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RESEARCH PAPER

Integrated Production and Distribution Scheduling in Mobile Facilities

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Abstract

Many supply chains lack flexibility and adaptability in today's competitive market, resulting in customer dissatisfaction, backorders, and several extra costs for the business. Additionally, the inability to quickly meet the customer's demands and the unnecessary transportation costs is also one of the significant challenges faced by the fixed facilities' supply chain. To address these challenges, this study analyzed the mobile facilities supply chain and the production, distribution, and delivery of goods conducted by trucks based on customer preferences. This study proposes a bi-objective mixed-integer linear programming model to ensure the mobile facilities' routing and manufacturing schedules are optimized to meet the customer's needs. Furthermore, this model minimizes production and distribution costs in the shortest amount of time. An exact decomposition algorithm based on Benders decomposition is used to find high-quality solutions in a reasonable amount of time to tackle the problem efficiently. We present several acceleration strategies for increasing the convergence rate of Benders' decomposition algorithm, including Pareto optimality cut and warm-up start. The warm-up start acceleration strategy itself is a meta-heuristic based on particle swarm optimization (PSO). Using the Benders decomposition, we demonstrate the superior accuracy of our solution methodology for large-scale cases with 10 kinds of products ordered by 30 customers using 10 mobile facilities.

Keywords:
Accelerated Benders Decomposition Algorithms;
Benders Decomposition;
Integrated Production and Routing Problem;
Mobile Facilities;
Mobile Facilities' Supply Chain.

Introduction

The supply chain includes all activities turning the raw materials into the final products and delivering them to the customers. In the supply chains consisting of the consecutive production, storage, and distribution of the products, every process is often optimized separately [2]. Production and distribution are the two chief factors in the supply chain, which seem vital in achieving optimal efficiency. On the other hand, scheduling problems are among the most critical issues in the contemporary world, significantly influencing the manufacturing and service-providing systems [3]. Several modern industries have adopted integrated production and distribution planning and scheduling. Such integration is more noticeable in the sectors taking care of the production based on the Make to Order (MTO), The on-time delivery with the lowest cost to the customers is controversial. To overcome these challenges, in addition to the more integration between the production and distribution, a practical production and distribution framework by considering the routing issue is essential [8].

Soon, there is the potential of the multi-level supply chain's replacement by an integrated production and distribution system, in a way that a mobile facility (MF) can replace all of the

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current factories; for instance, 3D printing manufacturing technology. Afterward, the competition will take place on the logistics [17]. Also, Tang and Veelenturf indicated that logistics is a competitive tool for companies to enhance their power [18].

Although the fixed factories produce numerous products delivered by their distribution network, they cannot be flexible and adaptable enough in the manufacturing centers and must look for novel solutions. The Distributed Manufacturing System can be a good idea for overcoming these challenges. The Mobile Supply Chain is formed based on this concept, aiming at producing close to the customers, upgrading the level of satisfying the customers' demands, and therefore, obtaining customer satisfaction [22].

So, MFs have been used to increase flexibility and robustness, and have been expanded to meet customer needs as quickly as possible to the customer. MFs have enabled companies to manage demand peaks and can help fixed facilities in critical situations such as high demand due to changes in the market. They can act as a backup when production lines fail. MFs can also be used to reduce costs such as transportation costs, unnecessary transportation in fixed facilities and so on.

For many years, MFs are employed due to their capability in production while being mobile and the possibility of transporting the manufacturing equipment to produce some of the products. However, their abilities for high-tech and modern production have not been fully taken advantage of. The mobile facilities return to their supply centers, satisfying their demands in terms of raw materials. The routing is executed according to the customers' initial demand, and during the movement to the destination, the production is taken care of. Afterward, a stop is made in an optimal location, and the customer's demand is satisfied.

In this article, a mathematical model for the production during the mobile facilities' movement is proposed; in this model, such facilities can produce multiple products. Each of these facilities moves toward the customers based on the customers' demands and stop in one of the determined points, satisfying their demands based on the specified time window. The customers move based on the distance towards the MF, getting their order. The closest case is likely to be the public benefit services, such as medicine or mask manufacturing under crises. Besides, the chief concern is the integrated production and routing planning, a particular product is delivered to the customer at the specified time, paving the way for JIT conditions.

Literature review

The literature review framework of this study is defined as follows. In literature, several research fields can be found which have some intersections with Integrated Production and Distribution Scheduling in Mobile Facilities. Some researchers have investigated the application, importance, challenges, and background of the mobile facilities. Also, a literature review of integrated distribution and production in the supply chain and a review of the issues pertinent to the mobile facilities, routing, and locating problems are shown. In the end, a summary of the literature review is indicated in Table 1.

Due to the increase in E-commerce, the Last Mile Logistic concept has been employed in various applications. By considering their favorable time window, the customers' demands satisfaction has been turned into one of the chief criteria in the micro supply chain and transportation industry [19]. Also, raising the online orders and the demand for its delivery on time or on the specified time is one of the main challenges of the companies, particularly in the big cities with heavy traffic. Moreover, in recent years, several investigations have been executed in the realm of the fixed facilities defects, such as redundant and vain transportation, higher construction costs, and the tendency to develop mobile facilities. All of these can be a persuasive reason for mobile facilities' employment [9]. The idea of mobile production is described as different titles in the literature review:

Factory in a box [23] and movable production system [24] and Reconfigurable manufacturing system [25] and plug and produce [26], all of which have the same subject but in different applications. Ask and Stillström have explained the requirements for establishing an MF and mentioned some examples of different industries [49].

