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Coordination of Mixed Model Assembly Line Sequencing and Outbound Logistics in the Automotive Industry

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COORDINATION OF MIXED MODEL ASSEMBLY LINE SEQUENCING AND OUTBOUND LOGISTICS IN THE AUTOMOTIVE INDUSTRY

By

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COORDINATION OF MIXED MODEL ASSEMBLY LINE SEQUENCING AND OUTBOUND LOGISTICS IN THE AUTOMOTIVE INDUSTRY

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The thesis addresses the mixed model assembly line sequencing and outbound logistics planning problems in the automotive industry at the operational level. Different from the sequential decision-making procedure used in practice, the thesis proposes a scheme that integrates production sequencing and logistics planning. Mixed integer programs are established for the production sequencing, logistics planning, and integrated problems. The integrated model cannot be solved by commercial solvers in a reasonable amount of time. After studying the optimality properties of the product mode, the thesis proposes a modified integrated model. The results of numerical experiments and simulations demonstrate the benefit of the integration by comparing the modified integrated model with two sequential schemes, the Production-First-Scheme and the Logistics-First-Scheme.

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CHAPTER I

INTRODUCTION

The Just-in-time (JIT) philosophy originated from the work of Taiichi Ohno at Toyota Motor Company and was introduced into the United States about 20 years ago (Askin and Goldberg 2002). The JIT philosophy is now adopted by most automakers all over the world. In a JIT system, inventory is considered such a big cost contributor that it is a major target to reduce inventory level to “zero” (Monden 1998). Therefore, manufacturing needs is in the center of production planning. Based on one project with one major automaker in the US that implements a JIT system, we found the production plan is determined based on dealer orders or forecasted demand with the concern of manufacturing needs such as mixed model assembly line balancing. Though logistics/distribution-related costs in the automotive industry account for about 15 percent to 30 percent of the final cost of a car (Abernathy 1999), the production planning considers few logistics needs in practice (Spencer 1993). In the literature, though there are many papers dealing with the integration between production and logistics at the *strategic* level, such as site locations and transportation mode selections, little research has been done to integrate manufacturing and logistics problems at the *operational* level for daily operation. Thus, this thesis will study the main trade-off between the production and outbound logistics costs and present new models to coordinate production and outbound logistics decisions to minimize the total operational costs that include production, inventory, transportation, and shortage costs.

This thesis will study the practice of production and logistics planning and propose an integrated scheme in section 3, followed by a literature review in Section 2. The production model, outbound logistics model, and integrated model are presented in Section 4. To address the computational complexity of the integrated model, we develop the modified integration model based on the assumption of one major bottleneck station in Section 5. Numerical experiment and simulation results are presented to compare the modified integration model with another two sequential schemes, the Production-First-Scheme and Logistics-First-Scheme, in Section 6. Section 7 concludes the thesis.

CHAPTER II

LITERATURE REVIEW

Though there are a vast literature in the models integrating production and inventory or integrating inventory and distribution, few papers study how to integrate production and logistics at the operations levels. Most integration papers focus on strategic designs of supply chains. For example, Cohen and Lee (1988) present a comprehensive model framework for linking decisions and performance throughout the material production-distribution supply chain. Dogan and Goetschalckx (1999) study production-distribution allocations with a mixed integer programming formulation. Kaminsky and Simchi-Levi (2003) develop a two-stage model for a manufacturing supply chain including capacitated production in stages and a fixed cost for transporting the product between stages. Chauhan, Nagi and Proth (2004) consider the problem of supply chain design at the strategic level when extra production/distribution caused by a new market opportunity has to be launched in an existing supply chain. More recently, Eskigun et al. (2005) study supply chain design problem to minimize fixed costs of facility location and transportation costs. Shen et al. (2005) consider a multi-commodity supply chain design problem in which they need to determine where to locate facilities and how to allocate customers to facilities so as to minimize total costs.

Routing issues are considered in some papers. For example, Chandra and Fisher (1994) discuss the value of integrating production and transportation routing by studying a plant that produces a number of products over time and maintains an inventory of finished goods at the plant. The products are distributed by trucks to retail outlets where the demand is known. Fumro and Vercells (1999) propose an integrated optimization model for production and distribution to optimally coordinate logistic decisions such as capacity management, inventory allocation, and vehicle routing. Lei et al. (2003) discuss the integrated production, inventory and distribution routing problem which involves heterogeneous transporters with non-instantaneous traveling times and many customer demand centers each with its own inventory capacities. Production scheduling is usually not included in the above integrated models. However, coordinating production scheduling and delivery planning can significantly reduce the supply chain costs (Hall and Potts 2003).

On the production side, a mixed model assembly line is one where a variety of different items are assembled (or processed) at different stations in small batch sizes. Such a line serves in a flexible manufacturing system to meet diverse demands from the customers. Most flexible manufacturing systems adopt the Just-In-Time (JIT) philosophy in their effort to minimize inventory. Hence, mixed-model assembly lines find good applications in JIT systems (Ventura et al. 2002). In this assembly environment, workers are expected to be more versatile and have better skills than those working in traditional systems (Bukchin et al. 2002). Paced assembly lines with closed-station and fixed-rate launching are the most common type of assembly lines in the US automotive industry (Matanachai et al. 2001). While the model-mix for production may be relatively stable and is determined ahead of time based on long-range forecast, the sequence of launching of products to the line must be determined by actual short range demand patterns and customer orders (make-to-order policy)(Bukchin et al. 2002). Our production model discusses the sequencing problem of a mixed model assembly line. In fact, the sequencing of vehicles to the mixed-model assembly line is different due to the different goals or purposes of controlling (Monden 1998). Yano and Rachamadugu (1991) address the problem of sequencing jobs on a paced assembly line to minimize the total amount of utility work. Tsai (1995) proves that the sequencing problem of minimizing either the total utility work or the risk of conveyor stoppage is NP-hard in the strong sense for a single station with arbitrary processing times. Bolat (1997) decomposes the sequencing problem into identical and repeating sets to maximize the total amount of work completed. Matanachai and Yano (2001) propose a new line balancing approach for mixed-model assembly line by considering short-term workload stability. Vilarinho and Simaria (2002) develop a two-stage procedure to minimize the number of workstations along the line, for a given cycle time, and balance the workloads between and within workstations. Zhao et al. (2004) assign the tasks of the models to the workstations so as to minimize the total overload time with given the daily assembling sequence of the models, the tasks of each model, the precedence relations among the tasks and the operations parameters of the assembly line.

CHAPTER III

SEQUENTIAL DECISION MAKING IN THE PRACTICE AND PROPOSED INTEGRATION SCHEME

This thesis is motivated by a prior project conducted for a major automotive company in the United States. As shown in Figure 3.1, operational planning in a JIT manufacturing system includes demand management, production planning, inbound logistics management, and outbound logistics management. The current decision making practice follows a sequential procedure: production planning is made first based on forecasted or actual demand; inbound and outbound logistics are planned; the planning information is then broadcasted to the transportation service providers: railway and/or truck companies; outbound transportation plans are determined by the transportation service providers.

