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Modeling and Solving an Integrated Supply Chain System

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We develop and optimize an integrated supply chain model that combines strategic decision (where to locate distribution centers) with the tactical decisions (production levels and inventory levels) and operational decisions (satisfying customer demand on time and coordinating logistics network). In previous studies, the integrated models for supply chain have been applied mostly in two areas: the first is the integration of production and inventory; and the second is the integration of production and distribution. We build a mixed-integer programming model to minimize the total costs of distribution, storage, inventory and operations, with production levels high enough to satisfy customer demand. Two heuristic solution methods are presented: horizontal staging and time slicing. The results show that the horizontal staging heuristic can provide solutions very close to the best solution of the optimal model and with significant savings in run time.

Significance: This research models and provides efficient and robust heuristic approaches to solve an integrated supply chain problem.

Keywords: Integrated Supply Chain, Logistics, Mixed Integer Programming, and Heuristics

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1. INTRODUCTION

Integrated supply chains include three levels of decisions: (i) strategic, (ii) tactical, and (iii) operational. As discussed in Schmidt and Wilhelm (2000), the strategic level prescribes a set of locations for facilities, production technologies employed at each facility, and the capacity of each plant. Strategic decisions thus determine the network through which, production, assembly and distribution serve the marketplace. The tactical level prescribes material flow management policies, including production levels at all plants, assembly policy, inventory levels and lot sizes. Finally, the operational level schedules operations to assure in-time delivery of final products to customers, thereby coordinating the logistics network to be responsive to customer demands.

In this paper, we propose an integrated model that combines decisions at three different levels: strategic, tactical and operational. In previous studies, the integrated models for supply chain have been applied mostly in two areas: the first is the integration of production and inventory; and the second is the integration of production and distribution. For the first type of integration, usually, closed-form mathematical formulations and analytical solutions are applied in the integrated production-inventory models. For example, Goyal (2000) develops a general policy for the single-vendor single-buyer integrated production-inventory model. Yang and Wee (2002) develop a single-vendor and multiple-buyers production-inventory policy for a deteriorating item with a constant production and demand rate. For the second type of integration, mixed- integer programming approach is often applied for the integrated production-distribution problem. For example, Chandra and Fisher (1994) build a mixed-integer programming model for the production scheduling and distribution problem, and, based on computational results, demonstrate that coordination of production and distribution is better than the case in which production and distribution are solved separately. Jayaraman and Pirkul (2001) also present a mixed-integer programming formulation to the integrated production and distribution problem. The solution approach based on Lagrangian relaxation and a real-world example are provided to explore the implications of the model. Lee et al. (2003) construct a dynamic programming algorithm for the single-product production and transportation problem, considering different types of vehicles. Kim et al. (2006) developed a joint economic production-shipment policy for a single manufacturer-multiple-item system. In most of the models dealing with integration of production and distribution, the aggregate inventory cost is also considered in the objective function to minimize the total cost, such as in Chandra and Fisher (1994), Jayaraman and Pirkul (2001), and more recently in Jang and Kim (2007). When inventory cost is not regarded as significant, then it is not included in the objective function, such as in Cunha and Mutarelli (2007).

We develop and optimize an integrated supply chain model that combines strategic decision (where to locate distribution centers) with the tactical decisions (production levels and inventory levels) and operational decisions (satisfying customer demand on time and coordinating logistics network). It is expected that our approach will produce a more efficient supply chain network than those in literature that lack consideration of coordination of decisions at three different levels.

There is a large body of literature in the field of integrated models for supply chain system. The literature review here consists of two parts. The first part is on previous reviews of the literature in this field, completed in the late 1990s or the early 2000s; and the second part is on the literature in most recent years, which are published after previous review papers.

Vidal and Goetschalckx (1997) present a review on the strategic production-distribution models with emphasis on global supply chain models. The review focuses on the mixed-integer programming models and their solution strategies and computation experiments. Different constraints and cost items considered in the applications are compared, especially from the perspective of global logistics. It is pointed out that one critical drawback of all the reviewed models is lack of consideration of uncertainties. Beamon (1998) provided a focused review of literature in multi-stage supply chain modeling by considering three main factors: (i) model types, (ii) performance measures, and (iii) decision variables. Sarmiento and Nagi (1999) also review the literature on integrated analysis of production-distribution system. They point out that the integration of the logistics (transportation) function into the production functions, such as inventory control, facilities and production planning, can provide significant benefit to companies, but few papers have covered the practicality and reality of the actual integrated system, since complexity of the models make them much harder to solve.

