying the latest finishing time of any activity implies the same delay for the project and all other activities in the project network. Furthermore, the objective function now only has two types of costs: inventory holding cost and project delay penalty. Figure 6 summarizes the numerical results with various penalty costs, π.

- In case 1 of the example, the savings are significant when the due date is in between the lower and upper limits. This observation is consistent with that of systems with expediting (see Figure 5).
- The percentage savings here can be more substantial than those of systems with expediting because the cost function does not include expediting cost, and therefore, the cost of sequential heuristic (which is the denominator) decreases.

- In case 2 of the example, joint optimization and sequential heuristic generate identical solutions, and therefore, the savings are zero. This is true because activity durations are fixed and material nodes are not on the critical path of the extended project network. Thus, carrying inventory at the material nodes does not reduce the total project duration for either solution.

In summary, when project activities cannot be expedited, coordinating project schedule with inventory decisions can still result in sizable savings when materials nodes are on the critical path of the extended project network, and when inventory cost is on the same magnitude as the project delay penalty cost, e.g., $\lambda * \pi \approx \sum_{k \in \mathcal{N}_m} h_k * z_\alpha * \sigma_k$. Intuitively, this is true because the joint optimization can optimally balance the project delay penalty and the inventory costs, while the sequential heuristic simply sets the delay penalty to the minimum, and then plans material supply accordingly.

6 Material Customization

So far, we focus on the materials and activities that are shared across all projects. In this section, we keep all assumptions of §3 unchanged except that we allow projects to be customized on material requirements. Specifically, we assume that all projects share identical project activities but can require different materials. This case is quite typical in many MTO manufacturing firms for products within one product family, such as the Boeing 737 series. We formulate the model and present solution methods in §6.1. We test these methods by a numerical study in §6.2.

6.1 Problem Formulation

Suppose there are N types of projects, $n = 1, ..., N$, each requires a different set of materials. Let $\mathcal{A}_I^n$ denote the arcs linking the material network and the project network for project type n. We need the following notation.

- λ^n: demand rate of project type n per unit of time. $\sum_{n=1}^{N} \lambda_n = \lambda$.
- $F_i^n, i \in \mathcal{N}_p$: finishing time of activity i of project type n.

Decision variables $X_k, k \in \mathcal{N}_m$ and $u_i, i \in \mathcal{N}_p$ remain the same as in §3. However, finishing times at activity i, $F_i^n, i \in \mathcal{N}_p$, and due date T^n can be project dependent. Therefore, the objective function and constraints of the problem (P) are modified as follows,

$$\begin{array}{llll} \min & \sum_{k\in\mathcal{N}_m} H_k(\widetilde{L}_k, X_k)+ & \sum_{i\in\mathcal{N}_p}\lambda(a_i-b_iu_i)+\sum_{n=1}^N\lambda^n\pi^n(F_J^n-T^n)^+ & \\ \text{s.t.} & \widetilde{L}_k\geq X_k, & \forall k\in\mathcal{N}_m, & \\ & X_j+L_{j,k}+L_k\leq\widetilde{L}_k, & \forall(j,k)\in\mathcal{A}_m, & \\ & F_i^n\geq X_k+u_i, & \forall(k,i)\in\mathcal{A}_I^n,\forall n, & \\ & F_i^n-F_j^n\geq u_i, & \forall(j,i)\in\mathcal{A}_p,\forall n, & \\ & LB_i\leq u_i\leq UB_i, & \forall i\in\mathcal{N}_p, & \\ & X_k\geq 0 \text{ and integer}, & \forall k\in\mathcal{N}_m, & \\ & F_i\geq 0 \text{ and integer}, & \forall i\in\mathcal{N}_p. & \end{array} \tag{6.13}$$

For a tree structure M&P network, the dynamic programming in §4 still applies. For the material network, the same solution procedure holds. Yet, for the project network, we rewrite the cost equation for each activity i in the project network as follows. Let $\mathbf{F}_i=\{F_i^n, n=1,...,N\}$ and $\overline{\mathbf{F}}_i=\{F_j^n|(j,i)\in A_p, n=1,...,N\}$.