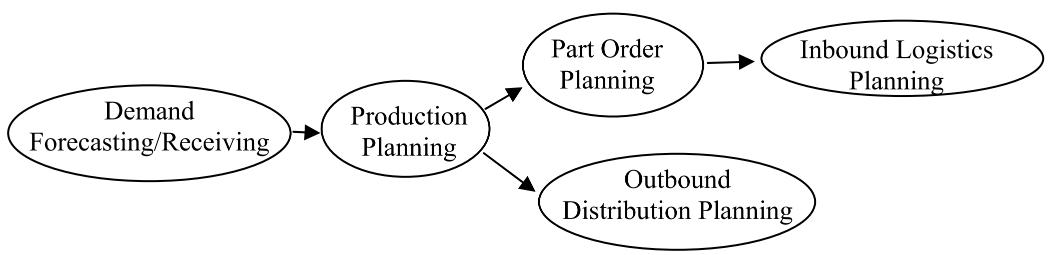

Figure 3.1 Current Operational Planning Process in the Automotive Industry

In recent years, the automotive industry has increased interest in lead-time reduction because it helps increase responsiveness to market changes, reduce pipeline inventory, and improve customer satisfaction (Eskigun et al. 2005). With JIT systems' emphasis on balancing in mixed-model assembly lines, especially on reducing variation in rate of consuming the parts

(Kubiak 1993), required parts reach the assembly plant in time without hurting the overall lead-time. Manufacturing lead-time is also relatively fixed without a large improvement space. Based on our observation, large improvement potential lies on outbound logistics.

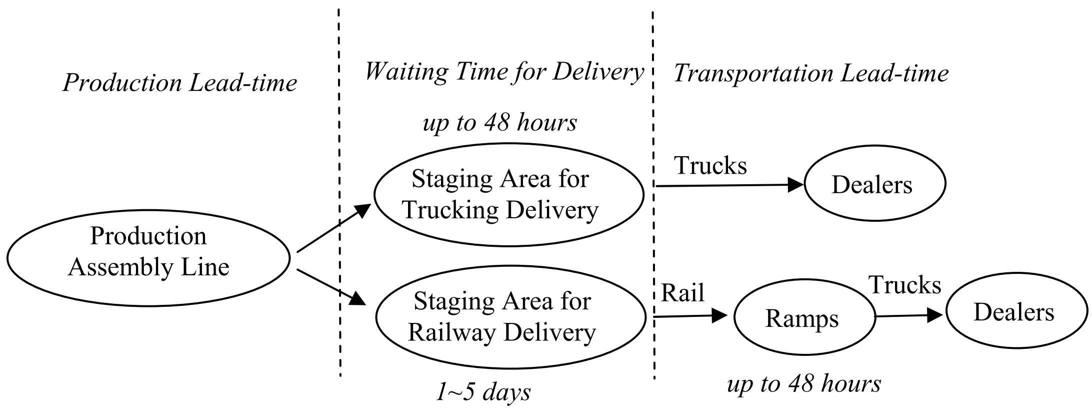

Figure 3.2 Outbound Distribution of the Automotive Industry

On the finished-vehicle distribution side, railway and highway, as shown in Figure 3.2, are two major modes to transport finished vehicles to dealers. Which mode is used for a specific dealer is in general determined based on its distance from the assembly plant. Railway is typically used for dealers who are more than 300 miles away from the assembly plant. Vehicles that are shipped via railway still are transported by trucks from a destination ramp to the dealer. In the US, about 70% of vehicles are shipped via railway according to a talk with a manager at Burlington Northern Santa Fe (BNSF) Railway Company. No matter which mode is used, loading factor is a big concern regarding transportation costs and lead-time. If vehicles in a railcar are for different destination ramps, additional loading and unloading operations cause extra costs and perhaps longer transportation lead-time on the immediate ramps in the route. If only trucks are used for a dealer, grouping vehicles in a truck for a dealer or dealers who are close to each other and served by the same trucking company can reduce transportation costs and lead-time. A huge staging area beside the assembly plan is used for finished vehicles waiting for shipment. Trucking companies usually promise to ship out vehicles in 48 hours, while vehicles via railway may be in the staging area for several days. A large amount of finished vehicle staying in the staging area significantly increases lead-time and inventory.

This thesis proposes an integrated optional decision scheme illustrated in Figure 3.3. The cost and lead-time incurred by inbound and outbound logistics are considered in daily production planning. Because of the large impact of outbound distribution plan on the overall lead-time and cost, we will only study the benefit of integrated production and distribution logistics in the following sections based on mathematical programming models.

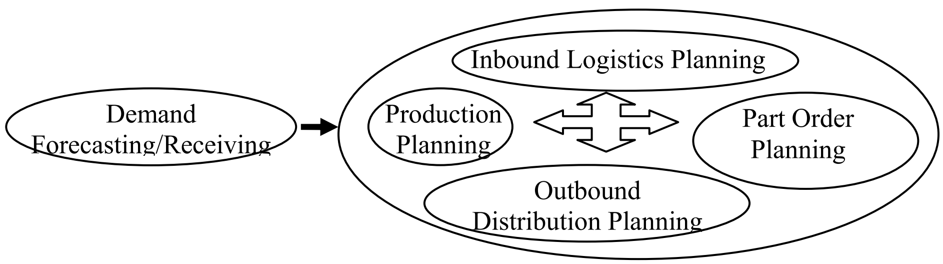

Figure 3.3 Proposed Operational Planning Process

CHAPTER IV

PROBLEM STATEMENT AND BASIC MODELS

The thesis considers integrated production and outbound logistic problem over T days (t is the day index) for an automaker that produces I models (i is the model index). Because of the concern on the loading factor in railway and trucking transportation, we group the dealers whose demand can be shipped together from the staging area via railway or highway. Assume there are totally M groups (m is the group index). E_m denotes the transportation batch size of vehicles for group m. For example, a bi-level railcar can hold about 10 vehicles while a vehicle transport truck can hold about 8 mid-size vehicles. A typical finished vehicle logistics network for one major automaker has 20~40 rail ramps in the US market. After considering the transportation lead-time, we denote D_{imt} to be the number of model i that should be shipped to dealer group m on day t to meet the demand on time. Each transportation batch (a railcar or truck) to dealer group m costs the automaker F_m, which is mainly determined by distance and demand volume. When one model i vehicle cannot be shipped out on time, a unit shortage cost U_i is incurred per vehicle per day. Waiting for shipment in the staging area causes the inventory holding cost H_i per vehicle per day for model i. Though shipping the multiple of E_m vehicles per day minimizes shipping cost, less-than-truck-load (LTL) or less-than-railcar-load shipping may save inventory and shortage costs.

