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Multi objective outbound logistics network design for a manufacturing supply chain

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Abstract Outbound logistics network (OLN) in the downstream supply chain of a firm plays a dominant role in the success or failure of that firm. This paper proposes the design of a hybrid and flexible OLN in multi objective context. The proposed distribution network for a manufacturing supply chain consists of a set of customer zones (CZs) at known locations with known demands being served by a set of potential manufacturing plants, a set of potential central distribution centers (CDCs), and a set of potential regional distribution centers (RDCs). Three variants of a single product classified based on nature of demand are supplied to CZs through three different distribution channels. The decision variables include number of plants, CDCs, RDCs, and quantities of each variant of product delivered to CZs through a designated distribution channel. The goal is to design the network with multiple objectives so as to minimize the total cost, maximize the unit fill rates, and maximize the resource utilization of the facilities in the network. The problem is formulated as a mixed integer linear programming problem and a multiobjective genetic algorithm (MOGA) called non-dominated sorting genetic algorithm—II (NSGA-II) is employed to solve the resulting NP-hard combinatorial optimization problem. Computational experiments conducted on randomly generated data sets are presented and analyzed showing the effectiveness of the solution algorithm for the proposed network.

Keywords Outbound logistics network (OLN) · Outbound logistics network design (OLND) · Manufacturing supply chain · Mixed integer linear programming · Multiobjective genetic algorithm · NSGA-II

Introduction

A firm in a civilized and/or industrialized society exists for the sole purpose of satisfying the needs of the society through its value added products/services. The needs are better addressed and well served if and only if a right product/service reaches a right customer, at right place, in right time, in right quantity, in right quality, and at a right price. The onus of achieving all these deliverables rests with the outbound logistics part of a supply chain. This emphasizes the importance of a better designed and well balanced outbound logistics network in any supply chain.

The outbound logistics network design (OLND) in a supply chain is a strategic decision-making problem, which is generally governed by multiple and conflicting objectives. The network design is affected and governed by four factors namely cost, quality, speed, and flexibility. The customers expect to be served always with best possible quality at least possible cost and at best possible levels of speed and flexibility. Thus, the degree of success of an outbound logistics network of a supply chain depends on how fast it is, how flexible it is, and how efficient it is in delivering quality products to its customers. The ever increasing levels of globalization and competition are putting a demand for innovative and flexible outbound logistics networks which can befittingly serve the aforementioned objectives. Hence, this paper proposes an innovative and flexible outbound logistics network for a manufacturing supply chain where three variants of a single product are shipped through three different delivery channels

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based on the nature of demand for each variant. The objective of the paper is twofold: (1) to design an efficient outbound logistics network which can deliver the product at desired speed through flexible delivery channels, and (2) to find different configurations of the network when the parameters are changed within the ambit of multiple objectives.

The remainder of the paper is organized as follows. The related literature is presented in the following section. Section 3 outlines the nature of the problem under consideration. The mathematical model is presented in section "Mathematical model". Section "Multi objective optimization" describes the concepts and principles of multi-objective optimization, multi-objective genetic algorithms, and non-dominated sorting genetic algorithm-II. The solution methodology employed for the resulting mixed integer linear programming (MILP) problem and the computational experiments carried out are discussed in section "Solution methodology and computational experiments". Results and discussions are presented in section "Results and discussions". Section "Managerial insights" outlines the managerial insights. Finally section "Conclusions" concludes the paper.

Literature review

The logistics as well as supply chain network design is and has been a favourite topic of study among the supply chain research community. Since the emergence of supply chain management (SCM) discipline in 1980s many have actively studied and rigorously researched this topic and many facets of the field have been showcased in different hues and cries. Since this paper discusses and proposes the design of an innovative hybrid and flexible outbound logistics network for a multi-objective, multi-stage (or multi-echelon), deterministic, single period, single country, and strategic decision making problem in a manufacturing supply chain, we consider here only the related literature which fall under this purview.

Researchers in the past have studied OLND in supply chains under various names and terminology. To quote them, we find in the literature terms like 'supply chain network design (SCND)', 'production-distribution network design (PDND)' 'production-distribution system design (PDSD)', 'logistics network design (LND)', 'outbound supply chain network design (OSCND)', 'supply chain configuration (SCC)', 'supply chain design (SCD)', etc., where majority of these connote the similar meaning and concept of planning and designing the physical structure of downstream supply chain, with a significant variation in case of SCC and SCD which do consider the entire gamut of supply chains i.e. from suppliers to customers.

Distribution, in plain terms, refers to the steps taken to move and store a product from the manufacturer stage to a customer stage in the supply chain. Distribution is a key driver of the overall profitability of a firm because it affects both the supply chain cost and the customer experience directly (Chopra et al. 2008). They assert that logistics network design decisions have a significant impact on performance because they determine the supply chain configuration and set constraints within which the other supply chain drivers can be used either to decrease supply chain cost or to increase responsiveness. Furthermore, it is widely felt and critically investigated that a distribution plan with low cost and high customer satisfaction in SCM is the need of present day industries (Lim et al. 2006).

Distribution system design (Goetschalckx 2008) focuses on the following five interrelated decisions:

1. Determining the appropriate number of plants and distribution centers
2. Determining the location of each plant and distribution center
3. Determining the customer allocation to each plant and/or distribution center
4. Determining the product allocation to each plant and/or distribution center
5. Determining the throughput and storage capacity of each plant and/or distribution center

The aforementioned steps imply that an outbound logistics network in a supply chain needs to be configured and/or reconfigured quickly and efficiently as and when it is affected by technological, economical, political, and environmental changes. Most of the literatures in OLND address this major aspect of research: Dogan and Goetschalckx (1999), Ioannou (2005), Rabbani et al. (2008), Altiparmak et al. (2009), Gebennini et al. (2009), Chandra and Grabis (2009), Kazemi et al. (2009), Cintron et al. (2010), Paksoy and Cavlak (2011) etc.

