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Modeling and optimization of an omnichannel retailing problem

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Abstract: *In this paper, we focus on a problem faced by an omnichannel retailer that operates multiple stores and a fulfillment center. The retailer sells products to customers over a selling horizon of the period through online and physical channels. This study aims to determine the joint tactical and operational decisions on fulfillment optimization and inventory management services in an integrated model. The multi-period horizon in our model allows more realistic planning, where various decisions can be taken at different periods. Besides, our model considers the lost-demand sale to reflect the actual sale. The proposed model helps omnichannel retailers to have an integrated tool for inventory management and fulfillment service with real-time monitoring the inventory levels across locations.*

Keywords: *Omnichannel retailer, Optimization, Inventory Management, Replenishment, fulfillment.*

Conference Topic(s): *logistics and supply networks; omnichannel & e-commerce logistics.*

Physical Internet Roadmap *(Link): Select the most relevant area for your paper: ☐ PI Nodes, ☐ PI Networks, ☒ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.*

1 Introduction

The world of retailing has expanded dramatically in the past few decades. The digital channel finds its way through all stages of the customer shopping journey because it provides a more convenient way of shopping, a wider choice of items, and the ability to access more information about items through customer reviews (Verhoef, 2021). Consequently, a growing number of retailers have started to integrate their traditional physical sales with online channels, moving towards omnichannel retailing to leverage their physical store channels(Bayram & Cesaret, 2021).

There are various definitions of omnichannel retailing and the understanding of the concept still varies. In general, definitions exhibit distinct features in the channel organization of the omnichannel, as discussed below:

1. Needs the consistent and fully integrated information, services, and process at any moment of its operation (Bayram & Cesaret, 2021; Bieberstein, 2015; Cummins et al., 2016; Fairchild, 2014; Fernie & Sparks, 2004a; Galipoglu et al., 2018; Kozlenkova et al., 2015a; Rigby, 2011; Saghiri et al., 2018; Wollenburg et al., 2018; Yrjölä et al., 2018a).
2. Includes customer touchpoints (Chauhan & Sarabhai, 2019; Cortiñas et al., 2019; Cummins et al., 2016; Heuchert et al., 2018; Pawar & Sarmah, 2015; Picot-Coupey et al., 2016; Verhoef et al., 2015; Yrjölä et al., 2018b, 2018a); any direct or indirect

communication or contact with the prospect customers, which is not necessarily an interaction (Mirsch et al., 2016; Pawar & Sarmah, 2015b).

3. Eliminates borders between channels and manages them as an integrated channel (Heuchert et al., 2018; Hübner et al., 2016; Melacini & Tappia, 2018; Menrad, 2020; Pawar & Sarmah, 2015b; Picot-Coupey et al., 2016; Trenz et al., 2020; Verhoef et al., 2015).
4. Provides a seamless shopping experience for customers (Abrudan et al., 2020; Hole et al., 2019; Jiu, 2022; Kozlenkova et al., 2015b; Menrad, 2020; Mosquera et al., 2017).

In this study, we define omnichannel retailing (Abrudan et al., 2020) a seamless shopping experience through fully integrated distribution and communication channels (Fairchild, 2014), allowing customers to purchase and return products from anywhere and allows retailers to fulfill orders from anywhere by eliminating borders between different channels (inspired by the definitions of (Bayram & Cesaret, 2021)). Performing the logistic operations in an omnichannel retailing network is not a simple task. This activity significantly increases the complexity in terms of *fulfillment planning*, *inventory management, and delivery services.*

An omnichannel retailer has the flexibility to fulfill online orders from a physical store (*Ship-From-Store (SFS) strategy*), fulfillment center, or their combinations (Difrancesco et al., 2021). Using stores to fulfill online orders is the most adopted strategy among omnichannel retailers (Bayram & Cesaret, 2021). Appropriately, a ship-from-store strategy needs the lowest initial investment (Gallagher & Vella-Brodrick, 2008), increases online sales by avoiding frustrating online stock-outs (Jiu, 2022b), and improves customer value and experience (Difrancesco et al., 2021). On the other hand, using store inventory increases the risk of stock-outs (Bendoly, 2004) and the risk of dissatisfaction and disloyalty of customers who can't find items in-store (Goedhart et al., 2022). To overcome this challenge and benefit from the advantages of different fulfillment strategies, this study focuses on the combined ship-from-store as well as fulfillment facilities.