Erenguc et. al. (1999) identify three stages in a supply chain: supplier stage, plant stage and distribution stage, and evaluate the literature on production-distribution planning at each stage. It is pointed out that substantial benefits can be achieved by building an integrated analytic model or simulation model for all three stages; and information sharing, which is difficult nowadays, is needed for coordinating decisions, such as inventory decisions, among different stages in a supply chain. Schmidt and Wilhelm (2000) review the papers on strategic, tactical and operational decisions for international logistics, and conclude that the decisions at three levels interact with each other, and therefore, an unified approach is needed to build an integrated model in designing and operating a global logistics network. Goetschalckx et. al. (2002) first review all the models for the global logistics system in literature, and then present two models to demonstrate the benefit of integrating the strategic and tactical decisions for the design of logistics network. The first model focuses on the setting of transfer prices in a global supply chain, and a heuristic iterative solution algorithm is proposed. The second model deals with the production and allocation in a single country with seasonal demand. An integrated design methodology is developed based on the primal decomposition method, and then a heuristic solution is also proposed.

More recently, research efforts in the field of integrated models have focused more on specific issues of the integration methodology or a specific case of an integrated problem. For example, Johnson et. al. (2002) formulate an integrated location/allocation/routing problem for home-delivered meals provision, and present and evaluate a GIS based heuristic to solve the problem. Cunha and Mutarelli (2007) propose a mixed-integer linear programming model for the integrated problem of producing and distributing a major weekly magazine, and use the spreadsheet to solve the model. More work is focused on developing analytic solutions for an integrated production-inventory model. Jang and Kim (2007) develop an integrated production, allocation, and distribution policy for a single period inventory problem in which one supplier faces stochastic demand from multiple customers. An optimal policy is presented for the two-customers problem and a heuristic policy is developed for a general case. Chung and Wee (2007) develop an optimal replenishment policy using an algebraic method to solve an integrated vendor-buyer inventory problem with backorder, without using derivatives. Zhou and Wang (2007) develop a general production-inventory model for a single-vendor-single-buyer integrated system. A closed-form analytical formulation, rather than a mixed-integer programming approach, is applied in the study. Ertogral et. al. (2007) incorporate the transportation cost explicitly into the integrated vendor-buyer model and develop optimal solution procedures for solving integrated models. Boute et. al. (2007) develop an integrated production and inventory model to dampen upstream demand variability in a two-echelon supply chain system with a single retailer and multiple customers' demand of identical independent distribution (i.i.d.). It is concluded that by including the order decisions on lead times, the order pattern can be smoothed without increasing the stock level, which is beneficial to both retailers and customers. Rau and OuYang (2007) develop an integrated production-inventory policy in a finite planning horizon and a linear trend in demand. An optimal solution procedure is introduced. Based on numerical examples, it is demonstrated that the performance of the integrated model is better than the performance of any independent decision from either the buyer or the vendor.

In summary, the integration of decisions of different functions (e.g. supply process, distribution, inventory management, production planning, facilities location, etc.) requires decision models to simultaneously optimize the decision variables of different functions that have been traditionally optimized sequentially. Many researchers have modeled and optimized subsets of the integrated production-inventory-distribution systems. However, these models have been developed considering the specific and practical needs of the problems the researchers were trying to address. Hence, different decision variables, different constraints, and different cost factors are considered in their models.

Different from the literatures above, in this paper, we build an integrated model that will consider three levels of decisions, such as location of distribution center, production level, inventory level, and customer service. A mixed-integer programming model is built to minimize the total costs of distribution, storage, inventory and operations, with production levels high enough to satisfy customer demand.

In Section 2 of this paper, a mathematical formulation of an integrated supply chain, in which we assume that the products under consideration get completed in one time period (no work-in-process), is presented. Two heuristic approaches are developed in Section 3. Based on an example, the performances of these heuristics are evaluated in Section 4. Finally, conclusions are presented in Section 5.

