Journal
of Achievements in Materials and Manufacturing Engineering
VOLUME 31
ISSUE 2
December
2008

An integrated model for the optimisation of a two-echelon supply network

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Received 23.09.2008; published in revised form 01.12.2008

Analysis and modelling

ABSTRACT

Purpose: The purpose of this paper is to develop a mixed integer formulation that extends the previous production-distribution models by the integration of Aggregate Production Plan and Distribution Plan.

Design/methodology/approach: This paper, firstly, presents a comprehensive review and analysis on the proposed production-distribution models and would develop a summary table to describe the main characteristics of the selected models outlining the level of complexity considered at each study. Based on the integration of Aggregate Production Plan and Transportation/Distribution Plan, over the second stage, the paper will develop a mixed integer formulation for a two-echelon supply network. The model incorporates multi-time periods, multi-products, multi-plants, multi-warehouses as well as multi-end users, and considers the real-world variables and constraints. Finally, the developed model will be analyzed in case of a realistic scenario-based production-distribution problem.

Findings: This paper developed a mixed integer formulation for the optimization of a two-echelon SN. Considering detailed production cost elements and a realistic range of variables and constraints in the proposed case study indicate the effectiveness of the developed model in the real-world applications.

Practical implications: The increasing interest in evaluating the performance of SNs over the last years indicates the need for the development of complex optimization models able to answer unsolved questions in the production-distribution network.

Originality/value: Implementation of a supply-chain (SC) system has crucial impacts on a company's financial performance. Overall performance of a Supply Network (SN) is influenced significantly by the decisions taken in its production-distribution plan integrating the decisions in production, transport and warehousing as well as inventory management. Thus, one key issue in the performance evaluation of SNs is the modeling and optimization of production-distribution plan considering its actual complexity.

Keywords: Optimization; Supply network; Supply chain management; Production-distribution plan; Mixed integer formulation; Integrated model

1. Introduction

Supply chain (SC) is the network of organizations, people, activities, information and resources involved in the physical flow of products from suppliers to customers. Supply Chain Management (SCM) is, therefore, the process of integrating and utilizing suppliers, manufacturers, warehouses, and retailers; so that products are produced and delivered to the end users at the right quantities and at the right time, while minimizing costs and satisfying customer requirements.

The implementation of a SC system has crucial impacts on an organization's financial performance. Manufacturing and distribution companies look for generic and customized software packages (depending on their particular needs and expectations) for the effective management of their logistics and SC activities through the selection of strategies, asset configurations, participants

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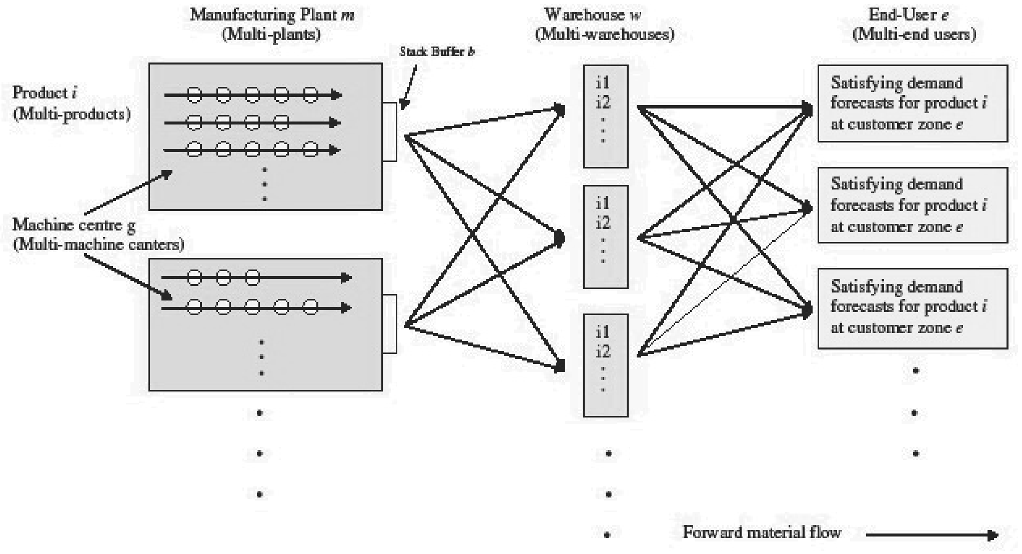

Fig. 1. The proposed two-echelon supply network

and operating policies. Thus, the increasing interest in evaluating the performance of SNs over the last years indicates the need for the development of complex optimization models able to answer unsolved questions in the production-distribution network.

