Coordination of production scheduling and vehicle routing problem with due dates
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Cooperation of Production Scheduling and Vehicle Routing Problem with Due Dates.

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Abstract. This work presents a study on a problem of production and distribution planning. The problem considers a make-to-order production-distribution system with one manufacturer and many customers. The manufacturer (at the depot) produces the products once customer orders have been received. Distributions to the customers associated with a set of orders should be done before the customer's due date to avoid any penalty for delay. The problem is the extension of the Vehicle Routing Problem with Release and Due Dates (VRPRDD) where deliveries start depending on the fix release dates. To achieve optimum efficiency in planning, it makes sense to coordinate production schedule with distribution planning. This is the subject of this study. The classical approach which treats these two planning sequentially is proposed, in which VNS is used as optimization method since it shows to be the most competent heuristic in the VRPRDD. The results shown that integrating production schedule and routing vehicle is significantly better compared to VRPRDD.

INTRODUCTION

Supply Chain Management (SCM) is the management of materials and information flows both in and between facilities, such as vendors, manufacturing and assembly, plants and distribution centers [1]. Over the past decades, SCM has received ever-growing interests both in the literature as well as from industrial practice [2,3]. Generally, the chain consists of a network of organizations, people, activities, information and resources involved in the physical flow of products from suppliers to end customers [4,5].

According to Fahimnia et.al.[5] and Thomas and Griffin [1], there are three stages in the supply chain:

- Procurement: the acquisition of raw materials and parts from suppliers and their transportation to the manufacturing plants;
- Production: the transformation and/or assembly of the acquired materials into finished products;
- Distribution: a network for channelling materials to and between plants, and delivering products to end users through distribution centers.

Previously, organizations have focused their efforts on making effective decisions within each facility. However, under today's competitive environments, decisions become complex as numerous activities spread over multiple functions and organizations need to be taken into considerations. Due to the complexity within multiple activities, all supply chain stages must work towards a well-coordinated system and integrate with each other. Integration among raw-material suppliers, manufacturers and distributors leads to increased information flows, reduced uncertainties and a more profitable supply chain. Thus, it becomes crucial to develop an overall logistics process in order to provide goods and services to the customer at low cost and high service level. The effectiveness of
integration in supply chain stages pose interesting challenges to the companies in order to maximize the potentials for converting competitive advantages into profitability.

**Production-Distribution Chain**

Kanda et al.[6] reviewed various perspectives on supply chain integration issues, such as those related to integration of production and distribution, procurement and production, production and inventory, and distribution and inventory. Lee and Kim [7] asserted that production and the distribution planning are the main processes in supply chain.

Generally, a supply chain starts at the production level where the manufacturer transforms the raw materials and parts into finished product. Then, the distributor will deliver the products to the end customers. Thus, the cost of a product does not only include the material handling costs and inventory, but also the cost of delivering goods and servicing the end customers.

As distribution planning connects manufacturers to end users, distribution/transportation is of course the most important stage in supply chain. However, prior to distribution, production planning is a state just as important as the former in the supply chain. Production planning covers the design and management of the entire manufacturing process [7]. Each of the stages involves operation costs which may not be dependent on the other. Ertogal [8] and Wang [9] reported that production cost is the largest, followed by transportation and inventory cost. This study will only consider the costs for production and distribution. A recent review of the integrated production and distribution scheduling models in the literature can be found in Chen [10].

Traditionally, production scheduling and distribution planning have been dealt with independently in a sequential manner with little or no integration [10]. Production scheduling which focuses on determination of schedule for production will be developed first. Minimizing the production cost is done without considering the routing plan and vice versa.

