Multi-period Multi-echelon Inventory Transportation Problem considering Stakeholders Behavioural Tendencies

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Article in ***International Journal of Production Economics, 2019***

Abstract:

An inventory transportation problem of manufacturing organization focusing on several stakeholders such as manufacturers, distributors, wholesalers, retailers and customers is addressed in this paper. The research study considered multi-echelon, multi-product, multi-modal and multi-period scenario. The mathematical model in the form of mixed integer non-linear programming is formulated to minimize the total cost associated with transportation, inventory holding and operational activities. A mathematical formulation based heuristic approach, which comprises of four algorithms, is proposed for solving purpose. The proposed heuristic approach considers the behavioural tendencies of stakeholders pertaining to the selection of shipment routes, transportation mode choice decisions and amount of products to be shipped. Fifteen practical problem instances are solved by using the developed heuristic approach while considering the behavioural aspects of stakeholders. Insights obtained from results will be beneficial for manufacturing organizations in making informed decisions related to transportation planning considering stakeholder's behavioural tendencies.

Keywords: Inventory; Transportation; Supply chain network; Manufacturing; Mixed integer non-linear programming; Heuristic

1. Introduction

Manufacturing organizations are facing a competitive environment due to the increased complexities in manufacturing products and then distributing them to specific distributors and retailers while aiming to mitigate the operational and transportation cost (Pan et al. 2013 and Mogale et al. 2018). Moreover, with the development of economy, the competition among the manufacturing organizations has changed into a competition among their respective supply chains (Dai et al. 2019). An appropriately strategized inventory transportation network for a multi-period scenario can reduce the overall transportation and operational cost and which in turn will reduce the price of products (Dai et al. 2019). A multi-echelon supply chain network does not allow the direct flow of products from manufacturers to customers, rather it involves the flow of products between different stakeholders comprising of manufacturers, wholesalers, distributors, retailers and customers (Moin et al. 2011 and Kumar et al. 2017). Multi-echelon supply chain distribution network can reap benefits in terms of adopting different sizes of vehicles, which can be used for shipment purpose, and thereby reducing the transportation cost and bringing economic benefits (Dai et al. 2019). In view of the aforementioned motivations, it is imperative to study the supply chain network comprising of multiple stakeholders or echelons and multiple vehicle sizes. Moreover, in the domain of manufacturing supply chain management, enormous data is majorly generated every day at the supplier and consumer side. This data can be related to demand data at the customer for multiple products type and supply data at the manufacturer end for various product types. The information related to the demand keeps on changing in different time periods (such as days or weeks) and it needs to be taken into account while designing the supply chain network. The variability with regard to the demand data for different product types needs to be considered for strategic decision making purpose, which might ultimately lead to an increased business profit, and reduced operational cost (LaValle et al. 2013 and Loshin 2013). Therefore, it is essential to investigate the supply chain network while taking into account multiple stakeholders and demand related to multiple product types in various time periods.

The research work of Mylan et al. (2014) and Cheraghalipour et al. (2019) addressed the business model of food production where private traders purchase the food grain from farmers during various time periods and sell the product to big food production firms. These firms produce different types of product (Bread) from wheat and transfer the product to customers via distributors and retailers. Big firms use the multi-modal transportation system for shipment of food products in bulk amount (Mylan et al. 2014 and Cheraghalipour et al.

2019). The research work of Soleimani et al. (2013) and Pasandideh et al. (2015) presented the business model of manufacturing supply chain comprising of multi-echelon scenario. Initially, Original Equipment Manufacturer (OEM) procures raw materials, small components and semi-finished products from suppliers. The OEM produces different types of products in the manufacturing plant and then the products are shipped to distributors, retailers, wholesalers and finally customers using different modes of transportation (Multi-modal) (Soleimani et al. 2013 and Pasandideh et al. 2015). Based on the aforementioned real-world examples, it is essential to look into the inventory transportation problem while considering the multi-echelon, multi-period and multi-product case, and such examples establish the motivation for this research work.

In the real world, decision-makers are not as perfectly rational as assumed in mathematical models. When stakeholders make decisions, they easily get distracted from the perfectly optimal rational policy and rather make a biased decision as per their intuition (Zhao et al. 2015). Although, it is essential for manufacturing organizations to improve the performance in a highly volatile, competitive and realistic environment. Therefore, it is imperative to examine the supply chain network while considering behavioural tendencies of different stakeholders such as manufacturers, distributors, wholesalers and retailers. In each time-period, manufacturer has to determine the number of different product types to be transported to distributors. Similarly, distributors, wholesalers and retailers have to estimate the number of various product types to be shipped to the next subsequent downstream stakeholder. This allocation between various echelons (stages) is not fixed in every time period and all stakeholders will act as per their individual perspectives. Thus, these behavioural patterns of the stakeholder concerning allocation decisions along with inventory decisions need to be integrated in the study. In terms of behavioural tendencies, majority of the stakeholders such as manufacturers, distributors, wholesalers and retailers follow the general tendency of shipping various product types via transportation routes with lesser distance or reduced tariff costs (Villa et al. 2018). Moreover, behavioural tendencies of stakeholders are highlighted when they need to choose between modes of transportation (rail or road transportation). In such cases, the stakeholder's strategy is to adopt a minimum threshold limit for the shipment of product types (Mogale et al. 2017). Limited number of heterogeneous capacitated vehicles are available at each echelon for shipment purpose and every stakeholder tries to use vehicles sequentially with their decreasing capacity (i.e. large, medium and small) to minimize the total number of vehicles utilized for transportation

(Mogale et al. 2019a). This behavioural aspect of various entities including manufacturer, distributor, wholesaler and retailer is related to the behaviour analysis of vehicle choice decisions for transportation. There are several mathematical models developed in the domain of logistics and supply chain management, which typically make explicit and implicit assumptions about the behaviours of stakeholders. These models overlook the need to address the biases related to human decision making and thereby highlighting a limitation in their mathematical model (Tokar 2010, Sarkar et al. 2015 and Villa et al. 2018). Such limitations include the behavioural tendencies of stakeholders related to the selection of transportation route and transportation mode choice decisions. There are certain analytical models addressing stakeholder's behavioural aspects, but there is hardly any research work which presented a mathematical model or heuristic approach while considering stakeholder's behavioural tendencies (Zhao et al. 2015). Fahimnia et al. (2019) highlighted the increasing need for addressing behavioural aspects of stakeholders while aiming to address supply-chain decision-making problem. Therefore, the current research work presented in this paper tries to overcome the limitation and incorporate behavioural tendencies of stakeholders while addressing the supply chain problem of a manufacturing organization.

Based on the aforementioned motivations, the contribution of the paper lies in developing a mathematical model for addressing a supply chain network problem of a manufacturing organization. The proposed model considers various stakeholders like manufacturers, distributors, wholesalers, retailers and customers. Several real-world and practical features of the manufacturing supply chain network encompassing multi-echelon, multi-product, multi-modal transportation and multi-period are incorporated while developing the mathematical formulation. The capacitated warehouses, operational costs, limitation on number of capacitated vehicles and vehicle capacity restrictions are also concurrently incorporated in the proposed model. The main aim of the model is to minimize the total cost while appropriately perform the planning and strategizing of movement and storage decisions for product types in a multi-period environment. It is quite challenging to incorporate some of the behavioural aspects of stakeholders within the mathematical model. Therefore, a mathematical formulation based heuristic approach is developed which consists of a combination of four algorithms and each of them addresses the behavioural tendencies of the manufacturers, distributors, wholesalers and retailers.

The rest of the article is structured in the following way. Section 2 presents the relevant literature and section 3 describes the problem statement. Section 4 provides the mathematical formulation. The solution methodology is presented in Section 5. Computational experiments and results are mentioned in Section 6. Finally, Section 7 concludes the paper and provides a future research direction.

2. Literature Review

In this section, the relevant literature focusing on the optimization model for multi-period multi-echelon supply chain distribution network are reviewed. Moreover, the published works related to behavioural research within supply chain management are discussed. Lastly, the research gaps and contributions are presented from the standpoint of the published works in the relevant area.

2.1. Multi-Period Multi-Echelon Inventory Transportation Models

Several authors have developed optimization models for various supply chain problems related to inventory management, logistics and distribution planning (Sainathuni et al. 2014, Wu et al. 2015, Petridis 2015, Mogale et al. 2016 and De et al. 2017a). Zhao et al. (2017) developed an optimization model, which minimizes the economic cost for a multi-echelon supply chain network, although overlooking the demand variability in their research. The work of Kaur et al. (2017) addressed the limitation and considered product demand for the multi-period scenario while dealing with a joint sustainable procurement and logistics problem. The research work of Rafiei et al. (2018) tried to overcome the limitation by developing a mathematical model for a four echelon supply chain network. They highlighted that the financial penalty of not meeting the customer demand is significant and therefore, it is imperative to consider the demand for a multi-period case. Although, their research considered the assumption of a single product and single transportation mode, which need to be addressed, as in reality supply chain networks are quite complex as it deals with multiple product types and various transportation modes (Ge et al. 2016). Although few researchers addressed some of the complex supply chain networks comprising of multi-period, multi-product and multi-echelon (Soleimani et al. 2013, Akbari et al. 2015, Pasandideh et al. 2015 and Peres et al. 2017). It has been observed that majority of the earlier published work overlooked the need to incorporate the decision making associated with the mode of transportation. Moreover, it is imperative to address the behaviour tendencies of the stakeholders responsible for transportation mode choice decisions. Mogale et al. (2017) incorporated the transportation mode choice decision within their proposed mathematical model, although overlooked the behavioural tendencies of the decision-makers. Next sub-section will try to address the importance of considering the behavioural tendencies of the stakeholders in the context of supply chain decision making.

2.2. Behavioural Research in the Context of Supply Chain Network

Samimi et al. (2011) highlighted that the research work considering the behavioural tendencies of stakeholders while choosing the mode of transportation (such as rail or road) as it is of greater importance for academia as well as industrial practice (such as policy-making). Majority of the mathematical models considering single transportation mode are developed by researchers such as Soleimani et al. (2013), Akbari et al. (2015), Pasandideh et al. (2015) and Saberi et al. (2018) for multiple-echelons, multiple-products and multiple time periods cases. These studies overlooked the key aspect of stakeholder's behavioural tendencies for transportation mode choice decisions. Moreover, behavioural research is of equal importance to supply chain management as it also involves the coordination and collaboration of various stakeholders (such as distributors, retailers etc.) or human decision-makers at multiple organizations (Tokar 2010). Very few research works are published with the focus of addressing and incorporating the knowledge associated with stakeholder's behaviour within supply chain optimization models (Tokar 2010, Sarkar et al. 2015, and Villa et al. 2018). Furthermore, there are empirical research works on stakeholder's behavioural perspective for a multi-echelon inventory management problem, but there is a lack of mathematical modelling or heuristic approach related research work addressing the behavioural aspect of stakeholders (Zhao et al. 2015). Moreover, Hofstra et al. (2015) stated that behavioural tendencies in decision-making can be incorporated by the development of heuristics while utilising the amount of information available and overcoming the systematic errors in decision-making. As the trend of adoption of behavioural aspect within a supply chain is continuously increasing (Fahimnia et al. 2019), therefore it can be interpreted that there is a greater need of developing more analytic models with behavioural aspects integration within supply chain decision-making. Additionally, from the aforementioned literature, it can be incurred that there is a lack of robust mathematical models within inventory transportation problem considering multi-period, multi-echelon and multi-product scenario. Also, stakeholder's behavioural tendencies for transportation mode choice decisions and choosing appropriate transportation routes are not simultaneously integrated in the extant literature.

2.3. Research Gaps and Contributions

Some of the earlier research works addressed the complexity within supply chain and presented mathematical models considering multi-echelon, multi-period and multi-product cases (Soleimani et al. 2013, Akbari et al. 2015, Pasandideh et al. 2015, Li et al. 2018 and Saberi et al. 2018). Although, their research work overlooked the need to consider the behaviour tendencies of stakeholders during supply chain decision-making. The exhaustive review of the previous studies presents an empirical, conceptual and theoretical framework based research work involving behavioural aspect within supply chain management context specifically involving transportation and inventory control operations (Tokar 2010, Sarkar et al. 2015 and Hofstra et al. 2015). Such works also highlighted a lack of optimization models related to various research addressing behavioural supply chain management problem. Although few research works developed analytical models for multi-echelon inventory transportation considering behavioural aspect, but it didn't provide any mathematical model or heuristic approach for mathematically representing the stakeholder's behavioural tendencies (Zhao et al. 2015). The current research work presented in this paper aims to bridge this research gap by developing a mathematical model for multi-period, multi-echelon and multi-product case while considering the various modes of transportation. The mathematical formulation is developed for a supply chain network comprising of manufacturers, distributors, wholesalers, retailers and customers. Thus, a novel heuristic approach is proposed while considering stakeholder's behavioural tendencies to support the decision making process associated with manufacturing supply chain network. The heuristic comprises of four algorithms. First algorithm aims to address manufacturer's behavioural tendencies related to choosing of transportation links for the shipment of products from manufacturer to distributor. The second algorithm depicts the behavioural tendencies of the distributor from the perspective of shipment of multiple product types and transportation mode choice decisions. Third algorithm addresses behavioural perceptions of the wholesaler in choosing transportation routes and wholesaler's behavioural tendencies based on the inventory level. Fourth algorithm aims to address behavioural tendencies of retailer related to determining appropriate transportation link based on shipment tariffs. The four algorithms addressing behavioural aspects of stakeholders are linked together to form the novel heuristic approach proposed for solving the multi-echelon multi-period multi-product supply chain problem.

