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

Yi Luo

A Thesis
Submitted to the Faculty of Mississippi State University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Engineering in the Department of Industrial and Systems Engineering

Mississippi State, Mississippi

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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.
## TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TABLE OF CONTENTS</td>
<td>ii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>v</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II. LITERATURE REVIEW</td>
<td>3</td>
</tr>
<tr>
<td>III. SEQUENTIAL DECISION MAKING IN THE PRACTICE AND PROPOSED INTEGRATION SCHEME</td>
<td>6</td>
</tr>
<tr>
<td>IV. PROBLEM STATEMENT AND BASIC MODELS</td>
<td>9</td>
</tr>
<tr>
<td>4.1 Production Model</td>
<td>10</td>
</tr>
<tr>
<td>4.2 Outbound Logistics Model</td>
<td>13</td>
</tr>
<tr>
<td>4.3 Integrated Production and Outbound Logistics Model</td>
<td>14</td>
</tr>
<tr>
<td>V. MODIFIED INTEGRATED PRODUCTION AND OUTBOUND LOGISTICS MODEL</td>
<td>17</td>
</tr>
<tr>
<td>VI. NUMERICAL EXPERIMENTS</td>
<td>22</td>
</tr>
<tr>
<td>6.1 Logistics First Scheme</td>
<td>22</td>
</tr>
<tr>
<td>6.2 Production First Scheme</td>
<td>23</td>
</tr>
<tr>
<td>6.3 Computational Results</td>
<td>26</td>
</tr>
<tr>
<td>6.4 Simulations</td>
<td>28</td>
</tr>
<tr>
<td>VII. CONCLUSION AND FUTURE WORK</td>
<td>31</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>32</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Numerical Experiment Results ( C \leq C_a )</td>
<td>27</td>
</tr>
<tr>
<td>6.2</td>
<td>Numerical Experiment Results ( C &gt; C_a )</td>
<td>27</td>
</tr>
<tr>
<td>6.3</td>
<td>Simulation Results with Rolling Horizon for 30 Days ( C \leq C_a )</td>
<td>29</td>
</tr>
<tr>
<td>A.1</td>
<td>One Instance of Demand with Random Data for Numerical Experiment</td>
<td>37</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Current Operational Planning Process in the Automotive Industry</td>
<td>6</td>
</tr>
<tr>
<td>3.2</td>
<td>Outbound Distribution of the Automotive Industry</td>
<td>7</td>
</tr>
<tr>
<td>3.3</td>
<td>Proposed Operational Planning Process</td>
<td>8</td>
</tr>
<tr>
<td>4.1</td>
<td>Movement Diagram of the Production Model</td>
<td>12</td>
</tr>
<tr>
<td>5.1</td>
<td>Movement Diagram for the Modified Production Model</td>
<td>18</td>
</tr>
</tbody>
</table>
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 Goetschalleck (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.

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.

Figure 3.1 Current Operational Planning Process in the Automotive Industry
(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.

![Diagram of Outbound Distribution of the Automotive Industry](image)

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 $C_r$ is the cycle time in time units 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 $k$th vehicle in the production sequence is model $i$ and $0$ otherwise;

$B_k$: The beginning position of the $k$th vehicle in the bottleneck workstation in time units;

$O_k$: The utility work in the major bottleneck workstation for the $k$th vehicle in time units;

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

$Q_{ia}$: 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 $t$;

$W_{mi}$: 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 is 10 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 larger than the length of the workstation (i.e. utility work = \[\text{beginning time} + \text{processing time} \ - \text{length of workstation}\] +). 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 = \[\text{cycle time} - \text{beginning time} - \text{processing time}\] +.