The purpose of this paper is to develop a mixed integer formulation that extends the previous production-distribution models by the integration of Aggregate Production Plan and Distribution Plan. The proposed model, which incorporates multi-time periods, multi-products, multi-plants, multi-warehouses and multi-end users, considers the real-world variables and constraints. The model will be then analyzed in case of a realistic scenario-based problem.

2. Literature review

The literature in the area of SC modeling and analysis indicates that the optimization and simulation modeling of the production-distribution plan has been an active research area over the last decade and that many solutions have been proposed to solve the associated problems.

A variety of SC models have been proposed for the optimization and simulation of SNs incorporating multiple manufacturing plants, multiple products, multiple distribution centers (warehouses), multiple end-users, and multiple time-periods [1-20]. The table in Appendix 1 summarizes and compares the major characteristics of the top-20 (in terms of complexity and effectiveness) models.

According to our survey on the current literature, none of the previous models has considered the major cost elements of manufacturing and/or assembling items (e.g. production/outsourcing alternatives), while taking this characteristic into consideration makes the developed model adaptable to a wider manufacturing and distribution scenarios. Also, paying less attention to considering a realistic range of variables and constraints may preclude the previously developed models from functioning effectively in actual manufacturing and distribution cases.

This study, therefore, proposes a complex model which integrates the Aggregate Production Plan and Distribution Plan and develops a mixed integer formulation for a two-echelon supply network considering all the real-world factors and constraints. In our model, the first echelon consists of multiple production plants and the second echelon includes multiple distribution centers (warehouses).

3. Model formulation

Fig. 1 bellow illustrates the complex production/distribution problem (a two-echelon SN) which is considered for modeling in this paper. In this problem, i types of products are produced in m different manufacturing plants on g various machine centers over t time-periods. Three production alternatives are considered at each plant: regular-time production, over-time production or outsourcing (each with different known costs). All products produced at plant m are temporarily stored at stack buffer b at that plant. From stack buffer b, finished products are distributed either directly to the end-user e or through w warehouses to meat the known customer demand at e. Shortages of not meeting demand forecasts are allowed at end-users under a known penalty (shortage) cost.

3.1. Assumptions

Followings are the assumptions considered in this model:

- Variety of products (*i*) to be produced is known;
- Number of customer-zones (*e*) and demand forecasts for each product is available at end-users;

- Number of plants/warehouses and their capacities are known;
- “Zero Switch” role is used in this model: the inventory level of all products (WIP inventory and inventory of finished products stored at stack buffer and warehouses) is to be zero at the start and end of each planning horizon;
- Products are shipped from the stack buffers once the buffer if full. This means that depending on the holding capacity of stack buffers, products may be carried to the destinations in more than one trip in a day (i.e. at the end of the day what actually remains in the buffer is less than the capacity of the buffer);
- Capacity limitations for regular-time and over-time production (capacity of machine centers), restrictions on capacity of raw material supply, limitations in storage capacity in stack buffers and warehouses, and distribution capacities are known;
- The orders for subcontracting items (if required) are made by each plant at the start of each period and the subcontractors would send the products directly to the stack buffer of that plant by the end of that period. The cost of subcontracting an item includes the shipment of the item to its source of order.

