

Shahmoradi-Moghadam, Hani; Schönberger, Jörn

**Article**

## Joint optimization of production and routing master planning in mobile supply chains

Operations Research Perspectives

**Provided in Cooperation with:**

Elsevier

*Suggested Citation:* Shahmoradi-Moghadam, Hani; Schönberger, Jörn (2021) : Joint optimization of production and routing master planning in mobile supply chains, Operations Research Perspectives, ISSN 2214-7160, Elsevier, Amsterdam, Vol. 8, pp. 1-9, <https://doi.org/10.1016/j.orp.2021.100187>

This Version is available at:

<https://hdl.handle.net/10419/246446>

**Standard-Nutzungsbedingungen:**

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

**Terms of use:**

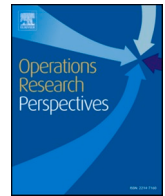
*Documents in EconStor may be saved and copied for your personal and scholarly purposes.*

*You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.*

*If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.*



<https://creativecommons.org/licenses/by/4.0/>



# Joint optimization of production and routing master planning in mobile supply chains

Hani Shahmoradi-Moghadam<sup>a,\*</sup>, Jörn Schönberger<sup>b</sup>

<sup>a</sup> Technische Universität Dresden, Boysen-TU Dresden-Research Training Group, Germany

<sup>b</sup> Technische Universität Dresden, Institute of Transport and Economics, Germany

## ARTICLE INFO

### Keywords:

Mobile supply chains  
Production routing problem  
Distributed manufacturing system  
Multi-objective optimization  
Mobile factory

## ABSTRACT

Many supply chains suffer from a lack of flexibility, adaptability, and robustness, which imposes customer dissatisfaction, transportation, backlog, and rework costs on companies. The mobile supply chain (MSC) is a newly developed idea that aims to rectify this problem. In this kind of supply chain, production, distribution, and delivery of a product family are performed by a mobile factory (MF), which can be carried by truck, while stationary production sites are no longer required. The production process is completed directly at the customer's location following customer detail requirements. In this paper, a mathematical model is developed to optimize the mobile factory routing problem as well as production scheduling at each customer's site, which is inspired by a real-world application of modular production in the chemical industry. For this purpose, due dates of customers' work orders and transportation costs should be considered simultaneously. The model results indicate that if these objective functions are taken into account separately, the results will be sub-optimal solutions causing substantial financial losses for customers and suppliers. The proposed bi-objective model using a multi-objective optimization approach proffers a Pareto frontier. Accordingly, decision-makers can choose from a range of solutions, from zero delayed orders to the lowest transportation costs. However, in many cases it is possible to reach zero delayed orders with just a small increase in transportation costs.

## 1. Introduction

In traditional supply chains, production sites are assumed to be stationary factories. These production sites typically produce a large number of products in a few central manufacturing sites to supply end customers using a distribution network [1]. This concept enables companies to take advantage of economies of scale and manage every production detail centrally. However, it cannot provide the desired robustness, flexibility, and adaptability in many cases, forcing companies to seek alternative solutions. So-called distributed manufacturing systems (DMS) represent an ideal approach to meeting challenges regarding the individualization of products, customer proximity, or more sustainable production [2].

The mobile supply chain (MSC) idea is based on the concept of DMS and aims to produce in close proximity to customers to enhance responsibility and service levels. In MSCs, manufacturing facilities are carried on vehicles to provide real-time services for geographically dispersed customers [3]. This idea can help companies to bring about the following benefits:

**To manage demand peaks.** Using mobile factories (MF) as temporary backup resources, companies can cover occasional demand peaks or machine shutdowns.

**To support mass customization.** By producing at the customer's location and including customer wishes and specific order details in the production process, companies can enhance their flexibility, adaptability, and accessibility significantly.

**To reduce asset investment costs.** By sharing (renting) expensive machines with low production rates or machines which are just needed for a short period, companies are able to lower their capital expenses.

**To optimize logistics costs.** Using the DM concept reduces not only transportation costs, but also modifies supply chain sustainability [4]. Moreover, using MFs enables companies to apply the concept of just-in-time (JIT) delivery, which can remove warehousing and inventory costs.

MFs are used in different industrial sectors for different purposes. In health care systems, blood donation units [5] and mobile X-ray units [6]

\* Corresponding author.

E-mail addresses: [hani.shahmoradi@tu-dresden.de](mailto:hani.shahmoradi@tu-dresden.de) (H. Shahmoradi-Moghadam), [joern.schoenberger@tu-dresden.de](mailto:joern.schoenberger@tu-dresden.de) (J. Schönberger).

<https://doi.org/10.1016/j.orp.2021.100187>

Received 13 August 2020; Received in revised form 19 April 2021; Accepted 19 April 2021

Available online 26 April 2021

2214-7160/© 2021 The Author(s).

Published by Elsevier Ltd.

This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

are being used to deliver service in remote areas. Floating production storage and offloading facilities (FPSO) have been utilized in the oil and gas industry for many years to reduce processing times and logistic costs [7]. Floating power plants are more resilient against natural disasters (e. g., earthquakes and tsunamis) and can be deployed to deliver energy to remote areas shortly after natural disasters or breakdowns of the aging power plants currently in use [8]. In the recycling industry, mobile plastic recycling plants, as well as mobile biomass pelletizer machines, can reduce the transportation costs of massive amounts of recyclable materials tremendously [9].

Modular manufacturing is one of the most extensive applications of MSCs which has developed in different chemical and process industries recently [10]. Processes have to quickly respond to market changes and individual customer requirements and utilizing modularization enables companies to deliver the product to market faster, to enhance the flexibility of product variety, and to increase production efficiency achieved by the reuse of facilities [11]. Small modular plants have low financial risks, are flexible, and can react quickly to fluctuations in demand; furthermore, modularization of chemical production can thus have significant economic and safety gains [12].

Carrying a factory in a container and producing at the customer's location introduces several challenges. First of all, facility location is categorized as a strategic level decision in supply chain management [13]. However, in the mobile supply chains, the MF location may change in short periods, meaning location is an operational-level decision in MSCs. Secondly, the MF should deliver services for several customers that have different due dates for their job orders; therefore, the vehicle routing problem (VRP) is another aspect of a MSC's optimization problem. Thirdly, production master planning at customers' plants should be matched with the movements and stays of the mobile factory (MF). Accordingly, production and routing planning should be coordinated in such a way that reduces delay time and transportation costs. Finally, in MSCs, there is no separated manufacturing level and distribution level because both levels are merged in mobile facilities, which can produce, distribute, and deliver simultaneously.

