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Joint production-planning and distribution optimization of perishable products under a combined shipment structure: A new hybrid policy-based approach

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Abstract. Following the pioneering challenge for joint optimization of decisions in supply chains, this paper newly provides an integrated framework to efficiently fulfill a production-planning and distribution problem in effect. In such an integrated scheme, a set of perishable family products is manufactured on a single batch-processing machine. These products are dispatched to the customers by a third-party logistics service provider with only two types of licensed eco-friendly transportation facilities. In order to efficiently deliver the manufactured products before they become unusable, we propose a combined shipment structure. To accomplish this, the problem is formulated in the context of a mixed-integer linear programming model. In particular, we aim to establish two manufacturing policies based on both increasing and decreasing rates of production and also two delivery policies expressing distinct preferences in fulfilling the customers' demands. The cost structures obtained from the established integrated planning and the resulting distribution configurations are investigated as well. Further, four heuristic algorithms are developed for solving the problem for each hybrid production/distribution scheme derived from the former policies. A numerical study is conducted to compare the mentioned procedures, illustrating the preferable efficiency of the plan obtained through the hybridization of the increasing-production-rate and decreasing-delivery-distance policies.

1. Introduction

Production and distribution are two major functions in a supply chain. Classical supply chains consider these two decisions consecutively. In this context, the optimal manufacturing plan is attained first, independent of the distribution schedule, and then, this obtained optimal scheme leads to finding the optimal distribution scheduling. This traditional approach does not concentrate on integrating the mentioned functions and, consequently, results in sub-optimal solutions for

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the problem [1–3]. Indeed, since the planning decisions are limited by the scheduling of the former process, the beneficial integration in the planning procedure has been neglected.

On the other hand, holistic coordination of production and distribution decisions aims to yield considerable economic benefits, which is gained significant attention in recent years [4]. Conventionally, this integration is conducted through a management decision, instead of originating from a concrete need of the inherent processes. Nevertheless, if the final products are perishable (e.g., foods, dairy) or even have a short shelf life due to intense competition in today's diverse market where the economics of scale has been replaced by the economics of diversity this integrated mechanism becomes a critical issue [4].

The motivation for adopting an integrated production/distribution planning system comes from its high applicability in different production environments such as just-in-time, make-to-order, and assemble-to-order, aiming to achieve a balance in inventory, customers' service level, transportation costs, and lead times. It is worth noting that integrating production and distribution functions can lead to significant cost savings and efficiency improvements.

Batch-processing machines are mainly utilized in many industries, such as semiconductor, metalworking, porcelain, and food-making (e.g., dairy) companies. In all of these enterprises, the manufacturing process often imposes the highest charge due to the long time intervals needed for producing a multiproduct batch in effect [1]. Therefore, efficient delivery of the manufactured batch enhances the supply chain performance and prevents the waste of expenses incurred in the production process. The delivery cost can be computed once the accurate distance of the corresponding route from the manufacturer to the retailer is known.

Rising production costs, along with competitive pressures, have resulted in increasing attention toward inventories and lead times. This has made companies strictly explore new ways to remain competitive. In this context, multiproduct-batch manufacturing is a technique in which products having similarities in geometry, process, and/or functions are grouped as a family and produced in a single facility. In this strategy, the product families are manufactured in corresponding facility cells. This leads to minimum setups, cleanings, and increased production speeds. Therefore, implementing such manufacturing environments can fulfill the need for integration in supply chain functions.

In scientific literature, the lack of integrated consideration of production planning and routing dimensions indicates a weakness in this regard. Furthermore, regardless of delivery efficiency, the majority of integrated studies, considering operational decisions, merely focus on whether direct or milk-run shipment policies [1,3,4]. In this regard, the economic-environmental and also perishability requirements may be ignored. Further, determining some needed priority measures based on which the manufactured products could be delivered, plays a significant role in associated practices. Indeed, exploring an efficient shipment approach is now inevitable and necessary to meet integration needs.

To cover the cited shortages in associated literature and due to the lack of a joint approach towards the production-planning and routing schemes, this study focuses on a novel and practical matter in a supply chain. In such circumstances, a single batch-processing facility produces a family of products constituting a multiproduct batch. The manufacturing facility can produce only one product at any given time, and shipments are made via a combined strategy, where deliveries are fulfilled to all the customer zones (or retailers) according to a coupled direct-milk run arrangement. Actually, according to the specified preferences in manufacturing the products and satisfying the customers' demands, and also to meet the perishability requirements, we use a mixed structure in effect. It is also noteworthy that the deliveries are made by a third-party logistics (3PL) service provider. This transportation company provides only two types of shipment facilities that have succeeded in obtaining environmental licenses.

Therefore, the specific and contributing features of our analysis differ from existing works in related areas in the following important ways:

(a) The production planning and routing decisions are integrated in terms of a joint platform. In such a scheme, manufacturing a multiproduct batch and dispatching the products to the customers are addressed under a combined shipment policy.

(b) Connecting the production part to the vehicle routing (carried out in the milk run delivery) leads to incorporating a production routing problem (PRP) as well.

(c) Two manufacturing policies according to respectively the increasing and decreasing rates of production and also two distribution policies in satisfying the customers' demands based on decreasing delivery distance and decreasing-demand-size measures are presented through the paper. Accordingly, four planning procedures (hybrid policies) are captured as the result of combining the above-mentioned policies that are:

   (i) Increasing-Production-Rate&Decreasing-Delivery-Distance (IPR&DDD);

   (ii) Increasing-Production-Rate&Decreasing-Demand-Size (IPR&DDS);

(iii) Decreasing-Production-Rate&Decreasing-Delivery-Distance (DPR&DDD);

(iv) Decreasing-Production-Rate&Decreasing-Demand-Size (DPR&DDS).

(d) Due to the complexity of the problem under discussion, four heuristic algorithms are developed for gaining optimal solutions.

The remainder of this paper is organized as follows. The next section is assigned to present the background and review of the relevant research literature. Section 3 describes the problem and its corresponding assumptions. Further, the MILP formulation of the problem is presented in this section. In Section 4, we develop the manufacturing and distribution policies and analyze the resulting cost structures and configurations as well. We suggest four heuristic algorithms for the schemes obtained from the mixture of the cited policies in Section 5. Section 6 is dedicated to the numerical studies in which the planning procedures are compared with each other, and the results are reported. We finally discuss some concluding remarks and outline the future research opportunities in Section 7.

2. Literature review

The majority of existing research on integrated production/distribution problems focuses on the strategic or tactical decision level. In the strategic dimension, decisions are made regarding facility location and plant capacity. The tactical level is dedicated to production lot sizes, inventory levels, and delivery decisions. Reviewing related studies illustrates the scarcity of literature corresponding to integrated operational level problems, i.e., the production and distribution scheduling decisions [4–6]. The traditional supply chains consider the above-mentioned decisions sequentially, leading to sub-optimality. For capturing an integrated production/distribution scheme, the classical Vehicle Routing Problem (VRP) must be integrated with the production scheduling problem. In the VRP, products are dispensed to a set of outspread retailers through the vehicles located at one or more manufacturing or storage points by making routes along a network so that all requirements are fulfilled [5].

Integrated production and distribution scheduling have drawn much interest in recent years. In this regard, Cakici et al. [6] studied a multi-objective integrated production-distribution scheduling problem in a supply chain of a single manufacturing line, several customers, and capacitated shipping vehicles. Armentano et al. [5] considered a multi-period integrated approach in a supply chain with a single plant, multiple customers, and homogenous transportation vehicles. Bilgen and Celebi [7] considered integrated planning in a yogurt production line of multiproduct dairy industries with some practical industrial features such as sequence-dependent setup times and minimum/maximum lot sizes.

Batch processing, as a practical procedure in real functions, allows a single machine to simultaneously process several jobs within a batch rather than processing them individually [8,9]. Garcia et al. [10] investigated an integrated production-distribution problem. They assumed that there was an adequate capacity to simultaneously manufacture multiple orders. Moreover, there is no restriction related to time windows other than considering corresponding due dates at which each order should be delivered exactly to the customers. They proposed an Integer Linear Programming (ILP) formulation to choose orders to maximize the profit gained concerning the distribution charges. Li and Ferrell [11] addressed an integrated production and distribution problem for a perishable product where the shipping vehicles are distinct in capacity and cost. Li and Ling [12] extended the preceding model presented by Li and Ferrell [11] in a way that the pickup-delivery operations were included in the corresponding formulation. Low et al. [13] studied an integrated scheduling scheme at a multi-product distribution center in which the customers' orders are packed within a single batch in case each customer orders various products. They formulated the problem in the context of an integer non-linear programming model to minimize the delivery time of the registered orders.