3. Problem Statement

The paper aims to address the problem of inventory transportation for a supply chain network of a manufacturing organization. The underline problem is in the form of multi-echelon, multi-product, multi-modal and multi-period setting. Five echelons are considered in the problem comprising of manufacturers, distributors, wholesalers, retailers and consumers. The manufacturing industry produces various product types at manufacturing plants using raw materials. The product types are then shipped using capacitated vehicles to distributors at various locations. Manufacturer's behavioural perspectives are highlighted over here as they predominantly tend to transport various products to distributors with distances lesser than a certain threshold distance. Such behavioural tendencies can be argued as it might not result in obtaining the optimal solution for the supply chain network, although in real-world scenario the stakeholder's generally tend to address lowering their individual operating and transportation cost rather than looking at the bigger picture of mitigating the overall cost associated with the supply chain network (Zhao et al. 2015). Therefore, it is imperative to address the behavioural perspectives of stakeholders while addressing the real-world supply chain network.

From the distributors, the various products are shipped to several wholesalers using road or rail mode of transportation. The behavioural tendencies of the distributors ensure that they choose transportation links with lesser distances between distributors and wholesalers for the shipment of products. Moreover, when the number of products to be shipped are more than a certain restricted limit, the distributor's general behavioural tendency is to choose rail mode of transportation over road transportation mode. This also highlights distributor's behavioural aspect related to transportation mode choice decisions. Maiyar and Thakkar (2017) stated a similar strategy used by the stakeholders related to the minimum product requirements in selecting rail over road as the mode of transportation. Now, from wholesalers, the shipment of products to the retailers are performed via various types of vehicles available with wholesalers. Then, these different types of products will reach consumers through various types of capacitated vehicles after passing through wholesalers and retailers. Behavioural tendencies of wholesalers and retailers are addressed as both stakeholders tend to choose transportation links with distances lesser than the certain threshold limit. The overall supply chain network comprising of manufacturers, distributors, wholesalers, retailers and customers considered in this study is depicted in Fig. 1.

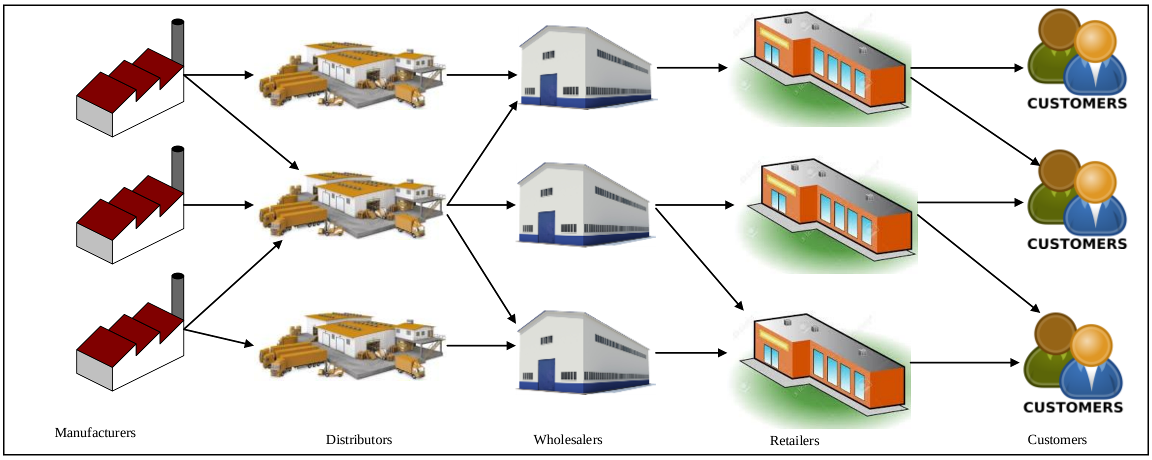


Fig. 1 Supply chain structure of considered problem

The novelty of the research lies in addressing the aforementioned problem and proposing a mathematical model, which is presented in section 4. Another novelty of the research is related to developing a heuristic approach while addressing behavioural tendencies of stakeholders and it is presented in section 5. The main aim of the mathematical formulation is to help stakeholders with the inventory and transportation related decision-making which involves minimizing the total cost associated with transportation, handling and inventory related operations in supply chain network. The novel features of the proposed model involve addressing storage limitation of capacitated warehouses, cost components associated with transportation, inventory and operations. Moreover, the model also addresses the restriction on the number of different capacitated vehicles available with stakeholders, demand satisfaction at the customer side, inventory flow balance for different stakeholders, vehicle capacity restrictions and consideration of multiple modes of transportation. There are various quantitative model parameters considered in the mathematical formulation with regard to the characteristics of large data sets. Multi-echelon, multi-product, multi-modal and multi-period scenarios are considered for the aforementioned problem with several parameters involving transportation, inventory holding and operational cost, stakeholder's storage capacity and vehicle capacity. The attribute of large data can also be illustrated from the fact that the significant volume of time dependent parameters (time varying demand and supply) are considered for the proposed model. This includes number of vehicle types available in different time period and their availability with each stakeholder, available manufacturer capacity in different time period and time-varying demand of various product types.

4. Mathematical model

In this section, a mixed integer non-linear programming (MINLP) model is presented for a multi-echelon supply chain network problem. The aim is to obtain a time-varying shipment plan for multiple types of products and determining the amount of inventory level associated with each facility while minimizing the objective function value. The notations, parameters and decision variables related to the mathematical formulation are defined and presented in appendix due to space constraint. The assumptions, objective function and different types of constraints used for solving the aforementioned problem are presented in this section along with suitable explanations.

Assumptions:

The following assumptions are taken into consideration while developing the mathematical model.

1. The number of products of each type available with the manufacturer and the demand of the customer is time-varying.
2. Finite number of vehicles and rakes are available with different facilities (such as manufacturer, distributor, wholesaler and retailer) in each time period.
3. The number of products supplied by the manufacturer in each time period is adequate to satisfy the demand of each customer and thereby not considering the backlog and shortage related issues.
4. For the shipment of a certain product type from distributor to wholesaler, a specific type of transportation mode (either road or rail) can be used.
5. Operational costs related to performing receiving and dispatching of products at distributor, wholesaler and retailer are taken into consideration.

Objective Function:

Minimize Total cost = Transportation Cost + Inventory Holding Cost + Operational Cost

(1a)

Transportation Cost =

$$\left.\begin{array}{l}\sum_{i\in I}\sum_{k\in K}\sum_{f\in F}\sum_{t\in T} c_a dis_{ik} Y_{ik}^{ft} X_{ik}^{ft} + \sum_{k\in K}\sum_{l\in L}\sum_{f\in F}\sum_{t\in T} c_a dis_{kl}^{a} Y_{kl}^{ft} X_{kl}^{ft} \alpha_{kl}^{aft} + \sum_{k\in K}\sum_{l\in L}\sum_{f\in F}\sum_{t\in T} c_b dis_{kl}^{b} Y_{kl}^{ft} X_{kl}^{ft} \delta_{kl}^{bft} \\ + \sum_{l\in L}\sum_{m\in M}\sum_{f\in F}\sum_{t\in T} c_a dis_{lm} Y_{lm}^{ft} X_{lm}^{ft} + \sum_{m\in M}\sum_{n\in N}\sum_{f\in F}\sum_{t\in T} c_a dis_{mn} Y_{mn}^{ft} X_{mn}^{ft}\end{array}\right\}$$

(1b)

Equation (1a) presents the objective function, which aims to minimize the overall cost of the multi-echelon supply chain comprising of the transportation cost, inventory holding cost and operational cost. Equation (1b) depicts the transportation cost, which comprises of five terms. The first term provides the cost of transporting products from manufacturers to distributors. The second and third terms present the road and rail transportation cost respectively between distributors and wholesalers. The product is transported from distributors to wholesalers through either rail or road. Fourth and fifth terms are related to the road transportation cost pertaining to the movement of products from wholesalers to retailers and retailers to customers respectively.

Inventory Holding Cost =

$$\sum_{k\in K}\sum_{f\in F}\sum_{t\in T} h_{kf} Z_k^{ft} + \sum_{l\in L}\sum_{f\in F}\sum_{t\in T} h_{lf} Z_l^{ft} + \sum_{m\in M}\sum_{f\in F}\sum_{t\in T} h_{mf} Z_m^{ft} \tag{1c}$$

Operational Cost =

$$\left.\begin{aligned} &\sum_{i\in I}\sum_{k\in K}\sum_{f\in F}\sum_{t\in T} Y_{ik}^{ft} oc_{kf} + \sum_{k\in K}\sum_{l\in L}\sum_{f\in F}\sum_{t\in T} Y_{kl}^{ft}\left(oc_{kf} + oc_{lf}\right) \\ &+\sum_{l\in L}\sum_{m\in M}\sum_{f\in F}\sum_{t\in T} Y_{lm}^{ft}\left(oc_{lf} + oc_{mf}\right) + \sum_{m\in M}\sum_{n\in N}\sum_{f\in F}\sum_{t\in T} Y_{mn}^{ft} oc_{mf} \end{aligned}\right\} \tag{1d}$$

Equation (1c) presents the inventory holding cost, which comprises of three terms. The first, second and third terms are associated with the inventory holding cost of distributors, wholesalers and retailers respectively. Equation (1d) provides the operational cost and it comprises of four terms. The first term depicts the operational cost for distributors while receiving the products from manufacturers. The second term presents the sum of the operational cost incurred for distributors while dispatching products and the operational cost of wholesalers while receiving products. The third term provides the sum of the operational cost for wholesalers while dispatching products and the operational cost for retailers while receiving products. The fourth term depicts the operational cost associated with dispatching products from retailers to customers.

Supply Constraints:

$$\sum_{k\in K} Y_{ik}^{ft} X_{ik}^{ft} \le A_{if}^{t} \qquad \forall i\in I,\ \forall f\in F,\ \forall t\in T \tag{2}$$

$$\sum_{l\in L} Y_{kl}^{ft} X_{kl}^{ft} \le Z_k^{ft} \qquad \forall k\in K,\ \forall f\in F,\ \forall t\in T \tag{3}$$

$$\sum_{m \in M} Y_{lm}^{ft} X_{lm}^{ft} \le Z_l^{ft} \qquad \forall l \in L,\ \forall f \in F,\ \forall t \in T \qquad (4)$$

$$\sum_{n \in N} Y_{mn}^{ft} X_{mn}^{ft} \le Z_m^{ft} \qquad \forall m \in M,\ \forall f \in F,\ \forall t \in T \qquad (5)$$

Equations (2), (3), (4) and (5) are the supply constraints. Constraint (2) presents the total number of products transported from each manufacturer should be less than or equal to the amount of products available with the manufacturer for a specific time period. Constraints (3), (4) and (5) ensure that the number of products of each type flowing from each distributor, wholesaler and retailer are limited to the maximum available inventory level in that specific period for each distributor, wholesaler and retailer respectively.

Capacity Constraint:

$$w_k \ge \begin{cases} \sum_{f \in F} Z_k^{f(t-1)} + \sum_{i \in I} \sum_{f \in F} Y_{ik}^{ft} X_{ik}^{ft}, & t > 1 \\ \sum_{f \in F} Z_k^{f0} + \sum_{i \in I} \sum_{f \in F} Y_{ik}^{ft} X_{ik}^{ft}, & t = 1 \end{cases} \qquad \forall k \in K,\ \forall t \in T \qquad (6)$$

$$w_l \ge \begin{cases} \sum_{f \in F} Z_l^{f(t-1)} + \sum_{k \in K} \sum_{f \in F} Y_{kl}^{ft} X_{kl}^{ft}, & t > 1 \\ \sum_{f \in F} Z_l^{f0} + \sum_{k \in K} \sum_{f \in F} Y_{kl}^{ft} X_{kl}^{ft}, & t = 1 \end{cases} \qquad \forall l \in L,\ \forall t \in T \qquad (7)$$

$$w_m \ge \begin{cases} \sum_{f \in F} Z_m^{f(t-1)} + \sum_{l \in L} \sum_{f \in F} Y_{lm}^{ft} X_{lm}^{ft}, & t > 1 \\ \sum_{f \in F} Z_m^{f0} + \sum_{l \in L} \sum_{f \in F} Y_{lm}^{ft} X_{lm}^{ft}, & t = 1 \end{cases} \qquad \forall m \in M,\ \forall t \in T \qquad (8)$$

Equations (6), (7) and (8) are the capacity constraints for distributor, wholesaler and retailer respectively. Constraints state that the sum of the total inventory available with each facility (distributor, wholesaler and retailer) from the previous period and the number of products arriving at that specific facility cannot be more than its capacity. Although, for an initial time period, the number of products received at the facility plus the initial inventory of the facility should be less than or equal to the storage capacity of the facility.