$$C_i(\overline{\mathbf{F}}_i,u_i,\mathbf{F}_i) \;=\; \lambda(a_i-b_iu_i)+\sum_{(k,i)\in\bigcup_{n=1}^N\mathcal{A}_I^n} f_k(\min_{\forall n:k\in\mathcal{A}_I^n}\{F_i^n\}-u_i)+\sum_{(j,i)\in\mathcal{A}_p} g_j(\mathbf{F}_j), \tag{6.14}$$

where

$$g_i(\mathbf{F}_i) \;=\; \min_{\overline{\mathbf{F}}_i,u_i} \quad C_i(\overline{\mathbf{F}}_i,u_i,\mathbf{F}_i) \tag{6.15}$$

$$\text{s.t.} \quad LB_i\leq u_i\leq UB_i, \tag{6.16}$$

$$F_i^n-F_j^n\geq u_i, \quad (j,i)\in\mathcal{A}_p,\forall n \tag{6.17}$$

$$\widetilde{EF}_j^n\leq F_j^n\leq\widetilde{LF}_j^n, \quad (j,i)\in\mathcal{A}_p,\forall n. \tag{6.18}$$

For node J, we have

$$\begin{aligned} C_J(\overline{\mathbf{F}}_J,u_J,\mathbf{F}_J) \;&=\; \lambda(a_J-b_Ju_J)+\sum_{n=1}^N\lambda^n\pi^n(F_J^n-T^n)^+ + \\ &\sum_{(k,J)\in\bigcup_{n=1}^N\mathcal{A}_I^n} f_k(\min_{\forall n:k\in\mathcal{A}_I^n}\{F_J^n\}-u_J)+\sum_{(j,J)\in\mathcal{A}_p} g_j(\mathbf{F}_j). \end{aligned}$$

Based on the above functions, we can use a similar DP algorithm as the joint optimization algorithm in §4 to solve this problem.

- We first preprocess on $\widetilde{EF}_i^n$ and $\widetilde{LF}_i^n$, in the same way as the joint optimization algorithm.
- We then compute $f_k(X_k)$ for each node in the material network.

- For each vector F_i, we compute $g_i(F_i)$.

- For node J, we enumerate F_J^n for all n to find the minimum $g_J(\mathbf{F_J})$.

Due to the vector decision variables $\mathbf{F}_i$, the complexity of this algorithm is $O(|\mathcal{N}_p| \cdot [\max_n\{\widetilde{LF}_J^n\}]^{N+1})$.

To develop a more efficient algorithm, we impose the following constraints: $F_i^n = F_i$ for $n = 1, 2, \ldots, N, \forall i \in \mathcal{N}_p$, i.e., all projects have the same finishing time at each activity node. Thus, the problem can be reformulated as follows,

$$\begin{array}{llll} \min & \sum_{k\in\mathcal{N}_m} H_k(\widetilde{L}_k, X_k)+ & \sum_{i\in\mathcal{N}_p} \lambda(a_i - b_i u_i) + \sum_{n=1}^N \lambda^n \pi^n \cdot (F_J - T^n)^+ & \\ \text{s.t.} & \widetilde{L}_k \geq X_k, & \forall k \in \mathcal{N}_m, & \\ & X_j + L_{j,k} + L_k \leq \widetilde{L}_k, & \forall (j,k) \in \mathcal{A}_m, & \\ & F_i \geq X_k + u_i, & \forall (k,i) \in \mathcal{A}_I^n, & \\ & F_i - F_j \geq u_i, & \forall (j,i) \in \mathcal{A}_p, & \\ & LB_i \leq u_i \leq UB_i, & i \in \mathcal{N}_p, & \\ & X_k \geq 0 \text{ and integer}, & \forall k \in \mathcal{N}_m, & \\ & F_i \geq 0 \text{ and integer}, & \forall i \in \mathcal{N}_p. & \end{array} \tag{6.19}$$