3.2. Indices and parameters

The proposed SC model in this paper is formulated using the following indices, parameters and decision variables:

Indices:

i = Product index

m = Plant index

b = Stack buffer index

w = Warehouse index

e = End user index

t = Time period index

g = machine centre index

Parameters:

D_{iet}	Forecasted demand for Product i at end-user e in period t
O_m	Fixed costs of opening and operating plant m for next planning horizon T
O'_w	Fixed costs of opening and operating warehouse w for next planning horizon T
H_{imt}	Unit WIP inventory holding cost for product i at plant m in period t
H'_{ibt}	Unit holding cost for finished product i at stack buffer b in period t
H''_{iwt}	Unit holding cost for finished product i at warehouse w in period t
HC_{ibt}	Holding capacity (maximum units) at stack buffer b for product i in period t
HC'_{iwt}	Holding capacity (units) at warehouse w for product i in period t
X^{Max}_{imt}	Maximum allowed WIP inventory (units) for the finished product i to be carried in plant m at the end of period t.
T_{ibwt}	Unit transportation cost for product i from stack buffer b to warehouse w in period t
T'_{iwet}	Unit transportation cost for product i from warehouse w to end-user e in period t
T''_{ibet}	Unit transportation cost for product i directly from stack buffer b to end-user e in period t
RP_{imt}	Unit regular-time production cost of product i at plant m in period t
OP_{imt}	Unit over-time production cost of product i at plant m in period t
OS_{imt}	Unit outsourcing cost of product i ordered by plant m in period t
P_{igmt}	Processing time to produce a unit of product i on machine centre g at plant m in period t
Q_{igmt}	Average time spent to produce a WIP unit of product i on machine centre g at plant m in period t
L_{igmt}	Labor/hour cost for regular-time production of product i on machine centre g at plant m in period t
L'_{igmt}	Labor/hour cost for over-time production of product i on machine centre g at plant m in period t
RM_{imt}	Cost of raw material for producing a unit of product i at plant m in period t
α_{imt}	Variable overhead costs of regular-time production of product i at plant m in period t
β_{imt}	Variable overhead costs of over-time production of product i at plant m in period t
SC_{iet}	Unit shortage cost (e. g. backordering cost of not meeting demand forecast) for product i at end-user e in period t
S^{Max}_{iet}	Maximum amount of shortage permitted (i.e. maximum units permitted for backordering) for product i at end-user e in period t
λ_{igmt}	Capacity hours for regular-time production of product i on machine centre g at plant m in period t
λ'_{igmt}	Capacity hours for over-time production of product i on machine centre g at plant m in period t
γ_{imt}	Capacity (units) of raw material supply for product i at plant m in period t
E_{ibt}	The distribution capacity at stack buffer b for product i in period t
E'_{iwt}	The distribution capacity at warehouse w for product i in period t

Decision variables:

I_{imt}	Quantity of product i produced in regular-time at plant m in period t
I'_{imt}	Quantity of product i produced in over-time at plant m in period t
I''_{imt}	Quantity of product i outsourced by plant m in period t
J_{ibwt}	Quantity of product i shipped from stack buffer b to warehouse w during period t
J'_{iwet}	Quantity of product i shipped from warehouse w to end-user e at the end of period t
J''_{ibet}	Quantity of product i shipped directly from stack buffer b to end-user e during period t
X_{imt}	WIP inventory amount for finished product i at plant m at the end of period t
Y_{ibt}	Inventory amount of finished-product i left at the stack buffer b at the end of period t
Z_{iwt}	Amount of product i stored at warehouse w at the end of period t
S_{iet}	Quantity of product i backordered at end-user e at the end of period t (i.e. shortage of not meeting demand)

$$F_{ibwt} = \begin{cases} 1 & \text{If i is shipped from b to w at t} \\ 0 & \text{Otherwise} \end{cases}$$

$$F'_{iwet} = \begin{cases} 1 & \text{If i is shipped from w to e at t} \\ 0 & \text{Otherwise} \end{cases}$$

$$F''_{ibet} = \begin{cases} 1 & \text{If i is directly shipped from b to e at t} \\ 0 & \text{Otherwise} \end{cases}$$

$$d_{iet} = \begin{cases} 1 & \text{If demand for i at e is not met at t} \\ 0 & \text{Otherwise} \end{cases}$$

3.3. Objective function

The objective function minimizes the sum of followings costs:

(1) Production costs in regular-time and over-time as well as outsourcing costs. Thus, production costs include:

- Fixed costs of opening and operating plants (e.g. rent of buildings, leasing of plant and equipment, local business rates, interest rates on loans, machines' depreciation and insurance premiums)
- Variable costs (e.g. labor costs paid by the hours worked, costs of raw material and variable overhead costs: including electricity, gas and depreciations)
- Outsourcing costs

(2) Inventory holding costs:

- Fixed costs of opening and operating warehouses (e.g. rent of buildings, local business rates, interest rates on loans and insurance premiums)
- Variable costs (e.g. WIP inventory holding costs, inventory holding costs in buffer stuck, and inventory holding costs in warehouses)

(3) Transportation costs:

- Transportation costs directly from plants to the end-users
- Transportation costs from plants to the end-users through a set of established warehouses

(4) Shortage costs:

- Penalty costs of not meeting the demand forecasts

Using the indices, parameters and decision variables defined in the previous section, the complete SC model is presented bellow followed by a detailed description and discussion for each of the constraints:

$$\begin{aligned} \text{Min Z} = {} & \sum_{m} O_m + \sum_{i}\sum_{m}\sum_{t} I_{imt} \,.\, RP_{imt} + \\ & \sum_{i}\sum_{m}\sum_{t} I'_{imt} \,.\, OP_{imt} + \sum_{i}\sum_{m}\sum_{t} I''_{imt} \,.\, OS_{imt} + \\ & \sum_{w} O'_w + \sum_{i}\sum_{m}\sum_{t} H_{imt} \,.\, X_{imt} + \sum_{i}\sum_{b}\sum_{t} H'_{ibt} \,.\, Y_{ibt} + \\ & \sum_{i}\sum_{w}\sum_{t} H''_{iwt} \,.\, Z_{iwt} + \sum_{i}\sum_{b}\sum_{w}\sum_{t} J_{ibwt} \,.\, T_{ibwt} \,.\, F_{ibwt} + \\ & \sum_{i}\sum_{w}\sum_{e}\sum_{t} J'_{iwet} \,.\, T'_{iwet} \,.\, F'_{iwet} + \\ & \sum_{i}\sum_{b}\sum_{e}\sum_{t} J''_{ibet} \,.\, T''_{ibet} \,.\, F''_{ibet} + \\ & \sum_{i}\sum_{e}\sum_{t} S_{iet} \,.\, SC_{iet} \,.\, d_{iet} \end{aligned} \tag{1}$$

In which:

$$\sum_{i}\sum_{m}\sum_{t} I_{imt} \,.\, RP_{imt} = \sum_{i}\sum_{m}\sum_{t}\left[I_{imt}\left(\sum_{g} P_{igmt} \,.\, L_{igmt} + RM_{imt} + \alpha_{imt} \right)\right] \tag{2}$$

And:

$$\sum_{i}\sum_{m}\sum_{t} I'_{imt} \,.\, OP_{imt} = \sum_{i}\sum_{m}\sum_{t}\left[I'_{imt}\left(\sum_{g} P_{igmt} \,.\, L'_{igmt} + RM_{imt} + \beta_{imt} \right)\right] \tag{3}$$

Subject to the following constraints:

$$I_{imt} + I'_{imt} \le \gamma_{imt} \qquad \forall\, i,m,t \tag{4}$$

Assuming: $\sum_{i}\sum_{g} Q_{igmt} = \dfrac{\sum_{i}\sum_{g} P_{igmt}}{2} \qquad \forall\, m,t$

Then:

$$\begin{aligned} & \sum_{i}\sum_{g} P_{igmt} \,.\, I_{imt} + \sum_{i}\sum_{g} P_{igmt} \,.\, I'_{imt} + \\ & \sum_{i}\sum_{g} Q_{igmt}\left(X_{imt} - X_{im(t-1)}\right) \le \sum_{i}\sum_{g}\left(\lambda_{igmt} + \lambda'_{igmt}\right) \qquad \forall\, g,m,t \end{aligned} \tag{5}$$

$$X_{imt} \le X^{Max}_{imt} \qquad \forall\, i,m,t \tag{6}$$

$$Y_{ibt} \leq HC_{ibt} \qquad \forall\, i,b,t \qquad (7)$$

$$Z_{iwt} \leq HC'_{iwt} \qquad \forall\, i,w,t \qquad (8)$$

$$\sum_{w} J_{ibwt} + \sum_{e} J''_{ibet} \leq E_{ibt} \qquad \forall\, i,b,t \qquad (9)$$