Inventory Balancing Constraint:

$$Z_k^{ft} = \begin{cases} Z_k^{f(t-1)} + \sum_{i \in I} Y_{ik}^{ft} X_{ik}^{ft} - \sum_{l \in L} Y_{kl}^{ft} X_{kl}^{ft}, & t > 1 \\ \sum_{f \in F} Z_k^{f0} + \sum_{i \in I} Y_{ik}^{ft} X_{ik}^{ft} - \sum_{l \in L} Y_{kl}^{ft} X_{kl}^{ft}, & t = 1 \end{cases} \qquad \forall k \in K,\ \forall f \in F,\ \forall t \in T \qquad (9)$$

$$Z_l^{ft} = \begin{cases} Z_l^{f(t-1)} + \sum_{k\in K} Y_{kl}^{ft} X_{kl}^{ft} - \sum_{m\in M} Y_{lm}^{ft} X_{lm}^{ft}, & t>1 \\ \sum_{f\in F} Z_l^{f0} + \sum_{k\in K} Y_{kl}^{ft} X_{kl}^{ft} - \sum_{m\in M} Y_{lm}^{ft} X_{lm}^{ft}, & t=1 \end{cases} \quad \forall l\in L,\ \forall f\in F,\ \forall t\in T \tag{10}$$

$$Z_m^{ft} = \begin{cases} Z_m^{f(t-1)} + \sum_{l\in L} Y_{lm}^{ft} X_{lm}^{ft} - \sum_{n\in N} Y_{mn}^{ft} X_{mn}^{ft}, & t>1 \\ \sum_{f\in F} Z_m^{f0} + \sum_{l\in L} Y_{lm}^{ft} X_{lm}^{ft} - \sum_{n\in N} Y_{mn}^{ft} X_{mn}^{ft}, & t=1 \end{cases} \quad \forall m\in M,\ \forall f\in F,\ \forall t\in T \tag{11}$$

Equations (9), (10) and (11) present the inventory balancing constraints for distributors, wholesalers and retailers respectively considering the first time period and also the remaining time periods. Constraints ensure that the total inventory level at the end of each period for each facility (distributor, wholesaler and retailer) is equivalent to the sum of the number of products received at the facility and the inventory of the facility in the previous period, minus the number of products dispatched from the facility. Although, for the first time period, the inventory level at each facility (distributor, wholesaler and retailer) should be equal to the initial inventory level of the facility plus the number of products received at the facility minus the number of products flowing out of the facility.

Initial inventory level for distributor, wholesaler and retailer associated with the current planning horizon can be determined by obtaining the ending inventory of the stakeholders from the last planning horizon. Suppose, if the proposed mathematical model is run for two subsequent planning horizons of six time periods each, then the ending inventory level of the stakeholder at the end of first planning horizon or sixth time period will be considered as the initial inventory level for the stakeholder associated with the second planning horizon.

Demand Constraint and Vehicle Capacity Constraint:

$$\sum_{m\in M} Y_{mn}^{ft} X_{mn}^{ft} = D_n^{ft} \quad \forall n\in N,\ \forall f\in F,\ \forall t\in T \tag{12}$$

$$\sum_{k\in K}\sum_{f\in F} Y_{ik}^{ft} X_{ik}^{ft} \le \sum_{p\in P}\sum_{f\in F} v_{ip}^{t} cap_p^f \quad \forall i\in I,\ \forall t\in T \tag{13}$$

$$\sum_{m\in M}\sum_{f\in F} Y_{lm}^{ft} X_{lm}^{ft} \le \sum_{g\in G}\sum_{f\in F} v_{lg}^{t} cap_g^f \quad \forall l\in L,\ \forall t\in T \tag{14}$$

$$\sum_{n\in N}\sum_{f\in F} Y_{mn}^{ft} X_{mn}^{ft} \le \sum_{p\in P}\sum_{f\in F} v_{mp}^{t} cap_p^f \quad \forall m\in M,\ \forall t\in T \tag{15}$$

$$\sum_{l\in L}\sum_{f\in F} Y_{kl}^{ft} X_{kl}^{ft} \le \sum_{q\in Q}\sum_{l\in L}\sum_{f\in F} v_{kq}^{t} cap_q^f \alpha_{kl}^{aft} + \sum_{r\in R}\sum_{l\in L}\sum_{f\in F} v_{kr}^{t} cap_r^f \delta_{kl}^{bft} \quad \forall k\in K,\ \forall t\in T \tag{16}$$

Constraint (12) ensures that the demand of a specific type of product for a customer must be met from various retailers. Equations (13), (14) and (15) are related to the vehicle capacity constraints for manufacturer, wholesaler and retailer respectively. Constraint (16) ensures that the total quantity of product dispatched from each distributor using either road or rail transportation should satisfy the maximum capacity of rakes and vehicles.

$$X_{kl}^{ft} = \alpha_{kl}^{aft} + \delta_{kl}^{bft} \qquad \forall k \in K,\ \forall l \in L,\ \forall f \in F,\ \forall t \in T \tag{17}$$

$$\delta_{kl}^{bft} = \left\lceil \frac{max\left(0, Y_{kl}^{ft} - \phi_f\right)}{max\left(0, Y_{kl}^{ft} - \phi_f\right) + 1} \right\rceil \qquad \forall k \in K,\ \forall l \in L,\ \forall f \in F,\ \forall t \in T \tag{18}$$

Constraint (17) ensures that either road or rail transportation can be used for the dispatching of a specific type of product from a distributor to a wholesaler in a certain time period. Constraint (18) aims to determine the rail transportation links from distributor to wholesaler for the movement of a particular product type in a certain time period. In this constraint, ϕ_f is denoted as the minimum threshold limit for the shipment of products through rail mode of transportation.

$$X_{ik}^{ft}, X_{kl}^{ft}, X_{lm}^{ft}, X_{mn}^{ft}, \alpha_{kl}^{aft}, \alpha_{kl}^{bft} \in \{0,1\}$$
$$\forall i \in I,\ \forall k \in K,\ \forall l \in L,\ \forall m \in M,\ \forall n \in N,\ \forall f \in F,\ \forall t \in T \tag{19}$$

$$Y_{ik}^{ft}, Y_{kl}^{ft}, Y_{lm}^{ft}, Y_{mn}^{ft}, Z_{k}^{ft}, Z_{l}^{ft}, Z_{m}^{ft} \in \mathbb{Z}^{+}$$
$$\forall i \in I,\ \forall k \in K,\ \forall l \in L,\ \forall m \in M,\ \forall n \in N,\ \forall f \in F,\ \forall t \in T \tag{20}$$

Constraints (19) and (20) present the binary variables and integer variables used in the mathematical formulation. The next section provides a detail discussion about the heuristic designed for resolving the mathematical formulation.

5. Solution Methodology

The nature of the problem is a multi-echelon, multi-period, multi-modal and multi-product, thereby making the problem quite challenging for solving purpose. Furthermore, more variables, constraints and parameters are considered in the developed model than the normal inventory transportation problems. Therefore, solving even small size problem instance of this problem is a challenging task and needs tremendous computational effort and memory requirement (Maiyar and Thakkar 2017, Mogale et al. 2017, De et al. 2019a, De et al. 2019b). Moreover, several equations and constraints presented in the developed model are in a non-linear form. For example - Eq. 1(b), which represents the transportation cost in the objective function, comprises of five terms and each term becomes non-linear due to the multiplication of binary and continuous variables. Moreover, the second and third terms of the objective function comprise of the multiplication of three types of decision variables and thereby making each of the respective terms as non-linear. Similarly, majority of constraints become non-linear due to the multiplication of binary and continuous variables. In addition to this, equation (18) which shows the minimum threshold limit for the selection of rail transportation link is another major non-linear equation which tries to address stakeholder's behavioural tendency in making transportation mode choice decisions. The linearization of these equations and constraints are quite challenging and moreover, additional constraints need to be taken into consideration for linearizing the mathematical model. This will lead to an increase in computational complexity inevitably (Yu et al. 2017). Some of the commercial solvers are incompetent to find the solution of optimization model with non-linear and discrete decision variables. Due to the aforementioned reasons, we have developed the problem based heuristic to solve the complex mathematical model within reasonable computational time.

The computation of the proposed mixed integer non-linear mathematical model based on the inventory transportation problem becomes extremely complicated as the problem size increases exponentially with the increase in number of manufacturers, distributors, wholesalers, retailers and customers. Moreover, with the increase in number of product types and time periods, the problem becomes even more challenging to solve due to large number of variables and constraints (De et al. 2016 and De et al. 2017b). More information about the number of variables and constraints related to different problem instances solved in the paper are presented in Table 1. It has been stated by several researchers that computational effort and memory requirement are tremendous when employing exact heuristic techniques for obtaining a lower bound while solving similar kinds of problems related to multi-echelon multi-period inventory transportation problem (Maiyar and Thakkar 2017, Mogale et al. 2019b, De et al. 2018 and De et al. 2019b). As it is extremely challenging and difficult to solve large problem instances for obtaining a lower bound by using exact heuristics, therefore we have opted to develop a novel heuristic procedure which aims to address the structure of the proposed mathematical model and also considers behavioural tendencies of stakeholders.

Furthermore, mathematical programming based heuristics are quite popular in literature as they are devised to obtain better-quality solutions within acceptable computational efficiency (Moreno et al. 2018 and De et al. 2019c).

In this section, a heuristic approach based on the mathematical formulation is proposed which also depicts behavioural tendencies of stakeholders associated with the supply chain network. The heuristic helps to compute values of decision variables used in the mathematical formulation such as binary variables which aim to determine which transportation links to be used by a stakeholder for the shipment of products (such as X_{ik}^{ft}, X_{kl}^{ft}, X_{lm}^{ft} and X_{mn}^{ft}) based on the values of distance parameters (dis_{ik}, dis_{kl}^{a}, dis_{kl}^{b}, dis_{lm} and dis_{mn}). It has been identified that one of the main decision of the stakeholder is associated with choosing transportation links based on distances between stakeholders. Therefore, the behavioural aspects of stakeholders are considered while performing the selection of transportation links which is linked to distances between stakeholders. Decision variables associated with the shipment of products (such as Y_{ik}^{ft}, Y_{kl}^{ft}, Y_{lm}^{ft} and Y_{mn}^{ft}) are computed using its relationship with the availability of products at manufactures, inventory variables and vehicles availability. Inventory variables (such as Z_{k}^{ft}, Z_{l}^{ft} and Z_{m}^{ft}) are determined by considering its relationship with products dispatched from facilities and the inventory level in the previous time period. The novel heuristic procedure can be divided into four algorithms. Algorithm (1) aims to address behavioural tendencies of manufacturers while making decisions about the shipment of product types from manufacturers to distributors. Algorithms (2.1) and (2.2) consider the behavioural perspectives of the distributors in choosing the transportation links and selecting the transportation modes for the shipment of multiple product types from distributors to wholesalers. Algorithm (3) takes into consideration wholesaler's behavioural tendencies associated with the decision making related to selection of transportation links and determining the amount of product types to be shipped from wholesalers to retailers. Algorithm (4) tries to capture the behavioural aspects of retailers in transportation routes selection and estimation of the number of products types to be shipped from retailers to customers.

5.1. Algorithm Addressing Behavioural Tendencies of Manufacturers

Manufacturer's behavioural tendencies associated with the shipment of product types are addressed by algorithm (1). The distances between manufacturer and distributors are used to determine the transportation links to be used for shipment of products from manufacturers to distributors. The following condition $dis_{ik} < \varepsilon_k$ needs to be satisfied if a transportation link is to be used by the manufacturer. Here, ε_k is the maximum distance up to which the shipment of products to distributor *k* can be performed. When the distance between a specific manufacturer and distributor is more than the acceptable limit (or, more than ε_k), then that particular transportation link is not utilised by the manufacturer for the shipment of products. The binary variable X_{ik}^{ft} takes a value 1 if a specific transportation link between manufacturer and distributor is used and 0 otherwise. The value of the binary variable X_{ik}^{ft} can be computed in the following way,

$$X_{ik}^{ft} = \begin{cases} 1, & if \;\; dis_{ik} \leq \varepsilon_k \\ 0, & if \;\; dis_{ik} > \varepsilon_k \end{cases} \qquad \forall i \in I,\ \forall k \in K,\ \forall f \in F,\ \forall t \in T \qquad (21)$$

Manufacturer's behavioural tendency can be understood from the fact that they tend to use the condition represented on equation (21) for determining the transportation links for product shipment. Now, the total number of transportation links available for a manufacturer to access different distributors can be determined using values of the binary variable X_{ik}^{ft}.