The mobile facilities can be designed in three types to enhance the performance based on the environmental conditions. The first type of MF is in a way that it can be installed inside a container of a truck. This type is suitable for single-product systems whose location changes daily or weekly such as a 3D printer for making dolls. The other type is the facilities, including multiple portable containers with the capability of producing and assembling multi-component products. This type is used for the cases whose location is changed monthly such as asphalt or cement manufacturing. In the end, we have plenty of mobile facilities consisting of multiple huge prefabricated products that are assembled in a suitable place and transported by truck. Those have various containers, ideal for the cases whose location is not changed for several years such as mobile hospitals in deprived areas [7].

The first mobile facility was designed by Preeman, and its patent was taken out in 1975. This MF was intended for asphalt manufacturing and could be employed in civil operations in any place [49]. However, thanks to Iranian youth efforts, the first asphalt mixing facility was built and implemented in 1995[†].

The mobile facilities are highly capable of the semi-finished products' montage, recycling, being employed in the construction industry, i.e., cement and perishable materials, and producing products required in crisis [9]. Besides, this kind of facility can act as an accelerator in places lacking in industrial areas and critical conditions, such as floods, earthquakes, and wars.

Also, other applications of them can be the maximum coverage of cell phone signals in various areas and humanitarian aid arrangements [10]. Another application of mobile facilities is providing service to remote areas where building a center is not economically feasible. One of the essential applications of them that are ubiquitous today and in Coronavirus outbreaks is employing mobile laboratories for conducting tests in remote areas so that all countries can take advantage of these services equally [11].

Generally, all studies and issues that have been conducted in the mobile facilities' modeling can be categorized into the combination of the following areas, each of which is reviewed first. Finally, the discrepancies between the current problem's differences with each are examined.

A) One of the most critical managers' decisions is locating new production facilities that have been accorded paramount importance as the supply chain management, which is the most critical frontier of competitive advantage, emerged [32]. Most of the studies conducted on mobile facilities' modeling are based on the Facility Location Problem that Weber addressed in 1962. He reviewed the literature in this field in Daskin's article in 2008. A lot of studies are carried out on the Location Problem of mobile facilities. In these types of problems, facilities can settle in different horizons in different places and provide services. The objective function in most of these problems is minimizing the customer's pathway to receiving services or minimizing the Transportation costs [15].

Locating mobile facilities is not a novel subject, and some studies are conducted in Durocher, S. and Kirkpatrick, D [20], in which customers and mobile facilities could move constantly.

This problem was first examined by Demaine et al. by referring to the concept of mobile facilities [33]. Güden et al. [16] also studied a location problem in construction management by employing mobile facilities. They determined the number and location of the route taken by the MF by minimizing the costs and took advantage of Branch and Price to solve the problem. A vast majority of studies conducted in this field are on obtaining approximations for upper and

[†] www.tmbr-co.com

lower bounds of this problem [10]. In 2015, Halper also investigated moving mobile facilities and allocating customers to these facilities to satisfy their demands to minimize the total transportation costs of customers and the mobile facilities. They employed the Local Search Neighborhood to solve this model.

Other problems that can fall into this category are the mobile hub location problem. In the investigation published by Bashiri et al., they have investigated the MFs in Hub Location Problem. The mobile facilities are located in Hub places and can respond based on changes in demand and overcome the additional costs in establishing facilities. The objective function of this study was minimizing the cost and maximizing the profit. This investigation demonstrated that mobile hub performs better and is more influential than the classic version of this network. They also developed a genetic algorithm with adjusted parameters and simulated annealing for solving the relevant model [21].

B) The TSP and VRP have been examined as two classic problems in the supply chain. The movement of vehicles in the network is planned, and the vehicles are responsible for picking up/delivering the services. However, in reality, some vehicles might be capable of providing the services. In this case, the capability of movement and motion is considered as an advantage. The movement of the mobile facility can also be modeled by a VRP problem with service time [30]. A comprehensive review of the studies conducted on this subject can be found in the article [31].

The routing problem of the mobile facilities is distinct from the problems mentioned above and has some differences. The first study on location problems of mobile facilities was conducted by Halper et al. in 2011 [5]. He accurately defined this problem as the MFRP aims at creating some routes for the mobile facilities so that the demands that are met by these facilities during the planning horizon are maximized constantly. They considered a wide range of places where mobile facilities could settle and provide services. Movement among these places was also possible, and time was regarded as a continuous variable. Besides, the objective function was maximizing the met demands. They also proposed three heuristic methods [7]. Consequently, Lei et al. [9] introduced a scheduling problem modeled by a two-stage stochastic programming method. In the first stage, mobile facilities' movement was decided. In the second stage, the way mobile facilities meet customers' demands based on various scenarios is examined. They employed a multi-cut L-shaped algorithm to solve this model.

After the investigation and introduction of the mobile facilities and studying their applications, we have examined some articles addressing integrated production and distribution planning and scheduling.

Although there are several separate articles in the planning and routing field, integrated studies have been conducted between the mentioned areas in the last few years. That is why facilities are required to economize to be more noticeable in the competitive market. Generally, a comprehensive investigation has been conducted in this field by Moons et al. [27].

In most of these studies, the commodity delivery is done after the production, and the routing problem for the delivery issue is not taken into account [14]. Nonetheless, in [8] and [15], the routing of the vehicles is considered for delivery to the customers.

It is worth mentioning that in none of these articles, the production is carried out shortly as possible after submitting the demand by the customer. However, in this article, such an important issue is addressed using the mobile facility concept.