2. MATHEMATICAL FORMULATION OF THE PROPOSED MODEL

2.1 Assumptions:

We assume that raw material arriving at each manufacturing plant is used to make various products and that in each time period raw material gets converted to a finished product in the very same time period. The finished products are shipped from the plants to the distribution centers at the end of each time period. Finished products are then held in inventory at the distribution centers. There is no work-in-process inventory at the manufacturing plants. Therefore, inventory at the end of each period at each manufacturing plant is in the form of raw material only. No backorder is allowed at the manufacturing plants as well as the distribution centers. The inventory holding costs are assessed per unit per time period at both the manufacturing plants and the distribution centers. We also assume that the logistics function of the company is outsourced with a given unit cost of transportation.

2.2 Notations Used:

The notations used in this paper include:

R = number of different types of raw materials used;
PL = number of manufacturing plants;
V =number of raw material vendors;
C = number of customer zones;
M = number of transportation modes;
D = number of distribution centers;
P = number of product types;
T = number of time periods in the planning horizon;
F_d = fixed cost of operating distribution center d;
Z_d = a binary variable, and is equal to 1 if the distribution center d is selected and is zero otherwise;
O_{dt} = cost of operating distribution center d in time period t;
VR_{ijkt} = number of units of raw material i shipped from vendor j to manufacturing plant k in time period t;
CR_{ijkt} = unit transportation cost of raw material i from vendor j to plant k in time period t;
W^{b}_{pkdmt} = no of units of product type p shipped from plant k to distribution center d by transportation mode m in time period t;
$CFPD_{pkdmt}$ = unit cost of transportation of finished product p from plant k to distribution center d by mode m in time period t;
W^{a}_{pkt} = number of units of product p produced at plant k in time period t;
X_{ikpt} = total number of units of raw material i used at plant k to make product p in time period t;
R_{ijt} = number of units of raw material i available at vendor j in time period t;
VR_{ijkt} = number of units of raw material i shipped from vendor j to plant k in time period t;
Y_{pdcmt} = number of finished product p transported from distribution center d to customer zone C by transportation mode m at the beginning of time period t;
$CFDC_{pdcmt}$ = unit cost of transportation of finished product p from distribution center d to customer zone c by transportation mode m in time period t;
IR_{ikt} = number of units of raw material i held in inventory at the end of period t at plant k;
ICR_{ikt} = inventory holding cost per unit per period of raw material i at plant k in time period t;
IF_{pdt} = number of units of finished product p held at distribution center d at the end of time period t;
ICF_{pdt} = inventory holding per unit per time period of finished product p at distribution center d in time period t;
PC_{pkt} = capacity of plant k in time period t to produce product p;
$TMCP_{pkmt}$ = transportation mode m capacity in time period t at plant k to ship product type p;
MR_{ipkt} = multiple of raw material i required per unit of product type p at plant k in time period t;
$TMCD_{pdmt}$ = transportation mode m capacity in time period t at distribution center d to ship product type p;

DP_{pct} = demand of product p at customer zone c in time period t;
DCC_{pdt} = capacity of distribution center d for product type p in time period t;
M = Total of all plant capacities;

2.3 Mathematical Formulation:
Based on the notations above, a mixed integer programming model can formulated as:

$$Minimize\ TC = \sum_{d=1}^{D} F_d Z_d + \sum_{t=1}^{T}\sum_{d=1}^{D} O_{dt} Z_d + \sum_{i=1}^{R}\sum_{j=1}^{V}\sum_{k=1}^{PL}\sum_{t=1}^{T} VR_{ijkt} CR_{ijkt} + \sum_{p=1}^{P}\sum_{k=1}^{PL}\sum_{d=1}^{D}\sum_{m=1}^{M}\sum_{t=1}^{T} W^b_{pkdmt} CFPD_{pkdmt}$$
$$+ \sum_{p=1}^{P}\sum_{d=1}^{D}\sum_{c=1}^{C}\sum_{m=1}^{M}\sum_{t=1}^{T} Y_{pdcmt} CFDC_{pdcmt} + \sum_{i=1}^{R}\sum_{k=1}^{PL}\sum_{t=1}^{T} IR_{ikt} ICR_{ikt} + \sum_{p=1}^{P}\sum_{d=1}^{D}\sum_{t=1}^{T} IF_{pdt} ICF_{pdt} \qquad (1)$$