Most of the literature is quite recent in case the products are perishable or soon-expired [1]. For instance, an exceedingly appealing theme of the research can be found in the food engineering literature. In this context, Marandi and Zegordi [14] investigated a practice-oriented integrated production and distribution scheduling with a focus on products having short lifespans. They developed a flow-shop scheduling framework in a single plant, a fleet of limited-capacity trucks for delivering the customers' orders with consideration of vehicle routing, and several customers with defined locations and demands. They aimed to design routes serving all customers within each trip and to schedule production in order to minimize the total tardiness and delivery costs. Hsu et al. [15] studied a vehicle routing problem with time windows to address food delivery from a distribution center and considered a random mechanism for food corruption and travel time. Lacomme et al. [16] considered an integrated production and transportation scheduling problem with multiple vehicles. They reflected a real concern for the industry resulting from a condition where the production and transportation sub-problems are commonly addressed independently or sequentially. They incorporated specific capacity constraints, the short lifespan of products, and the special case of a single vehicle, which has already been studied in the literature. Further, they offered a Greedy Randomized Adaptive Search Procedure (GRASP) with an Evolutionary Local Search (ELS) to solve some instances with a single vehicle as a special case. Rafiei et al. [17] addressed an integrated production-distribution planning problem within a four-echelon supply chain with two main objective functions, namely minimizing total chain cost and maximizing service level. They also modeled the problem under a competitive circumstance and compared the obtained results with a non-competitive market.

A large number of studies that consider integrated production and distribution planning have concentrated on relatively simple delivery procedures, e.g., direct shipment to retailers. A review of the related literature can be found in Wang et al. [2]. Some others utilized predetermined routes, such as Gupta et al. [18] or routes with a fixed order sequence, as in Armstrong et al. [20]. Zhang et al. [21] considered an integrated online order batching and distribution scheduling scheme where the maximum number of orders had to be accomplished before the vehicles' departure time (in the shortest service mode) reached. They investigated two objectives, including the number of delivered orders and service time, and proposed multiple novel rule-based solutions, including decision points, batching, and assigning rules. Also, they concluded that it is important to consider the degree of urgency of orders in order to increase the number of deliveries. Aiming at minimizing the vehicle delivery cost and the total customer waiting time, Li et al. [22] studied a class of multi-objective production-distribution scheduling problems with a single machine and multiple vehicles. They assumed that the orders in the same delivery batch are processed contiguously and their processing order is immaterial, which thus results in a way that the orders in the same delivery batch can be viewed as a block. Toptal et al. [23] considered a manufacturer's planning scheme to schedule production and distribution (to respective destinations). In this setup, they assumed that there are two vehicle types, the first of which is available in unlimited numbers, and the latter changes over time as it has high charges. They offered triple solutions of the myopic, the hierarchical, and the coordinated procedure varying in how the underlying production and transportation sub-problems are solved.

In contrast to transportation services, 3PL offers a wide spectrum of services, including packaging, warehousing, stockkeeping, information management, picking and labeling, invoicing, ordering, etc. [24]. The development of logistics outsourcing has been largely based on the needs that companies have to obtain cost savings and concentrate on their core competencies. One of the key advantages of using 3PL results from economies of scale and economies of scope

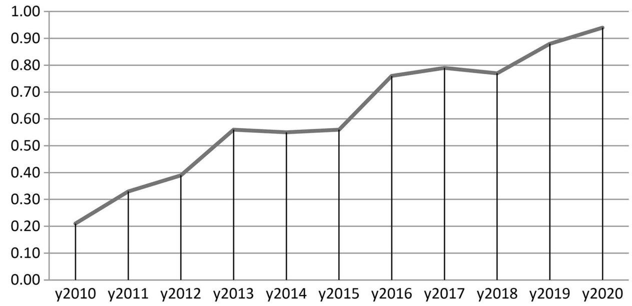

Figure 1. Share of integrated production-distribution planning in different years.

[25]. Using 3PL, companies can present their products to the market as soon as possible and save on capital investments, which reduces financial risk and spreads the logistic risk to sub-contractors [26]. Table 1 shows different studies done in the production distribution scheme with respect to multiple dimensions. Also, Figure 1 indicates the research trend in the corresponding area in recent years. As obvious, there is a strict tendency towards considering an integrated approach in production distribution planning.

Considering the mentioned hints and inefficiencies incurred in classical supply chains, this paper attempts to propose a new approach within a joint production-planning and distribution problem through which a multiproduct batch is produced on a single batch-processing facility. In this context, the products, which are perishable items, are delivered by a 3PL service provider. As such, several benefits, including minimum time spent, minimum transportation costs, fast delivery of products, and consequently a preferable competitive advantage, result from this procedure. Therefore, the paper contributes to the literature in multiple significant ways, including proposing an integrated platform for joint optimization of production planning and vehicle routing, utilizing a combined shipment structure (i.e., direct-milk run), using four different policies based on the production priority and the customers' satisfying criteria, outsourcing the production in case the whole demands are more than the available capacity and analyzing the respective cost structures as well, and providing four heuristic algorithms for solving the problem.

3. Problem assumptions and formulation

The supply chain under consideration in this paper consists of two echelons, namely a manufacturing centere and a set of demand points. There are $I = 3$ perishable family products that must be produced on a single batch-processing machine. Let $G = (N, E)$ be a complete undirected graph and $N = \{0, 1, 2, \ldots, J\}$ represent the set of the plant and the customers. Further, $E = \{(j, k) : j, k \in N, j \neq k\}$ is the set of

Table 1. Classification of literature based on different dimensions.

Publication	Integrated/ sequential planning	Manu. mechanism	Invent. Routing Problem (IRP)	Prod. Routing Problem (PRP)	Prod. Plan. and Routing Prob. (PPRP)	Dis. Plan. (DP)	Obj. (s)	Solving approach
Biuki et al. [4]	Integrated planning	–	IRP	–	–	–	Sustainability dimensions	Metaheuristic algorithm
Cakici et al. [6]	Integrated planning	Single-processing	IRP	–	–	–	Level of services	Hierarchical approach
Bilgen and Celebi [7]	Integrated planning	Batch–processing	–	–	–	–	Costs	Simulation approach
Salmasnia and Talesh -Kazemi [8]	Integrated planning	Batch–processing	–	–	–	–	Profit	Metaheuristic algorithm
Li and Ferrell [11]	Integrated planning	Single-processing	–	–	–	–	Costs	Simulation approach
Marandi and Zegordi [14]	Integrated planning	Single-processing	IRP	–	–	–	Costs time	Hierarchical approach
Hsu et al. [15]	Sequential planning	Single–processing	–	PRP	–	–	Time	–
Lacomme et al. [16]	Sequential planning	Single–processing	IRP	–	–	–	Costs time	Metaheuristic algorithm
Rafiei et al. [17]	Integrated planning	Single–processing	–	PRP	–	–	Costs level of service	–
Yaghin [19]	Integrated planning	Batch–processing	–	PRP	–	–	Profit	Convex hulls
Armstrong et al. [20] and Zhang et al. [21]	Integrated planning	Batch–processing	–	–	–	–	Time number of orders	–
Toptal et al. [23]	Integrated planning	Single–processing	IRP	–	–	–	Costs	Hierarchical coordinated
Aras and Bilge [24]	Integrated planning	Single–processing	–	–	–	–	Costs	Robust optimization
Maihami et al. [25]	Sequential planning	–	–	–	–	–	Price, replenishment schedule, order quantity	Exact approach
Hatami-Marbini et al. [26]	Sequential planning	Single–processing	–	–	–	–	Costs	Metaheuristic algorithm simulation
Rezaei and Maihami [27]	Integrated planning	–	IRP	–	–	–	Profit	Game theory

Table 1. Classification of literature based on different dimensions (continued).

Publication	Integrated/ sequential planning	Manu. mechanism	Invent. routing problem (IRP)	Prod. routing problem (PRP)	Prod. Plan. and routing prob. (PPRP)	Dis. Plan. (DP)	Obj.(s)	Solving approach
Guarnaschelli et al. [28]	Integrated planning	Single processing	–	–	–	–	Costs	Heuristic algorithm
Fatemi Ghomi et al. [29]	Integrated planning	–	–	PRP	–	–	Profit CO_2 emission	Metaheuristic algorithm
Bank et al. [30]	Integrated planning	Single processing	–	–	–	–	Costs	Metaheuristic algorithm
Gruson et al. [31]	Integrated planning	Single processing	–	–	–	–	Costs	Lagrangian approach
Ghadimi and Aouam [32]	Sequential planning	Single processing	–	–	–	–	Costs service level	Nested lagrangian relaxation Simulation
Wu et al. [33]	Integrated planning	–	IRP	–	–	–	Costs	Metaheuristic algorithm
Our paper	**Integrated planning**	**Batch-processing**	–	–	**PPRP**	**DP**	**Costs**	**Hybrid policy (Heuristic approach)**

edges connecting the graph's nodes, and $N_c = N\setminus\{0\}$ denotes the set of customers (or demand points). Over a planning period (or time cycle) T, the multiproduct batch can be manufactured at the plant and delivered by two types of environmentally licensed transportation facilities-which are provided by a 3PL service provider-within a coupled direct-milk run structure. Figure 2 depicts a general illustration of the problem.