A suitable inventory system would order the just-right size and take into account factors such as the ordering cost, the holding cost, the shortage cost, etc. (Shenoy & Rosas, 2018). Retailers need to decide how to retain their stocks across the channels to prevent risks of running out of stock and stockouts. Excessive stock levels may result in increasing storage, labor, and insurance costs and causing revenue loss and quality reduction depending on the type of product. On the other hand, the lack of inventory can lead to an inability to meet customer demand, lost sales, and customer dissatisfaction (Kilimci et al., 2019).

In recent years due to the busy lifestyle, many customers prefer products to be shipped to them as fast as possible. Most recently, the need for the home delivery service has a dramatic raise during the COVID-19 pandemic as a result of social distancing. The delivery process is an important part of the order fulfillment problem (Ishfaq & Raja, 2018). Shipping products to customers is affected by different factors such as distance, various service options, number of customers, weight, and volume of products per order.

Research in the domain of omnichannel retailing has seen various literature reviews and research studies. De Borba (2020) used a systematic literature review to identify barriers in omnichannel retailing. They categorized barriers in operations and inventory activities that need to be considered by future studies. Mahvedan and Joshi (2022) reviewed the research literature on omnichannel retailing over the period 2013–2020. They outlined that developing logistics, inventory optimization, operations, and endless combinations of fulfillment, delivery, customer service, and return logistics are important areas for retailers to focus on.

Bayram & Cesaret, (2021) investigated dynamic fulfillment decisions in which online orders can be shipped either from an online fulfillment center or from one of the stores. They construct a heuristic policy that maximizes the retailer's total profit. Difrancesco et al., (2021) study a fulfillment policy for both online and walk-in demand using store inventory under a variety of sources of uncertainty. The authors combine the simulation approach with exploratory modeling analysis to test various fulfillment policies in a variety of scenarios of analysis. Jiu, (2022b) study a joint replenishment, allocation, and fulfillment problem faced by an o-tailer. They formulate the problem as a two-stage approach, first deciding the replenishment links and then computing the appropriate quantities for replenishment and fulfillment. They proposed a two-phase approach to solving the problem.

The inventory control systems have Several variants in literature. Popular combinations include (1) continuous Review, Fixed Order Quantity (s, Q) System, (2) continuous Review, Order-Up-to-Level (s, S) System (3) Periodic Review, Order-Up-to-Level (T, S) System. The latter is the focus of our model. In periodic Review, Order-Up-to-Level (T, S) System the inventory level of items is reviewed at predetermined, fixed points in time. That is decisions are taken in at time $T, 2T, \ldots$.

This study aims to consider the tactical and operational decisions on the optimal amounts of inventory and replenishment, and the fulfillment location for an omnichannel retailer with the objective of maximizing the total revenue over a finite horizon.

We formulate the problem as an integer linear programming problem and examine the viability of the proposed model using a numerical example, inspired by an Australian omnichannel retailer.

The rest of the paper is organized as follows. In Section 2, the problem description and mathematical formulation of an omnichannel problem are described. The solution approach and computational results are described in Section 3. Section 4 presents a numerical study. Finally, the conclusion and future outlines are provided in Section 5.

2 Problem description

2.1. Problem statement

Figure 2 shows the structure of the omnichannel retailing network, where solid lines represent customers visiting stores and dashed lines represent products delivered to customers. The notations in the figure will be used in the mathematical modeling.

The network is divided into a number of *local zones* and hence customer locations. Each zone includes exactly one store. Customers are classified by their shopping channels and physical/delivery addresses. With respect to the shopping channel, the retailer deals with two types of customers: (i) walk-in customers, who physically come to the store and collect products from a store themselves, and (ii) online customers, who place orders through the retailer's website or mobile app (Govindarajan et al., 2021). Customers buying product(s) online would have the option of selecting the delivery service, with products directly shipped to their location, called *home delivery*, or collecting orders from a local store called *click-and-collect (C&C).*

C&C customers are defined as a part of online customers where the payment and purchase accrue at the online channel, but the pick-up happens at a nominated store, meaning that customers cross-buy (buy online and pick up in-store) (Jara et al., 2018). We emphasize that with the introduction of C&C, the retailer requires an integrated information system to provide customers with immediate access to the real-time inventory information at each store (Gallino & Moreno, 2019). In another word, the actual stock availability is promptly updated once a C&C order is processed by an employee or a walk-in customer makes a purchase in the store.