Moreover, manufacturers tend to have a contractual agreement with distributors about the number of products to be shipped to distributors (Panda et al. 2015). Such contractual agreement sometimes ensures that the manufacturer tends to transport a certain fixed amount of product to distributors. For algorithm (1), the number of products types allotted to each transportation links from a manufacturer to a distributor can be obtained by computing the value of the decision variable Y_{ik}^{ft} using the following equation,

$$Y_{ik}^{ft} = \left\lfloor \frac{A_{if}^{t}}{IC_{ift}} \right\rfloor, \qquad \forall i \in I,\ \forall k \in K,\ \forall f \in F,\ \forall t \in T \qquad (22)$$

The floor function is used to obtain integer values for the variable Y_{ik}^{ft}. IC_{ift} is the number of links available to the manufacturer *i* for the transportation of product type f in time period t and IC_{ift} can be obtained using the following relationship,

$$IC_{ift} = \sum_{k \in K} X_{ik}^{ft}. \qquad \forall i \in I,\ \forall f \in F,\ \forall t \in T \qquad (23)$$

Algorithm (1) provided in Appendix provides the pseudo-code of the algorithm developed for generating the values of the binary variable X_{ik}^{ft} and integer variable Y_{ik}^{ft} while addressing the behavioural tendencies of the manufacturer. Let P_k^{ft} be the number of products of *f* type delivered to distributor *k* in time period *t*. Then the value of P_k^{ft} can be obtained using the following relationship,

$$P_k^{ft} = \sum_{i \in I} Y_{ik}^{ft} \qquad \forall k \in K,\ \forall f \in F,\ \forall t \in T \tag{24}$$

It is assumed that the total capacity of all vehicles available with each manufacturer is more than the number of products to be transported from that specific manufacturer. Thus, the following equation can be written based on the assumption,

$$\sum_{f \in F} A_{if}^{t} \le \sum_{p \in P} \sum_{f \in F} v_{ip}^{t} cap_p^f \qquad \forall i \in I,\ \forall t \in T \tag{25}$$

Equation (2) can be represented in the following way,

$$\text{If, } \sum_{k \in K} Y_{ik}^{ft} X_{ik}^{ft} \le A_{if}^{t}, \text{ then } \sum_{k \in K} \sum_{f \in F} Y_{ik}^{ft} X_{ik}^{ft} \le \sum_{f \in F} A_{if}^{t} \tag{26}$$

Using equations (26) and (25), the following can be obtained which satisfies equation (13).

$$\sum_{k \in K} \sum_{f \in F} Y_{ik}^{ft} X_{ik}^{ft} \le \sum_{f \in F} A_{if}^{t} \Rightarrow \sum_{k \in K} \sum_{f \in F} Y_{ik}^{ft} X_{ik}^{ft} \le \sum_{p \in P} \sum_{f \in F} v_{ip}^{t} cap_p^f$$

Thus, equation (13) of the mathematical model is always satisfied by considering the aforementioned procedure.

5.2. Algorithm Integrating the Behavioural Perspective of Distributors

Distributor's behavioural tendencies are addressed in algorithms (2.1) and (2.2) which involves decision-making associated with choosing of transportation links and shipment of products from distributors to wholesalers. The binary variables X_{kl}^{ft} take a value 1 if a distributor plans to use a specific transportation link for the shipment of product types to a particular wholesaler and 0 otherwise. The value of the binary variable X_{kl}^{ft} is obtained using the distance value dis_{kl}^{a} between distributor *k* and wholesaler *l* and also considering the maximum distance up to which transportation of products to wholesaler *l* (ε_l) can be performed. The variable X_{kl}^{ft} can be computed using its relationship with dis_{kl}^{a} and ε_l as given below,

$$X_{kl}^{ft} = \begin{cases} 1, & if \ dis_{kl} \le \varepsilon_l \\ 0, & if \ dis_{kl} > \varepsilon_l \end{cases} \qquad \forall k \in K, \ \forall l \in L, \ \forall f \in F, \ \forall t \in T \qquad (27)$$

Distributor's behavioural perspectives can be highlighted from the fact that these stakeholders predominantly select transportation links based on the maximum permissible distance for shipment of products. Therefore, for choosing possible transportation links, distributors use the condition given in equation (27). Moreover, distributors consider the available inventory level and the number of products received from manufacturers to determine the number of products to be dispatched for next set of stakeholders. Distributor uses the condition given in equation (28) for determining the number of product types to be shipped from distributor to wholesaler. Moreover, if there is any initial inventory available then distributor generally tend to consider it while making decisions about the shipment of product underlining another behavioural tendency of the distributor. The integer variable Y_{kl}^{ft} related to the number of product types transported from distributor to wholesaler is generated considering its association with P_k^{ft} and Z_k^{ft}.

$$Y_{kl}^{ft} = \begin{cases} \dfrac{P_k^{ft} + Z_k^{f0}}{KC_{kft}}, & for \ X_{kl}^{ft} = 1 \ and \ t = 1 \\ \dfrac{P_k^{ft} + Z_k^{f(t-1)}}{KC_{kft}}, & for \ X_{kl}^{ft} = 1 \ and \ t > 1 \end{cases} \qquad \forall k \in K, \ \forall l \in L, \ \forall f \in F, \ \forall t \in T \qquad (28)$$

Here, KC_{kft} is the number of transportation links available to distributor *k* for the shipment of *f* type product in time period *t* and KC_{kft} can be obtained using the following equation,

$$KC_{kft} = \sum_{l \in L} X_{kl}^{ft} . \qquad \forall k \in K, \ \forall f \in F, \ \forall t \in T \qquad (29)$$

Algorithm (2.1) presented in appendix provides the pseudo-code of the algorithm developed for generating values of decision variables (X_{kl}^{ft} and Y_{kl}^{ft}). Another behavioural perspective of distributor highlighted over here is related to the choice of the transportation mode either road or rail. The decision-making associated with this behavioural aspect of distributor is supported by the condition given by equations (17) and (18) of the mathematical model. The binary variable δ_{kl}^{bft} takes a value 1 if rail mode of transportation is selected for the shipment of product from a certain distributor to a particular wholesaler and 0 otherwise. Also, the value of this binary variable δ_{kl}^{bft}, which helps in the decision-making process of the distributor, is obtained using equation (18), integer variable Y_{kl}^{ft} and minimum number of product type *f* required for rail transportation ϕ_f. The binary variable α_{kl}^{aft} associated with the road transportation is obtained using variables δ_{kl}^{bft}, X_{kl}^{ft} and equation (17). The value obtained for the binary variable α_{kl}^{aft} gives an idea to the distributor in terms of which road transportation link needs to be chosen over its corresponding rail transportation link. Algorithm (2.2) provided in the appendix presents the pseudo-code of the algorithm developed for generating decision variables α_{kl}^{aft}, δ_{kl}^{bft} and Z_k^{ft}. For distributor *k*, the inventory level of product type *f* in time period *t* can be obtained in the following way,

$$Z_k^{ft} = \begin{cases} P_k^{ft} + Z_k^{f0} - \sum_{l \in L} Y_{kl}^{ft}, & for\ t = 1 \\ P_k^{ft} + Z_k^{f(t-1)} - \sum_{l \in L} Y_{kl}^{ft}, & for\ t > 1 \end{cases} \qquad \forall k \in K,\ \forall f \in F,\ \forall t \in T \qquad (30)$$

Equation (30) helps the distributor to determine the inventory level for the current time-period considering the number of products delivered to the distributor from various manufacturers. It also helps to compute the number of products shipped from the distributor to several wholesalers. Distributor's behavioural perspective can be highlighted from the fact that inventory level related decisions are made considering the initial inventory at the facility for first time period. When time period is greater than 1 (or, $t > 1$), then equation (30) can be represented in the following way,

$$Z_k^{ft} = P_k^{ft} + Z_k^{f(t-1)} - \sum_{l \in L} Y_{kl}^{ft} \qquad for\ t > 1,\ \forall k \in K,\ \forall f \in F,\ \forall t \in T$$

$$\Rightarrow Z_k^{ft} = \sum_{i \in I} Y_{ik}^{ft} + Z_k^{f(t-1)} - \sum_{l \in L} Y_{kl}^{ft} \Rightarrow Z_k^{f(t-1)} + \sum_{i \in I} Y_{ik}^{ft} - \sum_{l \in L} Y_{kl}^{ft} = Z_k^{ft}$$

$$\Rightarrow Z_k^{f(t-1)} + \sum_{i \in I} Y_{ik}^{ft} X_{ik}^{ft} - \sum_{l \in L} Y_{kl}^{ft} X_{kl}^{ft} = Z_k^{ft}$$

Thus, inventory balancing equation (9) of the mathematical model is always satisfied when inventory of product type *f* for distributor *k* is determined using equation (30). The inventory balancing equation (9) for first time period can be satisfied in a similar way. The capacity of a distributor is enough to store the total number of products received from different manufacturers along with the inventory level from the previous period.

Based on the assumption related to the distributor capacity, the following equation can be represented,

$$w_k \geq \sum_{f \in F} Z_k^{f(t-1)} + \sum_{f \in F} P_k^{ft} \Rightarrow \sum_{f \in F} Z_k^{f(t-1)} + \sum_{i \in I} \sum_{f \in F} Y_{ik}^{ft} \leq w_k$$

$$\Rightarrow \sum_{f \in F} Z_k^{f(t-1)} + \sum_{i \in I} \sum_{f \in F} Y_{ik}^{ft} X_{ik}^{ft} \leq w_k$$

Thus, equation (6) of the mathematical model is satisfied based on the assumption. For the initial time period, the storage capacity constraint given in equation (6) can be satisfied in a similar way. It is assumed that for each distributor, the total capacity available considering all vehicles and rakes is more than the number of products to be shipped from that specific distributor. Based on the assumption, the following equation can be expressed,

$$\sum_{f \in F} P_k^{ft} + \sum_{f \in F} Z_k^{f(t-1)} \leq \sum_{q \in Q} \sum_{l \in L} \sum_{f \in F} v_{kq}^t cap_q^f \alpha_{kl}^{aft} + \sum_{r \in R} \sum_{l \in L} \sum_{f \in F} v_{kr}^t cap_r^f \delta_{kl}^{bft} \tag{31}$$

From equation (28), the following can be obtained,

$$\sum_{l \in L} \sum_{f \in F} Y_{kl}^{ft} X_{kl}^{ft} = \sum_{f \in F} P_k^{ft} + \sum_{f \in F} Z_k^{f(t-1)} \qquad \forall k \in K,\ \forall t \in T \tag{32}$$

Using (32), equation (31) can be rewritten in the following way

$$\sum_{l \in L} \sum_{f \in F} Y_{kl}^{ft} X_{kl}^{ft} \leq \sum_{q \in Q} \sum_{l \in L} \sum_{f \in F} v_{kq}^t cap_q^f \alpha_{kl}^{aft} + \sum_{r \in R} \sum_{l \in L} \sum_{f \in F} v_{kr}^t cap_r^f \delta_{kl}^{bft}$$

$\sum_{l \in L} \sum_{f \in F} Y_{kl}^{ft} X_{kl}^{ft}$ is the total number of products to be shipped from a particular distributor *k*. Hence, the vehicle capacity constraint (16) related to the distributor is satisfied considering the assumption. Suppose, P_l^{ft} be the number of *f* type products delivered to wholesaler *l* in time period *t*, then P_l^{ft} can be computed using the following equation,

$$P_l^{ft} = \sum_{k \in K} Y_{kl}^{ft} \qquad \forall l \in L,\ \forall f \in F,\ \forall t \in T \tag{33}$$

5.3. Algorithm Considering Wholesaler's Behavioural Characteristics

Wholesaler's behavioural tendencies can be highlighted from the fact that the transportation routes connecting wholesalers and retailers are determined using the distance parameters. While estimating the transportation links, wholesalers also take into account the maximum distance (ε_m) which can be accessed for the shipment of the products to the retailers. The following relationship is presented for determining the binary variable X_{lm}^{ft} (which takes a value 1, if a specific transportation link between a wholesaler and retailer is chosen and 0 otherwise),

$$X_{lm}^{ft} = \begin{cases} 1, & if\ dis_{lm} \le \varepsilon_m \\ 0, & if\ dis_{lm} > \varepsilon_m \end{cases} \quad \forall l \in L,\ \forall m \in M,\ \forall f \in F,\ \forall t \in T \tag{34}$$

After obtaining the value of the binary variable X_{lm}^{ft}, the number of product types shipped from wholesaler to retailer (depicted by integer variable Y_{lm}^{ft}) can be computed using the following condition,

$$Y_{lm}^{ft} = \begin{cases} \dfrac{P_l^{ft} + Z_l^{f0}}{LC_{lft}}, & for\ X_{lm}^{ft} = 1\ and\ t = 1 \\ \dfrac{P_l^{ft} + Z_l^{f(t-1)}}{LC_{lft}}, & for\ X_{lm}^{ft} = 1\ and\ t > 1 \end{cases} \quad \forall l \in L,\ \forall m \in M,\ \forall f \in F,\ \forall t \in T \tag{35}$$

Equation (35) gives an idea about wholesaler's behavioural aspect as they tend to consider the initial inventory level while determining the number of product types to be shipped to next echelon. Wholesaler gives equal preference to the product inventory available from the previous period and the amount of product received in the current period while making a decision about the number of product to be shipped to the retailer. LC_{lft} in equation (35) is the number of transportation links available to wholesaler *l* for delivering product *f* in time period *t*. LC_{lft} is related to the binary variable X_{lm}^{ft} in the following way,

$$LC_{lft} = \sum_{m \in M} X_{lm}^{ft} \quad \forall l \in L,\ \forall f \in F,\ \forall t \in T \tag{36}$$