In this paper, a mathematical model for modular production and MF routing master planning is developed to optimize delayed orders and transportation costs. All customers use multi batch processing machines (BPM) [14], which use a family of chemical materials to process on a predefined production line. Processing on a specific BPM can only start when the MF is available at the customer's location. The main concern in integrating production scheduling and vehicle routing research [15] is matching the production planning of suppliers with delivery and distribution schedules. However, in MSCs, all production steps are accomplished at the customer's plant and the MF routing problem should be integrated in such a way that meets JIT conditions.

The remainder of this paper is organized as follows. Section 2 briefly reviews related works and efforts and Section 3 explains the problem specification, mathematical modeling, and optimization approach. In Section 4, data generation and experimental results are presented and managerial insights are highlighted. Conclusions and recommendations for future research is described in Section 5.

## 2. Literature review

The idea of mobile manufacturing systems has appeared under different names in different publications, such as Factory in a Box [16], plug and produce [17], mobile on-site factory [18], location independent [19], movable production systems [20], and reconfigurable manufacturing system [21]. The main concept behind these subjects is the same, but they differ in their application.

Ask and Stillström [22] provide a summary of the requirements to utilizing the MF system, and present industrial examples of how, and under which conditions, the Factory in a Box concept could be adopted. [3] presented a research project in Sweden called Factory in a Box to extend mobile production capacity when and where necessary. The

concept of mobile manufacturing presented in [23] via the results of five prototype projects in the Factory in a Box research project as well as implementation difficulties. Rauch et al. [24] showed MFs to be well-suited for the construction industry, where long distances and high logistics costs can be expected. An analysis conducted by Benama et al. [25] presents features, assessment attributes, and decision criteria of the mobile manufacturing system.

In literature, several research fields can be found which have some intersections with MSC optimization. A comprehensive review of integrating production and distribution scheduling operations' mathematical models can be observed in the study carried out by Moons et al. [15]. In this research field, the production process is performed at the origin point, with the final product then being distributed to the end customer by a number of vehicles. Moreover, the MF movement can be modeled as a VRP with service time [26]. A complete review on this topic can be seen in [27]. Dynamic Facility Location (DFL) is another research area that looks at determining where and when to present capacity to meet customer need at the minimum cost [28].

The Mobile Facility Routing Problem (MFRP), first introduced by Halper and Raghavan [29], tries to find routes for a fleet of mobile facilities that maximize the service level by these MFs over a continuous-time planning horizon. A two-stage stochastic programming model for a mobile facility routing problem was proposed by Lei et al. [30], in which the first stage decision takes into account temporal and spatial movement of MFs and the second stage deals with MF service at the customer's location. To solve the model, they utilized an algorithm based on the multi-cut version of the L-shaped method. Qi et al. [31] presented a model for MFRP which considers the service-time related demand rate and fairness constraints.

Hohmann et al. [32] proposed general requirements for modules in process engineering and surveyed modules for specific applications in the chemical and biochemical industry, stating that modules, main equipment items, and databases are critical advantages to lessen many chemical products' lead times. Becker et al. [33] investigated the performance of three mixed-integer formulations for modular production network design under uncertainties. In the research proposed by Becker et al. [34], mixed-integer programming formulations for the tactical planning of production networks in the chemical industry were introduced. The models addressed the volume, location, and process of modular plants in the production network in a multi-period problem. For more studies on modular production applications and challenges in the chemical industry, readers are referred to [12].

From what has been discussed above, MSC is an exciting idea that aims to overcome supply chain shortcomings related to a lack of flexibility, adaptability, and logistics costs to meet customer orders. This idea has appeared with different names, and the MSC idea has become a promising approach in modular production, especially in the chemical industry. In this paper, some gaps in the mobile supply chain scope are covered, and the following contributions are categorized:

- Developing an optimization model for mobile supply chain optimization considering logistical costs
- Expanding the idea of the mobile supply chain to ensure this idea can meet customer needs in an efficient way
- Matching production and batching activities in each customer site with the vehicle (MF) routes as a new paradigm in the production routing problem
  - Implementation of the MSC concept on batch processing machines
- Contrary to existing problems such as MFRP, we assume some machines are already in place at production sites (customers) and the MF will be added to the production line as a temporary production machine to produce some intermediate products.

## 3. Problem definition and the proposed model

This problem is inspired by a real world application, and each

production step consists of one BPM. A BPM is a type of manufacturing machine in which various jobs are processed simultaneously, and all the jobs in a batch begin and end processing at the same time [35]. Industrial applications of BPMs can be found in semiconductor burn-in operations, environmental stress-screening (ESS) chambers, chemical, food, and mineral processing, etc. [36].

This paper addresses an application of MSC in chemical material production. As shown in Fig. 1., the mobile factory can produce some intermediate products. In this special industrial application, these chemical products are used in the electronics industry. The production line at each manufacturing site consists of two or more BPMs, which have a flow shop layout (See Fig. 2). Job orders are grouped in batches to be processed on BPMs respectively. Critical moveable production machines (e.g. reactor) are carried by the mobile factory and produce a product family locally and flexibly.

This problem addresses two main stakeholders of the MSC. The first one is the main supplier who owns the mobile factory fleet. The second stakeholder includes the manufacturing sites. To process a job order, each manufacturing site requires a specific chemical material which is provided by the MFs in one of the production steps. In order to start, and continue operation on one of the BPMs, the presence of an MF is necessary.

The main concern in this problem is the coordination of these two stakeholders of the MSC. Production planners in the manufacturing sites should consider the job orders' due dates and plan their production schedules accordingly. On the other hand, the MF fleet manager should minimize the associated transportation costs. The production schedules and the MFs' routes and time present at a location should be matched. Otherwise, the MF is already present at the manufacturing site before it is needed or, conversely, due dates of job orders would be missed because the MF arrives too late.

Production scheduling at the customers' production sites should be matched with the MF arrival time ( $Z_i$ ). In Fig. 3 an MSC is illustrated which indicates that, in this kind of supply chain, there is no separated manufacturing and distribution levels. As depicted in this figure, the MF has to move toward customer manufacturing sites ( $i \in I$ ) to provide some products at their location. These customers have their own job orders ( $n \in N$ ), and each order has a predefined due date ( $du_{ni}$ ). To operate on a specific batch processor machine in the production sites, they require a particular product that can be produced by the MF, which is managed by the original supplier. This MF can produce a family of products at the customers' locations upon their specific order details.