Moreover, in a study conducted by Behzad, an MINLP model is provided, aiming to maximize the profit. The production and routing scheduling from the supplier to the initial location of the mobile facility is examined. In the end, by employing the greedy algorithm, the problem is solved, and the sensitivity analysis is carried out [28]. In this article, a network of suppliers, several customers with predictable demand, and plenty of mobile facilities are observed. In this article, the main objective of the model is the cost, and the production planning facet is the subject of concern. The routing problem is considered for the customer directly, and they do not have a constrained time window in getting their products.

Table 1. An overview of the related literature and the research gap.

Year	Ref	Model	Problem Type	Immobile/Mobile Facilities	Opening cost	Relocation Costs	Solution	Objective function	Production Scheduling
2017	[6]	MINLP	Mobile facility routing and production problem	No/Yes		Yes	Heuristic	Min cost	Yes
2018	[21]	MIP	P-hub Location	Yes/Yes	Yes	Yes	Metaheuristic	Min cost	No
2011	[7]	MIP	MFRP	No/Yes	No	No	Heuristic	Max Demands	No
2015	[5]	MIP	MFLP	No/Yes	No	Yes	Metaheuristic	Min cost	No
2019	[6]	MIP	Dynamic P-median Problem	No/Yes	No	No	Branch and Price	Min Total Distance traveled	No
2021	[22]	MINLP	Mobile facility routing and production problem	No/Yes	No	No	Pareto Frontier	Min cost + Min Delay	Yes
2018	[35]	MINLP	IPDS	Yes/No			Exact Algorithm	Min cost	Yes
2020	[34]	MINLP	IPDS	Yes/No	No	No	Hybrid PSO, ε-constraint	Min demand + Max Satisfaction	Yes
2017	[36]	MINLP	IPDS	Yes/No	No	No	Branch and Bound (B&B), simulated annealing	Max Customer Satisfaction	Yes
Present Study		MIP	MFRPP	No/Yes	No	Yes	Benders Decomposition	Min cost + Min Delay	Yes

The production in trucks and delivering the commodities to the customers via this way is associated with various challenges as follows.

1- The routing of the equipment is categorized as the decision variables at the strategic level. Simultaneously, the mobile facilities are considered to be at the operational level due to the spatial changes in a short period [29].

2- Given that the mobile facilities are supposed to provide several customers, with respect to the time window constraint of each customer, the TWVRP problem is another facet of the routing problems in these facilities.

3- The production in the mobile facilities should be in a way that does not interfere with the customer's time window. Accordingly, the production and routing should be integrated to get a wide berth to the delays and fines.

According to the literature review, integrated production and distribution by using mobile facilities are new and applied issues in the industry. It can be employed to overcome some of the barriers like inflexibility, inadaptability, and higher logistics costs. In this article, some of these gaps are addressed, and the following contributions are categorized:

1. We are developing an optimal model for the mobile facilities' production and routing so that the desired product of the customer is delivered on time.
2. The integrated production during the distribution of the mobile facilities to mitigate the costs.
3. Making sure of satisfying the customer's demands using a proper solution.

Problem statement

Consider the integrated production and routing scheduling problem of the mobile facilities. In this problem, V facilities are to satisfy C customers' demands, including P products. The customers' demands are considered certain. The mobile facilities start over from the initial nods, moving towards the demand points based on the executed routing subject to the time duration between nodes and the demands in each nod. Through this pathway, the mobile facilities produce based on their capabilities, arriving at the demand points. Besides, based on the distance and the cost, the customers also reach the appropriate demand locations to satisfy their demands. The mobile facility may not have been able to produce all the products desired by the customer at the arrival moment. Thereby, it stops at the demand locations and continues making. When the customer's demand is met, it moves to the next node. In case it moves to the next node, the production process will be carried out to meet the total demands of the customers that are allocated to that node.

Assumptions

- The demands of the customers are assumed to be certain.
- The upper and lower limits of the product's production time are assumed to be certain in the problem.
- A limitation is considered for the mobile facilities' production number. Indeed, the mobile facilities have capacity.
- For the mobile facilities, merely the constant cost is seen in the case of use.
- Providing service and responding to the customers' demands starts when the MF arrives at the particular place and continues until leaving that node.
- Each customer is allocated to a node based on the distance the customer has from the nodes that supply the demands and must meet the customer's demand at that node.

Mathematical model

The Integrated Production and Distribution Scheduling in Mobile Facilities is formulated as follows.

Notations:

$i, j \in \ \omega = \{1, \dots, I\}$	Set of nodes where the demand is met
$r, r' \in \eta = \{1, \dots, R\}$	Set of MFs starting and endpoints
$h, h' \in \rho, \omega \cup \eta = \rho = \{1, \dots, H\}$	Set of all nodes
$p \in \Omega = \{1, \dots, P\}$	Set of products
$v \in \Gamma = \{1, \dots, V\}$	Set of mobile facilities
ξ_r	Set of mobile facilities, v, starting from node r
$c \in \ \theta = \{1, \dots, C\}$	Set of customers

Parameters:

M: A sufficiently large number

d_{cp}: number of product p demand by the c-th customer.

α_{pv}: Production rate of product p in mobile facility v per unit of time.