$$\sum_{e} J'_{iwet} \leq E'_{iwt} \qquad \forall\, i,w,t \qquad (10)$$

$$\sum_{m}\sum_{t}\left(I_{imt} + I'_{imt} + I''_{imt}\right) = \sum_{e}\sum_{t} D_{iet} \qquad \forall\, i \qquad (11)$$

$$S_{iet} \leq S^{Max}{}_{iet} \qquad \forall\, i,e,t \qquad (12)$$

$$Y_{ibt} = Y_{ib(t-1)} + \left[I_{imt} + I'_{imt} + I''_{imt}\right] - \left[\sum_{w} J_{ibwt} + \sum_{e} J''_{ibet}\right] \qquad \forall\, i,b,m,t \qquad (13)$$

$$Z_{iw(t-1)} + \sum_{b} J_{ibwt} \,.\, F_{ibwt} = \sum_{e} J'_{iwet} \,.\, F'_{iwet} + Z_{iwt}$$

$$\forall\, i,w,t \qquad (14)$$

$$\sum_{w} J'_{iwet} + \sum_{b} J''_{ibet} = D_{iet} + S_{iet} \,.\, d_{iet} + S_{ie(t-1)} \,.\, d_{ie(t-1)}$$

$$\forall\, i,e,t \qquad (15)$$

$$\sum_{t=0} X_{imt} = \sum_{t=T} X_{imt} = 0 \qquad \forall\, i,m \qquad (16)$$

$$\sum_{t=0} Y_{ibt} = \sum_{t=T} Y_{ibt} = 0 \qquad \forall\, i,b \qquad (17)$$

$$\sum_{t=0} Z_{iwt} = \sum_{t=T} Z_{iwt} = 0 \qquad \forall\, i,w \qquad (18)$$

$$I_{imt}, I'_{imt}, I''_{imt}, X_{imt} \geq 0 \qquad \forall\, i,m,t \qquad (19)$$

$$J_{ibwt} \geq 0 \qquad \forall\, i,b,w,t \qquad (20)$$

$$J'_{iwet} \geq 0 \qquad \forall\, i,w,e,t \qquad (21)$$

$$J''_{ibet} \geq 0 \qquad \forall\, i,b,e,t \qquad (22)$$

$$Y_{ibt} \geq 0 \qquad \forall\, i,b,t \qquad (23)$$

$$Z_{iwt} \geq 0 \qquad \forall\, i,w,t \qquad (24)$$

$$S_{iet} \geq 0 \qquad \forall\, i,e,t \qquad (25)$$

As discussed earlier, the objective function (Eq. 1) minimizes the total production, inventory holding, transportation and shortage costs. To ease the reading and understanding of the objective function, Eq. 2 and Eq. 3 give details of the production costs in regular-time and over-time respectively; referring to the second and third portions of Eq. 1 correspondingly. Eqs. 4~10 depict the capacity constrains. Eq. 11 and Eq. 12 are demand and shortage constrain. Balance constrains at stack buffers, warehouses and end-users are represented at Eqs. 13~18. Finally, Eqs. 19~25 demonstrate the ‘variables’ constrains.

Eq. 4 represents the raw material supply capacity restrictions. Eq. 5 implies the limitation for regular-time and over-time production against machine centre capacity constrains. The limitation in WIP inventory amount to be carried at each plant is represented in Eq. 6. Stack buffer capacity restriction which is shown in Eq. 7 implies the restriction on the stored products in the stack buffer at the end of a period. Eq. 8 stands for the limitations in warehouse holding capacity. The distribution capacity constraint from stack buffers and warehouses are represented in Eq. 9 and Eq. 10, respectively. Eq. 11 implies that the total amount of production and outsourcing for every product at all plants must meet the forecasted demand for that product at the end of planning horizon (e. g. complete satisfaction of all demands for every product at the end of the planning phase). Eq. 12 enforces the maximum allowed shortage at end-users. **E**q. 13 represents the inventory balance constraint in stack buffers. Eq. 14 and Eq. 15 are the balance equations for the warehouses and end-users. Eq. 15 ensures that the shipments of a product to an end-user either satisfy the demand for that product at period *t* or some amount of shortage would appear (no storage at end-user is allowed). Eqs. 16~18 imply the “Zero Switch” role to the model and indicate that the inventory level of all products (WIP inventory and inventory of finished products stored at stack buffer and warehouses) is to be zero at the start and end of each planning horizon. Eqs. 19~25 enforces non-negativity restriction for all the decision variables.