Designing and managing an outbound logistics network is an important strategic decision in supply chains which typically span over 10–15 years. Thanh et al. (2008), Bachlaus et al. (2008), Manzini and Gebennini (2008), Manzini et al. (2008), Kauder and Meyr (2009), Manzini and Bindi (2009), Tiwari et al. (2010) etc have effectively addressed the strategic nature of decision making in planning and designing outbound logistics networks.

The facilities in an outbound logistics network are found spatially dispersed across a given geographic area. This spatial factor leads to multi-stage or multi-echelon structure in the outbound logistics network and such networks are studied by various researchers (Syarif et al. 2002; Syarif and Gen 2003; Jayaraman and Ross 2003; Gen et al. 2006; Jawahar and Balaji 2009 etc.)

The literature abounds with rich review works in the area of outbound logistics network. The readers are referred to

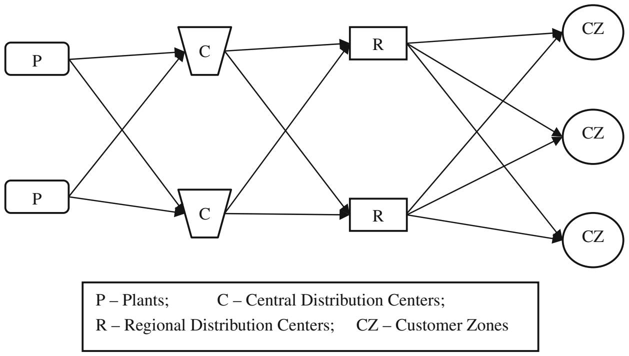


Fig. 1 Traditional outbound logistics network

Vidal and Goetschalckx (1997), Sarmiento and Nagi (1999), Goetschalckx et al. (2002), and Melo et al. (2009).

The ambit and complexity of outbound logistics networks design (OLND) in supply chains is such that they often have more than one objective. The multiple objectives are also conflicting in nature, thereby making the supply chain decision makers' job tough and challenging. The supply chain research community has contributed immensely to this domain of active research (Shen and Daskin 2005; Ding et al. 2006; Altiparamak et al. 2006; ElMaraghy and Majety 2008; Farahani and Elahipanah 2008; Kim and Moon 2008; Cheng et al. 2009; Cheng and Ye 2011; Pishvaee et al. 2010; Bhattacharya and Bandyopadhyay 2010; Liao et al. 2011). All these research works deal with either two or more than two objectives which are conflicting among themselves. Undoubtedly, the minimization of the total cost of the outbound logistics network is the most common among the objectives considered. Some researchers have considered maximization of profit after tax, minimization of inventory levels at different echelons, maximization of customer demands through fill rates, and maximization of responsiveness through shorter delivery lead times among others.

However, the unique feature of these works is that they all, as depicted in Fig. 1, have considered a traditional outbound logistics network, which means a multi-echelon (or multi-stage) outbound logistics network where goods move serially one after the other from the point of production (i.e. manufacturing plants) to the point of consumption (i.e. customers). However, the present-day complexity of customers' needs and demands warrant innovatively designed outbound logistics networks which are cost efficient, responsive, and also flexible. According to the best knowledge of the authors, in the recent past, Lin et al. (2009) presented an integrated multistage logistics network model where goods are delivered through three different delivery channels: normal delivery, direct delivery, and direct shipment so as to satisfy the varying needs of the customers. In practice, industrial giants like Dell and Grainger have already put in place and practicing innovatively designed outbound logistics networks for their line of activity (Chopra et al. 2008), and the respective industry has witnessed how far they have succeeded with their approaches. Furthermore, Chopra et al. (2008) opine that there is still enough room and scope for conceptualizing, planning, and designing innovative outbound logistics networks to cater to the ever changing customers' needs and industry trends. Thus, this paper contributes an innovative concept and design to this line of research. The nature and functioning of the proposed hybrid and flexible outbound logistics network for a manufacturing supply chain is narrated in the following section.

Problem environment

Today many industries are faced with the customers' desire for an increased variety of product variants (Bilgen and Günther 2010); and it very aptly applies to automotive industry where product variety leads to product diversity (Jiao et al. 2007). The automotive manufacturing supply chain is and has been a vibrant field of business and offers enough scope to study and implement the concepts of SCM. The automotive industry adopts a consumer focus in its development strategy to offer broader product ranges with shorter model lifetimes (Chandra and Kamrani 2003). The fast-paced technological developments and rapidly changing customer tastes and demands for innovative styles and designs make automotive industry market highly volatile and evolving in nature. The situation is further aggravated by stiff competition and global marketing. This forces the industry to roll out new models and/or improved variants and roll back the models which have sluggish movement. The overall result is the shorter and shorter life of automotive goods. In such a scenario, the traditional outbound logistics network happens to be a redundant and outdated one. Hence, an innovative and effective outbound logistics network needs to be devised for the present-day automotive industry. And this research makes a contribution in this direction.

The proposed outbound logistics network for an automotive manufacturing supply chain is hybrid and flexible in the sense that a separate distribution strategy and channel is employed for each variant/item of a product based on the nature of demand. There will be three variants/items of a product which are classified based on nature of demand. They are fast moving item, slower moving item, and very slow moving item. Different distribution strategies are adopted for these items. Fast moving items will be stocked and delivered by regional distribution centers (RDCs) which are situated closer to customer zones (CZs). Central distribution centers (CDCs) which are situated nearer to the plants will stock and deliver slower moving items to CZs. Plants with in-house storage facility will stock and deliver very slow moving items directly to CZs. Figure 2 depicts the concept of a hybrid and