However, due to market globalization nowadays, treating these components separately tends to result in substantial inefficiencies and, consequently, poor total system performance. Thus, in order to provide goods and services to customers at low costs but with high service levels, it seems that there is a strong need to overlay a coordinated system to have control of all functions in the supply chain [1,6,11]. Blumenfeld and Burns [12], Park [13], Chen and Vairaktarakis [14], Pundoor and Chen [15] and Coccola et al. [16] showed that there are significant benefits by using the optimal coordinated production-distribution schedule as compared to the schedule generated by a sequential approach in the context of the models they consider. Effective coordination within and beyond each boundary is needed to maximize the potential for converting competitive advantage into profitability or to minimize the total production and distribution costs.

Thus, the efficient coordination of production scheduling and distribution planning becomes a challenging problem as companies move towards higher collaborative and competitive environments. There have been many studies on this. Farahani et al.[17] in catering food company, Buer et al.[18], Russell et al.[19], Chiang et al.[20] in newspaper industry, Garcia and Lozano [21] in perishable product manufacturing, Li et al.[22] in consumer electronics manufacturing and Marchetti et al.[23] in industrial gas supply-chains are some examples showing that coordinating production and distribution operations becomes crucial for satisfying on-time delivery requirements.

On top of that, Chen [4,10] also has extensively reviewed the issue of integrated production and vehicle routing scheduling. In such an integrated system, linkage between production schedule and delivery process is extremely important. Chang and Lee [3], Chen and Vairaktarakis [14] and Pundoor and Chen [15] showed that there was significant benefit by using the optimal integrated production-distribution schedule. A recent survey by Ullrich [24] divided VRP literature into two main areas; studies that focus on rather 'simple' delivery considerations and others which allow for vehicle routing.

Most of the papers in literature focused more on production scheduling than vehicle routing. These include Li and Vairaktarakis [25], Pundoor and Chen [15], Cakici et al.[26] and Farahani et al.[27]. Relatively few papers gave more attention to vehicle routing. Among these, Chang and Lee [3] considered a single machine scheduling with a limited capacity vehicle which was assigned up to two destinations only. Chen and Vairaktarakis [14] extended the problem with single and parallel production machine with infinite number of capacitated vehicles. Ullrich [24] dealt with parallel machine scheduling with a fleet of vehicles where customer's time window was the constraint of the problem.
To fill the gap, this study will consider a single production line, focusing more on vehicle routing. The routing of a fleet of vehicles will take into account the availability of the product with reference to the time in which the products are released from the production line, and the latest time at which products need to arrive safely at customer's location. In order to see the performance of production-distribution operations in integrated manner, this study will be compared with vehicle routing problem with release and due dates (VRPRDD). In VRPRDD, we focus on the vehicle routing only by assuming that the release dates are provided before the distribution process begin. The results on VRPRDD has been published by Johar, F. et.al.[28]. Whilst in this study, the production sequence is highlighted.

**PRODUCTION SEQUENCE-VRPRDD (PS-VRPRDD)**

PS-VRPRDD is extended from VRPRDD which has been discussed in [28]. The problem assumes that deliveries can only be started as soon as all scheduled orders in the vehicle have been released from the production line which known as release date. In VRPRDD, fix release dates are used which known up front. To achieve optimum efficiency in planning, it makes sense to coordinate production schedule with distribution planning. This is the subject of this paper. The classical approach which treats these two planning sequentially is used. VNS is used as optimization method since it shows to be the most competent heuristic in the previous problem.

The study considers the production-distribution system which consists of one manufacturer and one or more customers. The supplying company produces the products once orders are received. The distribution process starts as soon as the orders are available and can be released. In this way, inventory, maintenance and warehousing which contribute significantly to the total of the supply management flow could be reduced or avoided altogether.

Boudia et.al. [29] reported that vehicle routing problems have been widely investigated, even for stochastic cases, with inventory constraints and under varied conditions. But the production decisions prior to distribution were usually ignored. In other studies, production planning has been discussed in detail but distribution is not taken into account.