The inventory level of product *f* available with wholesaler *l* at time period *t* can be determined using the following equation,

$$Z_l^{ft} = \begin{cases} P_l^{ft} + Z_l^{f0} - \sum_{m \in M} Y_{lm}^{ft}, & for\ t = 1 \\ P_l^{ft} + Z_l^{f(t-1)} - \sum_{m \in M} Y_{lm}^{ft}, & for\ t > 1 \end{cases} \quad \forall l \in L,\ \forall f \in F,\ \forall t \in T \tag{37}$$

Equation (37) ensures that the inventory level for product *f* is computed by considering the inventory level available from the previous time period and thereby satisfying the inventory balancing constraint (10). For the initial period, wholesaler takes into account the initial inventory of the facility while computing the inventory level available at the end of the initial time period. When time period is more than 1 ($t > 1$), the equation (37) can be represented in the following way,

$$Z_l^{ft} = P_l^{ft} + Z_l^{f(t-1)} - \sum_{m \in M} Y_{lm}^{ft},\ for\ t > 1,\ \forall l \in L,\ \forall f \in F,\ \forall t \in T$$

$$\Rightarrow Z_l^{ft} = \sum_{k\in K} Y_{kl}^{ft} + Z_l^{f(t-1)} - \sum_{m\in M} Y_{lm}^{ft},\ where,\ P_l^{ft} = \sum_{k\in K} Y_{kl}^{ft}$$

$$\Rightarrow Z_l^{f(t-1)} + \sum_{k\in K} Y_{kl}^{ft} - \sum_{m\in M} Y_{lm}^{ft} = Z_l^{ft} \Rightarrow Z_l^{f(t-1)} + \sum_{k\in K} Y_{kl}^{ft} X_{kl}^{ft} - \sum_{m\in M} Y_{lm}^{ft} X_{lm}^{ft} = Z_l^{ft}$$

Thus, inventory balancing equation (10) is satisfied while considering equation (37) for computing the values of the inventory variable Z_l^{ft} for wholesaler l. Algorithm (3) provided in appendix presents the pseudo-code for computing the decision variables related to determining transportation links X_{lm}^{ft}, estimating the number of products to be shipped from wholesaler to retailer Y_{lm}^{ft} and determining the inventory level of the product Z_l^{ft}. It is assumed that the capacity related to the wholesaler must be enough to store the inventory level of the product types from previous period and the total number of products received from different distributors. Based on the assumption related to the wholesaler capacity, the following equation can be represented,

$$w_l \geq \sum_{f\in F} Z_l^{f(t-1)} + \sum_{f\in F} P_l^{ft} \Rightarrow \sum_{f\in F} Z_l^{f(t-1)} + \sum_{k\in K}\sum_{f\in F} Y_{kl}^{ft} \leq w_l$$

$$\Rightarrow \sum_{f\in F} Z_l^{f(t-1)} + \sum_{k\in K}\sum_{f\in F} Y_{kl}^{ft} X_{kl}^{ft} \leq w_l$$

Thus, the capacity constraint (7) of the mathematical model is satisfied considering the assumption. Moreover, it is also assumed that the overall capacity for the vehicles available with the wholesaler must be enough to transport the total number of product types from the particular wholesaler to various retailers. Based on the assumption, the following equation can be represented,

$$\sum_{f\in F} P_l^{ft} + \sum_{f\in F} Z_l^{f(t-1)} \leq \sum_{g\in G}\sum_{f\in F} v_{lg}^{t} cap_g^{f} \qquad \forall l \in L,\ \forall t \in T \qquad (38)$$

Using equation (35), the following can be expressed,

$$\sum_{f\in F} P_l^{ft} + \sum_{f\in F} Z_l^{f(t-1)} = \sum_{m\in M}\sum_{f\in F} Y_{lm}^{ft} \qquad \forall l \in L,\ \forall t \in T \qquad (39)$$

Using equations (38) and (39), the following is obtained,

$$\sum_{m\in M}\sum_{f\in F} Y_{lm}^{ft} X_{lm}^{ft} \leq \sum_{g\in G}\sum_{f\in F} v_{lg}^{t} cap_g^{f}$$

Thus, the vehicle capacity constraint (14) related to the wholesaler is satisfied based on the assumption. General behavioural tendency of stakeholders is to ensure that they have enough vehicle capacity to transport the product types to the next down-stream stakeholders.

Majority of the time, stakeholders have a contractual agreement with the third-party logistics service providers who tends to supply vehicles as per the requirements. Now, let P_m^{ft} be the number of products of type *f* delivered to retailer *m* in time period *t* and P_m^{ft} can be determined using its relationship with the variable Y_{lm}^{ft}.

Hence, $P_m^{ft} = \sum_{l \in L} Y_{lm}^{ft} \qquad \forall m \in M,\ \forall f \in F,\ \forall t \in T \qquad (40)$

Equation (40) provides the total number of *f* type products received at each retailer from various wholesalers in a specific time period.

5.4. Algorithm Incorporating Retailer's Behavioural Tendencies

The behavioural tendencies of retailers are highlighted by algorithm (4) presented in appendix. Algorithm (4) tries to address the retailer's behaviour about decision-making in choosing the transportation routes from retailers to customers based on the distance of each links connecting retailers to customers. The threshold limit of maximum distance from retailer to customer (ε_n) is taken into consideration for assisting retailers in determining the transportation links. Retailer's behavioural tendency is addressed over here as certain transportation routes beyond the maximum threshold limit are not selected for the shipment of product types. The binary variable X_{mn}^{ft} (which takes a value 1, if a specific transportation link between a retailer and customer is chosen and 0 otherwise), is computed using the following relationship,

$$X_{mn}^{ft} = \begin{cases} 1, & if\ \ dis_{mn} \le \varepsilon_n \\ 0, & if\ \ dis_{mn} > \varepsilon_n \end{cases} \qquad \forall m \in M,\ \forall n \in N,\ \forall f \in F,\ \forall t \in T \qquad (41)$$

The value of the product flow variable Y_{mn}^{ft} is determined by using the number of products of *f* type available to the retailer *m* in time period *t* and number of transportation links from retailers to customers available for the shipment of products. Retailer's behavioural perspective is highlighted while performing the shipment of product types as retailer tend to provide equal importance to the available product as inventory level from previous period and also the amount of products received from different wholesalers. Retailers tend to give importance to the product inventory for reducing their inventory cost. On the initial time period, the behavioural aspect of the retailer is highlighted as they consider the initial inventory level of the facility along with the number of products received from wholesalers while computing the number of products to be shipped on different transportation links. The following relationship is employed for computing variable Y_{mn}^{ft},

$$Y_{mn}^{ft} = \begin{cases} \dfrac{P_m^{ft} + Z_m^{f0}}{MC_{mft}}, & for\ X_{mn}^{ft} = 1\ and\ t = 1 \\ \dfrac{P_m^{ft} + Z_m^{f(t-1)}}{MC_{mft}}, & for\ X_{mn}^{ft} = 1\ and\ t > 1 \end{cases} \qquad \forall m \in M,\ \forall n \in N,\ \forall f \in F,\ \forall t \in T \qquad (42)$$

Here, MC_{mft} is the number of transportation links available to retailer *m* for the shipment of product type *f* in time period *t*. MC_{mft} can be computed using its connection with binary variable X_{mn}^{ft} given in equation (43),

$$MC_{mft} = \sum_{n \in N} X_{mn}^{ft} \qquad \forall m \in M,\ \forall f \in F,\ \forall t \in T \qquad (43)$$

The inventory variable Z_m^{ft} associated with retailer *m* for product type *f* in time period *t* can be determined using equation (44). For the initial time period, the initial inventory level of the facility is taken into consideration while making decisions related to number of products to be shipped on different transportation links and this highlights an important behavioural perspective of the retailer.

$$Z_m^{ft} = \begin{cases} P_m^{ft} + Z_m^{f0} - \sum_{n \in N} Y_{mn}^{ft}, & for\ t = 1 \\ P_m^{ft} + Z_m^{f(t-1)} - \sum_{n \in N} Y_{mn}^{ft}, & for\ t > 1 \end{cases} \qquad \forall m \in M,\ \forall f \in F,\ \forall t \in T \qquad (44)$$

Equation (44) also determines the inventory of a specific product type while considering the inventory in the previous period. When time period is more than one ($t > 1$), then equation (44) can be expressed in the following way,

$$Z_m^{ft} = P_m^{ft} + Z_m^{f(t-1)} - \sum_{n \in N} Y_{mn}^{ft},\ for\ t > 1,\ \forall m \in M,\ \forall f \in F,\ \forall t \in T$$

$$\Rightarrow Z_m^{ft} = \sum_{l \in L} Y_{lm}^{ft} + Z_m^{f(t-1)} - \sum_{n \in N} Y_{mn}^{ft} \Rightarrow Z_m^{f(t-1)} + \sum_{l \in L} Y_{lm}^{ft} - \sum_{n \in N} Y_{mn}^{ft} = Z_m^{ft}$$

Hence, $Z_m^{f(t-1)} + \sum_{l \in L} Y_{lm}^{ft} X_{lm}^{ft} - \sum_{n \in N} Y_{mn}^{ft} X_{mn}^{ft} = Z_m^{ft}$

Thus, using equation (44), the inventory balancing constraint (11) of the mathematical model is satisfied. Algorithm (4) provided in appendix presents the pseudo-code of the algorithm developed for computing the binary variable X_{mn}^{ft}, product flow variable from retailers to customers Y_{mn}^{ft} and inventory variable Z_m^{ft}. It is assumed that the capacity of each retailer can store the previous period's inventory as well as the number of products received from several wholesalers. Based on this assumption, following expression can be written,

$$w_m \geq \sum_{f \in F} Z_m^{f(t-1)} + \sum_{f \in F} P_m^{ft} \Rightarrow \sum_{f \in F} Z_m^{f(t-1)} + \sum_{l \in L} \sum_{f \in F} Y_{lm}^{ft} \leq w_m$$

$$\Rightarrow \sum_{f \in F} Z_m^{f(t-1)} + \sum_{l \in L} \sum_{f \in F} Y_{lm}^{ft} X_{lm}^{ft} \leq w_m$$

Thus, retailer's capacity constraint (8) associated with the mathematical model is always satisfied while considering the assumption. Moreover, it is also assumed that the capacity of all vehicles available with each retailer can transport the number of products which need to be dispatched from the specific retailer. So, based on the assumption following equation can be provided,

$$\sum_{f \in F} P_m^{ft} + \sum_{f \in F} Z_m^{f(t-1)} \leq \sum_{p \in P} \sum_{f \in F} v_{mp}^{t} cap_p^f \qquad \forall m \in M,\ \forall t \in T \qquad (45)$$

From equation (42) the following can be obtained,

$$\sum_{n \in N} \sum_{f \in F} Y_{mn}^{ft} = \sum_{f \in F} P_m^{ft} + \sum_{f \in F} Z_m^{f(t-1)} \qquad \forall m \in M,\ \forall t \in T \qquad (46)$$

Using (45) and (46), the following equation can be represented, which is the vehicle capacity constraint for each retailer.

$$\sum_{n \in N} \sum_{f \in F} Y_{mn}^{ft} X_{mn}^{ft} \leq \sum_{p \in P} \sum_{f \in F} v_{mp}^{t} cap_p^f$$

Therefore, the vehicle capacity constraint (15) of the mathematical model is satisfied based on the assumption. Now, the total number of products of type f delivered to the customer always satisfies the demand constraint (12) of the mathematical model.

6. Computational Experiments and Results

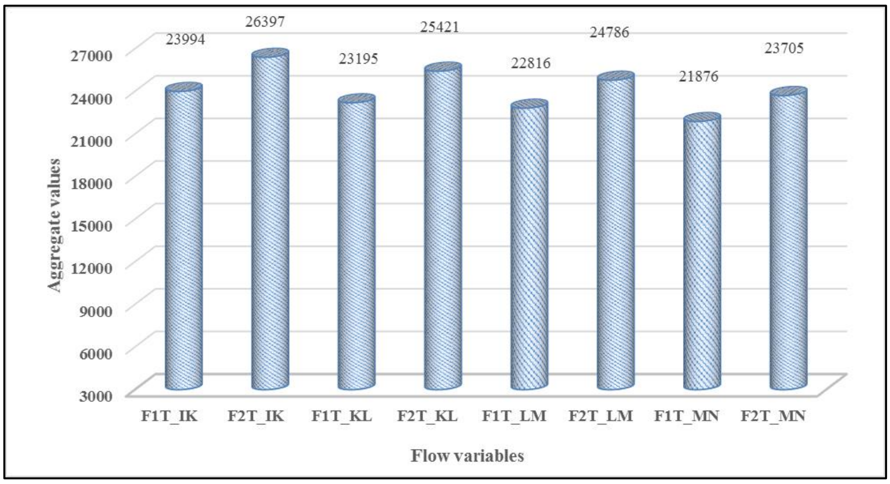
This section presents the comparative analysis performed based on different problem instances considered by varying the number of manufacturers, distributors, wholesalers, retailers and customers. The proposed heuristic approach is validated on medium and large-sized problem instances (fifteen problem instances) presented in Table 1 while taking into account a planning horizon comprising of multiple time periods and multiple product types. The computational complexity of the experiments associated with solving the problem instances can be observed from the presence of a large number of variables and constraints. The computational experiments are performed on MATLAB R2015b software having a processor of Intel Core i7 1.8 GHz with 8GB RAM and 64-bit Windows 7 operating system.