$t_{hh'}$: Interval between node h and h'.

ub_{ip}: Upper bound of product p production time for the i-th node if the node demand is met.

lb_{ip}: Lower bound of product p production time for the i-th node if the node demand is met.
c_{rivp}: Production cost of product p for the i-th node by machine *v* started from the depot r.
$f_{hh'v}$: Transport cost from node *h* to h' with mobile facility *v*.
a_{ic}: Transport cost of the c-th customer towards the i-th node to meet their demand.
R_c: Movement radius of the c-th costumer.
m_{ic}: Distance between the c-th customer and the i-th node, where their demand is met.
cap_{ip}: Facility capacity of the demand node *i* for product p.

Binary Decision Variables:
$X_{hh'v}$: Equals to one if there is a path between node h and h' with the mobile facility *v*, otherwise equals to zero.
E_{riv}: Equals to one, if the mobile facility *v* belongs to the starting point *r* and allocated to customer i, otherwise equals to zero.
Y_{ic}: Equals to one, if the *c*-th customer is allocated to the *i*-th node to meet their demand, otherwise equals to zero.
L_{ipv}: Equals to one, if the mobile facility *v* produces product *p* for the *i*-th node, otherwise equals to zero.

Positive Decision Variables:
AT_{hv}: Arrival and staying time at the customer location *h* with the mobile facility *v*.
B_{ivp}: Arrival and staying time for completing production of product p in the node *i* with the mobile facility *v*.
S_{hv}: Staying time at the customer location h with the mobile facility *v*.
Z_{rivp}: Production amount of product *p* to meet the needs of customer i by the mobile facility *v* extracted from the starting point *r*.
C_{max}: Maximum time to meet the whole system demand considering the limitations.

Auxiliary Variable:
b_{cp}: Demand matrix of product *p* by the *c-th* customer, which is equal to one if there is demand for product *p* and equals to zero, otherwise.
The mathematical model of this problem is as follows:

$$F_1 = \sum_{v=1}^{V}\sum_{h=1}^{H}\sum_{h'=1}^{H} f_{hh'v}.X_{hh'v} \tag{1}$$

$$F_2 = \sum_{v=1}^{V}\sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{r=1}^{R} c_{rivp}.Z_{rivp} \tag{2}$$

$$F_3 = \sum_{c=1}^{C}\sum_{i=1}^{I} a_{ic}.Y_{ic} \tag{3}$$

$$min(Z_1) = F_1 + F_2 + F_3 \tag{4}$$

$$min(Z_2) = C_{max} \tag{5}$$

$$\sum_{h=1}^{H} X_{ihv} = E_{riv} \qquad \forall i \in \omega, (r,v) \in \xi_r \tag{6}$$

$$\sum_{h=1}^{H} X_{hiv} = E_{riv} \qquad \forall i \in \omega, (r,v) \in \xi_r \tag{7}$$

$$\sum_{h'=1}^{H} X_{h'hv} = \sum_{h'=1}^{H} X_{hh'v} \qquad \forall h \in \rho, v \in \Gamma \qquad (8)$$

$$\sum_{h=1,h\neq h'}^{H} X_{rhv} + \sum_{h=1}^{H} X_{hiv} \leq 1 + E_{riv} \qquad \forall i \in \omega, (r,v) \in \xi_r \qquad (9)$$

$$\sum_{i=1}^{I} X_{riv}.M \geq \sum_{i=1}^{I} E_{riv} \qquad (r,v) \in \xi_r \qquad (10)$$

$$X_{riv} \leq E_{riv} \qquad \forall i \in \omega, v \in \Gamma, r \in \eta \qquad (11)$$

$$X_{rr'v} = 0 \qquad \forall v \in \Gamma, r \in \eta \qquad (12)$$

$$AT_{iv} \geq S_{iv} + t_{ri} - M.(1 - X_{riv}) \qquad \forall i \in \omega, (r,v) \in \xi_r \qquad (13)$$

$$AT_{hv} \geq AT_{iv} + S_{hv} + t_{ih} - M.(1 - X_{ihv}) \qquad \forall h \in \rho, v \in \Gamma, i \in I, i \neq h \qquad (14)$$

$$E_{riv} = 0 \qquad \forall i \in \omega, (r,v) \notin \xi_r \qquad (15)$$

$$B_{ivp} \geq AT_{iv} - M\big(1 - L_{ipv}\big) \qquad \forall i \in \omega, v \in \Gamma, p \in \Omega \qquad (16)$$

$$lb_{ip}.L_{ipv} \leq B_{ivp} \leq ub_{ip}.L_{ipv} \qquad \forall i \in \omega, v \in \Gamma, r \in R, p \in \Omega \qquad (17)$$

$$\sum_{r=1} z_{rivp} \leq \frac{S_{iv} + (\sum_{h\in H} t_{ih}.X_{ihv})}{\alpha_{vp}} \qquad \forall i \in \omega, (r,v) \in \xi_r, p \in \Omega \qquad (18)$$

$$\sum_{P=1}^{P} Z_{rivp} \leq E_{riv}.M \qquad \forall i \in \omega, (r,v) \in \xi_r \qquad (19)$$

$$\sum\nolimits_{p=1}^{P} Z_{rivp} \geq E_{riv} \qquad \forall i \in \omega, (r,v) \in \xi_r \qquad (20)$$

$$C_{max} > B_{ivp} \qquad \forall i \in \omega, v \in \Gamma, p \in \Omega \qquad (21)$$

$$\sum_{r=1}^{R}\sum_{v=1}^{V} Z_{rivp} \leq cap(i,p) \qquad \forall i \in \omega, (r,v) \in \xi_r, p \in \Omega \qquad (22)$$

$$\sum_{i=1}^{I} Y_{ic} = 1 \qquad \forall c \in \theta \qquad (23)$$

$$\sum_{v=1}^{V}\sum_{r=1}^{R} Z_{rivp} \geq \sum_{c=1}^{C} Y_{ic}.d_{cp} \qquad \forall i \in \omega, (r,v) \in \xi_r, p \in \Omega \qquad (24)$$

$$Y_{ic}.m_{ic} \leq R_c \qquad \forall i \in \omega, \forall c \in \theta \qquad (25)$$

$$L_{ipv}.M \geq \sum_{r=1}^{R} Z_{rivp} \qquad \forall i \in \omega, (r,v) \in \xi_r, p \in \Omega \qquad (26)$$

$$L_{ipv} \leq \sum_{r=1}^{R} Z_{rivp} \qquad \forall i \in \omega, (r,v) \in \xi_r, p \in \Omega \qquad (27)$$