First of all, different orders should be grouped into different batches ( $b \in B$ ), with operations on the first batch beginning on the first machine. It should be considered that the processing time of each batch on each machine ( $Q_{bmi}$ ) is equivalent to the max processing time of jobs ( $p_{mni}$ ) in the batch. Before processing on machine No. 2, the MF must be present at the customer's site because starting the process without availability of the specific product produced by the MF is not possible. Therefore, after the MF's arrival time ( $Z_i$ ), the process on the specific machine can start ( $ST_{mi}$ ), and a completion time ( $FT_{mi}$ ) of the last batch on BPM2 is calculable.

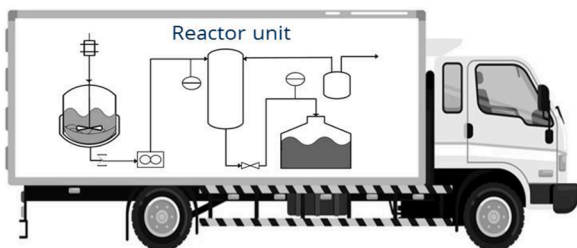


Fig. 1. Schematic of a mobile factory.

### 3.1. Assumptions and notations

The assumptions of the model are as follows:

- The MF fleet is homogenous.
- The MF can produce a product family.
- The MF has a fixed capacity.
- Each BPM has a fixed capacity.
- Each job order has a specific size.
- The manufacturing sites are homogenous.
- The production lines consist of two or more BPMs which have flow shop layouts.
- To start, continue, and finish operation on a pre-defined BPM, the presence of an MF is necessary.
- Each MF's tour starts and ends from the depot node.

The modeling indices, parameters, and decision variables are defined below.

#### Sets

$I$	Customer production sites, where $i, j \in I$
$N$	Jobs, where $n \in N$ .
$M$	Machines, where $m \in M$ .
$B$	Batches, where $b \in B$ .
$K$	Positions in sequence, where $k \in K$ .

#### Parameters

$p_{mni}$	Processing time of job $n \in N$ on the machine $m \in M$ in production site $i \in I$ .
$s_{ni}$	Size of job $n \in N$ in production site $i \in I$ .
$cap_m$	Capacity of machine $m \in M$ .
$d_{ij}$	Distance between node $i$ , and $j \in I$
$tc$	Average transportation cost rate, $\text{€}/\text{Km}$
$dm_i$	Demand of customer $i \in I$
$dc$	The mobile factory capacity
$\bar{v}_{ij}$	Average speed of the MF to cross arc $(i, j)$ $i, j \in I$
$du_{ni}$	Due date of job order $n \in N$ at customer site $i \in I$
$h$	Number of MFs

#### Variables

$X_{ibn}$	A binary variable indicates the assignment of job $n \in N$ to the batch $b$ at site $i$
$Q_{bmi}$	Processing time of batch $b \in B$ on the machine at site $i \in I$
$C_{b,m,i}$	Completion time of the $b$ th batch $b \in B$ on the machine $m \in M$ at site $i \in I$
$Cmax_{ni}$	Completion time of the of job $n \in N$ (makespan) at site $i \in I$
$ST_{mi}$	Starting time of service on machine $m \in M$ at site $i \in I$
$FT_{mi}$	Finishing time of service on machine $m \in M$ at site $i \in I$
$SE_i$	The mobile factory service time duration at site $i \in I$
$Y_{ij}$	A binary variable equals 1 if arc $(i, j)$ $i, j \in I$ appears in the solution
$F_{ij}$	Total amount of flow in arc $(i, j)$ $i, j \in I$
$Z_i$	Arrival time of the mobile factory at site $i \in I$ .
$DE_{ni}$	Delay value for job order $n \in N$ from customer $i \in I$ .

### 3.2. Mathematical formulation

The joint optimization model for production and MF routing in mobile supply chains can now be developed by incorporating the idea of mobile factories [16], production scheduling of batch processing machines [14], and the mobile factory routing problem.

#### 3.2.1. Objective function

There are two contradictory goals in the problem, each of which originates from a stakeholder in this problem. On the one hand, we have to optimize the associated transportation costs, which is relevant for transportation planner and the MFs' managers. On the other hand, we have to take into account customers' liabilities to the next level of the

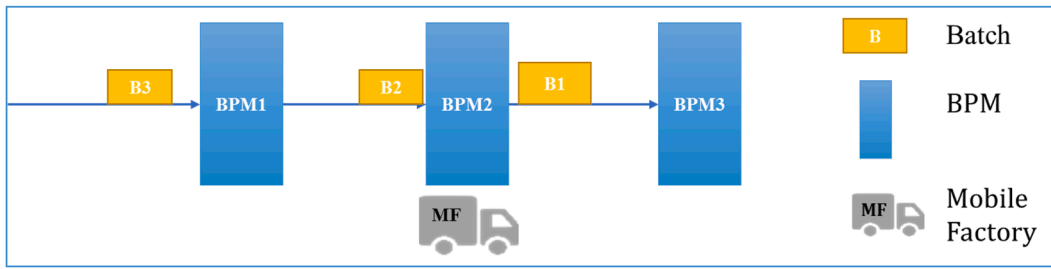


Fig. 2. Schematic of the production process.

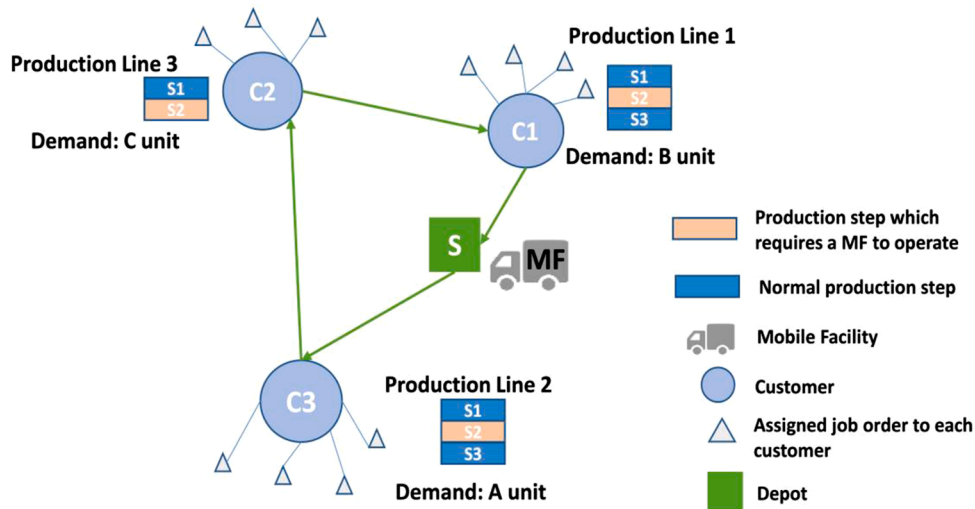


Fig. 3. Mobile supply chain illustration.