In the production, the automotive industry usually uses a constant speed on the assembly line (Matanachai and Yano 2001). We assume C_y is the cycle time in time unites and K is the total number of the vehicles produced in the planning horizon (k is the vehicle index). Based on the cycle time, we can calculate the maximal production capacity as C_a. The utility cost caused by imbalanced sequence is considered as the production cost in planning. For the purpose of simplicity, this thesis only considers the utility work on a major bottleneck workstation that is a closed station with the length of L in time units. The processing time of model i in the bottleneck workstation is assumed to be r_i. When a vehicle cannot be finished at the end of workstation, utility work is used at the cost of G per time unit. The integrated production and logistic problem has the following decision variables:

Y_{ik}: =1 if the kth vehicle in the production sequence is model i and 0 otherwise;

B_k: The beginning position of the kth vehicle in the bottleneck workstation in time units;

O_k: The utility work in the major bottleneck workstation for the kth vehicle in time units;

O_t: The utility work in the major bottleneck workstation in the day t in time unites;

Q_{it}: The number of model i produced on day t;

I_{imt}: The inventory level of model i for dealer group m in the assembly plant at the end of day t;

P_{imt}: The number of model i for dealer group m produced on day t;

W_{mt}: The number of railcars from the assembly plant to dealer group m on day t;

S_{imt}: The number of model i delivered to dealer group m on day t;

L_{imt}: The shortage of the model i for dealer group m on day t;

4.1 Production Model

We consider a paced assembly line with fixed-rated launch and closed workstations. Operators of all stations start their operations as early as possible, and the operators move downstream on the line to perform their tasks and then return upstream to meet the next vehicle. We assume the walking time of the operators to the next job is negligible (Scholl 1999). Utility work is used to finish the incomplete work. If the operators reach the upstream boundary of the station before the next vehicle arrives at the station, idle time occurs. The utility work and idle time of the bottleneck workstation is illustrated in Figure 4.1, in which there are three model types and total five vehicles produced in one workstation. The cycle time of the assembly line is 9 time units, and the length of the station is10 time units. The processing times of three model types in the station are 10, 8, and 9 time units respectively. The production sequence of the models is 1, 1, 2, 2, and 3. The utility work is required when the beginning time plus the processing time of the vehicle, which is decided by its model type, is lager than the length of the workstation (i.e. utility work = $[\text{beginning time + processing time – length of workstation}]^+$). The idle will happen when the beginning time plus the processing time of the vehicle is less than the cycle time (i.e. idle time = $[\text{cycle time-beginning time – processing time}]^+$.

Work overload has adverse effects on costs, quality, or both (Matanachai and Yano 2001). Idle time represents unused capacities of the line. The possible objective of production model is to minimize the total utility work caused by work overload and minimize the total idle time. However, the two objectives “Minimize the total utility work” and “Minimize the total idle time” are equivalent (Scholl 1999). The objective of our production model is to minimize the total utility work.

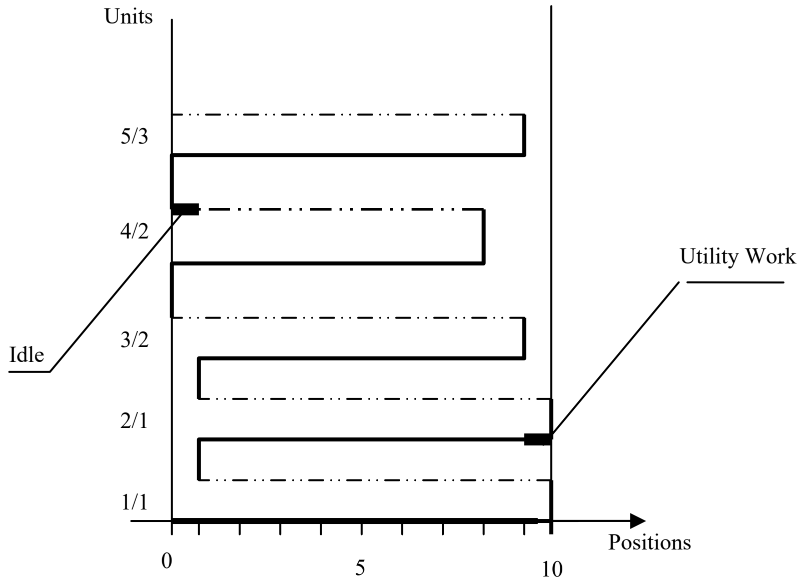

Figure 4.1 Movement Diagram of the Production Model

Since the bottleneck workstations are the most important among the workstation on the assembly line, we consider one closed workstation as the bottleneck workstation in the mixed-model line similar to the models proposed by Dar-El et al. (1995). The processing time of each model in the major bottleneck workstation and the cycle time of assembly line have been specified in advance. The cycle time is typically chosen to provide the desired annual output rate (Matanachai and Yano 2001). Under the assumption of the constant-pace line, the total production amount on each day should be equal to constant. When the total demand of T days deducting total initial inventories, which is equal to the total production amount of T days, is no larger than maximum production capacity of the assembly plant of T days, and the total production amount on each day is equal to constant C ($C = \frac{1}{T}(\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{I} D_{imt} - \sum_{m=1}^{M}\sum_{i=1}^{I} I_{im0})$), we have $C \leq C_a$. The production sequence on the assembly line is determined by the following mixed integer programming model ***P***:

P: Min $G\sum_{k=1}^{K} O_k$

Subject to: $\sum_{i=1}^{I} Y_{ik} = 1$; *k=1,2,…, K;* (1)

$$\sum_{k=1}^{K} Y_{ik} = \sum_{t=1}^{T}\sum_{m=1}^{M} D_{imt} - \sum_{m=1}^{M} I_{im0} \qquad i=1,2,\ldots,I; \qquad (2)$$

$$\sum_{k=(t-1)C+1}^{tC} Y_{ik} = Q_{it} \qquad i=1,2,\ldots,I,\ \ t=1,2,\ldots,T; \qquad (3)$$

$$B_k + \sum_{i=1}^{I} r_i Y_{ik} - O_k \le L \qquad k=1,2,\ldots,K; \qquad (4)$$

$$B_k + \sum_{i=1}^{I} r_i Y_{ik} - O_k - C_y \le B_{k+1} \qquad k=1,2,\ldots,K\text{-}1; \qquad (5)$$

$$B_1 = 0 \qquad (6)$$

$$O_k \ge 0;.\ \ B_k \ge 0;\ \ Q_{it} \ge 0;\ \ Y_{ik} \in \{0,1\}. \qquad (7)$$

Constraint set (1) and Constraint set (2) in problem ***P*** ensure that each required vehicle is assigned to exactly one position of the sequence. Constraint set (3) is for daily production capacity restriction. Utility work is obtained by constraint set (4). Constraint set (5) represents the evolvement of the beginning time. The mathematical model assumes the initial beginning time is 0 (constraint (6)).

4.2 Outbound Logistics Model

We consider inventory, shortage and transportation costs of the finished vehicles in the outbound logistics model. Backorder is not allowed at the end of the horizon (i.e. $\sum_{k=1}^{K} Y_{ik} = \sum_{t=1}^{T}\sum_{m=1}^{M} D_{imt} - \sum_{m=1}^{M} I_{im0}$, for *i=1,2,...,I*). The outbound logistics model ***L*** is as follows:

$$\textbf{\textit{L:}} \quad \text{Min} \quad \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{I} H_i I_{imt} + \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{I} U_i L_{imt} + \sum_{t=1}^{T}\sum_{m=1}^{M} F_m W_{mt}$$

Subject to:

$$I_{i,m,t-1} + P_{imt} - S_{imt} = I_{imt} \qquad i=1,2,...,I,\ m=1,2...,\ M,\ t=1,2,...,T; \tag{8}$$

$$\sum_{i=1}^{I} S_{imt} \le E_m W_{mt} \qquad m=1,2...,\ M,\ t=1,2,...,T; \tag{9}$$

$$\sum_{m=1}^{M}\sum_{i=1}^{I} P_{imt} = C \qquad t=1,2,...,T; \tag{10}$$

$$\sum_{j=1}^{t} D_{imj} - \sum_{j=1}^{t} S_{imj} \le L_{imt} \qquad i=1,2,...,I,\ m=1,2...,\ M,\ t=1,2,...,T; \tag{11}$$

$$L_{imT} = 0 \qquad i=1,2,...,I,\ m=1,2,...,M \tag{12}$$

$$P_{imt} \ge 0;.\ \ I_{imt} \ge 0;\ \ S_{imt} \ge 0;\ W_{mt} \ge 0, \text{int}\,eger;\ \ L_{imt} \ge 0. \tag{13}$$

Constraint set (8) considers the inventory evolvement. Constraint set (9) captures the fixed cost for a railcar or truck. Constraint set (10) indicates that the daily production amount is a constant decided by conveyor speed. Constraint set (11) is used to obtain the shortage amount. Constraint set (12) ensures zero shortage at the end of the planning horizon.