To formulate the problem, we state several assumptions and the notation utilized throughout the paper, as follows.

3.1. Assumptions

The key assumptions behind the model are:

- The planning period is assumed to be equal to the length of the production/distribution time cycle. This implies that the operational period is accomplished when the production and distribution decisions are made;
- The customers' demands are definitive. This assumption facilitates the adoption of planning and policy, especially when facing a single batch-processing machine for manufacturing a group of family products in cellular production environments. Besides, this results in an easier hybridization of planning procedures. However, this is a restriction regarding the realistic environment and could be broken in future extensions;
- The manufacturing center is configured based on a single batch-processing machine with limited capacity. In this cellular environment, triple perishable products, which belong to a single family (e.g., dairy), are produced within each batch. The setup and cleaning costs are immaterial as the products belong to the same family;
- Production outsourcing may occur if the operational capacity of the manufacturing facility is not sufficient to satisfy all of the customers' demands, i.e., the shortage is not permitted. This leads to significant savings in operations (e.g., shortages, shipments) and does not impose additional pressure on the manufacturing facility;
- Processing of each product begins only when the previous product (at the assigned sequence) is quite manufactured;
- As the total carrying capacity is limited and the products are perishable, we consider an approximately no-wait condition between the production and distribution of items within each time cycle (the

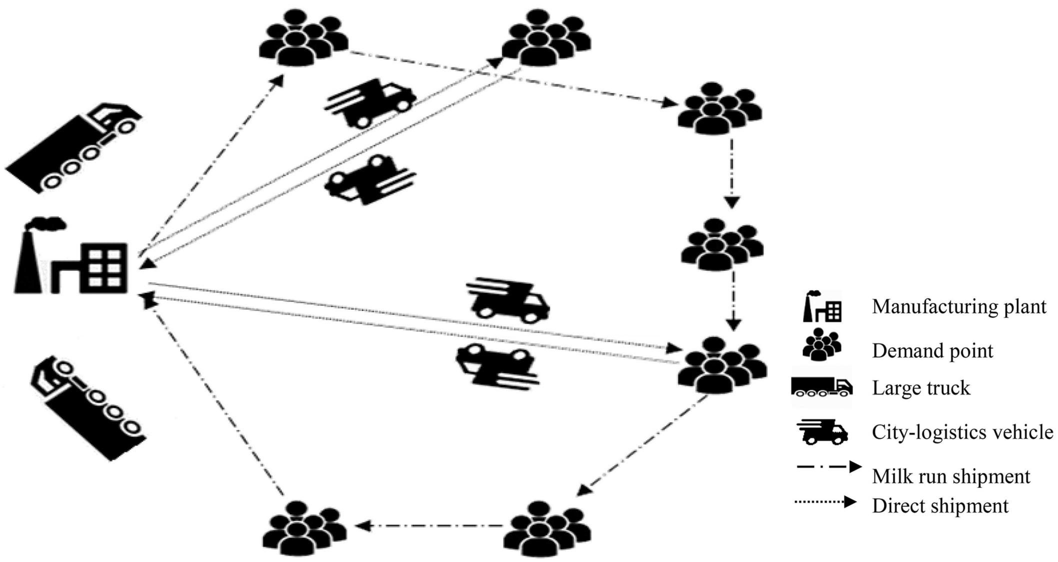

Figure 2. General illustration of the network.

temporary storage of the manufactured products imposes no charges);

- The demand nodes are distributed in a single geographic cluster. Thus, two customers located at the farthest distances from the plant, are at the nearest distance to each other, and so on;
- Each customer's demand may be partially satisfied through a direct shipment (i.e., more than one delivery may be needed for satisfying a particular demand point). In this regard, since the products are not instantly consumed at any demand point, only one direct shipment to each customer is allowed. Orders for more than one customer are dispatched via a single large truck passing the demand points based on the milk run procedure;
- We assume that the shipment expenses are incurred based on the carrying capacity of each transportation facility (i.e., the shipment costs are not taken into account per unit product).

3.2. Notation

The following notations are used in the formulation:

Indices

I	Set of perishable family-products $i = \{1,\ 2,\ \ldots,\ I\}$
J	Set of demand points $j = \{1,\ 2,\ \ldots,\ J\}$

Parameters

T	The common time cycle (planning period) (time units)
d_{ji}	Demand of customer j for product i in each time cycle (units)
r_i	Production rate of product i in each time cycle (units/unit time)
cap_i	Production capacity of product i in each time cycle (units)
o_i	Average forwarding rate of product i through direct shipment (units/unit time)
t_l	Preparation time of transmitting the manufactured products per shipment (time units)
H_i	Number of available city-logistics vehicles provided by the 3PL company for transmitting the product i in each time cycle (units)
${c_i}^c$	Shipment capacity of city-logistics vehicle for transmitting product i (units)
${c_i}^l$	Shipment capacity assigned to product i in large truck (units)
a_i	Unit manufacturing cost of product i (monetary units)
μ_i	Cost of production outsourcing per product i (monetary units)
δ	Fixed cost of hiring each city-logistics vehicle (monetary units)
γ_i	Unit cost of loading product i on city-logistics vehicle (monetary units)
α_i	Unit cost of loading product i on large truck (monetary units)
f_{0j}	Cost of travelling imposed in case the city-logistics vehicle departures from the manufacturing center to demand point j (monetary units)

m_{jk} Cost of travelling imposed in case the large truck departures from node j to node k (monetary units)

tr_{0j} Travel time spent by the city-logistics vehicle from the manufacturing center to demand point j (time unites)

tr'_{jk} Travel time spent by the large truck from node j to node k (time unites)

Decision variables

Q_i Number of manufactured products (type) i

ϕ_i Number of products type i outsourced (produced by a third party manufacturer)

w_i Number of products type i loaded on the large truck

e_j Load of the large truck before making a delivery to node j

$X^i{}_{0j}$ Equal to 1 if a city-logistics vehicle directly transfers products i from the manufacturing plant (0) to customer j, 0 otherwise

Y_{jk} Equal to 1 if the single large-truck departures from node j to node k, 0 otherwise

Further, we let:

$$M_i = \min\{cap_i, \sum_{j=1}^{J} d_{ij}\}$$

and,

$$M_{j'} = \min\left\{\sum_{i=1}^{I} c_i^l, \sum_{i=1}^{I} d_{ij}\right\}.$$

3.3. Model mathematical formulation

The production/distribution planning, coupled with the production routing problem, is formulated as follows:

$$\text{Min } Z = \sum_{i=1}^{I} a_i Q_i + \sum_{i=1}^{I} \mu_i \phi_i + \sum_{i=1}^{I}\sum_{j\in N_c} \gamma_i c_i^c X_{0j}^i + \sum_{i=1}^{I} \alpha_i w_i + \sum_{i=1}^{I}\sum_{j\in N_c} \delta X_{0j}^i + 2\sum_{i=1}^{I}\sum_{j\in N_c} f_{0j} X_{0j}^i + \sum_{(j,k)\in E} m_{jk} Y_{jk} \tag{1}$$

s.t.:

$$Q_i + \phi_i = \sum_{j\in N_c} d_{ij} \qquad \forall i \in I, \tag{2}$$

$$\sum_{j\in N_c} c_i^c X_{0j}^i + w_i = \sum_{j\in N_c} d_{ij}, \qquad \forall i \in I, \tag{3}$$

$$Q_i \le M_i \qquad \forall i \in I, \tag{4}$$

$$\sum_{j\in N_c} c_i^c X_{0j}^i = o_i \left(T - \sum_{\tau<i} (Q_\tau/r_\tau)\right) - t_l) \qquad \forall i \in I, \tag{5}$$

$$d_{ij} \ge c_i^c \qquad \forall i \in I,\ j \in N_c, \tag{6}$$

$$\sum_{j\in N_c} X_{0j}^i \le H_i \qquad \forall i \in I, \tag{7}$$

$$X_{0j}^i \le 1 \qquad \forall i \in I, j \in N_c, \tag{8}$$

$$0 \le w_i \le c_i^l \qquad \forall i \in I, \tag{9}$$

$$Y_{jk} \le \sum_{i=1}^{I} d_{ik} - \sum_{i=1}^{I} c_i^c X_{0k}^i \qquad \forall k \in N_c, \tag{10}$$

$$\sum_{k\in N_c} Y_{kj} = \sum_{k\in N_c} Y_{jk} \qquad \forall j \in N_c, \tag{11}$$