supply chain. They must complete job orders according to their due dates. For this purpose, the MF route ( $Y_{ij}$ ), order batching ( $X_{ibn}$ ), and batch sequencing ( $C_{b,m,i}$ ) should be determined in such a way that minimizes transportation costs and total job order delays simultaneously. Therefore, the objective function can be modeled as a bi-objective function problem as follows:

$$F1 = \text{Min Transportation Cost} : \sum_{i=1}^I \sum_{j=1}^J tc \times di_{ij} \times Y_{ij} \tag{1}$$

$$F2 = \text{Min Total Delay} : \sum_{i=1}^I \sum_{n=1}^N DE_{ni} \tag{2}$$

### 3.2.2. Constraints

Now, the problem constraints are formulated. As mentioned above, the main challenge in this problem is matching the production schedules of manufacturing sites and the MF fleet's routing planning. Furthermore, capacity, scheduling, and routing constraints should be taken into account. The problem constraints are as follows:

$$\sum_{b=1}^B X_{ibn} = 1 \quad \forall i \in I, n \in N \tag{3}$$

$$\sum_{n=1}^N s_{ni} X_{ibn} \leq cap_m \quad \forall b \in B, i \in I, m \in M \tag{4}$$

$$p_{mni} X_{ibn} \leq Q_{bmi} \quad \forall b \in B, i \in I, m \in M \tag{5}$$

$$Q_{bmi} \leq M \sum_{n=1}^N X_{ibn} \quad \forall b \in B, i \in I, m \in M \tag{6}$$

$$C_{1,m,i} \leq \sum_{r=1}^{r \leq m} Q_{1ri} \quad \forall b \in B, m \in M \tag{7}$$

$$C_{k,1,i} \leq \sum_{b=1}^B Q_{b1i} \quad \forall k \in B, i \in I \tag{8}$$

$$C_{b,m,i} \geq C_{b-1,m,i} + Q_{bmi} \quad \forall b > 1 \in B, m > 1 \in M \tag{9}$$

$$C_{b,m,i} \geq C_{b,m-1,i} + Q_{bmi} \quad \forall b > 1 \in B, m > 1 \in M \tag{10}$$

$$Cmax_{ni} \geq C_{b,m,i} \times X_{ibn} \quad \forall b \in B, i \in I, m \in M \tag{11}$$

$$ST_{mi} \leq C_{bmi} - Q_{bmi} \quad \forall b \in B, i \in I, m' \in M \tag{12}$$

$$FT_{mi} \geq C_{bmi} \quad \forall b \in B, i \in I, m' \in M \tag{13}$$

$$\sum_{i=1}^I Y_{ij} = 1 \quad \forall j \in I \tag{14}$$

$$\sum_{j=1}^I Y_{ij} = 1 \quad \forall i \in I \tag{15}$$

$$\sum_{j=1}^I Y_{0j} = h \tag{16}$$

$$\sum_{j=1}^I F_{ji} - \sum_{j=1}^I F_{ij} = dm_i \quad \forall i \in I \tag{17}$$

$$F_{ij} \leq (dc - dm_i) \times Y_{ij} \quad \forall i, j \in I$$

$$F_{ij} \geq dm_j \times Y_{ij} \quad \forall i, j \in I \quad (18)$$

$$Z_i - Z_j + SE_i + \frac{di_{ij}Y_{ij}}{\bar{v}_{ij}} \leq M(1 - Y_{ij}) \quad \forall i, j \in I, i \neq j, \text{ and } j > 0, 'm' \in M \quad (19)$$

$$\frac{di_{ij}Y_{ij}}{\bar{v}_{ij}} + FT_{mi} - Z_j \leq M(1 - Y_{ij}) \quad \forall i, j \in I, i \neq j, \text{ and } j > 0, 'm' \in M \quad (20)$$

$$Z_0 = 0 \quad (21)$$

$$FT_{mi} - ST_{mi} = SE_i \quad \forall i > 0 \in I, 'm' \in M \quad (22)$$

$$ST_{mi} \geq Z_i \quad \forall i > 0 \in I, 'm' \in M \quad (23)$$

$$Cmax_{ni} - du_{ni} = DE_{ni} \quad \forall i > 0 \in I, n \in N \quad (24)$$

$$Y_{ij}, X_{ibn} \in \{0, 1\} \quad (25)$$

$$ST_{mi}, Cmax_{ni}, FT_{mi}, SE_i, F_{ij}, DE_{ni}, C_{bmi}, Q_{bmi}, Z_i \geq 0$$

The bi-objective function (1) minimizes the MF transportation costs and total job order delays. Constraints (2)-(3) ensure that all jobs in all manufacturing sites are assigned to a batch, and machine capacity is not violated. The processing time of each batch and its completion time are calculated in constraints (5)-(9) and makespan of each job order is computed in limitation (10). Starting and finishing time of operation with a specific machine 'm' ∈ M, which works only when the MF is present at the manufacturing site, are expressed in constraints (11) and (12). Constraints (13) and (14) enforce that each customer should be visited once and constraint (15) states that the number of hired vehicles should not exceed 1. Constraints (16) to (18) ensure flow balance and constraints (19) to (22) compute arrival time and service time duration at each customer site, while constraint (23) ensures that operation on a specific machine cannot start before the arrival of the MF. Eq. (24) determines the delayed time of each job order and constraint.

### 3.3. Linearization

The model formulation (1)-(24) is nonlinear according to the term  $C_{b,m,i} \times X_{ibn}$  in constraint (10). This formulation can be linearized using a new auxiliary variable named  $A_{nbim}$  and new constraints (27) and (28). Therefore, the model reformulation is as follows:

$$F1 = \text{Min Transportation Cost} : \sum_{i=1}^I \sum_{j=1}^J tc \times di_{ij} \times Y_{ij}$$

$$F2 = \text{Min Total Delay} : \sum_{i=1}^I \sum_{n=1}^N DE_{ni} \quad (26)$$

Subject to constraints (2)–(9), (11)–(25), and:

$$\begin{cases} A_{nbim} \geq C_{bmi} + M(X_{ibn} - 1) \quad \forall b \in B, i \in I, m \in M \\ A_{nbim} \leq C_{kmi} + M(X_{ikn} - 1) \quad \forall b \in B, i \in I, m \in M \\ A_{nbim} \leq MX_{ibn} \quad \forall b \in B, i \in I, m \in M \end{cases} \quad (27)$$

$$Cmax_{ni} \geq A_{nbim} \quad \forall i > 0 \in I, m \in M, b \in B, n \in N \quad (27a)$$

$$A_{nbim} \geq 0 \quad (28)$$

### 3.4. Multi-objective reformulation

In order to solve the proposed multi-objective model, an efficient multi-objective approach, the so-called augmented ε-constraint method (AUGMECON) [37], is adopted. This approach avoids weak Pareto solution production and the whole procedure is faster as it avoids useless iterations.