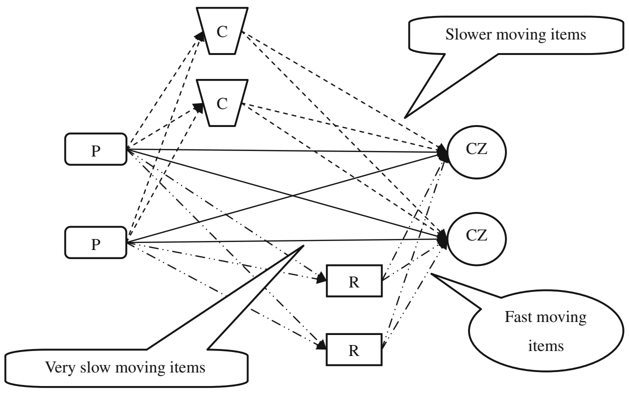


Fig. 2 Hybrid and flexible outbound logistics network

flexible outbound logistics network. Further the proposed delivery channels are based on the related delivery lead time involved in each case. The expected delivery lead time will be short, moderate and longer for fast, slower and very slow moving items respectively. The point of storage for each category of product is based on the possible roll-back strategy in future. According to this very slow moving items are held in plant itself, and slower moving items are stocked in CDCs which are closer to plants. Then as and when new items and/or improved items are released, they will be stocked in RDCs and existing fast moving items will gradually become slower moving items and will be shifted back to CDCs. The slower moving items will gradually become very slow moving items and thus will be shifted back to plants, and existing very slow moving items will thus become redundant and vanish from the scene. This process will keep on continuing as long as a firm is in business.

Mathematical model

In this section, we present the mathematical model developed for designing the proposed deterministic, single country, single period, multi objective, multi echelon, hybrid, and flexible OLN. The resulting model is a MILP model and it is NP-hard in nature (Amiri 2006). First of all, we give here below the assumptions used in framing the mathematical model:

- There are maximum four echelons with logistic facilities such as Plants, CDCs, RDCs and CZs
- The problem is modelled and solved for a single time period
- The values of customer demands and other model parameters are fixed and thus model is deterministic in nature
- The model is domestic in nature i.e. it refers to a single country and the CZs are at known locations and are dispersed geographically
- The model has multiple objectives: minimization of total cost of OLN, maximization of performance measures such unit fill rate (UFR) and resource (facility) utilization (RU) subject to a host of capacity, demand, flow, and other resource constraints
- There will be three delivery channels: fast moving items are delivered to CZs from RDCs; slower moving items are delivered to CZs from CDCs, and very slow moving items are delivered to CZs from Plants.
- The fast moving items and slower moving items are supplied to RDCs and CDCs respectively from the Plants.
- Lot-splitting is allowed
- Multi-sourcing is allowed i.e. more than one facility can serve a CZ for satisfying the demand of a particular item
- Shortages are not allowed

It is expected to achieve the following objectives on solving the developed mathematical model:

- To determine the required number of Plants, CDCs, and RDCs from among the potential locations so as to satisfy the demands of the CZs
- To determine the quantities of product flow between the facilities at different echelons
- To find the various possible configurations of the proposed OLN for different optimum as well as desirable levels of multiple objectives under consideration

Following are the notations used in the mathematical model:
Notations:

Indices

i : index of plant ($i = 1, 2, \ldots, I$)
j : index of Central Distribution Center (CDC) ($j = 1, 2, \ldots, J$)
k : index of Regional Distribution Center (RDC) ($k = 1, 2, \ldots, K$)
l : index of Customer Zone (CZ) ($l = 1, 2, \ldots, L$)
p : index of fast moving item
q : index of slower moving item
r : index of very slow moving item

Parameters

I : number of plants
J : number of CDCs
K : number of RDCs
L : number of CZs
P_i : plant i
CDC_j : CDC j
RDC_k : RDC k
CZ_l : CZ l
b_i^p : production capacity for fast moving item p in plant P_i

b_i^q : production capacity for slower moving item q in plant P_i

b_i^r : production capacity for very slow moving item r in plant P_i

d_l^p : demand for fast moving item p from CZ_l

d_l^q : demand for slower moving item q from CZ_l

d_l^r : demand for very slow moving item r from CZ_l

u_k^p : upper bound of the storage capacity of RDC_k for fast moving item p

u_j^q : upper bound of the storage capacity of CDC_j for slower moving item q

u_i^r : upper bound of the storage capacity of P_i very slow moving item r

f_i : fixed cost of opening and operating plant P_i

f_j : fixed cost of opening and operating CDC_j

f_k : fixed cost of opening and operating RDC_k

U : maximum number of P_i to be opened

V : maximum number of CDC_j to be opened

W : maximum number of RDC_k to be opened

c_{ij}^q : unit cost of producing and shipping item q from P_i to CDC_j

c_{ik}^p : unit cost of producing and shipping item p from P_i to RDC_k

c_{il}^r : unit cost of producing and shipping item r from P_i to CZ_l

c_{jl}^q : unit cost of handling and shipping item q from CDC_j to CZ_l

c_{kl}^p : unit cost of handling and shipping item p from RDC_k to CZ_l

Decision variables

x_{ij}^q : quantity of slower moving item q transported from plant P_i to CDC_j

x_{ik}^p : quantity of fast moving item p transported from plant P_i to RDC_k

x_{il}^r : quantity of very slow moving item r transported from plant P_i to CZ_l

x_{jl}^q : quantity of slower moving item q transported from CDC_j to CZ_l

x_{kl}^p : quantity of fast moving item p

: quantity of fast moving item p

z_i : 1 if plant P_i is opened; 0 otherwise

z_j : 1 if CDC_j is opened; 0 otherwise

z_k : 1 if RDC_k is opened; 0 otherwise

Objective functions:

$$\text{Min Z} = \left[\begin{array}{l} \sum_{i=1}^{I}\sum_{j=1}^{J} x_{ij}^q c_{ij}^q + \sum_{i=1}^{I}\sum_{k=1}^{K} x_{ik}^p c_{ik}^p + \sum_{i=1}^{I}\sum_{l=1}^{L} x_{il}^r c_{il}^r \\ + \sum_{j=1}^{J}\sum_{l=1}^{L} x_{jl}^q c_{jl}^q + \sum_{k=1}^{K}\sum_{l=1}^{L} x_{kl}^p c_{kl}^q + \sum_{i=1}^{I} f_i z_i + \sum_{j=1}^{J} f_j z_j + \sum_{k=1}^{K} f_k z_k \end{array}\right] \tag{1}$$