The data related to parameters of the mathematical model are generated from several reliable sources. Table 1 provides an idea about the computational complexity of the problem instances and presents the information about the total cost, transportation cost, inventory cost and operating cost associated with each of the problem instances. The computational experiments are performed on fifteen simulated problem instances. Two illustrative examples of different data sets and problem sizes are mentioned in the next sub-sections along with their respective results. The nomenclature of the discussed examples has following structure (T-P-M-D-W-R-C), where T, P, M, D, W, R and C stand for time periods, products, manufacturers, distributors, wholesalers, retailers and customers respectively. The following sub-sections provide the descriptions pertaining to two illustrative examples and their respective results obtained after solving using the proposed heuristic approach.

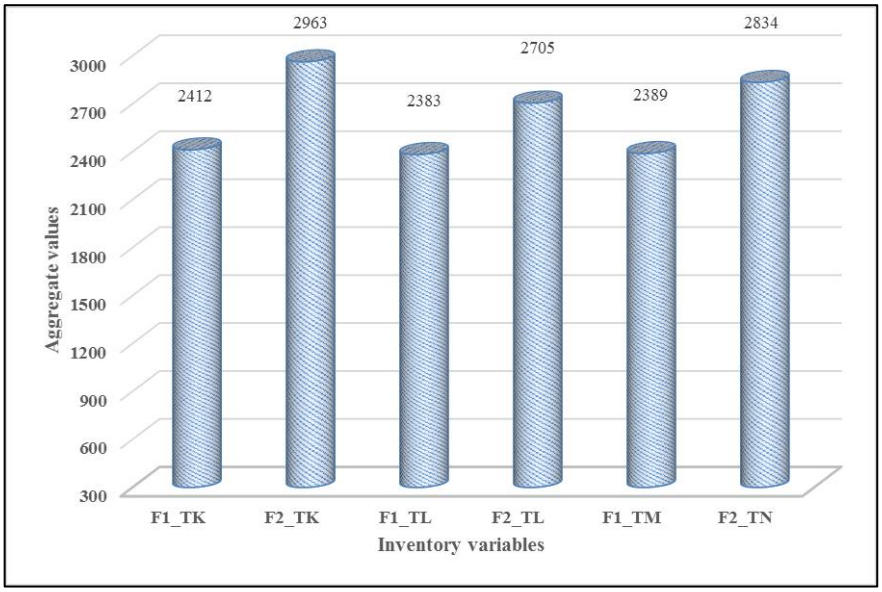
6.1. Analysis of Medium Sized Numerical Illustration

The illustrative example discussed in this sub-section is designed based on the first problem instance given in table 1 considering three time periods, two types of products, four manufacturers, five distributors, six wholesalers, eight retailers and twelve customers. The manufacturing supply chain organization aims to plan the logistics decisions related to the shipment of two types of products from manufacturers to customers via distributors, wholesalers and retailers. The inventory decisions for the overall planning horizon are also taken into consideration while resolving the problem as it is essential to reduce the inventory cost while trying to mitigate the transportation cost. The available storage capacity for distributors, wholesalers and retailers may vary in different time periods. Supply capacity of 2000 units for product 1 and 2200 units of product 2 are available with each manufactures in each time period. Demand of each customer is time-varying and therefore in first time period the demand is 1500 units of product 1 and 1600 units of product 2. In second period, demand of each customer is 2000 units of product 1 and 2100 units of product 2. For third time period, the demand of each customer is 2500 units of product 1 and 2600 units of product 2. Road transportation cost is 20 USD for each unit of product 1 and 25 USD for each unit of product 2. Rail transportation cost is 15 USD for each unit of product 1 and 20 USD for each unit of product 2. For each facility (distributor, wholesaler and retailer), the inventory holding cost at every time period is 200 USD for product 1 and 300 USD for product 2 and the operational cost at every time period is 100 USD for product 1 and 150 USD for product 2. Results associated with number of products flowing on different transportation links connecting manufacturers to distributors, distributors to wholesalers, wholesalers to retailers and retailers to customers are presented to give adequate information about the various transportation routes selected by stakeholders based on their behavioural tendencies. The other output deliverables of the mathematical model are inventory holding in each time period and choice of transportation modes between distributors to wholesalers. The summary of the aggregate amount of the product flow and inventory level values are depicted in Fig. 2a and 2b.

The details of the various acronyms used in Fig. 2 are given as follows. Fig. 2(a) illustrates aggregated flow variables between different stages for a given time period. F1T_IK: Amount of product 1 transported from manufacturers to distributors, F2T_IK: Amount of product 2 transported from manufacturers to distributors, F1T_KL: Amount of product 1 transported from distributors to wholesalers, F2T_KL: Amount of product 2 transported from distributors to wholesalers, F1T_LM: Amount of product 1 transported from wholesalers to retailers, F2T_LM: Amount of product 2 transported from wholesalers to retailers, F1T_MN: Amount of product 1 transported from retailers to customers and F2T_MN: Amount of product 2 transported from retailers to customers. In a similar way, aggregated inventories of product one and two over the given time period available at distributors, wholesalers and retailers are represented in Fig. 2(b). Various abbreviations utilised in this figure are described as follows. F1_TK: Inventory of product 1 available at all distributors, F2_TK: Inventory of product 2 available at all distributors, F1_TL: Inventory of product 1 available at all wholesalers, F2_TL: Inventory of product 2 available at all wholesalers, F1_TM: Inventory of product 1 available at all retailers and F2_TM: Inventory of product 2 available at all retailers.



(2a)



(2b)

Figure 2: Solution of problem instance 1 (3T-2P-4M-5D-6W-8R-12C). (a) Aggregate values of flow variables from manufacturer to customer and (b) Aggregate values of inventory available at distributors, wholesalers and retailers.

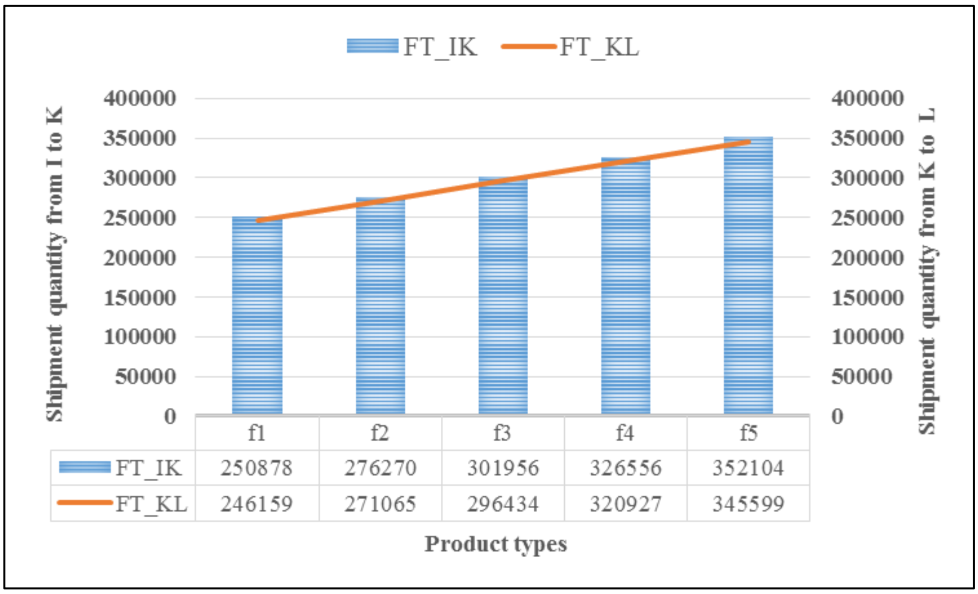
Table 1: Problem instances for computational experiment

Problem Instance	M	D	W	R	C	P	T	Number of variables	Number of constraints	Total cost (USD)	Transportation cost (USD)	Inventory cost (USD)	Operating cost (USD)	CPU time (sec)
1	4	5	6	8	12	2	3	2802	810	5.44×10^{8}	5.04×10^{8}	3.78×10^{6}	3.61×10^{7}	0.211
2	6	7	9	10	15	2	3	5052	1368	8.37×10^{8}	7.77×10^{8}	5.86×10^{6}	5.37×10^{7}	0.218
3	9	10	11	13	17	3	4	16584	4076	3.05×10^{9}	2.82×10^{9}	2.05×10^{7}	2.1×10^{8}	0.269
4	12	13	14	16	20	3	4	26052	6176	4.30×10^{9}	4.00×10^{9}	2.70×10^{7}	2.78×10^{8}	0.426
5	15	16	19	22	25	4	5	73780	15885	1.04×10^{10}	9.65×10^{9}	6.64×10^{7}	7.16×10^{8}	0.640
6	17	20	23	26	29	4	5	105860	22855	1.19×10^{10}	1.10×10^{10}	7.65×10^{7}	8.19×10^{8}	0.806
7	21	24	28	32	35	5	6	234360	48174	2.55×10^{10}	2.35×10^{10}	1.27×10^{8}	1.84×10^{9}	1.206
8	24	29	33	36	38	5	6	312900	66480	2.93×10^{10}	2.71×10^{10}	1.45×10^{8}	2.10×10^{9}	1.484
9	28	32	35	39	42	6	7	520128	107604	3.68×10^{10}	3.33×10^{10}	2.36×10^{8}	3.21×10^{9}	2.154
10	30	33	37	41	45	6	7	575358	116802	3.93×10^{10}	3.56×10^{10}	2.53×10^{8}	3.44×10^{9}	2.437
11	33	35	39	43	47	7	8	855848	172600	5.94×10^{10}	5.37×10^{10}	3.71×10^{8}	5.29×10^{9}	3.214
12	36	38	40	45	48	7	8	944104	190976	6.57×10^{10}	5.96×10^{10}	4.04×10^{8}	5.77×10^{9}	3.602
13	38	41	43	48	50	8	9	1384416	281934	8.92×10^{10}	8.10×10^{10}	5.61×10^{8}	7.59×10^{9}	4.564
14	45	48	51	55	58	8	9	1890432	385281	1.05×10^{11}	9.57×10^{10}	6.62×10^{8}	8.96×10^{9}	6.694
15	50	55	57	60	65	9	10	2956680	609550	1.50×10^{11}	1.37×10^{11}	9.36×10^{8}	1.21×10^{10}	9.366

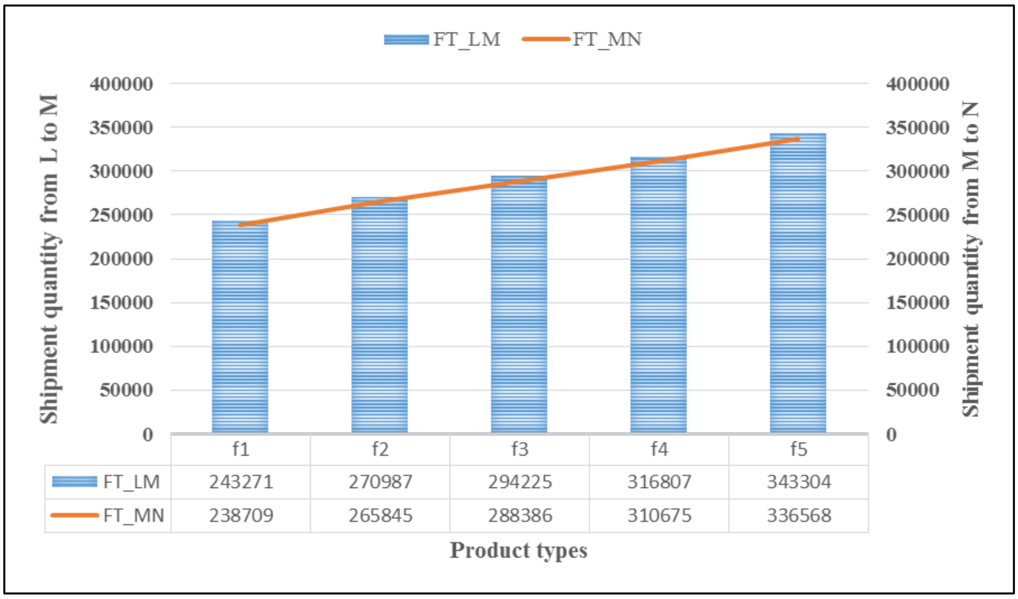
6.2. Results and Discussion for Large Sized Problem Instance

In this illustrative example, the available supply capacity of five types of products at each manufacturer is considered as 2000, 2200, 2400, 2600 and 2800 in each time period. Demand of five types of product is considered as 1500, 1600, 1700, 1800 and 1900 for each time period and the remaining data pertaining to the parameter values are similar to the first illustrative example presented in the earlier sub-section. The solutions of this problem instance in terms of amount of products transferred and inventory level available are depicted in Fig. 3(a) and 3(b). The FT_IK shows the amount of different products transferred from manufactures to distributors in a given time period. The different product types transferred from distributors to wholesalers are denoted by FT_KL. Next, FT_LM depicts the shipment quantity of different products from wholesalers to retailers and finally the number of various products dispatched from retailers to customers is shown by FT_MN.