4.3 Integrated Production and Outbound Logistics Model

In this subsection, we develop an integrated model that combines production and outbound logistics decisions to minimize the total costs, including utility work, inventory, shortage and transportation costs. The assumptions of integrated model include the assumptions from both production model and outbound logistic model. Since the number of model *i* produced on day *t* in the production model should be equal to the number of model *i* for all dealer groups produced on day *t* in the outbound logistic model, these two models can be connected by the constraint set (14) to form the integrated model ***I***:

$$\boldsymbol{I}: \quad \text{Min} \quad G\sum_{k=1}^{K} O_k + \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{I} H_i I_{imt} + \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{I} U_i L_{imt} + \sum_{t=1}^{T}\sum_{m=1}^{M} F_m W_{mt}$$

Subject to:

$$\sum_{i=1}^{I} Y_{ik} = 1 \qquad k=1,2,\ ...,K; \qquad (1)$$

$$\sum_{k=1}^{K} Y_{ik} = \sum_{t=1}^{T}\sum_{m=1}^{M} D_{imt} - \sum_{i=1}^{M} I_{im0} \qquad i=1,2,...,I; \qquad (2)$$

$$\sum_{k=(t-1)C+1}^{tC} Y_{ik} = Q_{it} \qquad i=1,2,...,I,\ \ t=1,2,...,T; \qquad (3)$$

$$B_k + \sum_{i=1}^{I} r_i Y_{ik} - O_k \le L \qquad k=1,2,...,K; \qquad (4)$$

$$B_k + \sum_{i=1}^{I} r_i Y_{ik} - O_k - C_y \le B_{k+1} \qquad k=1,2,...,\ K; \qquad (5)$$

$$Q_{it} = \sum_{m=1}^{M} P_{imt} \qquad i=1,2,...,I,\ t=1,2,...,T; \qquad (14)$$

$$\sum_{m=1}^{M}\sum_{i=1}^{I} P_{imt} = \sum_{i=1}^{I} Q_{it} = C \qquad t=1,2,...,T; \qquad (10)$$

$$I_{i,m,t-1} + P_{imt} - S_{imt} = I_{imt} \qquad i=1,2,...,I,\ m=1,2...,\ M,\ t=1,2,...,T; \qquad (8)$$

$$\sum_{i=1}^{I} S_{imt} \le E_m W_{mt} \qquad m=1,2...,\ M,\ t=1,2,...,T; \qquad (9)$$

$$\sum_{j=1}^{t} D_{imj} - \sum_{j=1}^{t} S_{imj} \le L_{imt} \qquad i=1,...,I,\ m=1,2...,\ M,\ t=1,2,...,T; \qquad (11)$$

$$B_1 = L_{imT} = 0 \qquad i=1,...,I,\ m=1,2...,\ M; \qquad (15)$$

$$O_k \geq 0;\ \ B_k \geq 0;\ \ Y_{ik} \in \{0,1\};\ P_{imt} \geq 0;.\ \ Q_{it} \geq 0; \tag{16}$$
$$I_{imt} \geq 0;\ W_{mt} \geq 0, \text{integer};\ S_{imt} \geq 0;\ L_{imt} \geq 0.$$

Constraint set (15) combines constraint sets (6) and (12). Constraint set (16) combines constraint sets (7) and (13). Above integrated model can coordinate production, outbound logistics to minimize the total operational costs. However, it is time consuming to use optimization solve (e.g. ILOG CPLEX) to directly solve the integrated model based on the numerical experiments. So, in order to solve the problem in reality, we develop a modified integrated production and outbound logistic model in the next section.

CHAPTER V

MODIFIED INTEGRATED PRODUCTION AND OUTBOUND LOGISTICS MODEL

Initial numerical experiments show the integrated model ***I*** cannot be directly solved by commercial optimization solver such as ILOG CPLEX. Therefore, we develop the following modified integrated production and outbound logistics model.

Assume that model i^* has the longest processing time ($r_{i^*} = \max\{r_1, r_2, ..., r_n\}$) and model i' has the shortest processing time ($r_{i'} = \min\{r_1, r_2, ..., r_n\}$) in the bottleneck workstation. If the cycle time of the assembly line C_y satisfies the inequality $r_{i'} + 1 \leq C_y \leq r_{i^*} - 1$, then the starting position of the next vehicle will increase when we sequence a model i^*. When the starting position of the vehicle is lager than $L\text{-}r_{i^*}$, utility work occurs if a model i^* is scheduled (Figure 5.1). Scholl (1999) claims that the two objectives of "minimizing the total utility work" and "minimizing the total idle time" are equivalent. Therefore, we assume the length of the workstation is long enough to avoid idle time if model i' is scheduled when the starting position is lager than $L\text{-}r_{i^*}$. In other words, the bottleneck workstation length satisfies $L \geq C_y + r_{i^*} - r_{i'} - 1$. Based on the assumptions stated above, we propose the following sequencing rule:

Proposition 1: For a given Q_{it} (the number of model i produced on day t), the optimal sequence on day t can be obtained by sequencing a model with the possibly largest processing time without causing utility work in all vehicles waiting for sequencing at the current position. If all waiting vehicles cause utility work, choose the *one with the smallest processing time. The sequencing rule yields the minimum utility work:*

$$O_t \geq \sum_{i=1}^{I} r_i Q_{it} - C_y C - L + C_y \ . \qquad t=1, 2, \ldots, T \qquad (17)$$

Actually, we obtain the optimal sequence for the multi-model on the assembly line if follow the above sequence rule in the production model. Please check the Appendix for the proof.

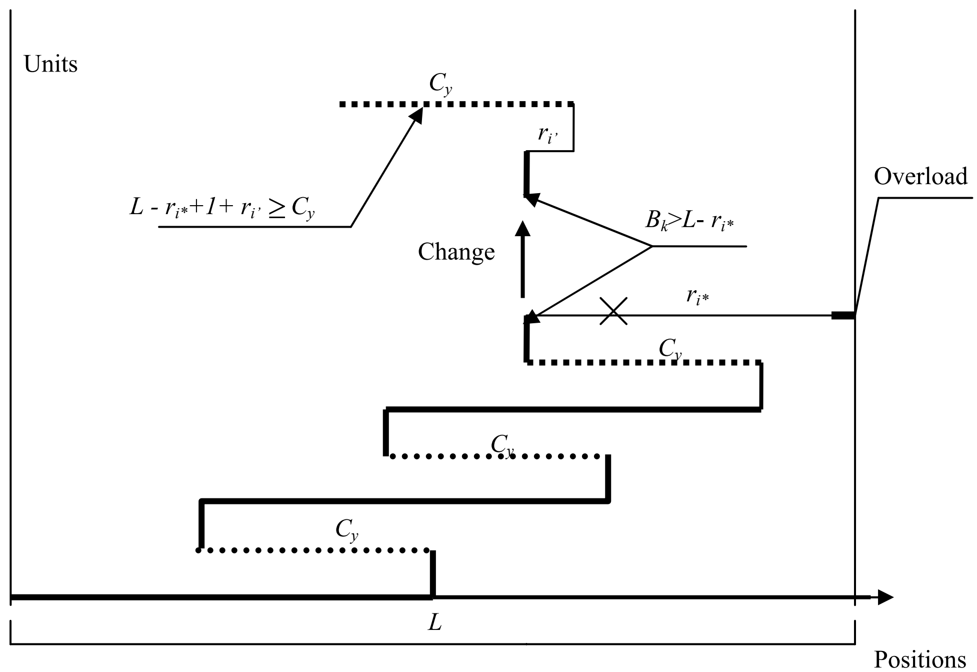

Figure 5.1 Movement Diagram of Modified Production Model

Based on the proof of the sequencing rule, when the total demand of T days deducting total initial inventories, which is equal to the total production amount of T days, is no larger than maximum production capacity of the assembly plant of T days ($C \leq C_a$), utility work is obtained by above constraint set (17). And the production model ***P*** can be simplified into the following mathematical model *MP1*:

MP1: Min $G\sum_{t=1}^{T} O_t$

Subject to: $O_t \geq \sum_{i=1}^{I} Q_{it} r_i - C_y C - L + C_y$ *t=1,2,…, T;* (17)

$$\sum_{t=1}^{T} Q_{it} = \sum_{t=1}^{T}\sum_{m=1}^{M} D_{imt} - \sum_{m=1}^{M} I_{im0}$$ *i=1,2,…,I;* (18)

$$\sum_{i=1}^{I} Q_{it} = C$$ *t=1,2,…,T;* (10)

$Q_{it} \geq 0$, integer ; $O_t \geq 0$, (27)

Constraint set (18) indicates that the number of the each type of vehicles produced in *T* days plus the initial inventories should meet the total demand of *T* days.

Therefore, we have the following modified integrated model ***MI*** by incorporating (17) and (18):

MI: Min $G\sum_{t=1}^{T} O_t + \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{I} H_i I_{imt} + \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{I} U_i L_{imt} + \sum_{t=1}^{T}\sum_{m=1}^{M} K_m W_{mt}$

Subject to:

$$Q_{it} = \sum_{m=1}^{M} P_{imt}$$ *i=1,2,…,I, t=1,2,…,T;* (14)

$$\sum_{m=1}^{M}\sum_{i=1}^{I} P_{imt} = \sum_{i=1}^{I} Q_{it} = C$$ *t=1,2,…,T;* (10)

$$I_{i,m,t-1} + P_{imt} - S_{imt} = I_{imt}$$ *i=1,2,…,I, m=1,2…, M, t=1,2,…,T;* (8)

$$\sum_{i=1}^{I} S_{imt} \leq E_m W_{mt}$$ *m=1,2…, M, t=1,2,…,T;* (9)

$$\sum_{j=1}^{t} D_{imj} - \sum_{j=1}^{t} S_{imj} \leq L_{imt}$$ *i=1,2,…,I, m=1,2…, M, t=1,2,…,T;* (11)

$$L_{imT} = 0$$ *i=1,2,…,I, m=1,2…, M;* (12)

$$O_t \geq \sum_{i=1}^{I} Q_{it} r_i - C_y C - L + C_y \qquad t=1,2,\ldots,T; \tag{17}$$

$$\sum_{t=1}^{T} Q_{it} = \sum_{t=1}^{T} \sum_{m=1}^{M} D_{imt} - \sum_{m=1}^{M} I_{im0} \qquad i=1,2,\ldots,I; \tag{18}$$

$$P_{imt} \geq 0;\ Q_{it} \geq 0, \text{integer};\ I_{imt} \geq 0;\ S_{imt} \geq 0;\ L_{imt} \geq 0;\ O_t \geq 0;\ W_{mt} \geq 0, \text{integer}. \tag{19}$$

When the total demand over T days deducting total initial inventories is lager than the maximal capacity of assembly plant per day ($C > C_a$), based on the proof of the sequencing rule, the utility work is obtained by the constraint set (20).

$$O_t \geq \sum_{i=1}^{I} Q_{it} r_i - C_y C_a - L + C_y\ . \qquad t=1, 2, \ldots, T \tag{20}$$

And the production model ***P*** can be simplified into the following mathematical model ***MP2***.

MP2: Min $\quad G\sum_{t=1}^{T} O_t$

Subject to:

$$O_t \geq \sum_{i=1}^{I} Q_{it} r_i - C_y C_a - L + C_y \qquad t=1,2,\ldots, T; \tag{20}$$

$$\sum_{i=1}^{I} Q_{it} = C_a \qquad t=1,2,\ldots,T; \tag{21}$$

$$\sum_{t=1}^{T} Q_{it} \leq \sum_{t=1}^{T} \sum_{m=1}^{M} D_{imt} - \sum_{m=1}^{M} I_{im0} \qquad i=1,2,\ldots,I; \tag{29}$$

$$Q_{it} \geq 0, \text{integer};\ O_t \geq 0, \tag{27}$$

Constraint set (21) indicates that the number of the vehicles produced per day is equal to the maximal production capacity per day in the assembly plant. Constraint set (29) guarantees the number of each type of model produced in the assembly plant plus the initial inventories of each model can not be lager than the demand of each model.

Therefore, we have the following modified integrated model ***MI'*** by incorporating (20):

MI': Min $G\sum_{t=1}^{T} O_t + \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{I} H_i I_{imt} + \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{I} U_i L_{imt} + \sum_{t=1}^{T}\sum_{m=1}^{M} K_m W_{mt}$

Subject to:

$$Q_{it} = \sum_{m=1}^{M} P_{imt} \qquad i=1,2,\ldots,I,\ t=1,2,\ldots,T; \qquad (14)$$

$$\sum_{i=1}^{I} Q_{it} = C_a \qquad t=1,2,\ldots,T; \qquad (21)$$

$$I_{i,m,t-1} + P_{imt} - S_{imt} = I_{imt} \qquad i=1,2,\ldots,I,\ m=1,2\ldots,\ M,\ t=1,2,\ldots,T; \qquad (8)$$

$$\sum_{i=1}^{I} S_{imt} \le E_m W_{mt} \qquad m=1,2\ldots,\ M,\ t=1,2,\ldots,T; \qquad (9)$$

$$\sum_{j=1}^{t} D_{imj} - \sum_{j=1}^{t} S_{imj} \le L_{imt} \qquad i=1,2,\ldots,I,\ m=1,2\ldots,\ M,\ t=1,2,\ldots,T; \qquad (11)$$

$$\sum_{i=1}^{I}\sum_{m=1}^{M} L_{imT} = \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{I} D_{imt} - \sum_{m=1}^{M}\sum_{i=1}^{I} I_{im0} - TC_a \qquad (23)$$

$$O_t \ge \sum_{i=1}^{I} Q_{it} r_i - C_y C_a - L + C_y \qquad t=1,2,\ldots,T; \qquad (20)$$

$$P_{imt} \ge 0;.\ \ Q_{it} \ge 0, \text{integer};\ \ I_{imt} \ge 0;\ \ S_{imt} \ge 0;$$
$$L_{imt} \ge 0;\ O_t \ge 0;\ \ W_{mt} \ge 0, \text{integer}. \qquad (19)$$

Backorder is allowed at the end of the horizon (constraint set (23)).