Eq. 1 calculates the transportation costs, and Eq. 2 calculates the production costs for each node. In the objective function (3), the transportation costs of customers are minimized. In the objective function (4), the maximum time of completing production in the system will be minimized.

Constraints 6 and 7 determine the previous and the following routes (the last and the following nodes) per node. This constraint also determines that each node can merely be visited by one mobile facility at a specific time. Constraint 8 specifies that if a *V*-type mobile facility enters a node, the same *V*-type facility must exit that node. Constraint 9 determines that each node must connect to the starting locations or other nodes according to the route and the performed allocation. Constraints 10 and 11 state that the *V* mobile facility moves from the starting location *r* to the next node when the mobile facility and the relevant node are selected. Constraint 12 determines that no mobile facility can go from the starting point to another starting point. Constraints 13 and 14 specifies the sum of the arrival and stay times at the nodes by each mobile facility. Constraint 15 determines that if the *V* mobile facility is not allocated to node *r*, the mobile facility is not allowed to exit that node. Constraint 16 determines the time it takes for a mobile facility to reach a node for producing the total demand of a customer must be greater than the time MF arrive. Constraint 17 specifies the time window for each product that is produced at each node and define a lower and upper bound for producing product *p*. Constraint 18 calculates the extent of production by the mobile facilities allocated to the starting location r according to the period of the stay time in the route and the time it spends to stay in the customer location. Besides, constraints 19 and 20 determines which mobile facilities have production. Constraint 21 determines the maximum time it takes the demand to be met in the system. Constraint 22 determines that the accumulation space for each node is limited, and this accumulation capacity must be taken into account. Constraint 23 ensures that each customer is allocated to one node. Constraint 24 determines that the minimum production for the product p belonging to node i at the mobile facility V must meet the demand of customer C in that node.

Constraint 25 determines that the customers can meet their demands at the nodes within the motion radius determined for that customer. Constraints 26 and 27 states that the mobile facility *V* cannot produce the product *p* for the demand group *i* unless that facility is allocated to that node.

Proposed Solution Approach

Our initial tests showed that the implementation of this model required significant computation time because of the complex structure of the developed model. The model is also strongly NP-hard. This section develops an accelerated benders decomposition algorithm to reduce the model's computational complexity. Solving the proposed model is done with the Benders Decomposition Algorithm. GAMS 24.1 was used on a PC platform running a Core i7 2.5 GHz processor and 8 GB of memory during all experiments. The following are detailed test sets that were adopted for each experiment. The Benders decomposition performance improved by Pareto accelerators and a warm-up strategy, and a convergence slowness result this algorithm was removed. Then, based on solution time, we compared these accelerators.

Benders Decomposition Method (BD)

In 1962, Benders suggested a decomposition method for solving large-scale mixed-integer linear programming (MILP) problems [37]. The main idea of BD is a row or constraint generation method. BD divides the problem into the Benders Main Problem (BMP) and Benders Sub-Problem (BSP). In reality, BD removes some variables from the main problem and handles them in BMP. In other words, BMP is a relaxed version of the main problem with a set of integers and related limitations. This method uses an upper and lower bound for optimality. In minimization problems, a lower bound is determined for the objective function after the problem has been solved. Also, the upper bound is selected by solving the sub-problem.

The Benders decomposition method, first, solves the main problem using a possible solution from non-complicating variables. Then, it selects a lower bound for the objective function and obtains the complicating variables [39]. In the second step, Benders decomposition solves BSP while taking into account the output of the complicated variables and sets an upper bound for the objective function from the output of the dual-objective sub-problem and the output from the main objective functions. The algorithm calculates the difference between the upper bounds and lower bounds during each step, and when the difference is below a certain threshold, the algorithm is stopped. In the case where the algorithm does not stop, the optimality cut is imposed on the BMP based on the results of the dual-objective sub-problem. Therefore, the main problem is solved again to obtain the complicating variable and problem-bound results. This algorithm is repeated until the difference between the upper and lower bounds becomes less than a set amount [38].

This model can be presented as below:

Benders Master Problem (BMP)

In a model with fixed variables for vehicle routing and production scheduling, the model becomes a simple problem identifying the quantities to be delivered to the customers at any given node. Our complicated variables are AT_{iv}, B_{ivp}, $X_{hh'v}$, E_{riv}, y_{ic}, L_{ipv}, and C_{max}. Therefore, in the Master Problem frame, they can be portrayed so that Eq. 5 can be used as the objective function and 6, 7, 8, 9, 10, 11, 12, 15, 18, 19, 20, 22, 23, 24, 25, 26, 27 as constraints.