At the beginning of planning, each customer places an order with the manufacturer. Next, the manufacturer processes the orders and attempts to distribute the goods to the customers. Each order has a specified date by which the customer expects to receive his/her order. However, orders may be delivered beyond their due dates due to variability in production schedule which may not meet the due date. Preferably, orders are delivered shortly after their completion. This facilitates the delivery process and prevents delays. On the other hand, this may increase the distribution cost. Hence, the manufacturer will try to consolidate the order delivery as much as possible to minimize the total distribution cost. This means that some completed orders may have to wait for other orders to be completed so that they can be delivered in the same vehicle. This results in a tradeoff between delivery timeliness and total distribution cost. Our study will focus on finding the joint schedule of order processing and delivery to optimize the tradeoff of the delivery timeliness and distribution cost.

Pundoor and Chen [15], stated that the maximum tardiness and total tardiness of orders are the two commonly used measurements of delivery timeliness which represent the worst and average service levels with respect to meeting the order's due dates, respectively. Scheduling problems with optimized maximum tardiness had been studied extensively in machine scheduling in which only production operation was considered. As such a problem deals only with the production part, there exists an optimal solution by scheduling the jobs in nondecreasing order of their due date on a single machine. In addition, some related studies also considered other elements such as jobs release date, due date and batch set-up time [30].

Since our study focuses on the integration of order processing and delivery schedule, we do not consider the problem at the detailed scheduling level. However, we may consider batching together a set of orders for delivery to reduce the total distribution cost. Potts and Kovalyov [31], in their review, stated that it may be cheaper and faster to process jobs in a batch than process them individually; which in our case is related to order delivery.

In this study, the initial release dates of the jobs are assumed to be given. Therefore, processing time of each order, \( p_i \) can be calculated by:

\[
\begin{align*}
    p_{s+1} &= r_{s+1} - r_s \\
    \text{where } s &= 1, 2, ..., N - 1 \text{ represents the sequence of jobs processing.}
\end{align*}
\]
To have a clear picture of this, the following table shows our data input for the problem studied.

<table>
<thead>
<tr>
<th>Order, $i$</th>
<th>Size of order, $q_i$</th>
<th>release date, $r_i$</th>
<th>due date, $d_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>17</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>45</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>80</td>
<td>25</td>
<td>35</td>
</tr>
</tbody>
</table>

**FIGURE 1:** An initial sequence of small problem size of VRPRDD in a single production line.

Completed orders will be delivered shortly to the customers by $K$ available vehicles which have same capacity limit, $Q$. The vehicle capacity limit refers to the maximum total size of the jobs that can be delivered. It is also assumed that each vehicle is only using one route where it starts and ends at the depot, $v$. Each customer is only served once and only by one vehicle.

Although a released order can be immediately loading into vehicle, one job might have to wait for others that has been scheduled in the same vehicle due to varied release dates. Therefore, the vehicle can leave the depot only after all orders scheduled on the route are available. Hence, there are possibilities of some late deliveries for which penalties are imposed. The penalty is a cost which can represent the cost of lost sales, or goodwill due to the customer inconvenience for not meeting the customer's due date. In this study, a linear loss function will be used, i.e. a penalty per unit time of tardy delivery.

**Mathematical Formulation**

In VRPRDD, each job is ordered by a specific customer and it has to be delivered directly to that customer. As PS-VRPRDD is an extension from the VRPRDD, the same initial solution will be used; i.e., parallel insertion method based on the fixed production sequence given. There are a total of $N$ jobs which correspond to $N$ customers. Jobs that are scheduled in the same vehicle will be considered as a batch. For instance, say the route for vehicle 1 is 0-2-6-3-0 which means the delivery starts from the depot, then customers 2, 6 and lastly to customer 3 before going back to the depot. Jobs numbers 2, 6 and 3 which corresponds to the customers 2, 6 and 3 will be batched as $B_1$. We note that $q_i$ corresponds to the size of the job $i$. Jobs and batches are numbered according to customer's orders and vehicle number respectively. Batches will be used for the process of finding the best sequence in a production line.