$$\sum_{k\in N_c} Y_{jk} \le 1 \qquad \forall j \in N_c, \tag{12}$$

$$e_j - e_k \ge \sum_{i=1}^{I} d_{ij} - M_{j'}(1 - Y_{jk}) \qquad \forall (j,k) \in E, \tag{13}$$

$$\sum_{i=1}^{I} (Q_i/r_i) + t_l = T \qquad \forall i \in I, \tag{14}$$

$$\sum_{j\in N_c} tr_{0j} X_{0j}^i + \sum_{(j,k)\in E} tr'_{jk} Y_{jk} \le T \qquad \forall i \in I, \tag{15}$$

$$Q_i, w_i, \phi_i \ge 0 \qquad \forall i \in I, \tag{16}$$

$$X_{0j}^i \in \{0,1\} \qquad \forall i \in I, \quad j \in N_c, \tag{17}$$

$$Y_{jk} \in \{0,1\} \qquad \forall (j,k) \in E. \tag{18}$$

The objective function (1), minimizing the total costs, consists of 7 components corresponding to the production, purchasing, and distribution charges. The first and second components describe the production and purchasing (or outsourcing) costs incurred during the production/forwarding time interval. The third and fourth components express the expenses imposed due to loading the manufactured products on the city logistics vehicle and the large truck, respectively. The last three components are related to the dispatching costs in the direct and milk run procedures. Eqs. (2) and (3) are the balancing equations. Eq. (2) reflects the conditions under which the sum of the whole products procured, whether in manufacturing or outsourcing, are equal to the total demands. Eq. (3) states that the total demands are also equal to the whole shipments dispatched through the coupled direct-milk run policy. Relation (4) restricts the production quantity by the minimum of the available manufacturing capacity and the total demands. Equation (5) expresses that the direct-transmitted products are equal to the average forwarded products before the milk run shipment starts. Relation (6) ensures that the demand size of each customer is at least as large as the carrying capacity of the city logistics vehicle. Relation (7) imposes that the number of direct shipments is restricted by the number of available city logistics vehicles provided by the 3PL service provider. Relation (8) implies whether or not the direct shipment to a particular customer is carried out. Relation (9) indicates the restrictions related to the number of products loaded on the large truck. Relation (10) ensures that the large truck departs to a particular customer only if its whole demands are not completely covered by the direct shipments previously accomplished. Relations (11) and (12) do not allow the large truck to return to the previous node. Relation (13) corresponds to the vehicle loading constraints and the sub-tour elimination restrictions. Relation (14) ensures that the whole production interval, together with the last transmitting preparation time, does not exceed the assigned production/forwarding period. Relation (15) expresses that the total travel times spent through the coupled direct-milk run shipments do not exceed the planning period (time cycle). Finally, the domain of the variables is limited by the Relations (16) to (18).

4. Policy development

When dealing with a group technology-based manufacturing environment, a manufacturer needs to know how to adjust its strategy. In such environments, the preparation time and cost between different items in the products' family are immaterial, and production planning is motivated by not exceeding the production cycle time, maximum satisfaction of customers' demands, increasing the duration of customers' access to products (especially in the case of perishable products) and reducing their distribution costs. Coordination between production and distribution plans to achieve the above-cited goals is another dimension of the manufacturer's decision. The manufacturer is dealing with soon-expired products. Therefore, on the one hand, it seeks to satisfy the customers with higher demands (not losing the market share) and, on the other hand, aims to reduce the risk of products' corruption in the distribution process in the intended geographical cluster. Although there may be other different strategies in this field, these approaches are considered the most challenging cases based on the integration of production and distribution planning in group-based manufacturing industries. Hence, we consider the problem under four planning procedures derived from a mixture of the following policies.

4.1. The production policies

The production-rate-oriented configurations provide a condition where the manufacturing operations are prioritized according to whether the ascending or decreasing rates of production correspond to each product. We analyze the resulting planning structures as follows:

4.1.1. Policy 1: Increasing-production-rate

As depicted in Figure 3, in this policy, the products are manufactured on a single batch-processing machine based on the measure of the ascending production rate. As cited before, a high production rate reflects a larger demand size as well, i.e.:

$$r_{(1)} \leq r_{(2)} \leq r_{(3)} \leq \ldots \leq r_{(n)} \leftrightarrow \sum_j d_{(1)j} \leq \sum_j d_{(2)j} \leq \sum_j d_{(3)j} \leq \ldots \leq \sum_j d_{(n)j}, \tag{19}$$

where $(1), (2), (3), \cdots, (n)$ denote the first, second, third, $\cdots$, and the nth production priority on the batch-processing machine, respectively.

In this regard, the manufactured products are directly shipped to the customers within an average forwarding rate until the milk run shipment starts. It is worth noting that if the production capacity falls behind the products demanded, production outsourcing may be required. Then, the products are consolidated in order to be concurrently sent to the customers through a single large truck.

4.1.2. Policy 2: Decreasing-production-rate

Unlike the previous scheme, this policy is configured based on decreasing rates of production, where the product with the highest manufacturing rate is initially produced. Furthermore, this product is also the most demanded item. Specifically,

$$r_{(1)} \geq r_{(2)} \geq r_{(3)} \geq \ldots \geq r_{(n)} \leftrightarrow \sum_j d_{(1)j} \geq \sum_j d_{(2)j} \geq \sum_j d_{(3)j} \geq \ldots \geq \sum_j d_{(n)j}. \tag{20}$$

Again, $(1), (2), (3), \cdots, (n)$ represent the first, second, third, $\cdots$, and the nth production priority on the batch-processing machine, respectively.

As long as the possible quantities of the last product (within the allocated order) are completely produced, the formerly manufactured products are delivered through direct shipment. In such cases, there are more direct transfers compared to the first

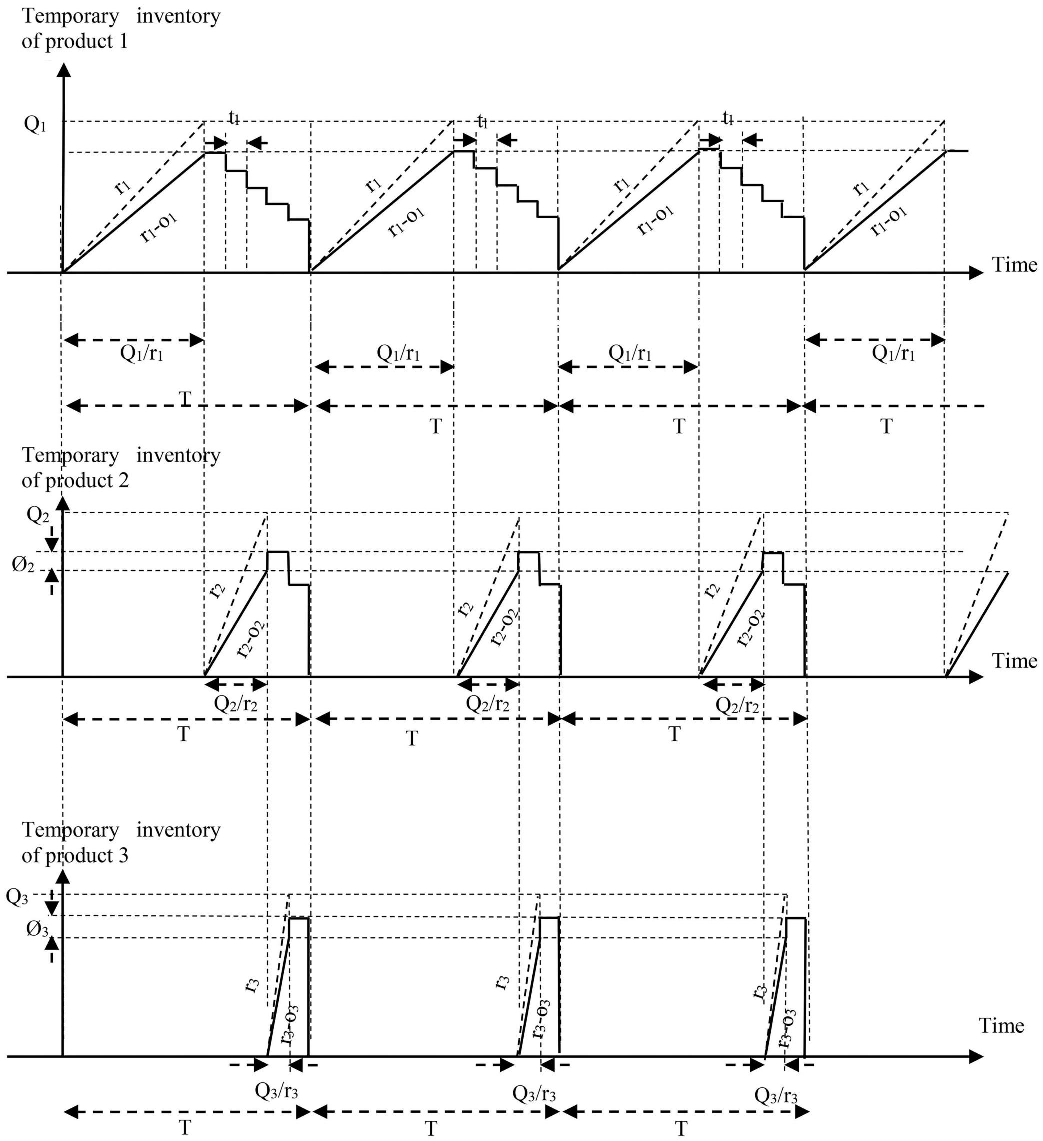

Figure 3. Temporary inventory-time diagrams in the Policy 1.

production scheme. That is, one or more of the products may be shipped using merely direct procedures. Also, production outsourcing is most likely to occur for products with lower production rates. Figure 4 indicates the second policy schematically.