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.
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 $C$ ($C = \frac{1}{T} (\sum_{m=1}^{M} \sum_{i=1}^{I} D_{int} - \sum_{m=1}^{M} \sum_{i=1}^{I} I_{i0})$), we have $C \leq C_n$. The production sequence on the assembly line is determined by the following mixed integer programming model $P$: 

![Figure 4.1 Movement Diagram of the Production Model](image_url)
\[ P: \quad \text{Min} \quad G \sum_{k=1}^{K} O_k \]

Subject to:

\[ \sum_{i=1}^{I} Y_{ik} = 1; \quad k=1,2,...,K; \quad (1) \]

\[ \sum_{k=1}^{K} Y_{ik} = \sum_{i=1}^{I} \sum_{m=1}^{M} D_{im} - \sum_{m=1}^{M} I_{im}; \quad i=1,2,...,I; \quad (2) \]

\[ \sum_{k=(r-1)}^{rC} Y_{ik} = Q_{it} \quad i=1,2,...,I, \quad t=1,2,...,T; \quad (3) \]

\[ B_k + \sum_{i=1}^{I} r_{ik} Y_{ik} - O_k \leq L \quad k=1,2,...,K; \quad (4) \]

\[ B_k + \sum_{i=1}^{I} r_{ik} Y_{ik} - O_k - C_{y} \leq B_{k+1} \quad k=1,2,...,K-1; \quad (5) \]

\[ B_1 = 0 \quad (6) \]

\[ O_k \geq 0; \quad B_k \geq 0; \quad Q_{it} \geq 0; \quad Y_{ik} \in \{0,1\}. \quad (7) \]

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. $\sum_{i=1}^{I} \sum_{m=1}^{M} D_{int} - \sum_{m=1}^{M} I_{int0} = 0$). The outbound logistics model $L$ is as follows:

$$L: \text{Min} \sum_{i=1}^{I} \sum_{m=1}^{M} \sum_{t=1}^{T} H_{i} I_{int} + \sum_{i=1}^{I} \sum_{m=1}^{M} \sum_{t=1}^{T} U_{i} L_{int} + \sum_{i=1}^{I} \sum_{m=1}^{M} W_{mt}$$

Subject to:

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

$$\sum_{i=1}^{I} S_{int} \leq E_{m} W_{mt} \quad m=1,2..., M, t=1,2,...,T; \quad (9)$$

$$\sum_{m=1}^{M} \sum_{i=1}^{I} P_{int} = C \quad t=1,2,...,T; \quad (10)$$

$$\sum_{j=1}^{J} D_{int} - \sum_{j=1}^{J} S_{int} \leq L_{int} \quad i=1,2,...,I, m=1,2..., M, t=1,2,...,T; \quad (11)$$

$$L_{intT} = 0 \quad i=1,2,...,I, m=1,2,...,M \quad (12)$$

$$P_{int} \geq 0; \quad I_{int} \geq 0; \quad S_{int} \geq 0; \quad W_{mt} \geq 0, \text{integer}; \quad L_{int} \geq 0. \quad (13)$$

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 \( I \):

\[
I: \quad \text{Min} \quad \sum_{k=1}^{K} O_k + \sum_{t=1}^{T} \sum_{m=1}^{M} \sum_{i=1}^{I} H_{imt} I_{imt} + \sum_{t=1}^{T} \sum_{m=1}^{M} \sum_{i=1}^{I} U_{imt} L_{imt} + \sum_{t=1}^{T} \sum_{m=1}^{M} F_m W_{mt}
\]

Subject to:

1. \( \sum_{i=1}^{I} Y_{ik} = 1 \) \( k=1,2, \ldots, K; \) (1)
2. \( \sum_{k=1}^{K} Y_{ik} = \sum_{t=1}^{T} \sum_{m=1}^{M} D_{imt} - \sum_{i=1}^{I} I_{im0} \) \( i=1,2,\ldots,I; \) (2)
3. \( \sum_{k=(t-1)C+1}^{tC} Y_{ik} = Q_{it} \) \( i=1,2,\ldots,I, \ t=1,2,\ldots,T; \) (3)
4. \( B_k + \sum_{i=1}^{I} r_i Y_{ik} - O_k \leq L \) \( k=1,2,\ldots,K; \) (4)
5. \( B_k + \sum_{i=1}^{I} r_i Y_{ik} - O_k - C_y \leq B_{k+1} \) \( k=1,2,\ldots,K; \) (5)
6. \( Q_{it} = \sum_{m=1}^{M} P_{imt} \) \( i=1,2,\ldots,I, \ t=1,2,\ldots,T; \) (14)
7. \( \sum_{m=1}^{M} \sum_{i=1}^{I} P_{imt} = \sum_{i=1}^{I} Q_{it} = C \) \( t=1,2,\ldots,T; \) (10)
8. \( I_{im,t-1} + P_{imt} - S_{imt} = I_{imt} \) \( i=1,2,\ldots,I, \ m=1,2,\ldots,M, \ t=1,2,\ldots,T; \) (8)
9. \( \sum_{j=1}^{J} S_{imt} \leq E_{mW_{mt}} \) \( m=1,2,\ldots,M, \ t=1,2,\ldots,T; \) (9)
10. \( \sum_{j=1}^{J} D_{imj} - \sum_{j=1}^{J} S_{imj} \leq L_{imt} \) \( i=1,\ldots,I, \ m=1,2,\ldots,M, \ t=1,2,\ldots,T; \) (11)
11. \( B_i = L_{imT} = 0 \) \( i=1,\ldots,I, \ m=1,2,\ldots,M; \) (15)
\[ O_k \geq 0; \quad B_k \geq 0; \quad Y_{ik} \in \{0,1\}; \quad P_{i\text{mt}} \geq 0; \quad Q_{it} \geq 0; \]
\[ I_{\text{int}} \geq 0; \quad W_{mt} \geq 0, \text{ integer}; \quad S_{\text{int}} \geq 0; \quad L_{\text{int}} \geq 0. \] (16)