In the ε-constraint method, first of all, the payoff table should be created. After that, the ranges from the payoff table are utilized to apply the method. The AUGMECON employs lexicographic optimization to build the payoff table (see Fig. 4). Then, the range of the *i*th objective function is split to *q<sub>i</sub>* intervals using *q<sub>i</sub>* - 1 grid points. Therefore, there are *q<sub>i</sub>* + 1 grid points altogether which are used to range the RHS (*e<sub>i</sub>*) of the *i*th objective function parametrically. Finally, the whole number of runs will be (q<sub>2</sub>+1) × (q<sub>3</sub>+1) × ... × (q<sub>n</sub>+1) [37]. Accordingly, the model should be reformulated as follows:

$$\text{Min } F1 = \sum_{i=1}^I \sum_{j=1}^J tc \times di_{ij} \times Y_{ij} + \varepsilon(S_2/r_2) \quad (29)$$

Subject to constraints (1) to (9), (11) to (28), and:

$$F2 = \sum_{i=1}^I \sum_{n=1}^N DE_{ni} \quad (30)$$

$$F2 + S_2 = e_2 \quad (31)$$

$$e_2 = UB_2 - \frac{i \times r_2}{g_2} \quad (32)$$

Where:

*UB<sub>2</sub>*: lower bound of F2

*r<sub>2</sub>*: range of F2

*g<sub>2</sub>*: number of grid points

*i*: a counter to produce Pareto optimal solutions

## 4. Experimental results

In this section, the computational results and sensitivity analysis are presented to evaluate the model's performance and effectiveness in practice.

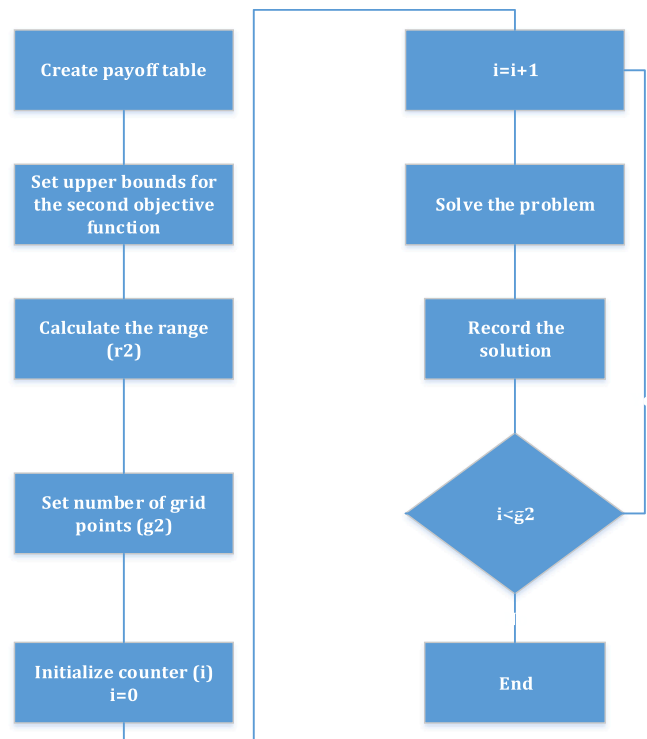


Fig. 4. Flowchart of the AUGMECON method for a bi-objective problem.

4.1. Experimental design

The application of the proposed model was examined by six different randomly generated examples with different problem sizes. The data examples and their random data generation pattern was inspired by a real-world application, as reported in Table 1. The computational experiments for these data sets were completed using CPLEX solver embedded in GAMS 30.3 on a laptop with Intel Core i5-8250U CPU @ 1.6 GHz and 8GB of RAM.

As described in Section 3, the MSC problem consists of two sub-problems, namely production scheduling and a facility routing problem. These sub-problems are interconnected as the production process on BPM2 can only be accomplished when the MF is made available at the production site, not before. The developed multi-objective model is solved via the above-mentioned method, AUGMECON [37].

4.2. Computational Results

In Table 2, the pay-off table for 12 different data sets is presented. The findings here clearly show that ignoring either sub-problem results in poor performance for each stakeholder. The generated examples include data sets from 4 to 9 customer production sites, 5-10 job orders, 1 to 2 MF, and 2 to 3 BPM. As a notation utilized in the paper, AiBnChDM corresponds to a test problem with A number of sites, B number of job orders in each site, C number of available MFs, and D number of BPMs. It should be noted that a data set with 4 production sites (i) and 10 job orders (n) has 40 job orders in total which are distributed among production sites equally without a loss of generality.

In all reported examples in Table 2, reaching 0 (or negligible) total delay is achievable; however, transportation costs increase by up to 43.5% when doing so. This table proves that considering each sub-problem (production scheduling and facility routing) separately would provide suboptimal or infeasible solutions and the model developed here can, depending on the problem size, prevent delays ranging from 34 to 698 h.

In Table 3 the model results in different data sets and the grid points are reported. As mentioned above, this problem consists of two sub-problem problems, i.e. the capacitated vehicle routing problem with service time and flow shop scheduling problem with batch processing machines. Considering that both sub-problems are NP-hard [38],[39], [35]], the main problem is NP-hard as well. Although solving this problem in large-scale data sets is time-consuming, the studied problem sizes can be solved in reasonable time. Finally, as expected, the problem solution time has a direct relationship with the number of job orders and sites, but an inverse relationship with the number of MFs.

Table 3 also presents a range of options from which decision-makers can choose their preferred one. Selecting the most conservative solution supports customers by decreasing delay time (F2). However, this solution leads to high transportation costs. Accordingly, decision-makers should trade off between the Pareto frontier nodes. Furthermore, it can be understood from data sets No. 3 and 5 that using only one MF not only fails to reach a zero delay time, but also increases solution time significantly.

The Pareto frontier for a few data sets is depicted in Fig. 5. According to this figure, conservative decision-makers, for whom customer service quality is more of a priority, have the possibility to choose a solution

Table 1  
Input data.

Parameter	Value	Parameter	Value
$p_{mi}$	$\sim u(2,10)$	$\bar{v}_{ij}$	$\sim u(30,80)$
$s_{ni}$	$\sim u(2,7)$	$dt_{ni}$	$\sim u(50,700)$
$d_{ij}$	$\sim u(200,800)$	$tc$	6€/Km
$dm_i$	$\sim u(20,50)$	$g_2$	4

Table 2  
Payoff table obtained by AUGMECON.