The functional equations are rewritten as,

$$C_i(\overline{F}_i, u_i, F_i) \;=\; \lambda_i(a_i - b_i u_i) + \sum_{(k,i)\in\bigcup_{n=1}^N \mathcal{A}_I^n} f_k(F_i - u_i) + \sum_{(j,i)\in\mathcal{A}_p} g_j(F_j), \tag{6.20}$$

where

$$g_i(F_i) \;=\; \min_{\overline{F}_i, u_i} \quad C_i(\overline{F}_i, u_i, F_i) \tag{6.21}$$

$$\text{s.t.} \quad LB_i \leq u_i \leq UB_i, \tag{6.22}$$

$$F_i - F_j \geq u_i, \quad (j,i) \in \mathcal{A}_p, \tag{6.23}$$

$$\widetilde{EF}_j \leq F_j \leq \widetilde{LF}_j, \quad (j,i) \in \mathcal{A}_p. \tag{6.24}$$

For node J, we have

$$\begin{aligned} C_J(\overline{F}_J, u_J, F_J) \;&=\; \lambda(a_J - b_J u_J) + \sum_{n=1}^N \lambda^n \pi^n (F_J - T^n)^+ \\ &\quad + \sum_{(k,J)\in\bigcup_{n=1}^N \mathcal{A}_I^n} f_k(F_J - u_J) + \sum_{(j,J)\in\mathcal{A}_p} g_j(F_j). \end{aligned}$$

We can solve this problem using the DP algorithm developed in §4 with the same computational complexity as that for the un-customized problems. We call this heuristic algorithm "the customization heuristic."

$h_{M1-1}, h_{M1-2}, h_{M1-3} =$	$\{10, 12, 15\}$			$\{0, 12, 15\}$		
$L_{M1-1}, L_{M1-2}, L_{M1-3} =$	$\{2, 4, 5\}$	$\{3, 3, 3\}$	$\{5, 4, 2\}$	$\{0, 4, 5\}$	$\{0, 3, 3\}$	$\{0, 4, 2\}$
Due dates={12,10,8}	0%	0	4	0	0	2.2
{3,2,1}	0	0	0	0	0	0
{1,2,3}	0	0	0	0	0	0
{5,10,12}	11.8	2.3	6.7	12.3	7	8.4
{8,10,12}	8.8	0	1.2	8.8	1.8	3.7

Table 3: The relative cost increment of the customization heuristic solution over the joint optimization solution.

6.2 A Numerical Study

We utilize the same example as in Figure 4 (b) except that we replace material node $M1$ by three different material nodes, M1-1, M1-2 and M1-3. Under this setting, we have three project types – project type 1 (2 or 3) requires material node M1-1 (M1-2 or M1-3, respectively). Material node $M2$ is a core component, which is required by all projects. The holding cost of $M2$ is 20 and the processing time is 3. Activities are shared by all projects. The lower and upper bounds of the activity duration are $\{3, 5\}, \{2, 5\}, \{2, 4\}, \{1, 3\}, \{1, 3\}$ for activities $1 - 5$ respectively. It is reasonable to assume that the demand rate is lower and the coefficient of variation is larger for the project type with more expensive material. Therefore, project demand rates, variances and penalty costs are set as follows: λ={2,2,1}, variance={4,6,9} and penalty cost={75,80,85}. Input parameters, a and b, follow those of case 1 in Table 2. We study 30 instances with varying project due dates, and varying processing times and holding costs.

Table 3 shows the relative cost increments of the customization heuristic solution over the joint optimization solution. In Table 3, we set $h_{M1-1} = 0$ and $L_{M1-1} = 0$ to represent a project type that does not require a material at activity node 1. Table 3 indicates that on average, the joint optimization outperforms the customization heuristic by 2.6%. In addition,

- the customization heuristic generates nearly as good solutions as the joint optimization when the due date of the most expensive project is tight, i.e., the due date can hardly be met under normal activity durations even if we assume immediate availability of all materials; see the cases with due dates $\{12, 10, 8\}$, $\{3, 2, 1\}$ and $\{1, 2, 3\}$. This is true because the customization heuristic sets the finishing time of all projects as close as possible to the due date of the most

$h_{M1-1}, h_{M1-2}, h_{M1-3} =$	$\{10, 12, 15\}$			$\{0, 12, 15\}$		
$L_{M1-1}, L_{M1-2}, L_{M1-3} =$	$\{2, 4, 5\}$	$\{3, 3, 3\}$	$\{5, 4, 2\}$	$\{0, 4, 5\}$	$\{0, 3, 3\}$	$\{0, 4, 2\}$
Due dates={12,10,8}	19%	18.3	8.4	19	18.3	10.3
{3,2,1}	1.1	1.2	1.1	1.1	1.2	1.2
{1,2,3}	1.1	1.1	1.1	1.1	1.1	1.1
{5,10,12}	1.2	9.8	5.2	2.4	5.6	4.2
{8,10,12}	3.7	13.5	10.7	3.7	10.6	8.8

Table 4: The relative cost increment of the sequential heuristic solution over customization heuristic solution.

expensive project to reduce penalty cost. Although some additional inventory costs can be generated from less expensive projects, these costs are not significant and so the customization heuristic performs well in these cases.