The entire fulfillment process of walk-in customers only is taken care of at the corresponding store in the local zone. We assume that customers who face a stock-out don't switch to other stores, and it is because of the long distance between stores. Therefore, the unfulfilled in-store demand of one store cannot be fulfilled by other stores. This assumption is in line with research in Bayram & Cesaret, (2021), and Jiu, (2022b). The retailer needs to decide from which location (a store or an FC) fulfills online orders. We stress that the fulfillment process in a fulfillment center is more efficient than in a store (Gallino & Moreno, 2019). The flowchart of fulfilling online orders is shown in Figure 1.

In this research, we study omnichannel retail operations to determine the decisions on fulfillment optimization and inventory management in an integrated model. In particular, the retailer determines the amount of inventory replenishment at selected times, the inventory policy at each store, and the fulfillment of the online orders for different selling channels.

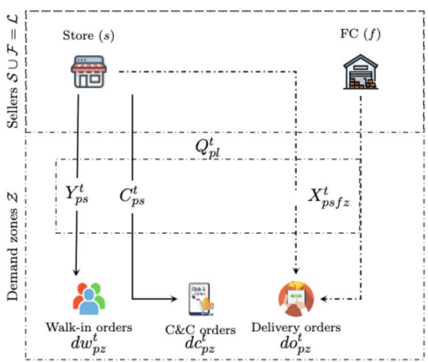

Figure 1: Structure of an omnichannel retail network

Assumptions used in the mathematical model have listed below:

- Unfulfilled demand of walk-in and click-and-collect customers for products that are out of stock is immediately lost.
- Customers don't switch between selling channels or stores in the case of stockout. That is, a) an online customer will not intend to buy products physically in store, and b) a walk-in customer does not choose delivery but collects product(s) from the store.
- All stores support walk-in, click-and-collect, and online demand.
- The replenishment occurs weekly.
- The actual inventory availability is changed in real time, meaning that the retailer has an integrated information system.

2.2. Mathematical model

Notations:

Consider a retailer selling products $p \in \mathcal{P} = \{1, \dots, P\}$ to customers in different demand zones $z \in \mathcal{Z} = \{1, \dots, Z\}$ over a finite planning horizon of periods $t \in \mathcal{T} = \{1, \dots, T\}$ (a period could represent a day for example). Let $s \in \mathcal{S} = \{1, \dots, S\}$ denotes the set of stores and $f \in \mathcal{F} = \{1, \dots, F\}$ denote the set of fulfillment centers respectively, and $\mathcal{L} = \mathcal{S} \cup \mathcal{F}$ represent the set of all seller locations. So, a seller or seller location refers to a store or a fulfillment center. For the complete list of notations, please see Table 1.

Table 1: Notations

Notation	Definition
$\mathcal{S}$	Set of stores ($s \in \mathcal{S}$)
$\mathcal{F}$	Set of fulfillment centers ($f \in \mathcal{F}$)
l	Set of sellers ($\mathcal{L} = \mathcal{S} \cup \mathcal{F}$)
$\mathcal{P}$	Set of products ($p \in \mathcal{P}$)
$\mathcal{T}$	Set of time periods ($t \in \mathcal{T}$)
$\mathcal{Z}$	Set of zones ($z \in \mathcal{Z}$)

Parameters:

do_{pz}^{t}	The online (home delivery) demand of zone z for product p at period t,
dw_{ps}^{t}	The walk-in demand of store s for product p at period t,
dc_{ps}^{t}	The click-and-collect demand of store s for product p at period t,
i_p	The retailer price of product p,
ch_{plz}	The cost of delivering product p from the seller l to a customer in zone z,

cf_{ps}	The walk-in fulfilment cost of product p at store s,
cr_{pl}	The replenishment cost of product p in seller l,
co_{pl}	Holding cost of product p in seller l,
$\bar{u}_l$	The inventory capacity of seller l ,
$\bar{k}_{lz}$	The capacity of transportation vehicle from seller l to customers in zone z,
lo_{pz}	Lost sale penalty cost for online customers in zone z for product p,
lw_{ps}	Lost sale penalty cost for walk-in customers in store s for product $p \in \mathcal{P}$.

Variables:

X_{plz}^t	The amount of product p ship to online customers in zone z from seller l at period t,
Y_{ps}^t	The amount of product p sold to walk-in customers in store s at period t,
C_{ps}^t	The amount of product p sold for click-and-collect orders in store s at period t,
I_{pl}^t	Inventory level of product p at location l at the beginning of period t,
R_{pl}^t	Replenishment amount of product p at location l in period t,
Q_{pl}^t	The total sale of product p at location l at period t.