Benders Dual Sub-Problem (B-DSP)

For fixed values of $AT_{iv} = AT.l_{iv}$, $B_{ivp} = B.l_{ivp}$, $X_{hh'v} = X.l_{hh'v}$, $E_{riv} = E.l_{riv}$, $y_{ic} = y.l_{ic}$, $L_{ipv} = L.l_{ipv}$, *and* $C_{max} = C.l_{max}$ and after associating the dual variables $w13 \geq 0, w14 \geq 0, w16 \geq 0, w17 \geq 0, w18 \geq= 0, w21 \geq 0$ with constraints (13), (14), (16), (17) and (21), respectively, the following dual linear problem is obtained:

$$
\begin{aligned}
Zdsp = {} & \sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{v=1}^{V} w18_{ipv} * (lb_{ip}.E.l_{ipv}) - \sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{v=1}^{V} w17_{ipv} * (ub_{ip}.E.l_{ipv}) \\
& + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{v=1}^{V} w14_{ijv} * \left(S.l_{iv} + t_{ih} - M.(1 - x.l_{ijv})\right) \\
& + \sum_{i=1}^{I}\sum_{r=1}^{R}\sum_{v=1}^{V} w13_{riv} * \left(S.l_{iv} + t_{ri} - M.(1 - x.l_{riv})\right) \\
& - \sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{v=1}^{V} w16_{ipv} * \left(-M(1 - L.l_{ipv})\right) \\
& + \sum_{v=1}^{V}\sum_{h=1}^{H}\sum_{h'=1}^{H} f_{hh'v}.X.l_{hh'v} + \sum_{v=1}^{V}\sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{r=1}^{R} c_{rivp}.Z.l_{rivp} + \sum_{c=1}^{C}\sum_{i=1}^{I} a_{ic}.Y.l_{ic}
\end{aligned}
\tag{33}
$$

$$\sum_{r,r\notin UU} w13_{riv} + \sum_{j,i\neq j} w14_{ijv} - \sum_{j,i\neq j} w14_{jiv} - \sum_{p} w16_{ipv} \leq 0 \tag{34}$$

$$-w17_{ipv} + w18_{ipv} + w16_{ipv} - w21_{ipv} \leq 0 \tag{35}$$

$$\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{v=1}^{V} w21_{ipv} \leq 1 \tag{36}$$

The BD effectively converges after a series of finite stages. This algorithm is less efficient in larger problems due to being time-consuming; therefore, accelerators are used to speed this algorithm up. First, many accelerators are implemented on the BMP to increase its convergence rate, decreasing the number of cuts while improving their quality. In this section, there must be a trade-off between the number of iterations and the computational running time. Therefore, two accelerators are presented in the next section to solve larger problems in a more acceptable timeframe.

Pareto-Optimal Cuts (POC)

A method was introduced by Magnanti and Wong (1981) that is used as a cut empowerment technique [40]. BSP might present multiple optimal answers. Therefore, these cuts in different sections can have different qualities and effects. An optimality cut can be created by selecting the more efficient solution, which is better than all other possible cuts, known as the Pareto-optimal Cut (POC).

In the following mathematical model, the variable y is considered as the complicated variable:

$$\min cx + dy \tag{37}$$
$$Ay \geq b \tag{38}$$
$$Ex + Fy \geq h \tag{39}$$
$$x \geq 0, y \in S \tag{40}$$

If the u_a optimal point dominates the u_b optimal point (both of which are optimal answers to the DSP problem), and only then, we will have:

$$\forall y \in S, dy + u_a(h - Fy) \geq \; dy + u_b(h - Fy) \tag{41}$$

If there is at least one $\bar{y} \in S$, we will have:

$$dy + u_a(h - Fy) > \; dy + u_b(h - Fy) \tag{42}$$

Based on the definition of the dominant cut, finding the optimal point for obtaining the dominant cut is of importance. According to [40], if M_u is the optimized multifold answer set of the following DSP model:

$$\max \; (h - f\bar{y})^T u + d\bar{y} \tag{43}$$
$$s.t: E^T u \leq c \tag{44}$$
$$u \geq 0 \tag{45}$$

Then, u_0 as the optimized answer of the following model will create the Pareto-optimal cut:

$$max \; (h - fy^o)^T u + dy^o \tag{46}$$
$$s.t: E^T u \leq c \tag{47}$$
$$u \in M_u \tag{48}$$

In this model, the y_0 variable is a core point integrated convex set of all $y \in S$, because it is not easy to obtain the Benders Master Problem core point. The following general rules are obeyed in calculating the core points [41]:

$$if \;\; y \geq 0 \; then \; y^o > 0 \tag{49}$$
$$if \;\; y \in \{0,1\} \; then \; 0 < y^o < 1 \tag{50}$$

$$if\ y \geq 0\ \&\ \sum_{j=1}^{k} y_j^o \leq P\ then\ \ y^o > 0, \sum_{j=1}^{k} y_j^o < P \tag{51}$$

Therefore, the Pareto model and core point of this problem will be as follows:

$CoreS_{iv}$: *Core Point of* S_{iv}
$Corex_{ijv}$: *Core Point of* x_{ijv}
$CoreL_{ipv}$: *Core Point of* L_{ipv}
$CoreE_{ipv}$: *Core Point of* E_{ipv}
$CoreZ_{rivp}$: *Core Point of* Z_{rivp}
$CoreY_{ic}$: *Core Point of* Y_{ic}

$$\begin{aligned}
&\sum_{i=1}^{I}\sum_{v=1}^{V}\sum_{j=1}^{J} w14_{ijv} * (t_{ij} + CoreS_{iv} - M * (1 - Corex_{ijv})\\
&+ \sum_{i=1}^{I}\sum_{v=1}^{V}\sum_{r=1}^{R} w13_{riv} * (CoreS_{iv} + t_{ri} - M * (1 - Corex_{riv})\\
&+ \sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{v=1}^{V} w16_{ipv} * \left(-1 + CoreL_{ipv}\right) * M\\
&+ \sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{v=1}^{V} w18_{ipv} * \left(lb_{ip} * CoreE_{ipv}\right) + \sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{v=1}^{V} w17_{ipv} * \left(ub_{ip} * CoreE_{ipv}\right) +\\
&\quad \sum_{v=1}^{V}\sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{r=1}^{R} c_{rivp}.CoreZ_{rivp} + \sum_{h=1}^{H}\sum_{h'=1}^{H}\sum_{v=1}^{V} f_{hh'v}.CoreX_{hh'v} + \sum_{c=1}^{C}\sum_{i=1}^{I} a_{ic}.CoreY_{ic}
\end{aligned} \tag{52}$$

$s.t$:

$$\begin{aligned}
zdsp.l = &\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{v=1}^{V} w18_{ipv} * \left(lb_{ip}.E.l_{ipv}\right) - \sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{v=1}^{V} w17_{ipv} * \left(ub_{ip}.E.l_{ipv}\right)\\
&+ \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{v=1}^{V} w14_{ijv} * \Big(S.l_{iv} + t_{ih} - M.\big(1 - x.l_{ijv}\big)\Big)_{ijv}\\
&+ \sum_{i=1}^{I}\sum_{r=1}^{R}\sum_{v=1}^{V} w13_{riv} * \left(S.l_{iv} + t_{ri} - M.(1 - x.l_{riv})\right)\\
&- \sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{v=1}^{V} w16_{ipv} * \Big(-M\big(1 - L.l_{ipv}\big)\Big)\\
&+ \sum_{v=1}^{V}\sum_{h=1}^{H}\sum_{h'=1}^{H} f_{hh'v}.X.l_{hh'v} + \sum_{v=1}^{V}\sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{r=1}^{R} c_{rivp}.Z.l_{rivp} + \sum_{c=1}^{C}\sum_{i=1}^{I} a_{ic}.Y.l_{ic}
\end{aligned} \tag{53}$$

$$\sum_{r,r\notin UU} w13_{riv} + \sum_{j,i\neq j} w14_{ijv} - \sum_{j,i\neq j} w14_{jiv} - \sum_{p} w16_{ipv} \leq 0 \tag{54}$$

$$-w17_{ipv} + w18_{ipv} + w16_{ipv} - w21_{ipv} \leq 0 \tag{55}$$

$$\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{v=1}^{V} w21_{ipv} \leq 1 \tag{56}$$

Heuristics

Because the set of complicated variables is used to determine cuts directly affects the number of iterations These solutions are traditionally found by exact or approximate methods solving the regular MP. For improving the quality or generating solutions faster, three approaches have been suggested: (1) using alternative formulations, (2) enhancing the BMP formulation, and (3) using heuristics to generate solutions independently or improve existing solutions.

Researchers have found that applying a heuristic or metaheuristic method to Benders' approach improves performance [43]. Even though the mentioned accelerators can highly reduce the gap resulting from Benders decomposition, there remains a problem of insufficient convergence after multiple iterations. The challenge here is developing an algorithm to solve the proposed model efficiently, but that is what this paper seeks to accomplish.

In order to extend the relaxed MP, Heuristics is used to create preliminary tight cuts as a warm-start strategy. There is no doubt that heuristic and meta-heuristic algorithms should pertain to the problem under study [44].

The meta-heuristic method is used for solving BMP, which is the standard execution of the Benders decomposition algorithm, to present a preliminary and feasible answer and create a cut based on it [45]. An essential intelligent optimization algorithm from swarm intelligence is particle swarm optimization (PSO). In 1995, James Kennedy and Russell C. Eberhart developed this algorithm based on observing animal social behavior, such as fish and birds that live in small and large crowds. Based on direct interaction, sharing information, and recollecting good memories between members of the answer population, the PSO algorithm solves the problems [46]. we present a computational-efficient algorithm for solving BMP, which is based on the principles of particle swarm optimization (PSO) [48].

Performance evaluation and computational results

The result of four solution approaches is compared in this section (CPLEX, Classic Benders Decomposition, Pareto optimality cut and Warm-up strategy). The optimality of all problems is determined, and in Table 5, you will find details such as the average number of iterations and average running time for each case. Twenty distinct instances exist for each class.

We randomly generated instances to assess the performance of the developed algorithms for a wide range of situations. Our test was composed of instances generated with the following parameters:

- Number of product p ordered by the customer C, d_{cp}: randomly generated number in the interval [10, 100].
- Upper bound of product p production time, ub_{ip}: randomly generated number in the interval [1000, 2000].
- Lower bound of product p production time, lb_{ip}: randomly generated number in the interval [300, 1500].
- Transport cost of the customer C towards the i-th node to meet their demand, a_{ic}: randomly generated number in the interval [100, 300].
- Interval between node h and h', $t_{hh'}$: randomly generated number in the interval [0.1, 0.8].
- Production rate of product p in mobile facility v based on each unit of time, α_{pv}: randomly generated number in the interval [0.1, 1].
- Production cost of product p for the $i-th$ node by machine v started from the depot r, c_{rivp}: randomly generated number in the interval [100, 300].