4.2. The distribution policies

In this section, we table the policies implying how to distribute the products throughout the network. Indeed, a vehicle routing problem is carried out within the suggested scenarios as follows.

4.2.1. Policy 1: Decreasing-delivery-distance

This policy expresses a distance-oriented distribution arrangement based on which the products are dispatched to the customers. Assuming that the direct shipments of products from the manufacturing plant to any demand point are conceivable, the products' distribution is established in a way that the manufactured items are respectively dispatched to the first farthest customer, the second farthest customer, etc. in both the direct and the milk run policies. Further, a vehicle routing problem is solved in the milk run shipment according to the adopted criterion. Therefore, as shown in Figure 5, the most distant routes are incorporated in the first stages of planning when the decreasing-delivery-distance policy is in effect.

4.2.2. Policy 2: Decreasing-demand-size

The policy under this section illustrates another principle in distributing the products. Aiming to avoid losing customers with the highest demands, the focus of this policy is on the demand size within each planning period. In other words, the manufactured products are transshipped to the customers from the highest to the lowest demand size, whether in direct or milk

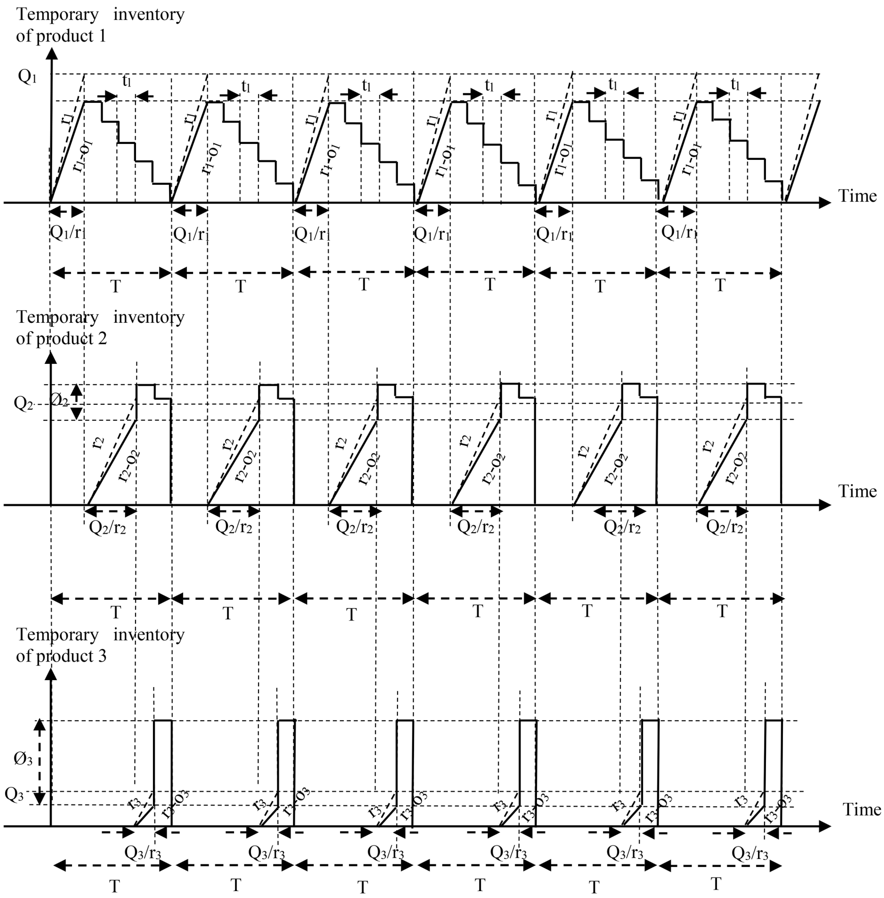

Figure 4. Temporary inventory-time diagrams in the production Scenario 2.

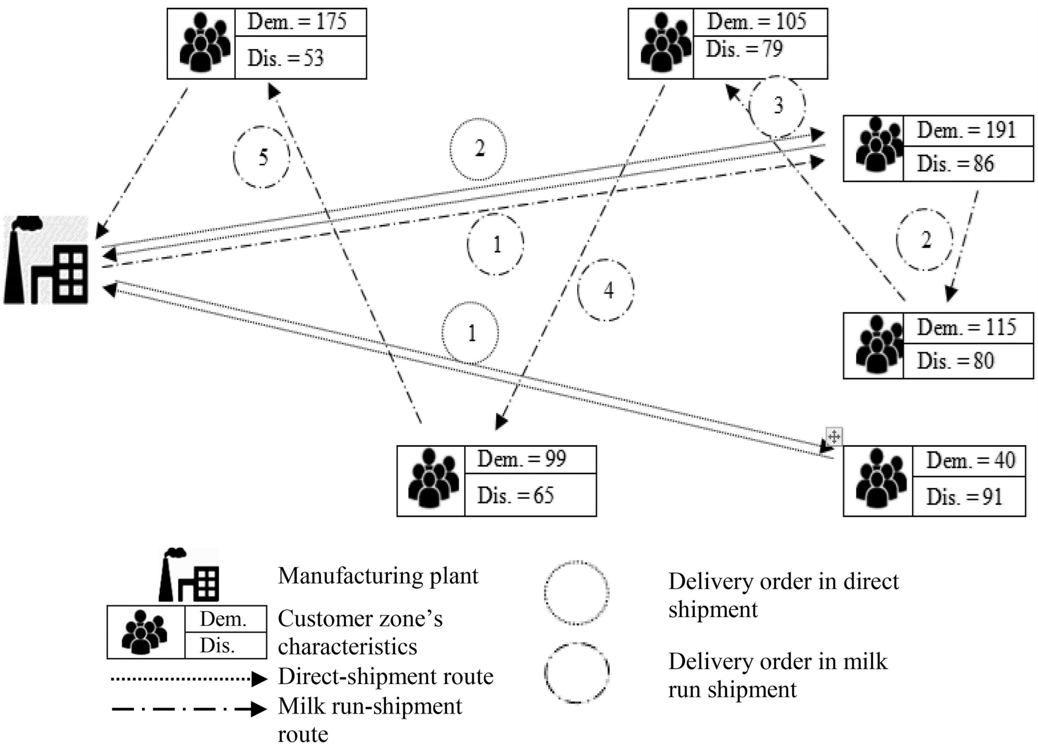

Figure 5. A particular illustration of the distribution Policy 1.