Before proceeding with the definitions, we describe the order of events during a period. The start inventory for product p in each period t at seller l is I_{pl}^t. Online and walk-in demands arrive over periods. Walk-in demands are immediately satisfied if the inventory level is positive, otherwise, they are lost. Online demand and the click-and-collect orders could be satisfied from either a store or by the fulfillment center (the pick-up location for click-and-collect orders is still the store). At the beginning of each period, the amount of product p replenished at seller l is denoted by R_{pl}^t.

The amount of sale for sellers: Let X_{plz}^t denote a decision variable representing the amount of product p shipped from seller l to satisfy the online demand of customers in zone z at time period t while Y_{ps}^t is the amount of the product used to fulfill the walk-in customers from the store s. Besides, C_{ps}^t represents the amount of the product for C&C orders. For ease of exposition, we substitute the total sale for the seller l for product p at time t by Q_{pl}^t as

$$Q_{pl}^t = \begin{cases} \sum_{z \in \mathcal{Z}} X_{psz}^t + Y_{ps}^t + C_{ps}^t, & \forall t \in \mathcal{T}, p \in \mathcal{P}, s \in \mathcal{S}, \\ \sum_{z \in \mathcal{Z}} X_{plz}^t & \forall t \in \mathcal{T}, p \in \mathcal{P}, l \in \mathcal{F}, \end{cases} \tag{1}$$

for store s and fulfillment center f, respectively.

The start inventory level for sellers: The replenished products arrive immediately and will only be available to serve the demand that occurs during the same period. The start inventory ($I_{pl}^{t} > 0$) is determined on the basis of the amount of total sale (fulfillment), replenishment amount, and the leftover inventory from the previous period $t-1$. We apply an order-up-to-level system, that is the start inventory raises to I_{pl}^{t} at the beginning of each period with zero lead time (Poormoaied, 2022). So,

$$I_{pl}^{t} = I_{pl}^{t-1} + R_{pl}^{t-1} - Q_{pl}^{t-1} \quad \forall t \in \mathcal{T}, p \in \mathcal{P}, l \in \mathcal{L}. \tag{2}$$

Unlike the fulfillment which occurs daily, the replenishment occurs weekly. So, we set $R_{pl}^{t} = 0 \ \ \forall\, t$ if $rem(t, 7) \neq 0$.

Supply constraint: To guarantee that the amount of products used by each seller to fulfill demands doesn't exceed the available inventory, we impose

$$Q_{pl}^{t} \leq R_{pl}^{t} + I_{pl}^{t} \qquad \forall t \in \mathcal{T}, p \in \mathcal{P}, l \in \mathcal{L}. \tag{3}$$

Capacity constraints: In our study, each seller has a limited storage capacity and so transportation vehicles are. To respect the capacity constraints, we have:

$$R_{pl}^{t} + I_{pl}^{t} \leq \bar{u}_{pl} \qquad \forall t \in \mathcal{T}, p \in \mathcal{P}, l \in \mathcal{L}, \tag{4}$$

$$\sum_{p \in \mathcal{P}} X_{plz}^{t} \leq \bar{k}_{lz} \qquad \forall t \in \mathcal{T}, p \in \mathcal{P}, l \in \mathcal{L}, z \in \mathcal{Z}. \tag{5}$$

Fulfillment constraint: Let do_{pz}^{t} denote the online demand of zone z for product p at period t. The demand for the walk-in and click-and-collect customers from local store s is presented by dw_{ps}^{t} and dc_{ps}^{t}, respectively. Then the fulfillment constraints are

$$\sum_{l \in \mathcal{L}} X_{plz}^{t} \leq do_{pz}^{t} \qquad \forall t \in \mathcal{T}, p \in \mathcal{P}, z \in \mathcal{Z}, \tag{6}$$

$$Y_{ps}^{t} \leq dw_{ps}^{t} \qquad \forall t \in \mathcal{T}, p \in \mathcal{P}, s \in \mathcal{S}, \tag{7}$$

$$C_{ps}^{t} \leq dc_{ps}^{t} \qquad \forall t \in \mathcal{T}, p \in \mathcal{P}, s \in \mathcal{S}, \tag{8}$$

which ensure that the sale is subject to the demand.