$$\text{Max UFR} = 100\left[\frac{\left(\sum_{i=1}^{I}\sum_{l=1}^{L} x_{il}^r + \sum_{j=1}^{J}\sum_{l=1}^{L} x_{jl}^q + \sum_{k=1}^{K}\sum_{l=1}^{L} x_{kl}^p\right)}{\left(d_l^p + d_l^q + d_l^r\right)}\right] \tag{2}$$

$$\text{MaxRU} = 100\left[\frac{\sum_{i=1}^{I}\sum_{l=1}^{L} x_{il}^r + \sum_{j=1}^{J}\sum_{l=1}^{L} x_{jl}^q + \sum_{k=1}^{K}\sum_{l=1}^{L} x_{kl}^p}{u_i^r + u_j^q + u_k^p}\right] \tag{3}$$

Constraints:

$$\sum_{i=1}^{I} x_{ij}^q \geq \sum_{l=1}^{L} x_{jl}^q, \quad \forall j \tag{4}$$

$$\sum_{i=1}^{I} x_{ik}^p \geq \sum_{l=1}^{L} x_{kl}^q, \quad \forall k \tag{5}$$

$$\sum_{l=1}^{L} x_{il}^r \leq b_i^r, \quad \forall i \tag{6}$$

$$\sum_{j=1}^{J} x_{ij}^q \leq b_i^q, \quad \forall i \tag{7}$$

$$\sum_{k=1}^{K} x_{ik}^p \leq b_i^p, \quad \forall i \tag{8}$$

$$\sum_{i=1}^{I} x_{il}^r \geq d_l^r, \quad \forall l \tag{9}$$

$$\sum_{j=1}^{J} x_{jl}^q \geq d_l^q, \quad \forall l \tag{10}$$

$$\sum_{k=1}^{K} x_{kl}^p \geq d_l^p, \quad \forall l \tag{11}$$

$$\sum_{i=1}^{I} z_i \leq U \tag{12}$$

$$\sum_{j=1}^{J} z_j \leq V \tag{13}$$

$$\sum_{k=1}^{K} z_k \leq W \tag{14}$$

$$x_{ij}^q, x_{ik}^p, x_{il}^r, x_{jl}^q, x_{kl}^p \geq 0, \quad \forall i, j, k, l \tag{15}$$

$$z_i, z_j, z_k \in \{0, 1\}, \quad \forall i, j, k \tag{16}$$

The three objectives of the model are depicted in Eqs. (1)–(3). Equation (1) defines the objective of minimizing the total cost of OLN, comprising of production costs, handling costs, transportation costs, and fixed costs of opening and operating the potential facilities. Equation (2) represents the maximization of a performance measure called unit fill rate (UFR) i.e.

the extent to which a facility can readily satisfy the demand received from a CZ from the available inventory. Equation (3) defines the maximization of another performance measure called resource utilization (RU) i.e. the extent to which the levels of floor capacity of the facilities can be utilized. All the three objectives are supposed to be optimized subject to a host of capacity, demand, flow, and other resource constraints. Among the constraints, Eqs. (4) and (5) enforce the constraints of flow of conservation between the facilities at different echelons. The constraints on production capacities at potential plants are imposed by Eqs. (6)–(8). The extent of demands for the items to be satisfied at different CZs is provided by Eqs. (9)–(11). The maximum number of facilities that can be opened to serve the demands of CZs in the proposed OLN is restricted by Eqs. (12)–(14). Equations (15) and (16) define the constraints of non-negativity and binary values for the intended decision variables respectively.

Multi objective optimization

The salient features of multi-objective optimization problem, Pareto optimality, multi objective genetic algorithms, and non-dominated sorting genetic algorithm-II are discussed in this section.

Multi objective optimization problem (MOP) and Pareto optimality

Multi-objective optimization problems (MOPs) deal with simultaneous optimization of several objective functions. The notion of optimality in case of a MOP is not as obvious as that of a single objective optimization problem. In the case of multiple objectives, a best or global solution may not exist with respect to all objectives. The presence of multiple objectives in a problem usually gives rise to a family of nondominated or non-inferior solutions, largely known as Pareto-optimal solutions (Sarkar and Modak 2005). In Pareto-optimal solutions, each objective component of any solution along the Pareto-front can only be improved by degrading at least one of its other objective components. Since none of the solutions in the nondominated set is absolutely better than any other, any one of them is an acceptable solution. As it is difficult to choose any particular solution for a multi-objective optimization problem without iterative interaction with the decision-maker, one general approach is to choose the entire set of Pareto-optimal solutions. The algorithms which are used to generate non-dominated Pareto-optimal solutions include tabu search, simulated annealing, Ant-Q algorithms, fuzzy logic, evolutionary strategies, neural networks, and genetic algorithms (Luh et al. 2003).

Multi objective genetic algorithms (MOGA)

Evolutionary algorithms (EAs) possess a unique ability to deal simultaneously with a set of possible solutions, which result into the evolution of an entire set of Pareto-optimal solutions in a single run instead of running a series of separate runs as in the case of traditional mathematical programming techniques. Thus, EAs are recognized to be well suited for multi-objective optimization problems. Furthermore, EAs are less amenable to the shape or continuity of the Pareto front (Coello 1999). These superior characteristics of EAs have led to the development of a slew of evolutionary multi-objective optimization algorithms.