No.	Size	Lower bound (LB)		Upper bound (UB)		Relative gap % $100 \times (UB - LB) / (UB)$	
		F1 (€)	F2(h)	F1(€)	F2(h)	F1	F2
1	4i5n1h3m	16326	0	18330	57	10.93%	100%
2	4i10n2h3m	18378	0	20556	74	10.60%	100%
3	5i5n1h3m	16758	8	21126	76	20.68%	89%
4	5i10n2h2m	19716	0	22404	269	12.00%	100%
5	6i5n1h3m	13842	12	15540	71	10.93%	83%
6	6i7n2h2m	16320	0	19740	140	17.33%	100%
7	6i10n2h3m	16320	4	22254	233	26.66%	98%
8	7i7n2h3m	14100	0	17802	48	20.80%	100%
9	7i10n2h2m	14100	0	20568	294	31.45%	100%
10	8i5n2h3m	12348	0	15756	34	21.63%	100%
11	8i7n2n2m	12348	0	16176	262	23.66%	100%
12	9i5n2h3m	11380	0	19038	47	40.22%	100%
13	9i7n2h2m	11380	0	20142	698	43.50%	100%

with zero delays. However, in some data sets (e.g. 6i10n2h3m), an elbow point can be identified in the Pareto frontier, indicating a mid-range point could be an appropriate solution. Therefore, choosing the best and most appropriate solution should be analyzed case by case, taking decision-maker preferences into consideration.

In order to present the model results and performance in more detail, one of the data sets has been chosen, with the most conservative solution (zero delayed job order). Data set 6i10n2h3m was chosen for this purpose, and the batching solution for arriving orders is reported in Table 4, where BPM2 begins work when and only when the MF is present at the customer’s production site. Furthermore, in this table the arrival time of MF,  $Z_i$ , as well as the makespan in each production plant (customer) is presented. This example consists of three BPM machines in a row, meaning the makespan time concludes when an operation on BPM3 is completed for the last batch. Service time of the MF is also recounted, which indicates the period between the starting time of the first batch and completion time of the last batch. This variable allows the transportation planner to determine how long the MF stays at each customer location.

In Fig. 6, a detailed schedule of different batches at each customer site on BPM2 is depicted, which indicates that customers 1 and 5 are the primary customers to whom services from MF2 and MF1, respectively, are delivered. Subsequently, MF1 moves to customers 3, and 2, respectively, and MF2 finishes its route by delivering service to customer number 6, and 4. Operation on BPM1 can be started at any time, but only once the work on BPM2 is completed can work on BPM3 be started. As can be seen in Fig 4, all operations on BPM2 ended by 96 h and the whole work was completed at 107 h.

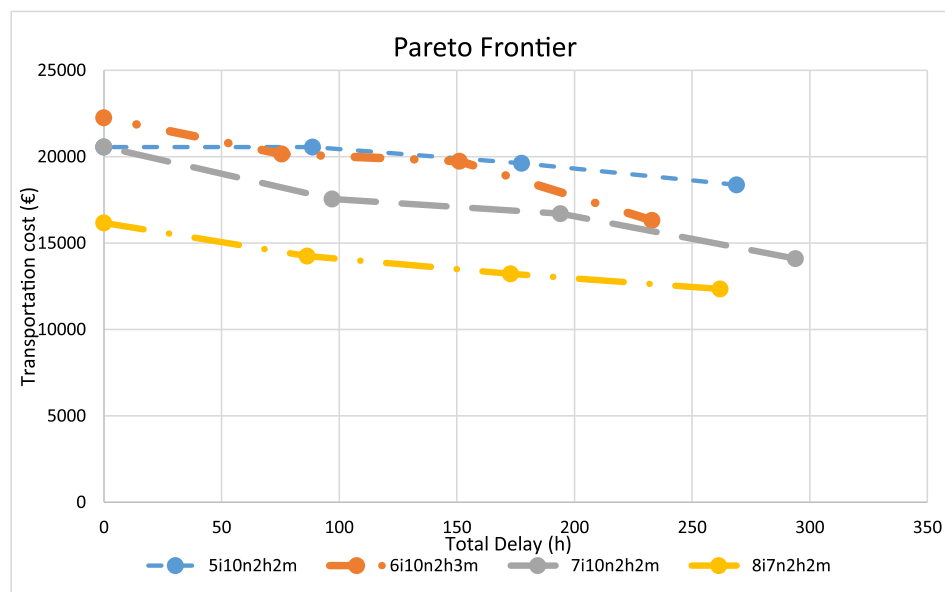
4.3. Managerial insights

From the above-mentioned experimental results, several important managerial insights can be concluded. The most important ones are as follows:

- The mobile supply chain is a useful business model to produce material locally and flexibly.
- This problem consists of two main stakeholders: production managers and MF fleet managers. Ignoring each of them will yield infeasible solutions and significant losses.
- To ensure an efficient mobile supply chain and deliver timely service, having an agile mobile factory fleet is necessary. Otherwise, managing customers’ due dates is difficult.
- The customers and MF fleet should work in a coordinated manner.
- The proposed optimization approach provides different solutions which can be chosen by decision-makers considering their preferences and the company’s priorities.

**Table 3**  
Grid points.

Data sets		Grid points								Avg. CPU time
No.	size	E1		E2		E3		E4		
		F1	F2	F1	F2	F1	F2	F1	F2	
1	4i5n1h3m	16326	57	17484	40	17682	20	18330	0	34
2	4i10n2h3m	18378	74	19623	50	20556	30	20556	0	47
3	5i5n1h3m	16758	76	19980	50	20292	20	21126	8	309
4	5i10n2h2m	19716	269	20226	200	20226	100	22404	0	238
5	6i5n1h3m	13842	71	15510	50	15540	40	15540	12	3012
6	6i7n2h2m	16320	140	16818	90	16818	40	19740	0	241
7	6i10n2h3m	16320	225	19740	150	20154	80	22254	0	1265
8	7i7n2h3m	14100	48	15854	30	16704	15	17802	0	1791
9	7i10n2h2m	14100	294	16704	200	17550	100	20568	0	2204
10	8i5n2h3m	12348	34	14418	20	14418	10	15756	0	951
11	8i7n2n2m	12348	262	13218	180	14250	80	16176	0	1671
12	9i5n2h3m	11380	47	13404	32	16446	15	19038	0	1320
13	9i7n2h2m	11380	698	12486	400	13380	200	20142	0	3195



**Fig. 5.** Pareto Frontier.

**Table 4**  
Production, routing, and master plan.

Customer site	$Z_i$	$SE_i$	Makespan	Job orders in each batch			
				B1	B2	B3	B4
1	7	26	43	2,4,5,6	1,3,7,10	8,9	—
2	76	20	106	2,5	3,7,10	1,4,6,8,9	—
3	36	26	72	2,5	3,6,8,9	1,4	10
4	72	24	107	2,6,8	5,10	1,3,4,7,9	—
5	5	23	38	1,2,4,6,7,10	1,3,8,9	5	—
6	47	24	81	3,8,9	1,4,5,10	6,7	2

**5. Conclusions**

The mobile supply chain concept has been developed as a response to the need for flexibility, adaptability, and robustness in supply chains. Using this novel idea may provide various advantages for companies which aim to move from mass production to mass customization, manage customers’ peak demand, and reduce asset investment costs. This idea brings the benefits of distributed manufacturing systems and results in lower logistics costs in comparison to central manufacturing systems. In MSCs, mobile factories can be carried to different sites on a truck, with these facilities taking on the task of not only the production of material, but also distribution and delivery.