Each job selected must be processed one after another continuously from its start in the production line to its completion, without any interruption between jobs, and without any waiting between the finish time of job $i - 1$ and starting time of job $i$. Associated with each job is the processing time and its due date for delivery specified by a customer.

Thus, the main task here is to deal with the problem of selecting and scheduling the orders to be processed by a manufacturer for immediate delivery to the customers. It is important to determine the best order of processing for departure time of vehicle through the generated release dates. In PS-VRPRDD the processing time of each customer's order is assumed to be known before routing process which can be calculated as shown in previous Figure 1. Thus, each customer's vertex is associated with:

i. a known order's size to be delivered, $q_i$ ($q_0 = 0$ for vertex 0).
ii. a processing time of each customer's order, $P_i$.
iii. a uniform service time for servicing at customer's location, $s_i$.
iv. a due date for each customer, $d_i$. 
Due to the production sequence that has been accounted in PS-VRPRDD, the positions of jobs (customer orders) are very important to determine the best release date for each customer. Without loss of generality, we assume that the vehicles are indexed so that the jobs of vehicle \( k \) appear as a batch of job sequenced in position \( k \) of the production schedule. Thus, the formulation of PS-VRPRDD is given as below:

**Mathematical Notations:**

\( n \) number of customers

\( N = \{1, 2, 3, \ldots, n\} \) the set of \( n \) customers

\( \bar{N} = \{0, 1, 2, \ldots, n\} \) the set of all nodes including the depot

\( h \) number of vehicles

\( K \) the fleet of vehicles

**Decision variables:**

\( x_{ijk} = \begin{cases} 1 & \text{if vehicle } k \text{ travels from customer } i \text{ to customer } j \\ 0 & \text{otherwise} \end{cases} \)

\( y_j \) tardiness for customer \( j \)

\( z_{ik} \) arrival time of vehicle \( k \) at customer \( i \)

\( z_{0k} \) departure time of vehicle \( k \) from depot

**Parameters:**

\( Q \) capacity of vehicle

\( q_i \) order size of customer \( i \) where \( q_0 = 0 \)

\( s_i \) service time of customer \( i \) where \( s_0 = 0 \)

\( d_i \) due date of customer \( i \)

\( r_i \) release date of customer \( i \)'s order

\( P_i \) processing time on the machine to manufacture the order for customer \( i \), where \( P_0 = 0 \)

\( t_{ij} \) travel time from customer \( i \) to customer \( j \)

\( c_{ij} \) travel cost from customer \( i \) to customer \( j \)

\( w_i \) tardiness penalty cost of customer \( i \)

\( M \) large positive integer number

**Formulation:**

\[
\min (\alpha) \left( \sum_{i \in N} \sum_{j \in \bar{N}} \sum_{k \in K} c_{ij} x_{ijk} \right) + (1 - \alpha) \left( \sum_{j \in \bar{N}} w_j y_j \right)
\]  

subject to:

\[
\sum_{k \in K} \sum_{j \in \bar{N}} x_{ijk} = 1 \quad \forall i \in N
\]  

\[
\sum_{j \in \bar{N}} x_{0jk} \leq 1 \quad \forall k \in K
\]  

\[
\sum_{j \in \bar{N}} x_{ij0} = \sum_{i \in N} x_{i0k} \quad \forall k \in K
\]  

\[
\sum_{j \in \bar{N}} x_{ijk} = \sum_{i \in N} x_{ipk} \quad \forall p \in N, k \in K
\]  

\[
\sum_{i \in N} \sum_{j \in \bar{N}} q_i x_{ijk} \leq Q \quad \forall k \in K
\]  

\[
\sum_{j \in \bar{N}} \sum_{i \in N} x_{ijk} \leq |S| - 1 \quad \forall C \subseteq N, |C| \geq 2, \forall k \in K
\]  