Subject to:

$$MR_{ipkt} W^a_{pkt} = X_{ikpt} \quad \text{for all i, p, k , and t} \qquad (2)$$

$$IR_{ikt} = IR_{ikt-1} + \sum_{j=1}^{V} VR_{ijkt} - \sum_{p=1}^{P} X_{ikpt} \quad \text{for all i, k, and t} \qquad (3)$$

$$W^a_{pkt} = \sum_{m=1}^{M}\sum_{d=1}^{D} W^b_{pkdmt} \quad \text{for all p, k, and t} \qquad (4)$$

$$IF_{pdt} = IF_{pdt\text{-}1} + \sum_{m=1}^{M}\sum_{k=1}^{PL} W^b_{pkdmt} - \sum_{m=1}^{M}\sum_{c=1}^{C} Y_{pdcmt} \quad \text{for all p, d, and t} \qquad (5)$$

$$\sum_{m=1}^{M}\sum_{d=1}^{D} Y_{pdcmt} \geq DP_{pct} \quad \text{for all p, c, and t} \qquad (6)$$

$$\sum_{m=1}^{M}\sum_{k=1}^{PL} W^b_{pkdmt} + IF_{pdt-1} \leq DCC_{pdt} \quad \text{for all p, d, and t} \qquad (7)$$

$$W^a_{pkt} \leq PC_{pkt} \quad \text{for all p, k, and t} \qquad (8)$$

$$\sum_{d=1}^{D} W^b_{pkdmt} \leq TMCP_{pkmt} \quad \text{for all p, k, m, and t} \qquad (9)$$

$$\sum_{c=1}^{C}\sum_{d=1}^{D} Y_{pdcmt} \leq TMCD_{pdmt} \quad \text{for all p, d, m, and t} \qquad (10)$$

$$\sum_{p=1}^{P} X_{ikpt} \leq \sum_{j=1}^{V} VR_{ijkt} \quad \text{for all i, k, and t} \qquad (11)$$

$$\sum_{k=1}^{PL} VR_{ijkt} \leq R_{ijt} \quad \text{for all i, j, and t} \qquad (12)$$

$$W^b_{pkdmt} \leq M * Z_d \quad \text{for all p, k, d, m and t} \qquad (13)$$

$$Y_{pdcmt} \leq M * Z_d \quad \text{for all p, d, c, m, and t} \qquad (14)$$

$$Z_d = 0 \text{ or } 1 \qquad (15)$$

$$VR_{ijkt}, W^a_{pkt}, W^b_{pkdmt}, X_{ikpt}, VR_{ijkt}, Y_{pdcmt}, IR_{ikt}, and\ IF_{pdt} \geq 0 \qquad (16)$$

The above mathematical formulation Eq. (1) – Eq. (16) determine the optimal values of the decision variables (Z_d, VR_{ijkt}, W^a_{pkt}, W^b_{pkdmt}, X_{ikpt}, VR_{ijkt}, Y_{pdcmt}, IR_{ikt}, and IF_{pdt}) by minimizing the sum of the total fixed and operating cost at distribution centers (the first and the second terms of the objective function Eq. (1), respectively), total transportation cost of raw material shipped from the raw material vendors to manufacturing plants (third term of the objective function), total transportation cost of finished products shipped from manufacturing plants to customer zones (fourth term of the objective function), total inventory holding cost of raw material at manufacturing plants (fifth term of the objective function), and total cost of holding finished products at distribution centers (sixth term of the objective function equation).