- Transport cost from node h to h' with mobile facility v, $f_{hh'v}$: randomly generated number in the interval [150, 450].
- Facility capacity of the demand node i for product p, cap_{ip}: randomly generated number in the interval [40, 120].
- Movement radius of the costumer C, R_c : randomly generated number in the interval [6, 9].
- Distance between customer C, and the *i-th* node, where their demand is met, m_{ic} : randomly generated number in the interval [150,*350*].

The sizes of the cases that are used in all cases are presented in Table 2. Table 3 presents the number of binary variables, integer variables, continuous variables, and the number of constraints of each case.

Table 2. Size of the cases

Type	Case	Number of binary variables	Number of Continuous Variables	Number of integer Variable	Number of Constraints
Small Size	Case 1	50	25	16	227
	Case 2	112	41	32	449
	Case 3	204	81	64	873
	Case 4	220	97	96	1097
	Case 5	508	257	400	3432
Medium Size	Case 6	710	353	576	4839
	Case 7	1210	371	500	5210
	Case 8	910	441	1080	8470
Large size	Case 9	11900	5101	13500	104520
	Case 10	25250	11001	40000	290700

Table 3. Number of the variables

Case	*h*	*i*	*r*	*v*	*p*	*c*
Case 1	4	2	2	2	2	5
Case 2	6	4	2	2	2	5
Case 3	6	4	2	4	2	5
Case 4	6	4	2	4	3	5
Case 5	7	5	2	4	10	20
Case 6	8	6	2	4	12	25
Case 7	12	10	2	5	5	20
Case 8	8	6	3	5	12	30
Case 9	20	20	3	15	15	40
Case 10	25	25	4	20	20	50

Table 4. Abbreviation of different methods

CBD	Classic Benders decomposition, without any acceleration techniques
PC	Pareto-optimal cuts
WS	Using MOPSO for feasible answer

A list of acceleration methods and some other abbreviations can be found in Table 4. Table 5 contains the results of Benders decomposition applied to 8 acceleration cases with various acceleration techniques. The CBD and PC algorithms are ineffective in solving this problem in small cases. However, there are improvements in large cases. For example, it is easier to produce optimality cuts when PC is used. However when working with large-scale cases, WS is better than other acceleration methods.

Table 5. Comparison of CPLEX, CBD, PC and WS

	Average number of iterations			Average running time (sec.)				Optimality	Gap
	CBD	PC	WS	CPLEX	CBD	PC	WS		
Case 1	3	4	1	0.134	0.909	1.29	0.166	Yes	0 %
Case 2	5	5	1	0.181	2.63	2.05	0.22	Yes	0 %
Case 3	6	5	1	0.332	1.887	1.8	0.386	Yes	0 %
Case 4	6	5	2	0.33	2.42	2.07	0.28	Yes	0 %
Case 5	5	4	2	0.37	2.6	2.2	0.32	Yes	0 %
Case 6	11	8	3	123.752	96.73	91.23	8.75	Yes	0 %
Case 7	15	10	6	660.84	145.63	120.2	11.41	Yes	0 %
Case 8	21	16	9	3621	362.235	312.82	42.33	Yes	0 %
Case 9	56	50	21	NA*	4145.63	4120.2	411.41	No	2 %
Case 10	93	72	31	NA	8362.235	8312.82	1042.33	No	5 %

* The time to solve this problem with this method was more than one day.

Sensitivity Analysis

We focus on the α_{vp} parameter due to its considerable effect on production to analyze the sensitivity. As was expected, the increase of the α_{vp} parameter leads to a decrease in the usage of the facility because an increase in this parameter leads to lower production and higher staying time at the node; therefore, the model is willing to move to feasibility and using other facilities even by increasing its costs.

In this section, an example with two MFs is analyzed and other parameter and variable is similar to Case 2. In the first MF, α_{vp} is greater than the second MF. In a typical example, each MF meets two nodes and responded to the demand of two customers, but when the parameter is manipulated, the first MF only meet one node and the second MF meet another one. So, increasing α_{vp} leads to a decrease in the usage of the v_1 facility.

Also, the model must find an answer to meet demands in the node with other constraints such as production capacity due to the facility limit, time window, radial, and time intervals. Therefore, even with the decreased α_{vp} of each facility, another facility does not undergo much change to optimize the target function generally. Another important point to note is no attention has been paid to the production rate in different facilities but in the real world, it has to be calculated.
Here the v_2 is analyzed:

Table 6. Sensitivity analysis

	Tolerance of α_{v_2p}	Number of nodes that v_2 visits.	Sum of weighted objective functions
α_{v_2p}	+70	0	3967446
	+50	1	3831508
	0	2	3773031
	-50	2	3772459

Conclusion

A mobile facility's integrated production and distribution stages scheduling at the operational level are crucial for reducing operational costs and customer wait times, two critical aspects of a company's success. Yet, the majority of integrated production and distribution scheduling models analyze only tactical or strategic decisions, and only a tiny number examine integrated operational decisions. Therefore, this study has tried to analyze mobile facilities as an innovation in production and distribution scheduling at the operational level. For this, a novel mathematical model for the integrated production and distribution scheduling problem was presented by considering some real-world attributes, which lead to a decrease in customer wait time alongside the costs. We propose Benders decomposition algorithm to solve the issue. Benders decomposition's two computational enhancements are also made, namely, the Pareto optimality cut and warm-up start heuristic. Based on the computational results, these acceleration strategies improve Benders decomposition efficiency for handling large instances. We can apply this model to all producers and distributors of perishable commodities with expiration dates, such as dairy products, pharmaceuticals, chemicals, and masks produced for our country's citizens during this pandemic.

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