The results obtained through this study would be beneficial for manufacturing organizations or Third Party Logistics Company who handles the supply chain activities of these manufacturing firms. Tactical decisions including movement and storage plan for each product types in a definite planning horizon can be made using the proposed model. Furthermore, this model will be helpful for proper planning and coordination decisions comprising of inventory planning, vehicle scheduling and optimal utilization of resources.



(3a)



(3b)

Figure 3: Solution of problem instance 7 (6T-5P-21M-24D-28W-32R-35C). (3a) Aggregate values of flow variables from manufacturers to wholesalers and (3b) Aggregate values of flow variables from wholesalers to customers

6.3. Sensitivity Analysis

For illustrative example 1, the maximum distance up to which products can be transferred is considered as 27 km for manufacturer to distributor, 630 km for distributor to wholesaler, 45 km for wholesaler to retailer and 18 km for retailer to customer. Sensitivity analysis is conducted on the problem instance 1 (3T-2P-4M-5D-6W-8R-12C) by changing values associated with the maximum distance up to which products can be transported. The maximum threshold distance for the shipment of products from manufacturer to distributor, distributor to wholesaler, wholesaler to retailer and retailer to customer is changed to 21 km, 490 km, 35 km and 14 km respectively. Figure 4 presents the transportation links between different echelons comprising of manufacturer, distributor, wholesaler, retailer and customer. For example, there are two transportation links from manufacture 1 (M1) to distributor 2 (D2) and distributor 3 (D3) or M1-D2 and M1-D3. Similarly, there are four transportation links from manufacturer 2 (M2) to distributor 1, 2, 3 and 4 or M2-D1, M2-D2, M2-D3 and M2-D4. Overall, thirteen transportation links between manufacturer to distributor, twelve transportation links between distributor to wholesaler, eighteen transportation links between wholesaler to retailer and fourteen transportation links between retailer to customer are used to transport products of each type. The transportation links which are less than the maximum threshold distances between two different types of stakeholders are considered for shipment purpose. Table 2 presents the number of products of each type shipped from manufacturer to distributor, distributor to wholesaler, wholesaler to retailer and retailer to customer in time period 1. Table 3a, 3b and 3c present the total inventory level at the end of each time period for distributors, wholesalers and retailers respectively. It must be noted that each facility keeps a minimum inventory level to ensure that less inventory cost is incurred.

Three scenarios are considered by changing the maximum distance limit up to which products can be transported between different echelons. For scenario 1, the maximum distance for transportation of products is 24 km for manufacturer to distributor, 560 km for distributor to wholesaler, 40 km for wholesaler to retailer and 16 km for retailer to customer. For scenario 2, the maximum distance up to which the products can be transported is 22.5 km for manufacturer to distributor, 525 km for distributor to wholesaler, 37.5 km for wholesaler to retailer and 15 km for retailer to customer. For scenario 3, the maximum distance up to which products can be transported is 21 km for manufacturer to distributor, 490 km for distributor to wholesaler, 35 km for wholesaler to retailer and 14 km for retailer to customer. Table 4 presents the results pertaining to the total cost, transportation cost, inventory cost, operating cost and total transportation links for each of the scenarios. It can be noted from the table that by lowering the maximum distance up to which products can be shipped, the number of transportation links also decreases. Thereby, it mitigates the overall transportation cost which includes shipping products from manufacturer to distributor, distributor to wholesaler, wholesaler to retailer and finally retailer to customer. Observation from the table also highlights the fact that the majority of the cost incurred for the multi-echelon supply chain network largely comprises of the transportation cost. Inventory cost and the operation cost is nearly negligible when compared with that of the transportation cost. Therefore, it is imperative to minimize the transportation cost by lowering the number of transportation links accessed for the shipping of product types. So, in certain cases, the behavioural tendency of stakeholders in reducing the number of accessible transportation links might be beneficial for them in terms of mitigating the transportation cost. It is also observed from table 4 that the inventory cost and operating cost for various scenarios remain analogous due to the shipment of a similar number of products for different cases. Slight variation in the inventory cost and operating cost is due to the fact that the inventory holding cost per unit and operating cost per unit changes for different facilities.

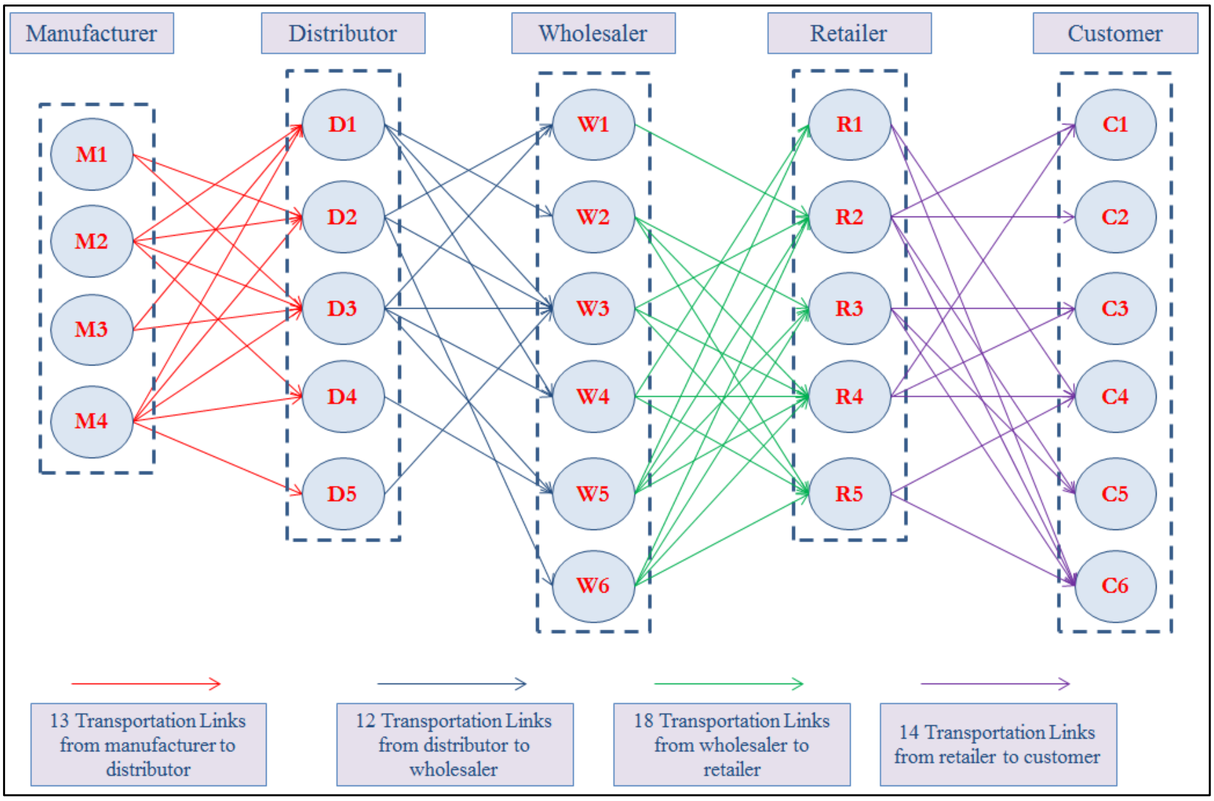


Figure 4: Transportation links between different echelons

Table 2: Number of products shipped on each transportation links in time period 1

Products (P) transported from Manufacturer (M) to Distributor (D)			Products (P) transported from Distributor (D) to Wholesaler (W)			Products (P) transported from Wholesaler (W) to Retailer (R)			Products (P) transported from Retailer (R) to Customer (C)		
Manufacturer (M) to Distributor (D)	Product 1	Product 2	Distributor (D) to Wholesaler (W)	Product 1	Product 2	Wholesaler (W) to Retailer R	Product 1	Product 2	Retailer (R) to Customer (C)	Product 1	Product 2
M1-D2	1000	1100	D1-W2	570	688	W1-R2	1130	1086	R1-C4	284	361
M1-D3	1000	1100	D1-W3	585	564	W2-R3	156	214	R1-C6	301	330
M2-D1	500	550	D1-W4	581	565	W2-R4	161	197	R2-C1	500	496
M2-D2	500	550	D2-W1	595	560	W2-R5	161	218	R2-C2	458	539
M2-D3	500	550	D2-W3	510	652	W3-R2	592	713	R2-C5	505	570
M2-D4	500	550	D2-W6	574	574	W3-R4	700	3692	R2-C6	523	522
M3-D1	1000	1100	D3-W1	585	656	W3-R5	677	667	R3-C3	180	219
M3-D3	1000	1100	D3-W3	700	765	W4-R1	382	413	R3-C5	186	185
M4-D1	440	400	D3-W4	629	737	W4-R4	375	425	R3-C6	192	181
M4-D2	440	400	D3-W5	703	649	W4-R5	364	410	R4-C1	475	510
M4-D3	440	400	D4-W5	764	806	W5-R1	317	321	R4-C3	516	522
M4-D4	440	400	D5-W3	367	364	W5-R2	342	359	R4-C4	461	525
M4-D5	440	400				W5-R3	302	310	R5-C4	596	626
						W5-R4	304	330	R5-C6	639	682
						W6-R2	115	159			
						W6-R3	142	137			
						W6-R4	143	136			
						W6-R5	118	158			

Table 3a: Inventory level for each product at each Distributor in different time periods

	Time period 1		Time period 2		Time period 3	
	Product 1	Product 2	Product 1	Product 2	Product 1	Product 2
Distributor 1	164	273	304	302	101	249
Distributor 2	221	237	281	69	251	261
Distributor 3	283	383	521	496	358	384
Distributor 4	136	184	93	100	113	203
Distributor 5	33	76	11	41	24	15

Table 3b: Inventory level for each product at each Wholesaler in different time periods

	Time period 1		Time period 2		Time period 3	
	Product 1	Product 2	Product 1	Product 2	Product 1	Product 2
Wholesaler 1	50	130	235	285	101	81
Wholesaler 2	92	59	51	78	111	117
Wholesaler 3	193	273	306	204	309	149
Wholesaler 4	89	54	149	82	165	179
Wholesaler 5	202	135	210	242	251	165
Wholesaler 6	56	51	71	80	67	62

Table 3c: Inventory level for each product at each Retailer in different time periods

	Inventory level at each Retailer					
	Time period 1		Time period 2		Time period 3	
	Product 1	Product 2	Product 1	Product 2	Product 1	Product 2
Retailer 1	114	43	89	138	24	94
Retailer 2	193	190	297	289	357	373
Retailer 3	42	76	73	159	166	96
Retailer 4	231	223	319	221	289	190
Retailer 5	85	145	124	148	146	341

Table 4: Results associated with all the scenarios

		Scenario 1	Scenario 2	Scenario 3
Total cost (USD)		4.86×10^8	4.63×10^8	4.27×10^8
Transportation cost from manufacturer to distributor (USD)		1.35×10^7	1.26×10^7	1.21×10^7
Transportation cost from distributor to wholesaler (USD)		3.89×10^8	3.67×10^8	3.29×10^8
Transportation cost from wholesaler to retailer (USD)		3.06×10^7	3.04×10^7	3.17×10^7
Transportation cost from retailer to customer (USD)		1.34×10^7	1.34×10^7	1.33×10^7
Total Transportation cost (USD)		4.46×10^8	4.23×10^8	3.87×10^8
Inventory cost for distributor (USD)		1.16×10^6	1.36×10^6	1.56×10^6
Inventory cost for wholesaler (USD)		1.21×10^6	1.12×10^6	1.26×10^6
Inventory cost for retailer (USD)		1.38×10^6	1.11×10^6	1.32×10^6
Total Inventory cost (USD)		3.76×10^6	3.60×10^6	4.15×10^6
Operating cost (USD)		3.56×10^7	3.60×10^7	3.64×10^7
Transportation links	Manufacturer to Distributor	15	14	13
	Distributor to Wholesaler	21	19	12
	Wholesaler to Retailer	19	18	18
	Retailer to Customer	21	18	14
Total number of transportation links		76	69	57

7. Conclusion and future scope

In this paper, multi-echelon, multi-product, multi-modal and multi-period inventory transportation problem of the manufacturing organization with behavioural tendencies of stakeholders is considered. A novel mathematical model is developed for minimizing the total cost including transportation, inventory and operational cost of different products. The model captured many real-world constraints associated with the inventory level balancing at various facilities, storage capacity restriction at several stakeholders, time-varying supply capacity with the manufacturer, time-varying demand of various product types at the customer end and restrictions associated with vehicle capacity. Due to the computational complexity associated with the problem, a mathematical formulation based heuristic approach is presented, which comprises of four algorithms addressing the behavioural tendencies of stakeholders during decision-making. Algorithms consider stakeholder's behavioural perspectives associated with selection of transportation routes, transportation mode choice decisions and determining the shipment of products types. Fifteen problem instances are considered for solving the mathematical model and validating the robustness of the proposed heuristic approach which also addresses the behavioural aspect of stakeholders. The comprehensive results of two selected problem instances pertaining to total cost, proportion of each entity within the total cost, aggregate values of product flow and inventory level values pertaining to each product types are reported. The present study can be extended by incorporating the stochastic aspects for addressing the uncertainty associated with customer demand and supply capacity. The incorporation of backlog and shortages in the model can give another future direction to the present study. Moreover, the current model can be extended in the multi-objective form by adding the carbon emission for addressing the sustainability aspect.