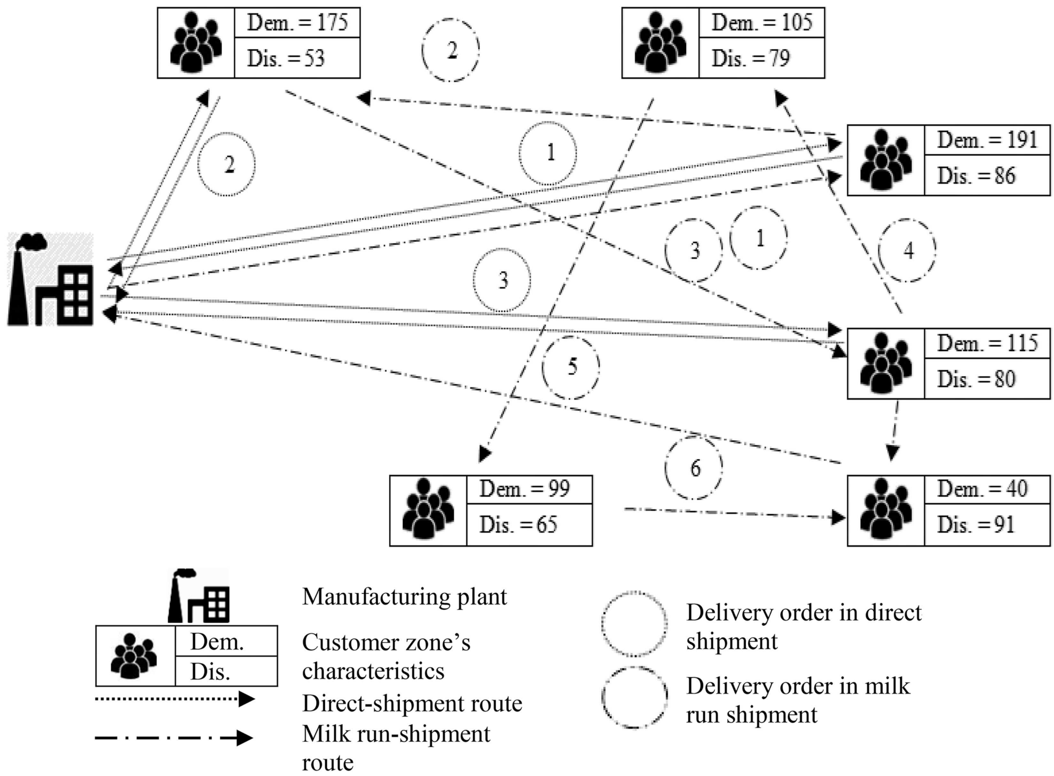

Figure 6. A particular illustration of the distribution Policy 2.

run procedures. Figure 6 depicts a general illustration of the distribution policy according to the decreasing demand size measure.

5. The heuristic solution approaches

Due to the complexity of the problem arising from developing an integrated approach in production and distribution planning, we propose four heuristic algorithms to solve each coordinated production/distribution scheme. These algorithms are based on an innovative platform and have been developed using the problem features in production distribution policies and the combined transshipment strategy. In other words, the structural features of the problem inspire the use of the mentioned algorithms. In this regard, we first consider some assumptions as: (i) The product quantities (procured whether through the manufacturing or by a third-party supplier) are assumed to be the same as the customers' demands (i.e., $Q_i+\phi_i=\sum_{j\in N_c} d_{ij} \quad \forall i$); (ii) At least two products are manufactured in the plant (not necessarily all the required quantities); (iii) The products ordered (outsourced) are received just after the manufacturing process (for each product) and The condition $o_i\left(T-\sum_{\tau<i}(Q_\tau/r_\tau)-t_l\right)\leq H_i c_i^c$ is satisfies for each product.

The stages of the heuristic algorithms are cited as follows (Figures 7 and 8):

- Algorithms 1&3: The IPR-DDD and DPR&DDD;
- Algorithms 2&4: The IPR&DDS and DPR&DDS;

6. Numerical study

This section is dedicated to numerical analyses and comparisons. Therefore, to experimentally evaluate the suggested approach, some particular illustrations of the problem are considered in Table 2. Further, to examine the efficiency of the suggested heuristic methods, the performances of MILP and heuristic algorithms are compared based on the whole cost, the CPU time, and the absolute and relative gaps (as depicted in Table 3). The implementation of the proposed algorithms is based on a common planning cycle. In other words, the algorithms continue to run until the manufacturing of the last product in the adopted policy is completed and the milk run distribution begins. Thus, the convergence of algorithms can be considered based on achieving an integrated optimal program in production distribution, wherein it is important to study the number of absolute and relative optimality gaps.

As observed in Table 3, the heuristic Method 1, which has been provided for solving the IPR&DDD scheme, yields a more preferable performance compared to the other solution approaches. Hence, it

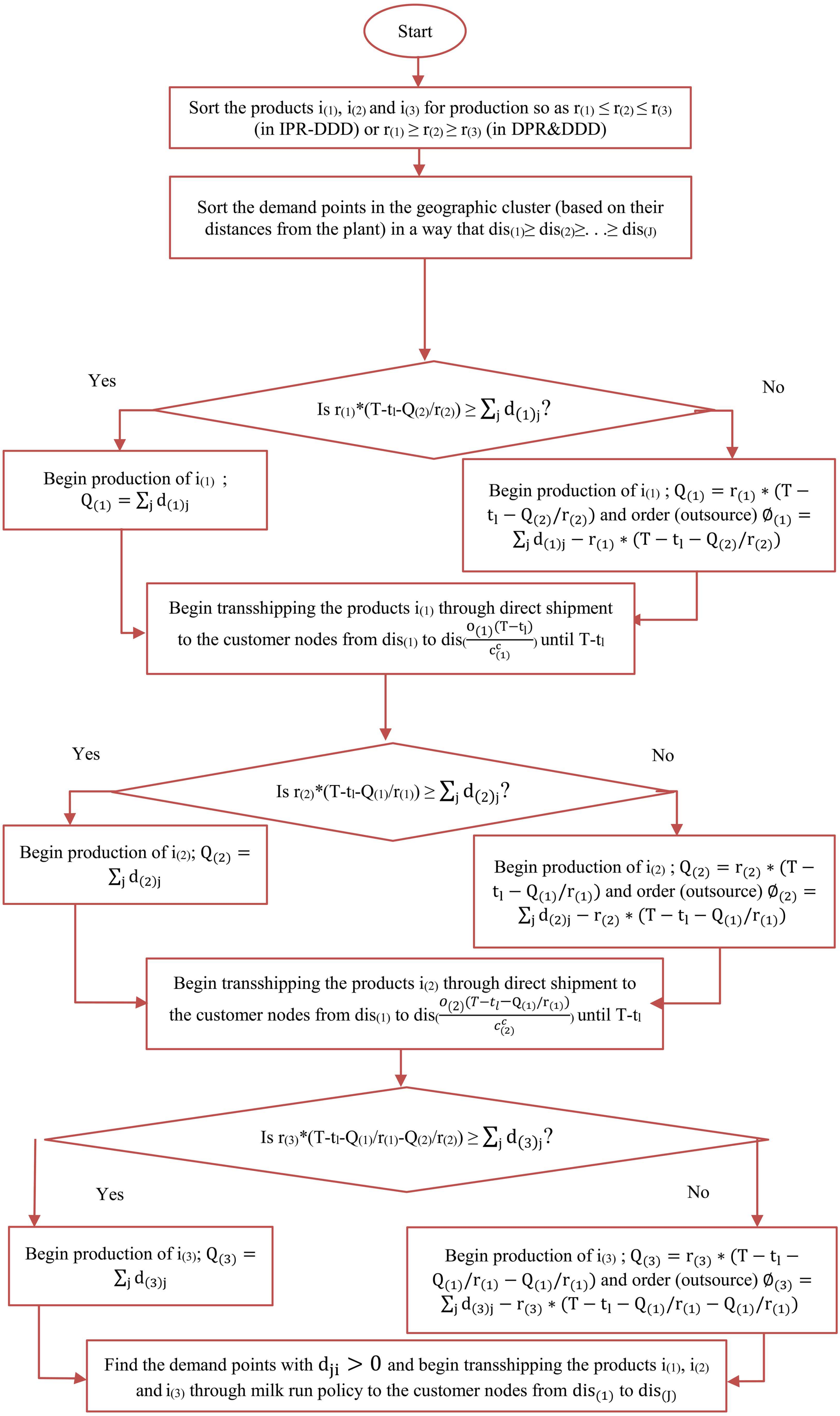

Figure 7. Flowchart of heuristic Algorithms 1 and 3 in the IPR&DDD and DPR&DDD.