CHAPTER VI

NUMERICAL EXPERIMETNS

In order to evaluate the benefit from integration, two sequential decision making processes are also tested: the *Logistics-First-Scheme* (LFS) and *Production-First-Scheme* (PFS).

6.1 Logistics First Scheme

In the LFS, the outbound logistics model is solved first to obtain the daily production amount for each model Q_{it}. The production-sequencing problem is then solved to obtain total utility work according to inequality (17). When the total demand of *T* days deducting total initial inventories is no larger than the maximal production capacity of the assembly plant of *T* days, we have $C \le C_a$, and the details of the Logistics First Heuristic are presented as follows:

<u>*Step 1*</u>

Solve the following mathematical model and obtained value of Q_{it}.

$$\text{Min} \quad \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{N} H_i I_{imt} + \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{I} U_i L_{imt} + \sum_{t=1}^{T}\sum_{m=1}^{M} F_m W_{mt}$$

Subject to:

$$Q_{it} = \sum_{m=1}^{M} P_{imt} \qquad i=1,\ldots,I,\ t=1,2,\ldots,T; \qquad (14)$$

$$\sum_{m=1}^{M}\sum_{i=1}^{I} P_{imt} = \sum_{i=1}^{I} Q_{it} = C \qquad t=1,2,\ldots,T; \qquad (10)$$

$$I_{i,m,t-1} + P_{imt} - S_{imt} = I_{imt} \qquad i=1,\ldots,I,\ m=1,2\ldots,\ M,\ t=1,2,\ldots,T; \qquad (8)$$

$$\sum_{i=1}^{I} S_{imt} \le E_m W_{mt} \qquad m=1,2\ldots,\ M,\ t=1,2,\ldots,T; \qquad (9)$$

$$\sum_{j=1}^{t} D_{imj} - \sum_{j=1}^{t} S_{imj} \le L_{imt} \qquad i=1,\ldots,I,\ m=1,2\ldots,\ M,\ t=1,2,\ldots,T; \qquad (11)$$

$$L_{imT} = 0 \qquad i=1,\ldots,I,\ m=1,2\ldots,\ M; \qquad (12)$$

$$P_{imt} \ge 0;.\ \ Q_{it} \ge 0;\ \ I_{imt} \ge 0;\ \ S_{imt} \ge 0;\ \ L_{imt} \ge 0;\ W_{mt} \ge 0, \text{int}\, eger. \qquad (24)$$

Step 2

Solve the following model based on the known Q_{it} from the step 1.

Min $\quad G\sum_{t=1}^{T} O_t$

Subject to:

$$O_t \ge \sum_{i=1}^{I} Q_{it} r_i - C_y C - L + C_y \qquad t=1,2,\ldots,T; \qquad (17)$$

$$O_t \ge 0. \qquad (25)$$

When the total demand of *T* days deducting total initial inventories is larger than the maximal production capacity of the assembly plant of *T* days, we have $C > C_a$. The Logistics First Schemes will also follow the above steps. Constraint set (10) will be changed into (21), constraint set (12) will be changed into (23), and constraint set (17) will be changed into (20).

6.2 Production First Scheme

In the PFS, a master sequence is obtained at first for all *T* days at first. Then, the outbound logistics model is solved based on Q_{it} to obtain a shipping plan to minimize the total logistics costs. When the total demand of *T* days deducting total initial inventories is no larger than the maximal production capacity of the assembly plant of T days, we have $C \le C_a$. The details of the Production First Scheme are presented as follows:

Step 1

Solve the following mathematical model, and obtain the value of Q_{it}.

Min $\quad G\sum_{t=1}^{T} O_t$

Subject to:

$$O_t \ge \sum_{i=1}^{I} Q_{it} r_i - C_y C - L + C_y \qquad t=1,2,\dots,T; \qquad (17)$$

$$\sum_{t=1}^{T} Q_{it} = \sum_{t=1}^{T}\sum_{m=1}^{M} D_{imt} - \sum_{m=1}^{M} I_{im0} \qquad i=1,2,\dots,I; \qquad (18)$$

$$\sum_{i=1}^{I} Q_{it} = C \qquad t=1,2,\dots,T; \qquad (10)$$

$$Q_{it} \ge 0, \text{integer}; \; O_t \ge 0. \qquad (27)$$

Step 2

Solve the following mathematical model based on the known Q_{it} from the step 1.

Min $\quad \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{N} H_i I_{imt} + \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{I} U_i L_{imt} + \sum_{t=1}^{T}\sum_{m=1}^{M} F_m W_{mt}$

Subject to:

$$\sum_{m=1}^{M} P_{imt} = Q_{it} \qquad i=1,2,\dots,I,\; t=1,2,\dots,T; \qquad (14)$$

$$I_{i,m,t-1} + P_{imt} - S_{imt} = I_{imt} \qquad i=1,2,\dots,I,\; m=1,2\dots,M,\; t=1,2,\dots,T; \qquad (8)$$

$$\sum_{i=1}^{I} S_{imt} \le E_m W_{mt} \qquad m=1,2\dots,M,\; t=1,2,\dots,T; \qquad (9)$$

$$\sum_{j=1}^{t} D_{imj} - \sum_{j=1}^{t} S_{imj} \le L_{imt} \qquad i=1,2,\dots,I,\; m=1,2\dots,M,\; t=1,2,\dots,T; \qquad (11)$$

$$L_{imT} = 0 \qquad i=1,2,\dots,I,\; m=1,2\dots,M; \qquad (12)$$

$$P_{imt} \geq 0; \;\; I_{imt} \geq 0; \;\; S_{imt} \geq 0\,; L_{imt} \geq 0; \;\; W_{mt} \geq 0 \, \text{int}\, eger. \qquad (28)$$

When the total demand of *T* days deducting total initial inventories is larger than the maximal production capacity of the assembly plant of *T* days ($C > C_a$), the Production First Schemes will follow the following steps:

Step 1

Solve the following mathematical model, and obtained the value of Q_{it}.

Min $\quad G\sum_{t=1}^{T} O_t$

Subject to:

$$O_t \geq \sum_{i=1}^{I} Q_{it} r_i - C_y C_a - L + C_y \qquad t=1,2,...,T; \qquad (20)$$

$$\sum_{t=1}^{T} Q_{it} \leq \sum_{t=1}^{T}\sum_{m=1}^{M} D_{imt} - \sum_{m=1}^{M} I_{im0} \qquad i=1,2,...,I; \qquad (29)$$

$$\sum_{i=1}^{I} Q_{it} = C_a \qquad t=1,2, \ldots,T; \qquad (21)$$

$$Q_{it} \geq 0, \text{integer}; O_t \geq 0. \qquad (27)$$

Step 2

Solve the following mathematical model based on the known Q_{it} from the step 1.