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Appendix

Notations of the mathematical model

Sets

I	Set of manufacturers
K	Set of distributors
L	Set of wholesalers
M	Set of retailers
N	Set of customers
T	Set of time periods
F	Set of types of products
P	Set of vehicle types available with manufacturers and retailers
R	Set of rake types available with distributors
Q	Set of vehicle types available with distributors
G	Set of vehicle types available with wholesalers

Indices

i	Manufacturers
k	Distributors
l	Wholesalers
m	Retailers
n	Customers
t	Time periods
f	Product types
p	Vehicle types available with manufacturers and retailers
r	Rake types available with distributors
q	Vehicle types available with distributors
g	Vehicle types available with wholesalers
a	Road transportation mode
b	Rail transportation mode

Parameters

A_{if}^{t} Availability of product type *f* with manufacturer *i* in time period *t*

D_{nf}^{t} Demand of product type *f* at customer *n* in time period *t*

w_k Total Capacity of distributor *k*

w_l Total Capacity of wholesaler *l*

w_m Total Capacity of retailer *m*

v_{ip}^{t} Number of *p* type of vehicles available with manufacturer *i* in time period *t*

v_{mp}^{t} Number of *p* type of vehicles available with retailer *m* in time period *t*

v_{lg}^{t} Number of *g* type of vehicles available with wholesaler *l* in time period *t*

v_{kr}^{t} Number of *r* type of rakes available with distributor *k* in time period *t*

v_{kq}^{t} Number of *q* type of vehicles available with distributor *k* in time period *t*

cap_{p}^{f} Capacity of *f* type product on *p* type vehicles

cap_{g}^{f} Capacity of *f* type product on *g* type vehicles

cap_{r}^{f} Capacity of *f* type product on *r* type rakes

cap_{q}^{f} Capacity of *f* type product on *q* type vehicles

ϕ_f Minimum requirement of *f* type product for using rail transportation

c_a Unit road transportation cost

c_b Unit rail transportation cost

h_{ef} Inventory holding cost per time period for *f* type product in facility *e*, $e \in \{k, l, m\}$

oc_{ef} Operational cost for *f* type product in facility *e*, $e \in \{k, l, m\}$

dis_{ik} Distance from manufacturer *i* to distributor *k*

dis_{kl}^{a} Distance from distributor *k* to wholesaler *l* through mode *a*

dis_{kl}^{b} Distance from distributor *k* to wholesaler *l* through mode *b*

dis_{lm} Distance from wholesaler *l* to retailer *m*

dis_{mn} Distance from retailer *m* to customer *n*

Z_{k}^{f0} Initial inventory of distributor *k* for product type *f*

Z_l^{f0} Initial inventory of wholesaler *l* for product type *f*

Z_m^{f0} Initial inventory of retailer *m* for product type *f*

Decision Variables

X_{ik}^{ft} 1, if *f* type product is transported from manufacturer *i* to distributor *k* in time period *t*, otherwise 0

X_{kl}^{ft} 1, if *f* type product is transported from distributor *k* to wholesaler *l* in time period *t*, otherwise 0

X_{lm}^{ft} 1, if *f* type product is transported from wholesaler *l* to retailer *m* in time period *t*, otherwise 0

X_{mn}^{ft} 1, if *f* type product is transported from retailer *m* to customer *n* in time period *t*, otherwise 0

α_{kl}^{aft} 1, if mode *a* is selected for transportation of *f* type product from distributor *k* to wholesaler *l* in time period *t*, otherwise 0

δ_{kl}^{bft} 1, if mode *b* is selected for transportation of *f* type product from distributor *k* to wholesaler *l* in time period *t*, otherwise 0

Y_{ik}^{ft} Amount of *f* type product transported from manufacturer *i* to distributor *k* in period *t*

Y_{kl}^{ft} Amount of *f* type product transported from distributor *k* to wholesaler *l* in period *t*

Y_{lm}^{ft} Amount of *f* type product transported from wholesaler *l* to retailer *m* in time period *t*

Y_{mn}^{ft} Amount of *f* type product transported from retailer *m* to customer *n* in time period *t*

Z_e^{ft} Inventory of *f* type product available at facility *e* at the end of time period *t*, $e \in \{k, l, m\}$

Algorithm (1): Pseudo-code for computing the binary variable X_{ik}^{ft} and integer variable Y_{ik}^{ft}

```
Procedure: Generation of variables X_ik^ft and Y_ik^ft
Assign values for the parameter A_if^t, dis_ik and initialize empty space for IC_if^t
c = 0
for t = 1 to total number of time periods
    for f = 1 to number of product types
        for i = 1 to number of manufacturers
            for k = 1 to number of distributors
                if Distance between i^th and k^th facilities ≤ Max. distance (or, dis_ik ≤ ε_k)
                    Assign value 1 to the binary variable X_ik^ft for the specific i and k
                    Increase the counter, c = c + 1
                end
            end
            Assign value c to IC_if^t or, IC_if^t = c
            c = 0
        end
    end
    for f = 1 to number of product types
        for i = 1 to number of manufacturers
            for k = 1 to number of distributors
                if binary variable X_ik^ft is equal to 1
                    Compute Y_ik^ft using the following equation, Y_ik^ft = ⌊ A_if^t / IC_if^t ⌋
                end
            end
        end
    end
end
```

Algorithm (2.1): Pseudo-code for computing binary variables X_{kl}^{ft} and integer variable Y_{kl}^{ft}

```
Procedure: Generation of variables X_{kl}^{ft} and Y_{kl}^{ft}
Assign values for the parameter dis_{kl} and initialize empty space for KC_{kft}
c = 0
for t = 1 to total number of time periods
    for f = 1 to number of product types
        for k = 1 to number of distributors
            for l = 1 to number of wholesalers
                if Distance between k^{th} and l^{th} facilities ≤ Max. distance (or, dis_{kl} ≤ ε_l)
                    Assign value 1 to the binary variable X_{kl}^{ft} for the specific k and l
                    Increase the counter, c = c + 1
                end
            end
            Assign value c to KC_{kft} or, KC_{kft} = c
            c = 0
        end
    end
    for f = 1 to number of product types
        for k = 1 to number of distributors
            for l = 1 to number of wholesalers
                if binary variable X_{kl}^{ft} is equal to 1 and time period = 1
                    Compute Y_{kl}^{ft} using, Y_{kl}^{ft} = ((P_k^{ft} + Z_k^{f0}) / KC_{kft}) × random number
                elseif binary variable X_{kl}^{ft} is equal to 1 and time period > 1
                    Compute Y_{kl}^{ft} using, Y_{kl}^{ft} = ((P_k^{ft} + Z_k^{f(t-1)}) / KC_{kft}) × random number
                else
                    Assign value 0 to the variable Y_{kl}^{ft}
                end
            end
        end
    end
end
```

Algorithm (2.2): Pseudo-code for computing the variables α_{kl}^{aft}, δ_{kl}^{bft} *and* Z_k^{ft}

$Procedure: Generation\ of\ variables\ \alpha_{kl}^{aft},\ \delta_{kl}^{bft}\ and\ Z_k^{ft}$

```
Assign values for the parameter φ_f
for t = 1 to total number of time periods
    for f = 1 to number of product types
        for k = 1 to number of distributors
            for l = 1 to number of wholesalers
                Compute δ_kl^bft using, δ_kl^bft = ⌈ max(0, Y_kl^ft − φ_f) / (max(0, Y_kl^ft − φ_f) + 1) ⌉
                if variable X_kl^ft is equal to 1 and value of δ_kl^bft is 0
                    Assign value 1 to the variable α_kl^aft
                end
            end
        end
    end
    for f = 1 to number of product types
        for k = 1 to number of distributors
            if time period = 1
                Compute Z_k^ft using equation, Z_k^ft = P_k^ft + Z_k^f0 − Σ_{l∈L} Y_kl^ft
            elseif time period > 1
                Compute Z_k^ft using equation, Z_k^ft = P_k^ft + Z_k^f(t−1) − Σ_{l∈L} Y_kl^ft
            else
                Assign value 0 to the variable Z_k^ft
            end
        end
    end
end
```

Algorithm (3): Pseudo-code for computing the variables X_{lm}^{ft}, Y_{lm}^{ft} and Z_l^{ft}

Procedure: *Generation of variables* X_{lm}^{ft}, Y_{lm}^{ft} *and* Z_l^{ft}

Assign values for the parameter dis_{lm} *and initialize empty space for* LC_{lft}

$c = 0$

for $t = 1$ *to total number of time periods*

    for $f = 1$ *to number of product types*

        for $l = 1$ *to number of wholesalers*

            for $m = 1$ *to number of retailers*

                if Distance between l^{th} *and* m^{th} *facilities* $\leq$ *Max. distance* $\left(or, dis_{lm} \leq \varepsilon_m\right)$

                    Assign value 1 *to the binary variable* X_{lm}^{ft} *for the specific* l *and* m

                    Increase the counter, $c = c + 1$

                end

            end

            Assign value c *to* LC_{lft} *or*, $LC_{lft} = c$

            $c = 0$

        end

    end

    for $f = 1$ *to number of product types*

        for $l = 1$ *to number of wholesalers*

            for $m = 1$ *to number of retailers*

                if binary variable X_{lm}^{ft} *is equal to* 1 *and time period* $= 1$

                    Compute Y_{lm}^{ft} *using*, $Y_{lm}^{ft} = \left(\left(P_l^{ft} + Z_l^{f0}\right) / LC_{lft}\right) \times random\ number$

                elseif binary variable X_{lm}^{ft} *is equal to* 1 *and time period* > 1

                    Compute Y_{lm}^{ft} *using*, $Y_{lm}^{ft} = \left(\left(P_l^{ft} + Z_l^{f(t-1)}\right) / LC_{lft}\right) \times random\ number$

                else

                    Assign value 0 *to the variable* Y_{lm}^{ft}

                end

            end

        end

    end

    for $f = 1$ *to number of product types*

        for $l = 1$ *to number of wholesalers*

            if time period $= 1$

                Compute Z_l^{ft} *using equation*, $Z_l^{ft} = P_l^{ft} + Z_l^{f0} - \sum_{m \in M} Y_{lm}^{ft}$

            elseif time period > 1

                Compute Z_l^{ft} *using equation*, $Z_l^{ft} = P_l^{ft} + Z_l^{f(t-1)} - \sum_{m \in M} Y_{lm}^{ft}$

            else

                Assign value 0 *to the variable* Z_l^{ft}

            end

        end

    end

end

Algorithm (4): Pseudo-code for computing the variables X_{mn}^{ft}, Y_{mn}^{ft} and Z_{m}^{ft}

Procedure: *Generation of variables* X_{mn}^{ft}, Y_{mn}^{ft} *and* Z_{m}^{ft}
Assign values for the parameter dis_{mn} *and initialize empty space for* MC_{mft}
$c = 0$
for $t = 1$ *to total number of time periods*
    for $f = 1$ *to number of product types*
        for $m = 1$ *to number of retailers*
            for $n = 1$ *to number of customers*
                if Distance between m^{th} *and* n^{th} *facilities* $\leq$ *Max. distance* $\left(or, dis_{mn} \leq \varepsilon_n\right)$
                    Assign value 1 *to the binary variable* X_{mn}^{ft} *for the specific* m *and* n
                    Increase the counter, $c = c + 1$
                end
            end
            Assign value c *to* MC_{mft} *or*, $MC_{mft} = c$
            $c = 0$
        end
    end
    for $f = 1$ *to number of product types*
        for $m = 1$ *to number of retailers*
            for $n = 1$ *to number of customers*
                if binary variable X_{mn}^{ft} *is equal to* 1 *and time period* $= 1$
                    Compute Y_{mn}^{ft} *using*, $Y_{mn}^{ft} = \left(\left(P_m^{ft} + Z_m^{f0}\right) / MC_{mft}\right) \times$ *random number*
                elseif binary variable X_{mn}^{ft} *is equal to* 1 *and time period* > 1
                    Compute Y_{mn}^{ft} *using*, $Y_{mn}^{ft} = \left(\left(P_m^{ft} + Z_m^{f(t-1)}\right) / MC_{mft}\right) \times$ *random number*
                else
                    Assign value 0 *to the variable* Y_{mn}^{ft}
                end
            end
        end
    end
    for $f = 1$ *to number of product types*
        for $m = 1$ *to number of retailers*
            if time period $= 1$
                Compute Z_m^{ft} *using equation*, $Z_m^{ft} = P_m^{ft} + Z_m^{f0} - \sum_{n \in N} Y_{mn}^{ft}$
            elseif time period > 1
                Compute Z_m^{ft} *using equation*, $Z_m^{ft} = P_m^{ft} + Z_m^{f(t-1)} - \sum_{n \in N} Y_{mn}^{ft}$
            else
                Assign value 0 *to the variable* Z_m^{ft}
            end
        end
    end
end