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 \( (r_{i^*} = \max\{r_1, r_2, \ldots, r_n\} \) and model \( i' \) has the shortest processing time \( (r_{i'} = \min\{r_1, r_2, \ldots, r_n\} \) 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 larger than \( L - r_{i^*} \), 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 larger than \( L - r_{i^*} \). 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:

\[ O_t \geq \sum_{i=1}^{T} r_i Q_{it} - C_y C - L + C_y \]  \[ t = 1, 2, \ldots, T \]  (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 \( MP1 \):
**MPI:** Min \( G \sum_{i=1}^{T} O_i \)

Subject to:
\[ O_t \geq \sum_{i=1}^{I} Q_{it} r_i - C_y C - L + C_y \quad t=1,2,..., T; \]  \hspace{1cm} (17)

\[ \sum_{t=1}^{T} O_t = \sum_{i=1}^{M} \sum_{m=1}^{M} D_{int} - \sum_{m=1}^{M} I_{int0} \quad i=1,2,...,I; \]  \hspace{1cm} (18)

\[ \sum_{i=1}^{I} Q_{it} = C \quad t=1,2,...,T; \]  \hspace{1cm} (10)

\[ Q_{it} \geq 0, \text{ integer;} \quad O_t \geq 0, \]  \hspace{1cm} (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 \( G \sum_{i=1}^{T} O_i + \sum_{i=1}^{M} \sum_{m=1}^{M} \sum_{j=1}^{I} H_{imt} J_{int} + \sum_{i=1}^{T} \sum_{m=1}^{M} \sum_{j=1}^{I} U_{imt} L_{int} + \sum_{i=1}^{T} \sum_{m=1}^{M} K_{mW_{mt}} \)

Subject to:
\[ Q_{it} = \sum_{m=1}^{M} P_{imt} \quad i=1,2,...,I, t=1,2,...,T; \]  \hspace{1cm} (14)

\[ \sum_{m=1}^{M} \sum_{i=1}^{I} P_{imt} = \sum_{i=1}^{I} Q_{it} = C \quad t=1,2,...,T; \]  \hspace{1cm} (10)

\[ I_{i,m,t-1} + P_{imt} - S_{imt} = I_{imt} \quad i=1,2,...,I, m=1,2..., M, t=1,2,...,T; \]  \hspace{1cm} (8)

\[ \sum_{j=1}^{I} S_{imt} \leq E_{ntW_{mt}} \quad m=1,2..., M, t=1,2,...,T; \]  \hspace{1cm} (9)

\[ \sum_{j=1}^{I} D_{imt} - \sum_{j=1}^{I} S_{imt} \leq L_{imt} \quad i=1,2,...,I, m=1,2..., M, t=1,2,...,T; \]  \hspace{1cm} (11)

\[ L_{imT} = 0 \quad i=1,2,...,I, m=1,2..., M; \]  \hspace{1cm} (12)
\begin{align}
O_t & \geq \sum_{i=1}^{I} Q_a r_i - C_y C_a - L + C_y \quad t=1,2,\ldots,T; \quad (17) \\
\sum_{t=1}^{T} Q_a & = \sum_{t=1}^{T} \sum_{m=1}^{M} D_{itm} - \sum_{m=1}^{M} I_{im0} \quad i=1,2,\ldots,I; \quad (18) \\
P_{int} & \geq 0, Q_{it} \geq 0, \text{ integer} \; ; \quad I_{int} \geq 0, \; S_{int} \geq 0, \; L_{int} \geq 0; \quad Q_i \geq 0; \; W_{mt} \geq 0, \text{ integer}. \quad (19)
\end{align}