The constraints of the model are as follows:

Constraint (2) determines the total number of units of raw material i used at plant k to make product p in time period t;
Constraint (3) is the inventory balance equation for raw material i at plant k;
Constraint (4) determines the number of units of product type p produced at plant k in time period t;
Constraint eq. (5) is the inventory balance equation for finished product type p at distribution center d in time period t;
Constraint (6) ensures that the demand constraint is satisfied for each product type at each customer zone c in time period t;
Constraint (7) represents the distribution center d's capacity to store each product type p in time period t;
Constraint (8) ensures that the plant k's capacity constraint to produce product type p in time period t is satisfied;
Constraint (9) ensures that the transportation mode m capacity to transport product type p from plant k in time period t is satisfied;
Constraint (10) ensures that the transportation mode m's capacity to transport product type p from distribution center d is satisfied;
Constraint (11) ensures that the amount of raw material i used at plant k in making various products in time period t will not exceed total amount of raw material i available at plant k in time period t;
Constraint (12) ensures that the total amount of raw material i shipped from vendor j to various plants will not exceed the total amount of raw material i available at vendor j;
Constraint (13) ensures that the products are shipped to distribution center d only if distribution center d gets selected;
Constraint (14) ensures that the products are shipped out of distribution center d to customer zones if the distribution center d is selected;
Constraint (15) represents a binary variable for selecting each distribution center d;
Constraint (16) represents the non-negativity condition on the other variables.

Based on the formulation above, the problem may be too cumbersome and time consuming to solve. To solve this problem, two heuristic methods are presented in the next section.

3. HEURISTICS METHODS – HORIZONTAL STAGING AND TIME SLICING

Depending on the size of the problem, a feasible solution may not exist. Hence, two heuristic methods, horizontal staging and time slicing, are proposed to simplify model computation.

The horizontal staging method is decentralizing and dividing the original network for customers, distributors, and manufacturers into two stages horizontally. Two local objectives are achieved separately by using upstream stage output (customer/distributor) as input for the downstream predecessor (distributor/manufacturer). The first objective of the horizontal method minimizes the cost between customers and distributors, and the second objective minimizes the cost between the distributors and manufacturers. The two local objectives are solved separately by using upstream stage output as input for the downstream stage, which are shown below based on the same notations as in Section 2:

Stage 1: Objective function - Minimizing the cost between distributions and customers.

$$Minimize\ TC = \sum_{d=1}^{D} F_d Z_d + \sum_{t=1}^{T}\sum_{d=1}^{D} O_{dt} Z_d + \sum_{p=1}^{P}\sum_{d=1}^{D}\sum_{c=1}^{C}\sum_{m=1}^{M}\sum_{t=1}^{T} Y_{pdcmt}\, CFDC_{pdcmt} + \sum_{p=1}^{P}\sum_{d=1}^{D}\sum_{t=1}^{T} IF_{pdt}\, ICF_{pdt}$$

Stage 2: Objective function - Minimizing the cost of plants

$$MinimizeTC =$$

$$\sum_{t=1}^{R}\sum_{j=1}^{V}\sum_{k=1}^{P}\sum_{t=1}^{T} VR_{ijkt} CR_{ijkt} + \sum_{p=1}^{P}\sum_{k=1}^{PL}\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{d=1}^{D} W_{pkdmt} PC_{pkt} Z_d + \sum_{p=1}^{P}\sum_{k=1}^{PL}\sum_{d=1}^{D}\sum_{m=1}^{M}\sum_{t=1}^{T} W_{pkdmt} CFPD_{pkdmt} Z_d +$$

$$\sum_{i=1}^{R}\sum_{k=1}^{PL}\sum_{t=1}^{T} IR_{ikt} ICR_{ikt}$$

The time slicing heuristic solves the problem one period at a time. This method is based on the assumption that forecasting demand is highly unpredictable and actual demand will be used. Hence, at the beginning of each season, demand is occurred and production and transportation plans are deployed based on it. The remaining raw material and products, at the end of each period, become inventory for the next time period.

The next section compares the performance of the two heuristic methods with that of the model formulation of the complete supply chain network.