\[
z_{0k} = \sum_{k' = 1}^{K} \sum_{i \in N, j \in \bar{N}} P_{jk} x_{ijk} \quad \forall k \in K
\]  

\[
z_{ik} + s_i + t_{ij} + M(x_{ijk} - 1) \leq z_{jk} \quad \forall i \in \bar{N}, \forall j \in N, \forall k \in K
\]  

\[
z_{jk} + s_j - d_j + M(\sum_{i \in N} x_{ijk} - 1) \leq y_j \quad \forall j \in N, \forall k \in K
\]  

\[
x_{ijk} = 0 \quad \forall i, j \in \bar{N}, \forall k \in K
\]  

\[
x_{ijk} \in \{0,1\} \quad \forall i, j \in \bar{N}, \forall k \in K
\]  

\[
y_j \geq 0 \quad \forall j \in N
\]  

\[
z_{ik} \geq 0 \quad \forall i \in \bar{N}, \forall k \in K
\]  

Equation (2) is the objective function that is to minimize the weighted total costs of travelling and tardiness. The constraint (3) means that each customer is only visited once and only by one vehicle. Each vehicle used for routing originates from the depot, as shown in constraint (4). Constraint (5) states that once a vehicle leaves the depot, it must go back to the depot again. Route continuity is represented by equation (6), i.e. if a vehicle enters a customer...
node, it must exit from that node. Capacity constraint for each vehicle is shown in equation (7) where the summation of order sizes of a route must be less than or equal to vehicle capacity limit. The set of constraints in (8) has the goal of avoiding subtour.

The constraint connecting the VRPRDD and PS-VRPRDD is written as constraint (9), in which departure time of vehicle is summation of all processing time of the order scheduled in vehicles 1 to \( K \). This can be done as we assume that orders scheduled in one vehicle are considered as one batch in production scheduling. Next, arrival time at each customer location is computed in equation (10). Finally, the tardiness of each customer is computed in equation (11). Tardiness is defined as difference between arrival time of vehicle at customer's location and its due date. Decision variables are shown in (12)-(15).

INTEGRATED APPROACH

Before we go further to the algorithms, it is necessary to explain the terms used.

- **Batch Formation**
  A batch is a set of orders/jobs which will be delivered in the same vehicle. Thus, all the orders scheduled on vehicle \( k \) are considered as orders belonging to batch \( k \) where \( k = 1, 2, 3, \ldots, K \).

- **Latest Start Time (LST)**
  Latest start time of vehicle \( k \) is the latest time where vehicle \( k \) should depart from the depot so that the delay in the distribution activity can be minimized. Assume batch 1 contains jobs of customers 5, 2, 7 and 4.

<table>
<thead>
<tr>
<th>Table 2: Batch 1: Arrival and Due Dates of Jobs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job, ( i )</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

Table 2 above shows the arrival and due date of each job in batch 1. The lateness of each job can simply be calculated by subtracting the due date from the arrival time of vehicle for each location as in Table 3 below.

<table>
<thead>
<tr>
<th>Table 3: Batch 1: Lateness of Jobs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job, ( i )</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

Table 3 above shows the lateness time, \( L \), of each job. It can be seen clearly that maximum \( L \) is -3. It can be concluded that LST of batch 1 is 3 which can be written as \( LST_k = 3 \). For this example, if vehicle 1 leaves the depot at time, \( t < 3 \) the distribution of customer's orders can be done on time (initially start time from depot is equal to 0).

In order to construct a production sequence, \( \sigma \), order the jobs (in a batch) in non-decreasing \( LST_k \) value. Note that swapping and relocating batches in a production line are done to improve the current solution cost based on the new generated release date which has been embedded in proposed approach.