When the total demand over \( T \) days deducting total initial inventories is larger 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).

\begin{align}
O_t & \geq \sum_{i=1}^{I} Q_a r_i - C_y C_a - L + C_y \quad t=1,2,\ldots,T \quad (20)
\end{align}

And the production model \( P \) can be simplified into the following mathematical model \( MP2 \).

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

\text{Subject to:} \quad O_t \geq \sum_{i=1}^{I} Q_a r_i - C_y C_a - L + C_y \quad t=1,2,\ldots,T; \quad (20)

\begin{align}
\sum_{t=1}^{T} Q_a & = C_a \quad t=1,2,\ldots,T; \quad (21) \\
\sum_{t=1}^{T} Q_a & \leq \sum_{t=1}^{T} \sum_{m=1}^{M} D_{itm} - \sum_{m=1}^{M} I_{im0} \quad i=1,2,\ldots,I; \quad (29) \\
Q_a & \geq 0, \text{ integer} \; ; \quad O_t \geq 0, \quad (27)
\end{align}

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 larger than the demand of each model.

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

$$MI': \text{Min} \quad G \sum_{t=1}^{T} Q_t + \sum_{i=1}^{M} \sum_{m=1}^{I} \sum_{l=1}^{L} H_{i,m} L_{im} + \sum_{i=1}^{M} \sum_{m=1}^{I} \sum_{l=1}^{L} U_{i} L_{im} + \sum_{t=1}^{T} \sum_{m=1}^{M} K_{m} W_{mt}$$

Subject to:

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

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

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

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

$$\sum_{j=1}^{J} D_{ij} - \sum_{j=1}^{J} S_{ij} \leq L_{imt} \quad i=1,2,\ldots,I, \quad m=1,2,\ldots,M, \quad t=1,2,\ldots,T; \quad (11)$$

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

$$O_{t} \geq \sum_{i=1}^{I} Q_{it} r_{i} - C_{y} C_{a} - L + C_{y} \quad t=1,2,\ldots,T; \quad (20)$$

$$P_{imt} \geq 0; \quad Q_{it} \geq 0, \text{ integer}; \quad I_{imt} \geq 0; \quad S_{imt} \geq 0; \quad L_{imt} \geq 0; \quad O_{t} \geq 0; \quad W_{mt} \geq 0, \text{ integer}. \quad (19)$$

Backorder is allowed at the end of the horizon (constraint set (23)).
CHAPTER VI
NUMERICAL EXPERIMENTS

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 $C \leq C_a$, and the details of the Logistics First Heuristic are presented as follows:

**Step 1**

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

\[
\begin{align*}
\text{Min} & \quad \sum_{t=1}^{T} \sum_{m=1}^{M} \sum_{i=1}^{N} H_{imt} I_{int} + \sum_{t=1}^{T} \sum_{m=1}^{M} \sum_{i=1}^{I} U_{imt} L_{int} + \sum_{t=1}^{T} \sum_{m=1}^{M} F_{m} W_{mt} \\
\text{Subject to:} & \quad Q_{it} = \sum_{m=1}^{M} P_{imt} \quad i=1, ..., I, t=1,2, ..., T; \quad (14) \\
& \quad \sum_{m=1}^{M} \sum_{i=1}^{I} P_{imt} = \sum_{i=1}^{I} Q_{it} = C \quad t=1,2, ..., T; \quad (10)
\end{align*}
\]
\[ I_{i,m,t-1} + P_{int} - S_{int} = I_{int} \quad i=1,\ldots,I, \ m=1,2\ldots, M, \ t=1,2,\ldots,T; \quad (8) \]
\[ \sum_{i=1}^{I} S_{int} \leq E_{m}W_{mt} \quad m=1,2\ldots, M, \ t=1,2,\ldots,T; \quad (9) \]
\[ \sum_{j=1}^{I} D_{mij} - \sum_{j=1}^{I} S_{mij} \leq L_{int} \quad i=1,\ldots,I, \ m=1,2\ldots, M, \ t=1,2,\ldots,T; \quad (11) \]
\[ L_{intT} = 0 \quad i=1,\ldots,I, \ m=1,2\ldots, M; \quad (12) \]
\[ P_{int} \geq 0; \quad Q_{it} \geq 0; \quad I_{int} \geq 0; \quad S_{int} \geq 0; \quad L_{int} \geq 0; \quad W_{mt} \geq 0, \text{integer}. \quad (24) \]