4. Model analysis

To validate the developed model and demonstrate the significance of considering detailed (microscopic) production cost elements (i.e. all costs of production and outsourcing alternatives), we compared two different scenarios of a realistic scenario-based production-distribution problem. For this purpose, the following case study was studied:

Four types of products (i_1-i_4) are produced in four different manufacturing plants (m_1-m_4). In each plant there are four machine centers (g_1-g_4). Each item is produced by passing through all four machine centers. Plants m_1 and m_2 have the facilities to produce products i_1, i_2, i_3 & i_4. Plant m_3 produces products i_1 & i_2 and plant m_4 has the facilities to produce products i_1 & i_3. Regular-time production, over-time production and outsourcing are the production alternatives at each plant. Each plant has a stack buffer (b_1-b_4, respectively in plants m_1-m_4) temporarily storing the finished products. Products are distributed either directly to five end-users (e_1-e_5) or through six warehouses (w_1-w_6) to meat the customer demand at the end-users. Shortages of not meeting demand forecasts are allowed at end-users at a known penalty.

In the first scenario (table 1), according to the developed objective function in this paper (Eq. 1), a combination of regular-time/over-time production and outsourcing alternatives was considered to compute the total production-distribution cost. Instead of considering the production cost elements (from production alternatives), in the second scenario (table 2) an average unit cost was considered for calculating the production costs (based on the traditional models - previous studies). In both scenarios, distribution costs (either directly from the plants to the

Appendix 1
Summary table - the top 20 proposed supply network models

		Model features / Characteristics considered									
	Author(s) Year	Type of work: M = Mathematical modeling O = Optimization S = Simulation modeling	TC = Total cost minimization P = Profit maximization	Effective transportation (Optimum routings)	Production alternatives[1]	Multiple periods	Multiple plants	Multiple products	Multiple warehouses / DCs	Multiple end-users	Methods Applied
1	Cohen & Lee 1988 [1]	M & O	TC	X[2]	---[3]	---	X	X	X	---	Generating a series of linked, approximate sub-models and Introducing a heuristic optimization procedure
2	Chandra and Fisher 1994 [2]	M	TC	X	---	---	---	X	X	---	Comparing two approaches in managing production and distribution networks and computing the reduction in operating costs
3	Pyke and Cohen 1994 [3]	M & O	TC	X	---	---	---	X	---	---	SSD Approximation (approximate steady state distribution) to compute associated costs and find near-optimal values for decision variables
4	Alfieri and Brandimarte 1997 [4]	M & S	TC	X	---	---	X	---	---	X	Developing a simplistic object-oriented simulation model for a multi-echelon inventory management system using MODSIM II
5	Barbarosoglu and Ozgur 1999 [5]	M & O	TC	X	---	X	---	X	X	X	Using mixed integer mathematical modeling and the Lagrangean relaxation method to provide optimum solutions
6	Young Hae and Sook Han 2000 [6]	Hybrid: Analytic + Simulation	TC	X	---	X	---	X	X	X	Modeling/formulation: linear program (LP) + GAMS (General Algebraic Modeling System) Simulation: ARENA simulation package
7	Jayaraman and Pirkul 2001 [7]	M & O	TC	X	---	X	X	X	X	X	Using mixed-integer programming formulation and Lagrangian relaxation scheme Proposing a heuristic solution to evaluate the model performance

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[1] This may include regular-time and overtime production as well as the choice of outsourcing
[2] X = Considered
[3] --- = Ignored