4. ANALYSIS AND PERFORMANCE OF THE HEURISTICS

Based on an example, we apply the heuristic approaches introduced above, and evaluate the performances of these heuristics in this section. The supply chain network structure considered in this case includes two vendors (Vendor 1 and Vendor 2), two manufacturers located in Santa Fe, NM and Flag Staff, AZ, six distributors located in Yuma, AZ, Fresno, CA, Tucson, AZ, Pomona, CA, Las Vegas, NV, St. George, UT), and six customers. Three raw materials (Material 1, Material 2, and Material 3) are used to produce four different products. Two transportation modes (large trucks and small trucks) are used to transport finished goods from the plant to distribution centers and from distribution centers to customers. Planning horizon is considered to be one year. Specifically, four time periods (quarters) are considered. Unit transportation cost from each plant to each distribution center is calculated as the product of the unit transportation cost per mile and the corresponding distances traveled. Unit transportation cost from each distribution center to each customer is similarly calculated as the product of the unit transportation cost per mile and the corresponding distances traveled.

The numerical data for the problem are generated from actual and simulated data. Based on this network, the original model formulation contains 1806 variables and 2289 constraints. Our analysis here compares the performance of the optimum formulation with the horizontal staging and time slicing heuristics. For this study, demand varies from 25% to 200% of the original levels, and plant, truck and distribution center capacities vary from 25% to 200% of original levels. The models are solved using LINGO 9.1.

The study is performed both for computed objective values (minimization of total cost) and for the execution time of the methods. Table 1 shows the results for the total cost value derived from the various methods, and Table 2 shows the percent increase in the total cost value from the heuristics methods to the optimum solution derived from Lindo. Table 3 shows the execution run time for the various methods, and Table 4 shows the percent decrease in the run time of the heuristic methods from running the optimal model directly in Lindo. Table 1 shows the legend for for Tables 2-4.

Table 1: Legends for Tables 1 to 4

×	Optimal model Optimum method
▲	Horizontal Staging method
●	Time Slicing method

Table 2. Total Cost Values for the Various Methods

Capacity	Total Cost (10^7)	Demand 25%	50%	75%	100%	125%	150%	175%	200%
25%	×	2.048							
	▲	2.054							
	●	2.440							
50%	×	1.931	3.834						
	▲	1.966	3.916						
	●	2.428	4.345						
75%	×	1.906	3.759	5.656					
	▲	2.024	3.973	5.803					
	●	2.427	4.324	6.283					
100%	×	1.889	3.726	5.588	7.495				
	▲	1.897	3.738	5.670	7.653				
	●	2.427	4.320	6.255	8.227				
125%	×	1.884	3.702	5.547	7.454	9.309			
	▲	1.895	3.752	5.706	7.753	9.343			
	●	2.427	4.317	6.249	8.191	10.158			
150%	×	1.882	3.698	5.535	7.403	9.235	11.115		
	▲	1.895	3.971	5.739	7.662	10.048	11.287		
	●	2.427	4.317	6.245	8.182	10.092	12.080		
175%	×	1.853	3.690	5.524	7.368	9.155	11.038	12.927	
	▲	1.853	3.762	5.644	7.641	9.452	11.181	13.178	
	●	2.427	4.317	6.242	8.177	10.061	12.010	14.007	
200%	×	1.852	3.672	5.519	7.356	9.118	10.953	12.846	14.731
	▲	1.852	3.797	5.650	7.645	9.144	11.179	13.143	14.779
	●	2.427	4.317	6.240	8.173	10.035	11.974	13.934	15.925

Tables 2 and 3 clearly show that the horizontal staging heuristic method generates solutions much closer to that from the optimal model than the time slicing method. In most cases, the horizontal staging method generated solutions that are within 4% of the best solution for the optimal model. Tables 4 and 5 show that a significant run time reduction can be achieved with the heuristic methods. There was no significant difference in run time between the heuristic methods.