**Step 2**

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

\[
\text{Min} \quad G \sum_{i=1}^{T} O_{i} \\
\text{Subject to:} \\
O_{i} \geq \sum_{i=1}^{T} Q_{it} r_{i} - C_{y} C - L + C_{y} \quad t=1,2,\ldots,T; \quad (17) \\
O_{i} \geq 0. \quad (25) 
\]

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 \( C \leq C_a \). 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 \( G \sum_{t=1}^{T} O_t \)

Subject to:

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

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

\[
\sum_{i=1}^{I} Q_{it} = C \quad t=1,2,\ldots,T; \tag{19}
\]

\[
Q_{it} \geq 0, \text{ integer; } O_t \geq 0. \tag{27}
\]

**Step 2**

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

Min \( \sum_{t=1}^{T} \sum_{m=1}^{M} \sum_{i=1}^{I} H_{imt} + \sum_{t=1}^{T} \sum_{m=1}^{M} \sum_{i=1}^{I} U_i L_{imt} + \sum_{t=1}^{T} \sum_{m=1}^{M} F_m W_{mt} \)

Subject to:

\[
\sum_{m=1}^{M} P_{imt} = Q_{it} \quad i=1, 2,\ldots,I, t=1,2,\ldots,T; \tag{14}
\]

\[
I_{i,m,t-1} + P_{imt} - S_{imt} = I_{imt} \quad i=1, 2,\ldots, I, m=1,2,\ldots, M, t=1,2,\ldots,T; \tag{15}
\]

\[
\sum_{j=1}^{I} S_{imj} \leq E_{m} W_{mt} \quad m=1,2,\ldots, M, t=1,2,\ldots,T; \tag{16}
\]

\[
\sum_{j=1}^{I} D_{imj} - \sum_{j=1}^{I} S_{imj} \leq L_{imt} \quad i=1, 2,\ldots, I, m=1,2,\ldots, M, t=1,2,\ldots,T; \tag{17}
\]

\[
L_{imT} = 0 \quad i=1, 2,\ldots, I, m=1,2,\ldots, M; \tag{18}
\]
\[
P_{int} \geq 0; \quad I_{int} \geq 0; \quad S_{int} \geq 0; \quad L_{int} \geq 0; \quad W_{mt} \geq 0 \text{ integer.} \tag{28}
\]

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 \( Q_{it} \).

\[
\text{Min } \sum_{t=1}^{T} O_t
\]

Subject to:

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

\[
\sum_{t=1}^{T} Q_{it} \leq \sum_{i=1}^{I} \sum_{m=1}^{M} D_{int} - \sum_{m=1}^{M} I_{int0} \quad i=1, 2, \ldots, I; \tag{29}
\]

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

\[
Q_{it} \geq 0, \text{ integer}; \quad O_t \geq 0. \tag{27}
\]

**Step 2**

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

\[
\text{Min } \sum_{t=1}^{T} \sum_{m=1}^{M} \sum_{i=1}^{I} \sum_{r=1}^{N} H_{ir} I_{int} + \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{m=1}^{M} \sum_{r=1}^{N} U_{ir} L_{int} + \sum_{t=1}^{T} \sum_{m=1}^{M} F_{mt} W_{mt}
\]