8	Syarif, Yun and Gen 2002 [8]	M & O	TC	X	---	---	X	---	X	X	Using mixed integer linear programming for mathematical modeling and developing spanning tree-based GA approach (based on Prufer numbers) for the problem optimization.
9	Syam 2002 [9]	M & O	TC	X	---	---	X	X	X	X	Developing and comparing two methodologies based on Lagrangian relaxation and simulated annealing
10	Bhutta et al. 2003 [10]	M	P	X	---	X	X	X	---	X	Using a mixed integer linear formulation
11	Chan et al. 2005 [11]	M &O	TC	X	---	---	X	---	---	X	Using AHP for the criteria weighting and Genetic Algorithms to determine the job allocations
12	Gen and Syarif 2005 [12]	M & O	TC	X	---	X	X	X	---	X	Using spanning tree-based hybrid genetic algorithms and Fuzzy Logic Controller (FLC) for auto-tuning GA parameters
13	Yeh 2005 [13]	M & O	TC	X	---	---	X	---	X	X	Using mixed integer programming for mathematical modeling and developing a hybrid heuristic algorithm using a greedy method improved through a hybrid local search method (combing linear programming with pair-wise exchange procedure, the insert procedure and the remove procedure)
14	Yeh 2006 [14]	M & O	TC	X	---	---	X	---	X	X	Proposing a memetic algorithm (MA), combining GA, greedy heuristic, and local search methods
15	Lim et al. 2006 [15]	M & S	TC	X	---	X	X	X	X	X	Using Microsoft Excel premium Solver for mathematical modeling and IBM supply chain analyzer (SCA) as the simulation optimizer tool
16	Nishi et al. 2007 [16]	M & O	TC	---	---	X	---	X	X	---	Using a commercial MILP and Lagrangian decomposing to decompose the optimization problem into three sub-problems
17	Aliev et al. 2007 [17]	M & O	P	X	---	X	X	X	X	X	Using fuzzy programming for the formulation of the model and Genetic Algorithms to find the optimum solution
18	Altiparmak et al. 2006 [18]	M & O	TC	X	---	X	X	---	X	X	An experimental study: a mixed-integer non-linear programming model for multi-objective optimization of SCN and a genetic algorithm (GA) approach to solve the problem
19	Altiparmak et al. 2007 [19]	M & O	TC	X	---	X	X	X	X	X	Proposing a steady-state GA and comparing the achieved results with those obtained through other approaches
20	Farahani and Elahipanah 2008 [20]	M & O	TC	X	---	X	---	X	X	X	A mixed-integer linear programming bi-objective model A multi-objective GA was applied to solve the problem

end-users or through the established warehouses) consist of transportation, storage and inventory carrying costs. All the costs are calculated based on a planning horizon of two weeks. Tables 1~2 summarize the outcomes of our calculations for production and distribution costs in 1000 dollars for scenario 1 and 2, respectively.

Table 1.
'Production/distribution costs' for Scenario 1

Scenario 1 ($ *1000)	Regular-time Production Costs	Over-time Production Costs	Outsource Costs	Distribution Costs
m_1	74.2	29.5	21	35.5
m_2	60.7	26.6	18.4	43.4
m_3	28.8	17.7	9.5	31.1
m_4	33.6	16	8.2	23.1
Total	197.3	89.8	57.1	133.2

Table 2.
'Production/distribution costs' for Scenario 2

Scenario 2 ($ *1000)	Average Production Costs	Distribution Costs
m_1	152.1	39.4
m_2	129.3	48.4
m_3	67.3	36.4
m_4	64.8	25.8
Total	413.5	150

From tables 1~2, total production-distribution costs for scenario 1 is $477,720 and for scenario 2 is $563,530 which indicates achieving less total cost through applying the developed model. It was shown that considering production alternatives in our developed model not only has contributed to the more accurate calculation of production costs, but it also accordingly contributes to the more effective transport routings and more efficient distribution plans.

5. Conclusions

Based on the integration of Aggregate Production Plan and Transportation/Distribution Plan, this paper developed a mixed integer formulation for the optimization of a two-echelon SN. Considering detailed production cost elements and a realistic range of variables and constraints in the proposed case study indicate the effectiveness of the developed model in the real-world applications.

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