Table 3. Percent Increase from Optimum Cost Solution for the Heuristic Methods

Percentage of cost increement		Demand 25%	50%	75%	100%	125%	150%	175%	200%
Capacity 25%	×	-							
	▲	0.31%							
	●	19.18%							
50%	×	-	-						
	▲	1.84%	2.14%						
	●	25.74%	13.33%						
75%	×	-	-	-					
	▲	6.18%	5.68%	2.59%					
	●	27.29%	15.02%	11.08%					
100%	×	-	-	-	-				
	▲	0.41%	0.30%	1.48%	2.10%				
	●	28.43%	15.94%	11.95%	9.76%				
125%	×	-	-	-	-	-			
	▲	0.58%	1.36%	2.87%	4.01%	0.37%			
	●	28.77%	16.62%	12.65%	9.89%	9.12%			
150%	×	-	-	-	-	-	-		
	▲	0.70%	7.38%	3.67%	3.50%	8.81%	1.54%		
	●	28.93%	16.74%	12.81%	10.52%	9.28%	8.68%		
175%	×	-	-	-	-	-	-	-	
	▲	0.00%	1.95%	2.16%	3.71%	3.24%	1.29%	1.95%	
	●	30.94%	17.01%	12.98%	10.97%	9.89%	8.81%	8.36%	
200%	×	-	-	-	-	-	-	-	-
	▲	0.00%	3.39%	2.38%	3.93%	0.29%	2.07%	2.31%	0.33%
	●	31.05%	17.56%	13.07%	11.10%	10.06%	9.33%	8.47%	8.11%

Table 4. Run Time (Sec) for the Various Methods

Elapsed Runtime		Demand 25%	50%	75%	100%	125%	150%	175%	200%
Capacity 25%	×	21							
	▲	3							
	●	8							
50%	×	67	34						
	▲	5	5						
	●	8	8						
75%	×	84	47	26					
	▲	6	15	7					
	●	8	8	8					
100%	×	72	53	25	8				
	▲	7	17	5	5				
	●	8	8	8	8				
125%	×	81	30	24	38	23			
	▲	6	12	6	10	11			
	●	8	8	8	8	8			
150%	×	106	28	28	34	30	26		
	▲	6	12	12	7	6	10		
	●	8	8	8	8	8	8		
175%	×	9	44	26	21	32	26	11	
	▲	2	9	9	7	7	8	10	
	●	8	8	8	8	8	8	8	
200%	×	8	11	33	16	37	10	23	8
	▲	2	7	14	8	8	6	5	6
	●	8	8	8	8	8	8	8	8

Table 5. Percent Run Time Reduction for the Heuristic Methods from Optimum Method

Elapsed Runtime Percentage Reduction		Demand							
Capacity		25%	50%	75%	100%	125%	150%	175%	200%
25%	×	-							
	▲	85.71%							
	●	61.90%							
50%	×	-	-						
	▲	92.54%	85.29%						
	●	88.06%	76.47%						
75%	×	-	-	-					
	▲	92.86%	68.09%	73.08%					
	●	90.48%	82.98%	69.23%					
100%	×	-	-	-	-				
	▲	90.28%	67.92%	80.00%	37.50%				
	●	88.89%	84.91%	68.00%	0.00%				
125%	×	-	-	-	-	-			
	▲	92.59%	60.00%	75.00%	73.68%	52.17%			
	●	90.12%	73.33%	66.67%	78.95%	65.22%			
150%	×	-	-	-	-	-	-		
	▲	94.34%	57.14%	57.14%	79.41%	80.00%	61.54%		
	●	92.45%	71.43%	71.43%	76.47%	73.33%	69.23%		
175%	×	-	-	-	-	-	-	-	
	▲	77.78%	79.55%	65.38%	66.67%	78.13%	69.23%	9.09%	
	●	11.11%	81.82%	69.23%	61.90%	75.00%	69.23%	27.27%	
200%	×	-	-	-	-	-	-	-	-
	▲	75.00%	36.36%	57.58%	50.00%	78.38%	40.00%	78.26%	25.00%
	●	0.000	0.273	0.758	0.500	0.784	0.200	0.652	0.000

5. CONCLUSION

In this paper, we develop an integrated supply chain model that combines strategic decision with the tactical decisions and operational decisions. Our approach is different from most of models in literature, which only consider a subset of the problem. We build a mixed-integer programming model to minimize the total costs of distribution, storage, inventory and operations, with production levels high enough to satisfy customer demand. Two heuristic solution methods are presented: horizontal staging and time slicing. The results show that the horizontal staging heuristic can provide solutions very close to the best solution of the optimal model and with significant savings in run time. In practice it is important to do integrated supply chain planning for shorter life-cycle products. The developed model is useful in integrating production planning, inventory management and distribution planning for shorter life-cycle products.

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