Min $\quad \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{N} H_i I_{imt} + \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{I} U_i L_{imt} + \sum_{t=1}^{T}\sum_{m=1}^{M} F_m W_{mt}$

Subject to:

$$\sum_{m=1}^{M} P_{imt} = Q_{it} \qquad i=1, 2,...,I, t=1,2,...,T; \qquad (14)$$

$$I_{i,m,t-1} + P_{imt} - S_{imt} = I_{imt} \qquad i=1, 2,..., I, m=1,2..., M, t=1,2,...,T; \qquad (8)$$

$$\sum_{i=1}^{N} S_{imt} \leq E_m W_{mt} \qquad m=1,2..., M, t=1,2,...,T; \qquad (9)$$

$$\sum_{j=1}^{t} D_{imj} - \sum_{j=1}^{t} S_{imj} \le L_{imt} \qquad i=1, 2, \ldots, I, \; m=1,2\ldots, M, \; t=1,2,\ldots,T; \tag{11}$$

$$\sum_{i=1}^{I}\sum_{m=1}^{M} L_{imT} = \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{I} D_{imt} - \sum_{m=1}^{M}\sum_{i=1}^{I} I_{im0} - TC_a \tag{23}$$

$$P_{imt} \ge 0; \;\; I_{imt} \ge 0; \;\; S_{imt} \ge 0; L_{imt} \ge 0; \;\; W_{mt} \ge 0 \text{ integer}. \tag{28}$$

We will find the solutions and computational time of the modified integration model and the benchmarks in the next subsection.

6. 3 Computational Results

Our numerical experiments use the data that we collected from a project with a major US automaker with small modifications. The following is a detailed list of the data:

- Four models, twenty dealer groups, three days and one bottleneck workstation in the auto-maker assembly plant.
- The transportation cost per truck (or railcar) for dealer groups: F_1=2150, F_2=1700, F_3=2200, F_4=2090, F_5=1500, F_6=2000, F_7=2050, F_8=2300, F_9=1660, F_{10}=2020, F_{11}=2115, F_{12}=1680, F_{13}=2020, F_{14}=2080, F_{15}=1800, F_{16}=1950, F_{17}=2190, F_{18}=2180, F_{19}=1765, F_{20}=2350.
- Other costs: H=\$30; U=\$20; G=\$25; E_m=10; C_y =60 seconds; L=100seconds.
- The processing time for model in the bottleneck station: 45, 78, 70 and 58 seconds.

Dealers' daily demands per vehicle type are randomly generated by a uniform distribution defined on the interval [0, 50]. A total of 10 instances are generated. We give one instance of the demand with random data in the Appendix (Table 8.1). Table 6.1 summarizes the solutions and the computational time for the modified integration model, the LFS, and the PFS when the total demand of T days deducting total initial inventories is no larger than the maximal production capacity of the assembly plant of T days ($C \le C_a$). Table 6.2 summarizes the solutions and the computational time for the modified integration model, the LFS, and the PFS when the total demand of *T* days deducting total initial inventories is larger than the maximal production capacity of the assembly plant of *T* days ($C > C_a$). We use ILOG CPLEX 9.0 on a Pentium-4 PC with a CPU at 2.80GHz and 512 MB of RAM.

Table 6.1 Numerical Experiment Results (C $\leq C_a$)

Ins	Modified Integrated Scheme				LFS				PFS			
	Log. Cost	Prod. Cost	Total Cost	Time (s)	Log. Cost	Prod. Cost	Total Cost	Time (s)	Log. Cost	Prod. Cost	Total Cost	Time (s)
1	496,375	2,250	498,625	764	496,325	12,875	509,200	726	502,750	2,175	504,925	458
2	503,820	8,925	512,745	680	503,760	19,225	522,985	570	515,800	8,850	524,650	390
3	505,640	9,750	515,390	610	505,580	18,975	524,555	540	512,890	9,700	522,590	480
4	499,115	52,850	551,965	287	499,035	85,550	584,585	312	509,725	52,850	562,575	212
5	538,810	3,150	541,960	710	538,770	21,300	560,070	476	560,480	3,050	563,530	254
6	499,085	10,575	509,660	998	499,035	17,200	516,235	754	509,725	10,500	520,225	534
7	498,785	3,950	502,735	651	498,735	13,300	512,035	875	520,295	3,900	524,195	768
8	499,410	5,700	505,110	589	499,360	24,375	523,735	302	510,990	5,675	516,665	212
9	498,835	75	498,910	77.66	498,805	18,525	517,330	291	518,605	0	518,605	62
10	498,250	7,725	505,975	421	498,220	21,750	519,970	347	509,450	7,675	517,125	276

Table 6.2 Numerical Experiment Results (C $> C_a$)

Ins.	Modified Integrated Scheme				LFS				PFS			
	Log. Cost	Prod. Cost	Total Cost	T (s)	Log. Cost	Prod. Cost	Total Cost	T (s)	Log. Cost	Prod. Cost	Total Cost	T (s)
1	576,435	37,375	613,810	21	575,955	100,225	676,180	34	595,335	37,125	632,460	41
2	576,705	23,200	599,905	35	576,455	74,900	651,355	47	596,615	23,150	619,765	36
3	577,315	50	577,365	21	577,105	23,200	600,305	15	595,685	0	595,685	59
4	575,455	75	575,530	18	575,270	35,525	610,795	32	593,980	0	593,980	43
5	575,500	14,550	590,050	25	574,890	85,550	660,440	55	592,920	14,425	607,345	80
6	579,040	39,950	618,990	45	578,990	106,125	685,115	92	594,090	39,925	634,015	106
7	575,810	50	575,860	61	575,770	44,400	620,170	45	593,980	0	593,980	77
8	577,200	81,225	658,425	20	576,980	132,350	709,330	90	593,860	81,175	675,035	124
9	579,035	120,425	699,460	6	578,115	178,325	756,440	14	594,725	120,425	715,150	32
10	575,475	50	575,525	38	575,455	40,025	615,480	68	594,145	0	594,145	76

Based on the numerical experiments, the modified integrated production and outbound logistics model can solve the real problem of the auto-maker in the reasonably computational time, whereas the previous integrated model can not do that. Compared with the benchmarks, the approximately optimal solutions can be obtained from the modified integration model no matter when the demand of T days is less than the maximum capacity of the assembly plant of T days or not. We also find that the total operational cost of the modified integration model is 4% less than that of LFS in average and 3.3% less than that of PFS in average when $C \leq C_a$; the total operational cost of the modified integration model is 8.2% less than that of LFS in average and 3.2% less than that of PFS in average when $C > C_a$. In the case of $C > C_a$, since the shortages will always happen at the end of the T days, PFS can do a better job than LFS. Though the percentages seem small, note that the corresponding absolute cost saving is significant because of large production and logistics costs in the automotive industry. The integration will result in millions of dollar saving when we estimate annual savings. Paired T-test shows both savings are statistically significant with a confidence level at 99.5%.

6.4 Simulations

In practice, the decision making process follows a rolling horizon concept. The plan is determined for the next T days but only implemented for the next day. Another T-day problem is solved again on the next day with new information. We simulate this process for one month (30 days) for all three schemes with ten different seeds of random numbers. Because of the computational time, we use following data to do the simulations for the modified integration model, the LFS, and the PFS:

- Four models, five dealer groups, three days and one bottleneck workstation in the auto-maker assembly plant with rolling horizon for 30 days.

- The uniform distribution [0, 5] is used for the demand of each model for each dealer group in each day. The uniform distribution [0, 3] is used for the initial inventories of each model for each dealer group.
- The transportation cost per truck (or railcar) for dealer groups: F_1=2150, F_2=1700, F_3=2200, F_4=2090, F_5=1500.
- Inventory holding cost H=\$30; shortage cost U=\$20; utility cost G=\$20; transportation batch size E_m=10; cycle time C_y =60 seconds; the length of workstation L=100seconds.
- The processing time for model in the bottleneck station: 45, 78, 70 and 58 seconds.