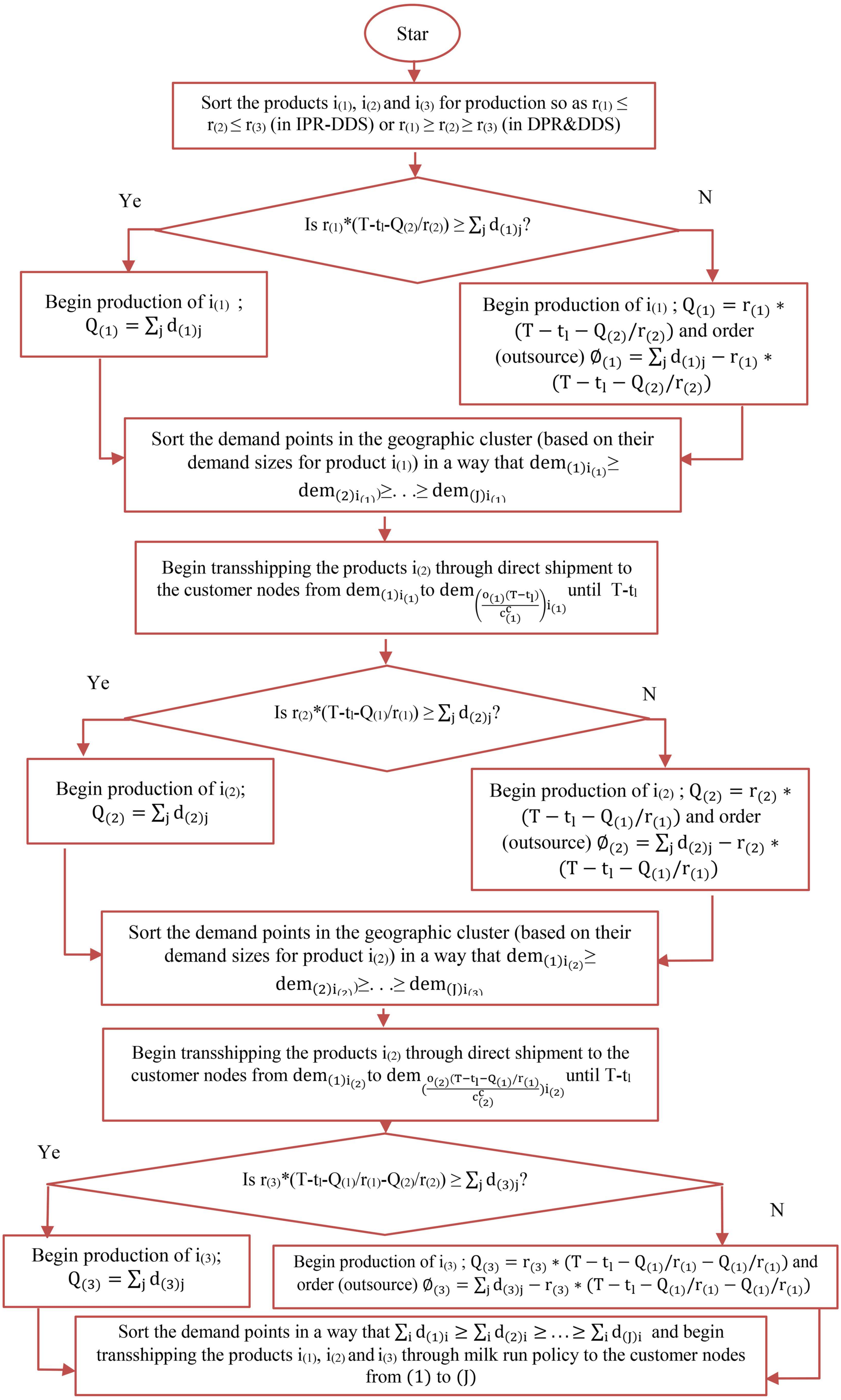

Figure 8. Flowchart of heuristic Algorithms 2 and 4 in the IPR&DDS and DPR&DDS.

Table 2. Particular instances of the problem.

	i	T	d_{ji}	r_i	cap_i	o_i	t_l	H_i	c_i^c	c_i^l	a_i	μ_i	δ	γ_i	α_i	f_{oj}	m_{jk}	tr_{oj}	tr'_{jk}
1	1		7100	69	10500	41		18	199	5858	42	79		16	16.99	[440,565]	[250,491]	[0.027,0.035]	[0.031,0.042]
	2	0.19	6855	65	9685	39	0.014	16	194	6197	47	93	1350	18	19.01				
	3		8220	73	11698	46		20	212	6500	39	75		14.5	16.23				
	1		10500	52	9680	35		26	159	8989	81	152		23	24.12	[491,593]	[291,550]	[0.021,0.030]	[0.031,0.039]
2	2	0.21	11020	59	10669	40	0.012	28	166	9200	75	136	1410	20	22				
	3		9664	46	10500	29		23	153	7993	91	177		25	26.01				
3	1		12000	75	14100	51		29	259	12119	95	179		31	32.5	[501,612]	[310,599]	[0.022,0.029]	[0.029,0.0375]
	2	0.25	13100	96	20000	70	0.014	33	299	14150	81	154	1499	27	27.91				
	3		12500	81	16880	62		30	285	13612	89	166		28	29.41				

Table 3. The comparative results obtained from the MILP and the heuristic approaches.

	The whole cost					CPU time					Absolute gap					Relative gap				
Pro.	**MILP**	**Algo. 1**	**Algo. 2**	**Algo. 3**	**Algo. 4**	**MILP**	**Algo. 1**	**Algo. 2**	**Algo. 3**	**Algo. 4**	**MILP**	**Algo. 1**	**Algo. 2**	**Algo. 3**	**Algo. 4**	**MILP**	**Algo. 1**	**Algo. 2**	**Algo. 3**	**Algo. 4**
1	449.112	350.505	521.101	421.441	581.233	0.37	0.13	0.14	0.129	0.133	0.17	0.025	0.089	0.007	0.101	0.33	0.102	0.225	0.191	0.303
2	524.669	449.889	581.113	485.306	621.315	0.541	0.139	0.155	0.131	0.145	0.35	0.11	0.29	0.201	0.291	0.512	0.201	0.485	0.312	0.528
3	598.116	478.991	612.331	561.781	701.128	0.64	0.141	0.159	0.138	0.141	0.39	0.093	0.44	0.221	0.401	0.401	0.331	0.339	0.388	0.445

shows that in case the products are perishable and have different manufacturing rates, capturing Algorithm 1 derived from the mixture of the increasing-production-rate and the decreasing-delivery-distance criteria will result in a better function.

6.1. Sensitivity analysis

Some beneficial sensitivity analyses are investigated below. In this regard, the manufacturing rates of products (r_i), the average direct-shipping rates (o_i), the manufacturing cost (a_i), and the cost of production outsourcing (μ_i) are considered. Therefore, we analyze the impact of an increase in the cited parameters on the total planning cost.

Since production outsourcing imposes high charges on the company, the increasing production rate (r_i) leads to the majority of customers' demands being manufactured by the plant. Thus, by increasing the production rate (r_i), the overall cost of planning decreases (as shown in Figure 9). This result can improve the productivity of the products manufactured and will bring more satisfaction to the company. This cost reduction is observed in both the MILP model and the heuristic algorithms. However, the cost reduction slope (with increasing production rate) varies in different procedures. Since the production planning is conducted at the incremental rate of manufacturing among the same-family products in Algorithms 1 and 2, increasing the production rate leads to less direct shipment compared to Algorithms 3 and 4, which are developed based on the descending production rate.

As seen in Figure 10, increased average rates of direct shipments to the demand points (before the milk run shipment starts) result in an increased planning cost. Indeed, an increment in o_i implies an increase in the number of direct shipments and

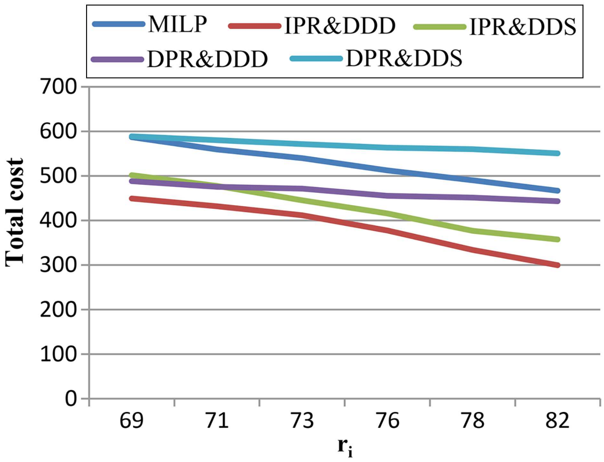

Figure 9. Sensitivity analyses based on an increasing r_i in the MILP and heuristic procedures.

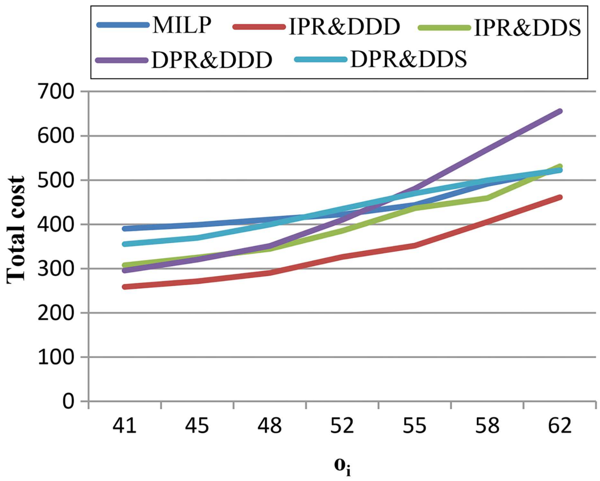

Figure 10. Sensitivity analyses based on an increasing o_i in the MILP and heuristic procedures.

also a decrease in the forwarding preparation time as well. Although this minimizes the risk of product degradation and timely delivery, it leads to an increase in the use of city logistics facilities, the density, and congestion of linking paths (as well as environmental pollution). Therefore, an increasing trend in the total cost of planning can be observed. Meanwhile, the increasing slope of the total cost of planning in approach DPR&DDD is greater. This implies that organizing the planning based on the declining rate of production further increases direct shipments and imposes more costs on the decision-maker. After that, approaches DPR&DDS, IPR&DDD, and IPR&DDS have the highest incremental slope.