Multi-objective genetic algorithms have been categorized as Pareto-based methods and Non-Pareto based methods. The concept of Pareto optimality is used explicitly in the former and the latter do not incorporate the concept of Pareto optimality directly. Vector Evaluated Genetic Algorithm (VEGA) is a Non-Pareto based method and was the first GA proposed for multi-objective optimization. A number of Pareto-based evolutionary multi-objective optimization algorithms were developed based on two principles, Pareto dominance and niching, as proposed by Goldberg (1989). The principle of Pareto dominance helps to exploit the search space in the direction of the Pareto front while the niching principle helps to explore the search space along the Pareto front to maintain diversity. Pareto-based methods include Multi-objective Genetic Algorithm (MOGA), Niched Pareto Genetic Algorithm (NPGA), Non-dominated Sorting Genetic Algorithm (NSGA), Strength Pareto Evolutionary Algorithm (SPGA), Multi-objective Evolutionary Algorithm (MOEA) etc. Readers are referred to Konak et al. (2006) for an in-depth tutorial on multi-objective optimization using genetic algorithms, and to Coello (1999) and Deb (2001) for excellent review on the state of the art in the field.

Non-dominated sorting genetic algorithm-II (NSGA-II)

Goldberg (1989) was the first to suggest the concept of non-dominated sorting genetic algorithm (NSGA) and Srinivas and Deb (1995) were the first to implement it. The central idea of the non-dominated sorting procedure is that a ranking selection method is used to identify good points and a niching method is used to maintain a stable subpopulation of good points. NSGA differs from a simple GA only in the way the selection operator works. The efficacy of NSGA lies in the way multiple objectives are reduced to a single fitness measure by the creation of number of fronts, sorted according to nondomination.

Although NSGA has been effectively used to solve a variety of MOPs, its main drawbacks are: (i) high computational complexity of nondominated sorting with where is the number of objectives and is the population size, (ii) lack of elitism, and (iii) the need for specifying a tunable sharing parameter. Hence, in order to address these limitations, Deb et al. (2002) proposed an improved version of NSGA called NSGA-II. NSGA-II alleviates the limitations of NSGA by introducing a fast non-dominated sorting procedure with computational complexity, an elitist-preserving approach, and a parameterless niching operator for preserving diversity. NSGA-II, in the recent past, has been successfully employed by some researchers in solving optimal control problems and SCM problems: Sarkar and Modak (2005) had used NSGA-II to solve a multi-objective optimal control problem; NSGA-II was employed for optimizing networked enterprises by Ding et al. (2006), Serrano et al. (2007) had applied NSGA-II to handle multiple objectives in case of supply chain disruptions; Amodeo et al. (2008) used NSGA-II to guide the optimisation search process towards high-quality solutions for effective inventory management across a supply chain for reducing inventory costs and improving services to customers; The utility of NSGA-II was suitably employed in SCM where firms are constantly under pressure to cut costs and improve profit margins while maintaining customer satisfaction at desired levels by Koo et al. (2008), Bhattacharya and Bandyopadhyay (2010) have solved a bi-objective facility location problem formulated in mixed integer nonlinear programming by NSGA II; Cheng and Ye (2011) have successfully applied NSGA-II to find the feasible solution set of Pareto for a supply chain problem with two objectives where the orders are to be split among parallel suppliers for improving agility and competitiveness.

However, to the best of our knowledge, there is no literature which makes use of NSGA-II approach for solving an OLND problem. Hence, to solve our multi-objective mathematical model for the proposed outbound logistics network, we have selected NSGA-II. Following are the few additional features of NSGA-II (Cheng and Ye 2011) which merit its selection as our solution approach:

(i) its modular and flexible structure
(ii) the possibility of upgrading a single-objective GA to NSGA-II, and
(iii) its successful application to a wide range of optimization problems.

The following section describes the solution methodology followed in applying NSGA-II to our model and the computational experiments carried out to obtain the results for the proposed outbound logistics network.

Solution methodology and computational experiments

The NSGA-II algorithm makes use of a fast non-dominating sorting approach to discriminate solutions, which is based on the concept of Pareto dominance and optimality. The pseudocode of the algorithm is presented in Table 1. We have solved the proposed problem based on the standard framework of NSGA-II algorithm alone. The programs are coded in MATLAB 7.8.0.347 (R2009a) and all the computational experiments are executed on a system with Intel (R) Core (TM) i3 CPU M350 @ 2.27 GHz and 3 GB RAM. For a typical outbound logistics network with 4 manufacturing plants (I), 3 CDCs (J), 5 RDCs (K), and 7 CZs (L), there will be $I*J+I*K+I*L+J*L+K*L=116$ continuous variables and I+J+K = 12 binary variables. The parameters used for optimization in NSGA-II algorithm are listed in Table 2.

The set of experimental values used for the parameters of the mathematical model are generated randomly using uniform distribution and are listed in Table 3. Two data sets comprising of potential facilities and the maximum number of facilities to be opened are presented in Table 4. The codes are run at different combinations of population and generation to obtain possible optimum configurations for the proposed outbound logistics network with better performance measures.

Table 1 Pseudocode of NSGA-II

```
1) Generate initial solution of random solutions
2) Repeat
        2.1) Evaluate fitness of each solution in the population
        2.2) Pareto Front = 1
        2.3) Repeat
            2.3.1) Find non-dominated solutions in the current population
            2.3.2) Rank Pareto optimal front from among the nondominated solutions
            2.3.3) Apply Crowding Distance strategy to maintain diversity in the solutions
            2.3.4) Remove non-dominated solutions from the current front from further consideration
            2.3.5) Pareto Front = Pareto Front + 1
        2.4) Until all the solutions in the front are ranked
        2.5) Select solutions based on non-dominated rank for reproduction
        2.6) Apply genetic operators crossover and mutation to generate new solutions
3) Until the termination conditions are satisfied
```

Table 2 NSGA-II parameters used for optimization

Parameter	Value
Population size	200
Selection strategy	Roulette wheel selection
Crossover type (binary)	Multi-point crossover
Crossover type (real)	Simulated binary crossover
Mutation type (binary)	Bitwise mutation
Mutation type (real)	Polynomial mutation
Crossover probability	0.85
Mutation probability (binary)	0.08
Mutation probability (real)	0.05
Distribution index (crossover)	25
Distribution index (mutation)	125
Maximum number of generations	2,000
Termination criterion	Specified number of generations