The Algorithm

We begin to solve the problems of production schedule and vehicle routing as an integrated problem. The integrated approach decomposes the problem as two subproblems to be tackled one after the other and merge the resulting solutions into an overall solution to the integrated problem. Briefly, the algorithm should improve the production sequence order without changing the route order and vice versa. There exists some integration, where improvement on production schedule is done based on the current best routing. The same goes for routing schedule.
improvement which is based on the current best sequence of production line. The improvement is done separately but depending on the current best schedule.

The process of re-batching, re-scheduling and re-routing is continued until stopping condition is met. Improvement process is continued if it shows better results than the current best solution. If there is no improvement, the procedure is terminated. The algorithm is shown as follow:

**Algorithm 1: Integrated Algorithm**

1: Construct an initial routing by Parallel Insertion Heuristic

2: for loop = 1 to MaxLoop do

3: Batch Formation: Consider a set of customer’s order in the same shipment as a batch.

4: for Vehicle = 1 to MaxVehicle do

5: for CustNo = 1 to MaxCust[Vehicle] do

6: Batch[Vehicle][CustNo] ← Route[Vehicle][CustNo]

7: end for

8: end for

9: To construct a production schedule:

i) Calculate the LST of each vehicle

ii) Sort LST in non-decreasing order i.e. set of customer’s order with smallest LST will be in 1st batch on production line and so forth. Generate the new generated release date.

iii) Then, re-calculate the new routing cost based on the current release date which based on the obtained production schedule.

iv) Improve the production schedule by swapping and insert-delete among and between batches. Re-calculate the release date and new routing cost.

10: Improve the routing cost found above by VNS with the current release date.

11: if met stopping condition then

12: STOP the iteration

13: end if

14: end for

The initial production scheduling is obtained through the Latest Start Time (LST) of vehicle. As previously mentioned, a production sequence, $\sigma$ is constructed through the order of the jobs (in a batch) in non-decreasing $LST_k$ value. Please refer to Figure 1 for an example. Sets of customer orders or batches will be sequenced according to the non-decreasing order of LST. In other words, the batch with the smallest LST will be produced first to enable it to be delivered before its due date. The sequence of customers in the route is considered as the sequence of those customer's processing order in each particular batch. Therefore, these sequences will be considered for our initial production scheduling. The new sequence of orders in production line determines the new release date of each order. Then the new routing cost is calculated based on the new generated release dates. According to the new routing cost found, production scheduling is improved by using swapping, and, inserting and deleting operators between batches.

Next, we attempt to improve the routing cost by VNS which has previously been proven as an effective algorithm for solving VRPRDD [28]. Different release dates may affect the departure time of each vehicle causing changes to the cost of the objective function. Any update of the vehicle departure time and delivery orders creates a potential for improving the quality of the solution cost through re-routing them without increasing the total transportation cost.

**COMPUTATIONAL RESULTS**

The performance of the Integrated Algorithm has been tested using the same modification of 56's Solomon instances as used in the VRPRDD. Again, 30 s of CPU time is used as our stopping condition of the iterations. The best solution obtained within the time is considered as the solution for the method. The experiment is done on three fleet-size cases with three different weights each. Consequently 504 cases are tested.

For each case, the algorithm is run for 10 times, and the average of the solution is taken and summarized as follow:
Table 4 shows the average solution cost of each class of problem. The average costs obtained indicates the performance of the integrated approach on the different fleet-size cases, weights and instance classes. It can be seen clearly that for all cases, integrated approach is able to improve the results in VRPRDD. Overall, up to 50% improvement can be seen in those cases except in class C2. It is observed that for those instances of class C2 for all fleet-size cases and weights, both approaches do not show noteworthy effects of the fleet-size. However, it still shows around up to 5% improvement compared to VRPRDD.

CONCLUSION

The integrated approach is proposed in order to improve the solution obtained in VRPRDD. The algorithm is run on the three fleet-size, and three different weights each with 56 instances. Comparison results between the VRPRDD and PS-VRPRDD. In general, the results shown that integrating production schedule and routing vehicle is significantly better compared to VRPRDD.

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