The MSC problem consists of two sub-problems: production planning and a mobile factory routing problem. In this paper, a mathematical model with a bi-objective function was developed to optimize total delays for job orders as well as total transportation costs. The model results demonstrated that considering each sub-problem separately will trigger significant transportation costs and more delays for job orders. Consequently, customer dissatisfaction and backlogged orders would be inevitable. The proposed model enabled zero delayed orders with a minimization of the transportation costs still possible. However, a range of possible solution scenarios were attainable, as seen with the depicted Pareto frontier.

This problem consists of two NP-hard sub-problems. For this reason,



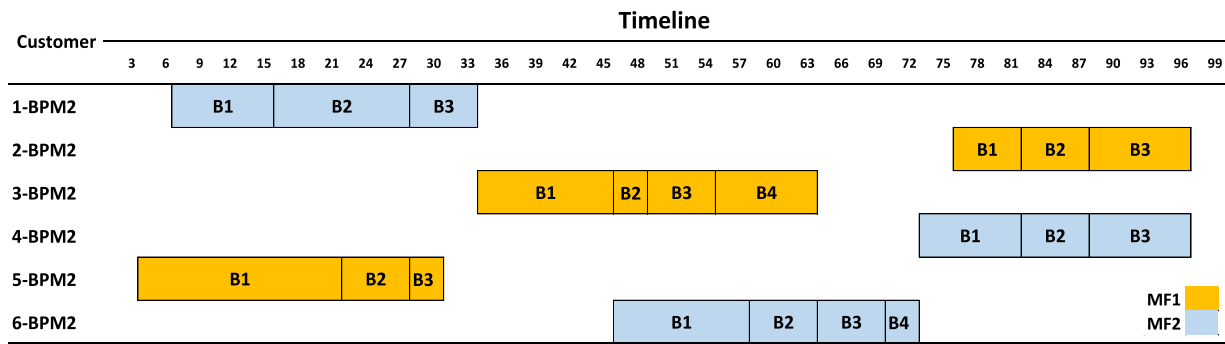


Fig. 6. Production schedule on BPM2.

solving this problem in large-scale data sets using a heuristic or meta-heuristic algorithm is recommended for future research. Furthermore, using decentralized decision-making approaches to manage the complexity of the problem, finding an approach to managing job orders with arrive after the initial planning, and optimizing under uncertainty are open research fields.

### CRedit authorship contribution statement

**Hani Shahmoradi-Moghadam:** Conceptualization, Methodology, Investigation, Writing – original draft, Validation, Visualization. **Jörn Schönberger:** Conceptualization, Writing – review & editing, Supervision.

### Declaration of Competing Interest

None.

### Acknowledgement

The authors would like to thank the Boysen-TU Dresden-Research Training Group for the financial support that has made this publication possible. The Research Training Group is co-financed by TU Dresden and the Friedrich and Elisabeth Boysen-Foundation.