Table 6.3 summarizes the results and the computational time of the simulations for the modified integration model, the LFS, and the PFS when the total demand of T days deducting total initial inventories is no larger than the maximal production capacity of the assembly plant of T days ($C \le C_a$).

Table 6.3 Simulation Results with Rolling Horizon for 30 Days (C $\le C_a$)

Ins.	Modified Integrated Scheme				LFS				PFS			
	Logistics Cost	Prod. Cost	Total Cost	Comp. Time (hour)	Logistics Cost	Prod. Cost	Total Cost	Comp. Time (hour)	Logistics Cost	Prod. Cost	Total Cost	Comp. Time (hour)
1	412,070	67,120	479,190	0.63	410,610	128,520	539,130	0.42	452,120	58,720	510,840	0.15
2	331,980	52,200	384,180	0.68	329,090	92,320	421,410	0.33	359,060	50,900	409,960	0.12
3	354,340	57,800	412,140	0.61	353,100	80,100	433,200	0.38	395,920	50,980	446,900	0.23
4	347,270	61,160	408,430	0.65	345,060	111,140	456,200	0.30	376,820	61,080	437,900	0.31
5	334,050	49,940	383,990	0.67	331,290	89,040	420,330	0.52	385,180	48,660	433,840	0.15
6	358,170	71,260	429,430	0.62	352,130	100,380	452,510	0.48	399,980	70,600	470,580	0.18
7	388,890	64,000	452,890	0.57	377,450	102,160	479,610	0.41	419,600	63,960	483,560	0.22
8	388,860	43,800	432,660	0.49	376,230	94,560	470,790	0.48	430,820	43,480	474,300	0.32
9	317,160	48,080	365,240	0.56	312,570	93,980	406,550	0.53	343,410	45,560	388,970	0.19
10	367,560	80,440	448,000	0.71	366,670	106,460	473,130	0.58	389,560	76,220	465,780	0.18

Based on the simulation results with rolling horizon in one month, the costs from the integrated scheme are on average 9.2% smaller compared to the LFS and 8.5% compared to the PFS. Paired T-test shows both savings are statistically significant with a confidence level at

99.5%. With fewer dealer groups, the integration has more impact on cost saving because of the smaller chance to have a good sequence in the LFS and to have a good logistics plan in the PFS.

CHAPTER VII

CONCLUSION

This thesis addresses the production sequencing and logistics planning decision problems at the operational level. An integrated scheme is proposed that coordinates these two decisions based on the industrial needs identified by a prior project. Mathematical programming models for production sequencing, logistics planning, and the integrated scheme are proposed. These models are used to perform numerical comparisons and show the benefit of the integration. Because of the size and complexity of the integrated model, we propose a new modified integrated MIP model based on the assumptions that there is only one closed bottleneck workstation in the assembly line and the assembly line has a constant pace. The modified model can be solved for real-world instances to obtain optimal solutions in reasonable time. Numerical experiments demonstrate significant cost savings by integrating production and distribution decisions.

A possible future research direction is to consider multiple workstations in the sequencing problem. With multiple workstations, the optimal sequence cannot be obtained by any simple rules. Heuristics, including dispatching rules, will be necessary in practice. Then, the impact of the integration needs to be reinvestigated under these dispatching rules.

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APPENDIX

PROOF OF PROPOSITION 1, AND TABLE OF ONE INSTANCE OF DEMAND WITH RANDOM DATA FOR NUMERICAL EXPERIMENT

A.1 Proof of Proposition 1

We prove it by two facts:

Fact 1:

Overload and idle time do not both happen in a sequence created by using the sequencing rule.

Fact 2:

The sequencing rule can provide the optimal sequence with minimum utility work.

Proof of fact 1:

Given a sequence created based on the sequencing rule, let the first overload happen to the k^{th} vehicle. Since no overload happens right after processing the $(k\text{-}1)^{th}$ vehicle, the starting position of the k^{th} vehicle will be $B_k \leq L\text{-}C_y$. Assume that the k^{th} vehicle belongs to model v. Because of the overload, $B_k + r_v > L$. The processing times of all vehicles sequenced after the k^{th} one is at least C_y, because, based on the sequencing rule, model v has the smallest processing time compared to the models of the vehicles sequenced after the k^{th} vehicle (including the k^{th} vehicle). Therefore, $r_v \geq C_y$. As a result, the starting position for all vehicles sequenced after the k^{th} will be at least $L\text{-}C_y$. In other words, no idle time will happen after the k^{th} vehicle.

Now let investigate the vehicles sequenced before the k^{th} vehicle. The vehicles that are sequenced before the k^{th} vehicle and have a starting positions earlier than $L\text{-}r_v$ have a processing time greater than or equal to r_v. Based on the sequencing rule, $r_v \geq C_y$. Therefore, no idle time happens after finishing these vehicles. For the vehicles that are sequenced before the k^{th} vehicle and starting positions later than $L\text{-}r_v$, no idle time happens after processing them because of the assumption that $L \geq C_y + r_{i^*} - r_{i'} - 1$, where r_{i^*} and $r_{i'}$ are the largest and smallest processing times of all models. Thus, when there is utility work in a sequence created by using the sequencing rule, there is no idle time in the sequence.

Following a similar logic, we can prove that if there is idle time in a sequence created by using the sequencing rule, there is no utility work in the sequence.

Proof of fact 2:

In any production schedule, the total required work plus total idle time must equals the total available time plus the total utility work. For given production amount Q_{it} on day t, total required work at the workstation is equal to $\sum_{i=1}^{I} r_i Q_{it}$. The total available time of the workstation is equal to $(\sum_{i=1}^{I} Q_{it}$ -1) $C_y + L$. Since the sequencing rule guarantees that idle time and overload do not happen both, the minimum total utility work is

$$[\sum_{i=1}^{I} r_i Q_{it} - (C_y \sum_{i=1}^{I} Q_{it} - C_y + L)]^+ = \left[\sum_{i=1}^{I} (r_i - C_y) Q_{it} + C_y - L \right]^+ .$$

□

Table A.1 One Instance of Demand with Random Data for Numerical Experiment

Dealers	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	Day 1																			
Model 1	35	11	2	1	7	1	14	9	11	17	1	8	23	14	1	8	10	7	19	19
Model 2	6	8	8	9	7	2	7	10	3	8	6	9	10	9	9	3	3	7	9	10
Model 3	10	9	10	6	3	10	10	2	1	14	6	9	10	1	7	21	5	11	4	9
Model 4	13	1	1	22	5	16	30	14	0	34	6	9	25	15	24	50	21	23	11	21
	Day 2																			
Model 1	7	6	9	10	3	11	17	9	19	3	2	32	21	8	9	19	3	13	22	13
Model 2	35	5	10	8	4	9	4	7	3	15	6	3	9	8	1	2	2	10	3	1
Model 3	13	3	12	10	10	10	16	12	1	11	1	5	8	12	14	1	13	7	9	20
Model 4	5	13	5	13	20	20	20	8	6	9	11	28	2	22	7	13	34	6	28	21
	Day 3																			
Model 1	1	2	16	2	18	10	39	1	1	19	2	6	4	21	8	3	8	8	12	50
Model 2	10	3	5	2	8	4	8	2	4	8	1	4	10	8	10	8	9	13	8	22
Model 3	1	12	3	1	1	9	10	10	9	2	10	8	2	8	10	3	10	3	2	11
Model 4	13	36	6	23	42	8	32	17	41	13	43	9	6	6	20	3	11	10	4	34