Table 3 Range of parameter values

Parameter	Value
Production capacities (in units) of plants	
Fast moving items	35,000–36,000
Slower moving items	17,000–18,000
Very slow moving items	3,500–3,600
Demand quantities (in units) from CZs	
Fast moving items	9,000–10,000
Slower moving items	4500–5,000
Very slow moving items	900–1,000
Fixed cost $ of facilities	
Plants	5,400,000–6,300,000
CDCs	1,600,000–1,800,000
RDCs	2,500,000–2,700,000
Unit cost $ of transportation	
Fast moving items (from Plants to RDCs)	10–15
Fast moving items (from RDCs to CZs)	6–9
Slower moving items (from Plants to CDCs)	6–9
Slower moving items (from CDCs to CZs)	16–20
Very slow moving items (from Plants to CZs)	21–27
Storage capacities (in units) of each facility[a]	
Fast moving items (at RDCs)	20,000
Slower moving items (at CDCs)	20,000
Very slow moving items (at Plants)	4,000

[a] Fixed values

The results obtained and the corresponding graphs are elaborated in the following section.

Results and discussions

We consider two data sets for conducting the computational experiments for our proposed outbound logistics network.

Table 4 Datasets

Facilities	Potential number of facilities	Maximum number of facilities to be opened
Dataset 1		
Plants	4	2
CDCs	3	2
RDCs	5	4
Dataset 2		
Plants	4	3
CDCs	5	3
RDCs	7	5

The number of potential facilities considered in data set 1 is 4 plants, 3 CDCs, and 5 RDCs. The maximum number of facilities to be opened is restricted to 2 plants, 2 CDCs, and 4 RDCs to satisfy the customer demands from 7 CZs. Similarly, in data set 2, the number of potential facilities is 4 plants, 5 CDCs, and 7 RDCs, and maximum number of facilities to be opened to satisfy customer demands from 9 CZs is 3 plants, 3 CDCs, and 5 RDCs. A minimum datum line of 80 % is set for both performance measures: UFR and resource utilization (RU) for the proposed OLN. The UFR implies the level of customers' demands met immediately from the available stocks, while RU stands for the quantum of capacity utilization of facilities in the network.

The computational results obtained for the various combinations of populations and generations for data set 1 are listed in Table 5. The cost of OLN, the resulting configuration of the network, the percentages of UFR and RU are tabulated. The summary of overall results obtained from all the experiments for data set 1 is listed in Table 6. It can be observed that the most minimum cost obtained is 4.38E+07 and the corresponding configuration will have 2 plants (2nd and 3rd), 1 CDC (3rd) and 3 RDCs (1st, 2nd, and 4th) opened to satisfy the customers' demands with 91 % of UFR and 81 % of RU. The network configuration with highest possible UFR (96 %) at minimum possible cost (6.33E+07) will have 2 plants (1st and 3rd), 2 CDCs (2nd and 3rd), and 3 RDCs (2nd, 4th, and 5th). Similarly the highest possible RU of 84 % at minimum possible cost of 5.10E+07 will have a network configuration of 2 plants (1st and 4th), 2 CDCs (1st and 2nd), and 3 RDCs (1st, 2nd, and 4th). The 100 % of UFR and RU is achieved at a cost of 8.72E+07 and 9.71E+07 respectively.

The similar computational results obtained for data set 2 are listed in Table 7 and Table 8.

A few sample configurations of the outbound logistics network (OLN) obtained from the computational study for data set 1 and data set 2 are pictorially presented in Tables 9 and 10 respectively with the corresponding values for cost, UFR and RU.

Furthermore, the graphical representations of computational study are presented in Figs. 3, 4, 5 and 6.

Table 5 Computational results for data set 1

S no	Cost of OLN $	Configuration of OLN[a]			UFR (%)	RU (%)	Remarks
		Plants	CDCs	RDCs			
Population: 40; Generations: 400							
1	*6.11E + 07*	*0 0 1 1*	*1 0 1*	*1 0 0 1 1*	*86*	*80*	*Min Cost*
2	7.21E+07	0 0 1 1	1 0 1	1 1 0 1 1	90	80	–
3	7.71E+07	0 1 0 0	0 0 1	0 0 1 1 1	80	85	–
4	9.71E+07	0 1 0 0	0 0 1	0 0 0 1 1	83	100	–
5	*1.36E + 08*	*1 1 0 0*	*0 0 1*	*1 1 1 0 1*	*100*	*95*	*Max Cost*
Population: 70; Generations: 700							
1	*6.33E + 07*	*1 0 1 0*	*0 1 1*	*0 1 0 1 1*	*96*	*83*	*Min Cost*
2	8.27E+07	1 0 1 0	0 1 1	0 1 1 1 1	99	80	–
3	8.72E+07	1 0 1 0	0 1 1	0 1 1 1 1	100	80	–
4	*3.09E+08*	*0 0 1 0*	*0 0 1*	*0 0 0 0 1*	*83*	*99*	*Max Cost*
Population: 90; Generations: 900							
1	*4.38E+07*	*0 1 1 0*	*0 0 1*	*1 1 0 1 0*	*91*	*81*	*Min Cost*
2	5.96E+07	0 1 1 0	0 1 1	1 1 0 1 0	95	80	–
3	1.21E+08	0 1 1 0	0 1 1	1 1 0 1 1	100	86	–
4	*2.86E+08*	*1 0 0 0*	*0 0 1*	*0 0 0 0 1*	*86*	*99*	*Max Cost*
Population: 160; Generations: 1600							
1	*8.54E+07*	*1 0 1 0*	*0 0 1*	*1 0 0 0 1*	*95*	*81*	*Min Cost*
2	1.45E+08	1 0 1 0	0 1 1	1 1 0 0 1	99	80	–
3	2.33E+08	1 0 1 0	0 1 1	1 0 1 0 1	100	81	–
4	*1.64E+09*	*1 0 0 1*	*0 0 1*	*0 0 0 0 1*	*87*	*97*	*Max Cost*
Population: 200; Generations: 2000							
1	*5.10E+07*	*1 0 0 1*	*1 1 0*	*1 1 0 1 0*	*90*	*84*	*Min Cost*
2	*1.64E+09*	*1 0 0 1*	*1 0 1*	*1 0 1 1 1*	*100*	*80*	*Max Cost*