- The customization heuristic performs less efficiently when due dates are not tight and vary substantially across projects; e.g., the cases with due dates $\{5, 10, 12\}$ and $\{8, 10, 12\}$. This is expected because the customization heuristic assigns identical activity finishing times for each activity, while the joint optimization allows them to be different.

- Among the cases with non-tight due dates, we observe that the customization heuristic tends to perform less efficiently in the case where the due date and customized material lead times follow the same pattern than in the case where they follow a reverse pattern, see, e.g., the example with due date $\{8, 10, 12\}$ and customized material lead times $\{2, 4, 5\}$ and the example with due date $\{8, 10, 12\}$ and material lead times $\{5, 4, 2\}$. This is true because in the former, the joint optimization can delay the finishing times of the longer lead time projects to take advantage of the pattern but the customization heuristic cannot, which leads to poor performance of the customization heuristic. In the latter case, neither joint optimization nor the customization heuristic can take advantage of the pattern, and thus their performance gaps are small.

Next, we compare the customization heuristic with the sequential heuristic in Table 4:

- Similar to non-customized cases in §5, when the due dates of all projects are tight, the savings of the customization heuristic diminish.

- The savings from the customization heuristic seem greater when the customized materials have identical lead times. This is true because the customization heuristic tends to perform as well as the joint optimization in these cases.

7 Conclusion

In this paper, we identify a new class of practical problems – the project driven supply chains, which are combinations of material supply chains and project networks that face random demand for customized projects. We present a modeling paradigm to integrate supply chain inventory decisions with project scheduling/resource planning decisions so as to achieve shorter project durations and cost efficiency simultaneously. The model captures the trade-off between material inventory costs and project costs for recurring projects. We show that the joint optimization of material supply and project activities can result in substantial savings relative to a heuristic that optimizes material supply and project decisions sequentially. We also develop insights on the conditions under which the savings are significant.

There are many real-world problems that can be modeled as project-driven supply chains. Some problems have significant time or cost in the project activities but not in material supplies, such as some R&D projects with minimum material requirement (e.g., high tech products which can be built digitally); some others have significant time or cost in the material supplies but not in project activities, such as some service-oriented supply chains (e.g., restaurants and hospitals). The models developed in this paper work best for the problems with comparable costs and times in both the material supplies and project activities, such as those found in MTO manufacturing, engineering and construction industries.

In addition to material customization, many companies also customize projects by activities. Activity customization often occurs among different product families, such as the Boeing 767 series and 737 series. If different product families do not share the material and project networks, the problem can be solved for each product family separately. Otherwise, one has to include activity customization in the modeling framework. Activity customization introduces substantial challenges: Because projects require different subsets of the activities, it may not be reasonable to set identical finishing times for common activities across projects. Furthermore, their due dates can be very different. Thus, the customization heuristic developed in §6 is not adequate. To solve activity customization problems, one can use metaheuristic such as branch and bound or simulated annealing. One can also approximate the objective function by piecewise linear functions which lead to mixed integer programming problems.

An important research direction is to extend the models to allow multiple activities to share common materials. The challenge here is that the combined network becomes acyclic, and therefore the dynamic programming algorithm does not work. One option to solve this problem is to use metaheuristics. Finally, we are interested in incorporating stochastic considerations in the models, such as utilizing the stochastic service-time model for the material supply chains and allowing activity durations to be random for the project networks.

Acknowledgments

The authors would like to thank seminar participants from Rutgers Center of Operations Research (RUTCOR) and 2007 INFORMS annual conference, as well as Dr. Arthur Hsu from United Technologies Research Center (UTRC) for helpful comments and suggestions.

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