### References

- Jabbarzadeh A, Fahimnia B, Sheu J-B, Moghadam HS. Designing a supply chain resilient to major disruptions and supply/demand interruptions. *Transp Res Part B Methodol* 2016;94:121–49. <https://doi.org/10.1016/j.trb.2016.09.004>.
- Rauch E, Dallasega P, Matt DT. Distributed manufacturing network models of smart and agile mini-factories. *Int J Agil Syst Manag* 2017;10:185. <https://doi.org/10.1504/IJASM.2017.10009457>.
- Jackson M, Zaman A. Factory-in-a-box-mobile production capacity on demand. 2007.
- Rauch E, Dallasega P, Matt DT. Sustainable production in emerging markets through Distributed Manufacturing Systems (DMS). *J Clean Prod* 2016;135: 127–38. <https://doi.org/10.1016/j.jclepro.2016.06.106>.
- Haghjoo N, Tavakkoli-Moghaddam R, Shahmoradi-Moghadam H, Rahimi Y. Reliable blood supply chain network design with facility disruption: a real-world application. *Eng Appl Artif Intell* 2020;90:103493. <https://doi.org/10.1016/j.engappai.2020.103493>.
- Kjelle E. Mobile x-ray services; outcome for nursing home residents and society - a literature review. *Int J Integr Care* 2016;16:35. <https://doi.org/10.5334/ijic.2978>.
- FPSO/FSO Shimamura Y. State of the art. *J Mar Sci Technol* 2002;7:59–70. <https://doi.org/10.1007/s007730200013>.
- Lee K-H, Kim M-G, Lee J, Lee P-S. Recent advances in ocean nuclear power plants. *Energies* 2015;8:11470–92. <https://doi.org/10.3390/en81011470>.
- Albashaheh NT, Heier Stamm JL. Optimization of lignocellulosic biomass-to-biofuel supply chains with mobile pelleting. *Transp Res Part E Logist Transp Rev* 2019;122:545–62. <https://doi.org/10.1016/j.tre.2018.12.015>.
- Ladiges J, Fay A, Holm T, Hempten U, Urbas L, Obst M, et al. Integration of modular process units into process control systems. *IEEE Trans Ind Appl* 2018;54:1870–80. <https://doi.org/10.1109/TIA.2017.2782679>.
- Weyer S, Schmitt M, Ohmer M, Gorecky D. Towards Industry 4.0 - standardization as the crucial challenge for highly modular, multi-vendor production systems. *IFAC-PapersOnLine* 2015;48:579–84. <https://doi.org/10.1016/j.ifacol.2015.06.143>.
- Baldea M, Edgar TF, Stanley BL, Kiss AA. Modular manufacturing processes: Status, challenges, and opportunities. *AIChE J* 2017;63:4262–72. <https://doi.org/10.1002/aic.15872>.
- Ivanov D, Tsioulanis A, Schönberger J. Erratum to: global supply chain and operations management, 2017, p. E1. [https://doi.org/10.1007/978-3-319-24217-0\\_15](https://doi.org/10.1007/978-3-319-24217-0_15).
- Shahmoradi-Moghaddam H, Akbari K, Sadjadi SJ, Heydari M. A scenario-based robust optimization approach for batch processing scheduling. *Proc Inst Mech Eng Part B J Eng Manuf* 2016;230:2286–95. <https://doi.org/10.1177/0954405415584977>.
- Moons S, Ramaekers K, Caris A, Arda Y. Integrating production scheduling and vehicle routing decisions at the operational decision level: a review and discussion. *Comput Ind Eng* 2017;104:224–45. <https://doi.org/10.1016/j.cie.2016.12.010>.
- Jackson M, Wiktorsson M, Bellgran M. Factory-in-a-box — demonstrating the next generation manufacturing provider. In: *Manuf. syst. technol. new front.* London: Springer London; 2008. p. 341–6. [https://doi.org/10.1007/978-1-84800-267-8\\_70](https://doi.org/10.1007/978-1-84800-267-8_70).
- Antzoulatos N, Castro E, Scrimieri D, Ratchev S. A multi-agent architecture for plug and produce on an industrial assembly platform. *Prod Eng* 2014;8:773–81. <https://doi.org/10.1007/s11740-014-0571-x>.
- Rauch E, Matt DT, Dallasega P. Mobile On-site Factories &#x2014; scalable and distributed manufacturing systems for the construction industry. In: *2015 Int. Conf. Ind. Eng. Oper. Manag. IEEE*; 2015. p. 1–10. <https://doi.org/10.1109/IEOM.2015.7093746>.
- Peltokoski M, Volotinen J, Lohtander M. Location independent manufacturing – a software solution for supply chains. *Procedia Manuf* 2017;11:863–70. <https://doi.org/10.1016/j.promfg.2017.07.189>.
- Fox S. Reliable autonomous production systems: combining industrial engineering methods and situation awareness modelling in critical realist design of autonomous production systems. *Systems* 2018;6:26. <https://doi.org/10.3390/systems6030026>.
- Koren Y, Gu X, Guo W. Reconfigurable manufacturing systems: principles, design, and future trends. *Front Mech Eng* 2018;13:121–36. <https://doi.org/10.1007/s11465-018-0483-0>.
- Ask A, Stillström C. Mobile manufacturing systems: market requirements and opportunities. In: *Proc. 2006 IJME-intertech int. conf*; 2006.
- Stillström C, Jackson M. The concept of mobile manufacturing. *J Manuf Syst* 2007; 26:188–93. <https://doi.org/10.1016/j.jmsy.2008.03.002>.
- Rauch E, Matt DT, Dallasega P. Mobile factory network (MFN)–network of flexible and agile manufacturing systems in the construction industry. *Appl. Mech. Mater.* 2015;752:1368–73. *Trans Tech Publ.*
- Benama Y, Thecle A, Perry N. Framework definition for the design of a mobile manufacturing system. In: *Adv. mech. des. eng. manuf.* Springer; 2017. p. 111–8.
- Shahmoradi-Moghadam H, Samani O, Schönberger J. A hybrid robust-stochastic optimization approach for the noise pollution routing problem with a heterogeneous vehicle fleet. *Int. Conf. Dyn. Logist.* 2020:124–34. [https://doi.org/10.1007/978-3-030-44783-0\\_12](https://doi.org/10.1007/978-3-030-44783-0_12).
- Braekers K, Ramaekers K, Van Nieuwenhuysse I. The vehicle routing problem: state of the art classification and review. *Comput Ind Eng* 2016;99:300–13. <https://doi.org/10.1016/j.cie.2015.12.007>.
- Jena SD, Cordeau J-F, Gendron B. Dynamic facility location with generalized modular capacities. *Transp Sci* 2015;49:484–99. <https://doi.org/10.1287/trsc.2014.0575>.
- Halper N, Raghavan S. The mobile facility routing problem. *Transp Sci* 2011;45: 413–34. <https://doi.org/10.1287/trsc.1100.0335>.
- Lei C, Lin W-H, Miao L. A multicut L-shaped based algorithm to solve a stochastic programming model for the mobile facility routing and scheduling problem. *Eur J Oper Res* 2014;238:699–710. <https://doi.org/10.1016/j.ejor.2014.04.024>.
- Qi M, Cheng C, Wang X, Rao W. Mobile facility routing problem with service-time-related demand. In: *2017 Int. conf. serv. syst. serv. manag. IEEE*; 2017. p. 1–6.
- Hohmann L, Kössl K, Kockmann N, Schembecker G, Bramsiepe C. Modules in process industry – a life cycle definition. *Chem Eng Process Process Intensif* 2017; 111:115–26. <https://doi.org/10.1016/j.ciep.2016.09.017>.
- Becker T, Lutter P, Lier S, Werners B. Optimization of modular production networks considering demand uncertainties. In: *Oper. Res.* 2016. Springer; 2018. p. 413–8. [https://doi.org/10.1007/978-3-319-55702-1\\_55](https://doi.org/10.1007/978-3-319-55702-1_55).

- [34] Becker T, Lier S, Werners B. Value of modular production concepts in future chemical industry production networks. *Eur J Oper Res* 2019;276:957–70. <https://doi.org/10.1016/j.ejor.2019.01.066>.
- [35] Shahnaghi K, Shahmoradi-Moghadam H, Noroozi A, Mokhtari H. A robust modelling and optimisation framework for a batch processing flow shop production system in the presence of uncertainties. *Int J Comput Integr Manuf* 2015:1–15. <https://doi.org/10.1080/0951192X.2014.1002814>.
- [36] Damodaran P, Srihari K. Mixed integer formulation to minimize makespan in a flow shop with batch processing machines. *Math Comput Model* 2004;40:1465–72. <https://doi.org/10.1016/j.mcm.2005.01.005>.
- [37] Mavrotas G. Effective implementation of the  $\epsilon$ -constraint method in Multi-Objective Mathematical Programming problems. *Appl Math Comput* 2009;213:455–65. <https://doi.org/10.1016/j.amc.2009.03.037>.
- [38] Lenstra JK, Kan AHGR. Complexity of vehicle routing and scheduling problems. *Networks* 1981;11:221–7. <https://doi.org/10.1002/net.3230110211>.
- [39] Damodaran P, Kumar Manjeshwar P, Srihari K. Minimizing makespan on a batch-processing machine with non-identical job sizes using genetic algorithms. *Int J Prod Econ* 2006;103:882–91. <https://doi.org/10.1016/j.ijpe.2006.02.010>.