The values in italic are the minimum and maximum costs of the outbound logistics network (*OLN*) with the corresponding values for unit fill rate (*UFR*) and resource utilization (*RU*)

[a] 1 indicates OPEN facility and 0 indicates NON-OPEN facility

Managerial insights

The results obtained in this study offer a wider scope for operations managers to explore and exploit them to the best possible advantage. The results can be best utilised to select any desired network configuration based on any of the objectives: lower network cost or higher UFR or higher RU or any combination of UFR and RU at an available network cost. For example, some of the options the managers will have at their discretion are as follows:

Table 6 Summary of overall results for data set 1

Overall results

S no	Cost of OLN $	Configuration of OLN[a]			UFR (%)	RU (%)	Remarks
		Plants	CDCs	RDCs			
1	4.38E+07	0 1 1 0	0 0 1	1 1 0 1 0	91	81	Most Min Cost
2	5.10E+07	1 0 0 1	1 1 0	1 1 0 1 0	90	84	Min Cost with Highest RU
3	6.33E+07	1 0 1 0	0 1 1	0 1 0 1 1	96	83	Min Cost with Highest UFR
4	8.72E+07	1 0 1 0	0 1 1	0 1 1 1 1	100	80	Highest UFR
5	9.71E+07	0 1 0 0	0 0 1	0 0 0 1 1	83	100	Highest RU

OLN outbound logistics network, *UFR* unit fill rate, *RU* resource utilization

[a] 1 indicates OPEN facility and 0 indicates NON-OPEN facility

Table 7 Computational results for data set 2

S no	Cost of OLN $	Configuration of OLN[a]			UFR (%)	RU (%)	Remarks
		Plants	CDCs	RDCs			
Population: 40; Generations: 400							
1	1.2937E+15	1000	10011	1000010	93.30	89.30	Min Cost
2		0010	10000	0111000	98.30	100	
3	1.2940E+15	1101	10001	0101101	88.30	92.50	Max Cost
Population: 70; Generations: 700							
1	1.2937E+15	1010	11100	0101100	93.14	99.30	Min Cost
2		1001	01110	1110100	92.60	96.30	
3		1101	01011	0010111	91.40	90.90	
4	2.2939E+15	0011	00100	0101101	80.60	91.34	Max Cost
Population: 90; Generations: 900							
1	1.2937E+15	1100	01000	1000001	96.20	88.4	Min Cost
2		1100	00101	0010001	94.70	88.8	
3		0010	00011	1000111	92.30	86.8	
4	2.2939E+15	1000	01000	1000111	82.90	93.6	Max Cost
Population: 160; Generations: 1600							
1	1.2937E+15	0111	11100	0011100	93.90	94.10	Min Cost
2		1101	01110	0000010	96.70	93.80	
3		0111	01011	1010010	96.11	89.10	
4	3.2938E+15	1110	01101	0101001	92.80	89.10	Max Cost
Population: 200; Generations: 2000							
1	1.2937E+15	0111	01101	0101010	96.60	96.30	Min Cost
2		1110	00011	1110110	95.60	89.20	
3	2.2939E+15	1000	01001	0000100	90.70	89.60	Max Cost

OLN outbound logistics network, *UFR* unit fill rate, *RU* resource utilization

[a] 1 indicates OPEN facility and 0 indicates NON-OPEN facility

Table 8 Summary of overall results for data set 2

Overall results

S no	Cost of OLN $	Configuration of OLN[a]			UFR (%)	RU (%)	Remarks
		Plants	CDCs	RDCs			
1	1.2937E+15	1101	01011	0010111	91.40	90.90	Most Min Cost
2	1.2937E+15	0010	10000	0111000	98.30	100	Min Cost with Highest RU
3	1.2937E+15	0010	10000	0111000	98.30	100	Min Cost with Highest UFR
4	1.2937E+15	0010	10000	0111000	98.30	100	Highest UFR
5	1.2937E+15	0010	10000	0111000	98.30	100	Highest RU

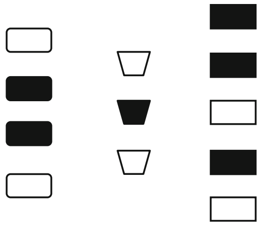
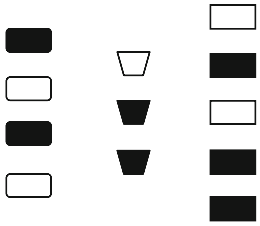
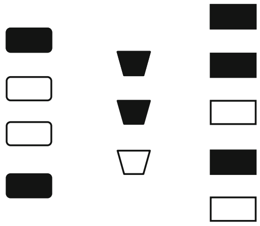
OLN outbound logistics network, *UFR* unit fill rate, *RU* resource utilization

[a] 1 indicates OPEN facility and 0 indicates NON-OPEN facility

- A configuration which has least total cost for the network with UFR and CU above the datum line of 80 percent
- A configuration which has highest possible level of UFR with an acceptable level of total network cost
- A configuration which has highest possible level of RU with an acceptable level of total network cost
- A configuration which has 100 percent of UFR irrespective of total network cost
- A configuration which has 100 percent of RU irrespective of total network cost

Thus the managers will have numerous choices to suit any kind of practical situation and constraints.