As shown in Figures 11 and 12, with a rise in the production and outsourcing unit charges, the whole planning costs increase. According to the considered joint cycle, the reaction of different methods to the increase in the unit cost of production, as well as

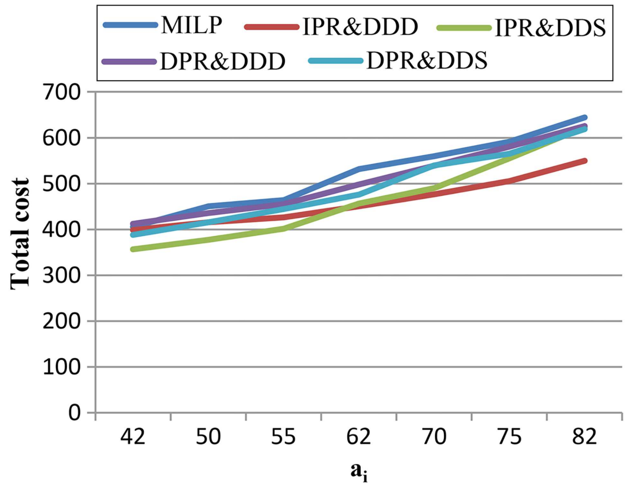

Figure 11. Sensitivity analyses based on an increasing a_i in the MILP and heuristic procedures.

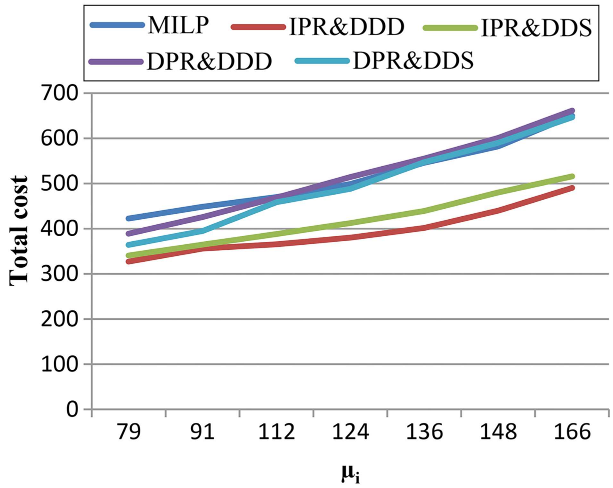

Figure 12. Sensitivity analyses based on an increasing μ_i in the MILP and heuristic procedures.

the outsourcing, is different. Since in the IPR&DDS and IPR&DDD planning approaches, a larger volume of on-demand products is processed in the plant, increasing the unit cost of production can lead to a further increase in the total planning charges in these approaches. In other words, in these methods, the products are included in the integrated program according to the ascending production rate. Given that the manufacturing rate of products is proportional to their demand, an increase in the unit cost of production will have a greater impact on their total charges. Thus, in line with an increase in the unit production cost, the increasing slope of the total charges can be observed in the algorithms IPR&DDS, IPR&DDD, DPR&DDS, and DPR&DDD. On the other hand, with the aim of compensating for the shortages resulting from different production rates in the considered joint cycle, outsourcing is another planning strategy. Upon this strategy, if the amount of products manufactured is less than their demand, production will be outsourced. Since the share of outsourced products in algorithms DPR&DDS and DPR&DDD is higher, it is expected that the slope of increasing total charges in these methods is higher. Therefore, in proportion to the increase in the cost of outsourcing, the rate of increase in the cost slope will be observed in the algorithms DPR&DDS, DPR&DDD, IPR&DDS, and IPR&DDD.

6.2. Managerial insights

The proposed scheme in this study provides a helpful tool for supply chain practitioners, in terms of integrating a cycle-based production schedule with distribution planning and selecting an appropriate policy of transshipment. In such an environment that is representative of group technology- based manufacturing (cellular manufacturing), a multi-product batch-processing machine is utilized. There are lots of industries such as semi-conductor, metalworking, porcelain, and food-making (e.g., dairy) that can take advantage of the approach taken for optimizing their operational decisions. Relatively many examples can be found in various industries that have been impressed by decision-making in isolated environments. Lack of coherence and integration in decisions related to production and distribution planning has led to the lack of necessary effectiveness. This is especially more important in multi-processing situations.

In the proposed approach of this paper, the requirements of production preparation (in terms of time and financial dimensions) are ignored due to the inclusion of products in a single-family and the similarity of their production processes. In this situation, it is very important for a manufacturer how to organize the production schedule of its products in order to achieve the necessary effectiveness in meeting the market demand at the lowest possible cost. The coordination of production and distribution policies in the geographical area under study facilitates achieving the determined goals. Two policies based on ascending and descending rates of production, as well as two policies based on descending distance and demand in terms of using a hybrid transshipment strategy (direct-milk run), are included in this study. The manufacturer, through the optimal combination of the abovementioned policies, seeks to meet the maximum demand of customers and not lose market share, as well as to prevent the expiration of manufactured products and the imposition of additional costs. One of the questions answered in this study is when the manufacturer decides to produce and when to outsource, given the current situation. This decision must be made in coordination with the distribution policy in order to be effective in various aspects. Although other strategies may be considered by researchers and craftsmen in this regard, the proposed approaches are among the most important concerns of decision-makers in this area and have been developed in line with two important goals (as mentioned). As shown in the numerical results, the hybrid policy based on incremental production rate and descending delivery distance has led to the best performance based on evaluation indicators among the proposed methods. The results of the sensitivity analyses also indicate that the change in total costs is due to the increase in production rate, shipping rate, unit production cost, and unit outsourcing cost. As argued in the relevant subsection, the increase or decrease in total costs can be justified based on changes in the amount and speed of production, the amount of outsourcing, and the amount of direct transshipment of products.

7. Conclusions and future directions

The joint production-planning and distribution optimization problem is one of the significant issues in the corresponding decision-making areas, especially in case the product shelf life is too short. This paper discusses one such problem where a set of family products is manufactured on a single batch-processing machine and delivered by a third-party logistics service provider with only two types of shipment facilities that are environmentally licensed. In this context, the characteristics of the product make a condition under which an approximately no-wait condition with no setup(s) and cleaning(s) charges is developed. Besides, a combined shipment structure based on the direct-milk run procedures is applied to efficiently deliver the manufactured products. Further, we propose an MILP formulation to connect the production, planning, and routing sections.

Aiming at covering the practical needs, we consider four planning procedures including: (i) Increasing-production-rate & decreasing-delivery-distance (IPR&DDD); (ii) Increasing-production-rate & decreasing-demand-size (IPR&DDS); (iii) Decreasing-production-rate & decreasing-delivery-distance (DPR&DDD); (iv) Decreasing-production-rate & decreasing-demand-size (DPR&DDS).

For solving the problem (which has already been acknowledged as NP-hard), four heuristic algorithms are developed.

The numerical results show that the procedure planned according to the hybrid of the increasing-production-rate and decreasing-delivery-distance policies has a better performance. Moreover, the sensitivity analyses illustrate a straightforward relation between the overall planning cost and the manufacturing rates of products (r_i). An incremental trend in the average direct-shipping rates (o_i) makes an increase in the planning expenses. Also, production and outsourcing cost parameters (a_i and μ_i) have a direct impact on total planning charges, depending on the type of policy adopted. Indeed, due to policy adopted for production as well as distribution, an increase in these costs can lead to an increase in the total planning charges.

The approach proposed in this paper can be well utilized by supply chain experts. The question "What policy should a manufacturer adopt to produce and distribute its products?" can be answered through this research. Despite examining the various aspects of decision-making using an integrated approach, some shortcomings of this research can be regarded. Among these limitations are a lack of coverage of more realistic conditions due to non-consideration of uncertainty in modeling parameters (demand, etc.), lack of investigation of the suggested approach in different production environments, including series and parallel systems, and lack of consideration of preparation time and cost for non-family products. Hence, there are several striking features that extend the paper ahead. One of the appealing facets is to consider a real condition in the related industries (e.g., dairy and food parts) and utilize the presented approach. Investigating the obtained results in an uncertain environment can provide a better view of the problem. In order to consider the sustainability requirements, one can study the environmental and social pillars in the context of a multi-objective programming model. Another interesting research field is to consider some other structures in both production and distribution parts. Also, it would be noteworthy to investigate the suggested approach for heterogeneous products with setup and cleaning costs. Developing other heuristic and metaheuristic solving methods is an extending aspect that is also open.

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