Subject to:

\[
\sum_{m=1}^{M} P_{int} = Q_{it} \quad i=1, 2, \ldots, I, \quad t=1, 2, \ldots, T; \tag{14}
\]

\[
I_{i, m, t-1} + P_{int} - S_{int} = I_{int} \quad i=1, 2, \ldots, I, \quad m=1, 2, \ldots, M, \quad t=1, 2, \ldots, T; \tag{8}
\]

\[
\sum_{i=1}^{I} S_{int} \leq E_{mt} W_{mt} \quad m=1, 2, \ldots, M, \quad t=1, 2, \ldots, T; \tag{9}
\]
\[
\sum_{j=1}^{I} D_{imj} - \sum_{j=1}^{I} S_{imj} \leq L_{int}
\]

\[i=1, 2, \ldots, I, m=1,2, \ldots, M, \quad t=1,2, \ldots, T;\] (11)

\[
\sum_{i=1}^{I} \sum_{m=1}^{M} L_{intT} = \sum_{t=1}^{T} \sum_{m=1}^{M} \sum_{i=1}^{I} D_{int} - \sum_{m=1}^{M} \sum_{i=1}^{I} I_{im0} - TC_a
\]

(23)

\[
P_{int} \geq 0; \quad I_{int} \geq 0; \quad S_{int} \geq 0; \quad L_{int} \geq 0; \quad W_{mt} \geq 0 \text{ integer.} \] (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: \(H=$30; U=$20; G=$25; E_m=10; C_y=60 \text{ seconds}; L=100 \text{ seconds.}\)

- 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 (\(C \leq C_a\)). 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 ($C \leq C_a$)

<table>
<thead>
<tr>
<th>Ins.</th>
<th>Modified Integrated Scheme</th>
<th>LFS</th>
<th>PFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>496,375</td>
<td>2,250</td>
<td>498,625</td>
</tr>
<tr>
<td>2</td>
<td>503,820</td>
<td>8,925</td>
<td>512,745</td>
</tr>
<tr>
<td>3</td>
<td>505,640</td>
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<tr>
<td>4</td>
<td>499,115</td>
<td>52,850</td>
<td>551,965</td>
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<tr>
<td>5</td>
<td>538,810</td>
<td>3,150</td>
<td>541,960</td>
</tr>
<tr>
<td>6</td>
<td>499,085</td>
<td>10,575</td>
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<tr>
<td>7</td>
<td>498,785</td>
<td>3,950</td>
<td>502,735</td>
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<tr>
<td>8</td>
<td>499,410</td>
<td>5,700</td>
<td>505,110</td>
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<td>9</td>
<td>498,835</td>
<td>75</td>
<td>498,910</td>
</tr>
<tr>
<td>10</td>
<td>498,250</td>
<td>7,725</td>
<td>505,975</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Ins.</th>
<th>Modified Integrated Scheme</th>
<th>LFS</th>
<th>PFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>576,435</td>
<td>37,375</td>
<td>613,810</td>
</tr>
<tr>
<td>2</td>
<td>576,705</td>
<td>23,200</td>
<td>599,905</td>
</tr>
<tr>
<td>3</td>
<td>577,315</td>
<td>50</td>
<td>577,365</td>
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<tr>
<td>4</td>
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<td>75</td>
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<tr>
<td>5</td>
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<td>575,810</td>
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<td>10</td>
<td>575,475</td>
<td>50</td>
<td>575,525</td>
</tr>
<tr>
<td>11</td>
<td>575,475</td>
<td>50</td>
<td>575,525</td>
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</tbody>
</table>
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 $L = 100$ seconds.

• 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 ($C \leq C_a$).

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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.
REFERENCES


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 $(k-1)^{th}$ vehicle, the starting position of the $k^{th}$ vehicle will be $B_k \leq L - C_y$. 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 $L - C_y$. 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 $L - r_v$ 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 $L - r_v$, no idle time happens after processing them because of the assumption that $L \geq C_y + r_v - r_i - 1$, where $r_i$ and $r_v$ 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 $Q_i$ on day $t$, total required work at the workstation is equal to $\sum_{i=1}^{I} r_i Q_i$. The total available time of the workstation is equal to $(\sum_{i=1}^{I} Q_i - 1) C_{y} + L$. Since the sequencing rule guarantees that idle time and overload do not happen both, the minimum total utility work is

$$\left[\sum_{i=1}^{I} r_i Q_i - (C_{y} \sum_{i=1}^{I} Q_i - C_{y} + L)\right]^+ = \left[\sum_{i=1}^{I} (r_i - C_{y}) Q_i + C_{y} - L\right]^+ .$$
### Table A.1  One Instance of Demand with Random Data for Numerical Experiment

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