Table 9 Sample configurations for data set 1 with corresponding values for three objectives

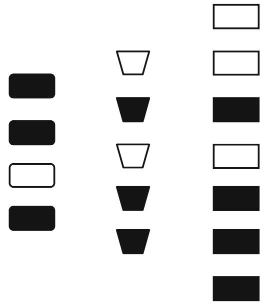
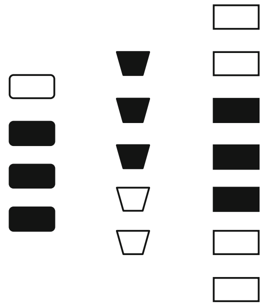
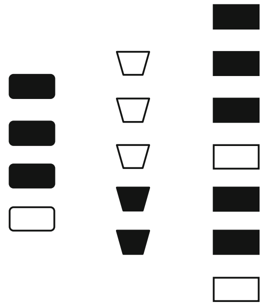
S No	Configuration of OLN	Cost of OLN ($)	UFR (%)	RU (%)
1		4.38E+07	91	81
2		6.33E+07	96	83
3		5.10E+07	90	84

Note: Filled in facilities are open facilities in the respective configuration
■ Plants; ▼ CDCs; ■ RDCs

Conclusions

In this paper, we have proposed the design of an innovative and hybrid outbound logistics network for an automotive manufacturing supply chain for delivering three variants of a product labelled as fast moving, slower moving, and very slow moving items based on their nature of demand to CZs at known locations through a set of potential facilities like manufacturing plants, CDCs, and RDCs in a deterministic, single time period, single country, and multi objective context. The proposed network is designed so as to minimize the total network cost, maximize the UFR, and maximize the resource (facility) utilization subject to a host of capacity, demand, flow, and resource constraints. The MILP model formulated for the problem under investigation is NP-hard and a multi objective evolutionary algorithm called NSGA-II is employed to solve the problem and obtain different configurations of the network. A host of different configurations of the network are obtained with varying levels of performance measures viz, UFR and resource utilization at competitive cost values. The outcomes of the study prove to be beneficial for the managerial community of similar supply chains. The possible extensions of this concept and study may include: a global network, multiple time periods, scalable capacities for facilities, and elements of uncertainty in demands, unit costs, and capacities etc to make the problem more pragmatic in approach and scope.

Table 10 Sample configurations for data set 2 with corresponding values for three objectives

S No	Configuration of OLN	Cost of OLN ($)	UFR (%)	RU (%)
1		1.2937E+15	91.40	90.90
2		1.2937E+15	93.90	94.10
3		1.2937E+15	95.60	89.20

Note: Filled in facilities are open facilities in the respective configuration
■ Plants; ▼ CDCs; ■ RDCs

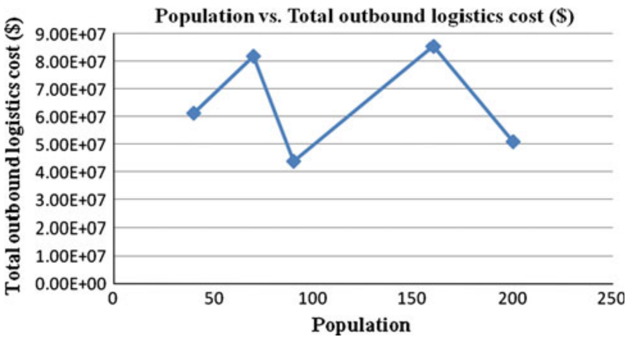


Fig. 3 Population versus minimum cost of the OLN

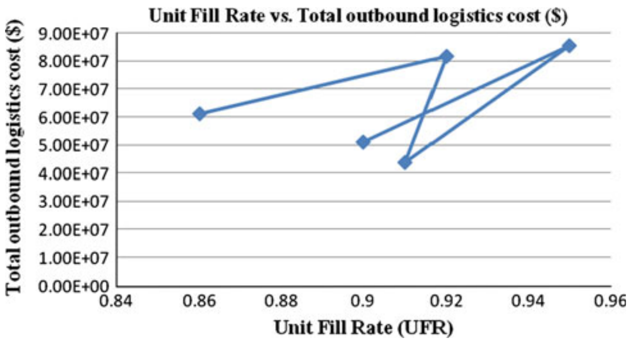


Fig. 4 Unit fill rate (UFR) versus minimum cost of the OLN

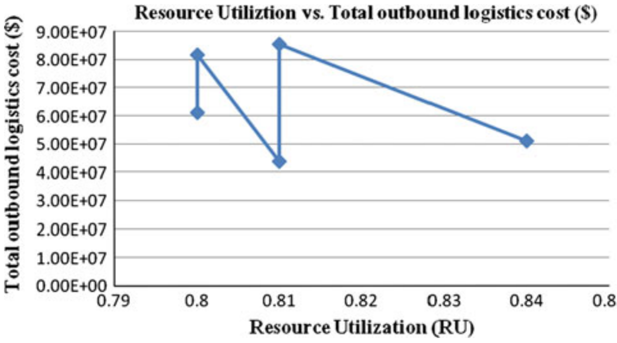
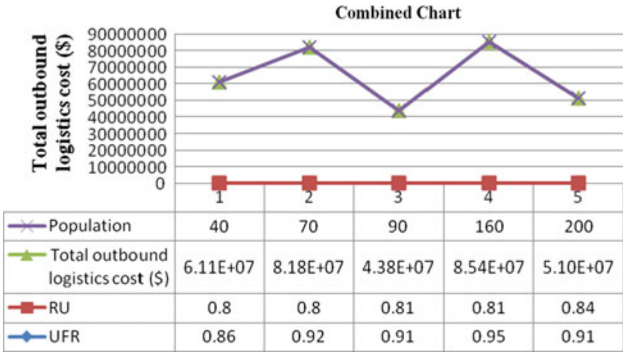


Fig. 5 Resource utilization (RU) versus minimum cost of the OLN



	1	2	3	4	5
Population	40	70	90	160	200
Total outbound logistics cost ($)	6.11E+07	8.18E+07	4.38E+07	8.54E+07	5.10E+07
RU	0.8	0.8	0.81	0.81	0.84
UFR	0.86	0.92	0.91	0.95	0.91

Fig. 6 Combined results of the computational experiments

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