Income: The total cumulative profit from physical and online sales is

$$A_{0p} = \sum_{t\in\mathcal{T}} \sum_{p\in\mathcal{P}} \sum_{l\in\mathcal{L}} i_p^t \, Q_{pl}^t. \tag{9}$$

The holding costs: Leftover products remaining at the end of each time period incur a holding cost, and the unit cost is co_{pl}. This cost could represent the total of the costs of capital tied up, fulfillment center, space, insurance, taxes, and so on. In our setting, the holding cost is assessed only on inventory left at the end of a period and carries over to the next period. The total holding cost is presented by

$$A_{1c} = \sum_{t\in\mathcal{T}} \sum_{p\in\mathcal{P}} \sum_{l\in\mathcal{L}} co_{pl} \, I_{pl}^t. \tag{10}$$

Unsatisfied demand cost: Retailers policy prohibits deliberately planning for shortages of any of its products. However, a shortage of products occasionally crops up. Consequently, the amount of the product required (demand) exceeds the available stock. Unfulfilled demand for products that are out of stock is immediately lost and incurs penalty costs.

$$A_{2\_1c} = \sum_{t\in\mathcal{T}} \sum_{p\in\mathcal{P}} \sum_{z\in\mathcal{Z}} lo_{pz} \big(do_{pz}^t - \sum_{l\in\mathcal{L}} X_{plz}^t\big), \tag{11}$$

$$A_{2\_2c} = \sum_{t\in\mathcal{T}} \sum_{p\in\mathcal{P}} \sum_{l\in\mathcal{L}} lw_{ps}^t \big(dw_{ps}^t + dc_{ps}^t - Y_{ps}^t - C_{ps}^t\big). \tag{12}$$

The replenishment cost: The retailer pays cr_{pl} unit variable cost for replenishing product p for seller l. The replenishment cost is given by

$$A_{3c} = \sum_{t\in\mathcal{T}} \sum_{p\in\mathcal{P}} \sum_{l\in\mathcal{L}} cr_{pl} \, R_{pl}^t. \tag{13}$$

The total handling cost: The handling cost for online demand of zone z associated with preparing and shipping product p for seller l is given by ch_{plz}. The handling cost for online orders is calculated by

$$A_{4c} = \sum_{t\in\mathcal{T}} \sum_{p\in\mathcal{P}} \sum_{l\in\mathcal{L}} \sum_{z\in\mathcal{Z}} ch_{pls} X_{plz}^t \tag{14}$$

The store fulfillment cost: The unit cost cf_{ps} for fulfilling the demand of walk-in and click-and-collect orders including rent, overhead, labor, etc. are associated with products type, stores, and periods, that is the cost of store s for product p. So, the total store fulfillment cost is given by

$$A_{5c} = \sum_{t\in\mathcal{T}} \sum_{p\in\mathcal{P}} \sum_{s\in\mathcal{S}} cf_{ps} \left(Y_{ps}^{t} + Z_{ps}^{t}\right). \tag{15}$$

Non-negativity constraints are

$$I_{pl}^{t}, R_{pl}^{t}, Q_{pl}^{t}, X_{plz}^{t}, Y_{ps}^{t}, Z_{ps}^{t} \geq 0 \qquad \forall t \in \mathcal{T}, p \in \mathcal{P}, l \in \mathcal{L} \tag{16}$$

The objective is given as

$$Max\left(A_{0p} - A_{1c} - A_{2_{1c}} - A_{2_{2c}} - A_{3c} - A_{4c} - A_{5c}\right). \tag{17}$$

4 Numerical experiments

This section presents a case study, explains the set of parameters, how the data was generated, and discusses the numerical results.

Data Generation:

The time horizon $\mathcal{T}$ is fixed to 14 time periods (days). The replenishment schedule of each seller was set to be at the beginning of each week, and during weeks there is no replenishment opportunity. The start inventory level is set as 120 and 250 per product for each store and fulfillment center, respectively. The walk-in, online, and click-and-collect demand for each customer zone was generated randomly as $U_d[1{,}100], U_d[1{,}60],\ U_d[1{,}35]$, respectively.

The available transportation and storage capacity for each store were estimated 1.2 higher than the total mean (walk-in, click-and-collect, and online) demand of a zone (7,74) while for the fulfillment center was 1.2 higher than the online mean demand of all zones (56,56).

The other values for the settings and parameters are present in Table 2.

Table 1: Instance generation parameters

Parameters	Store	Fulfillment center
Price per product: $40		
Replenishment charge per price	8%	8%
Holding charge per price	8%	8%
Handling charge per price	Vary per distance [2.5,7] Increase per distance for other zones	Vary per distance [2.5,7] Increase per distance for other zones
Lost sale cost per price	50%	50%
Walk-in fulfilment cost per price	15%	-

The demand distribution for the walk-in, click-and-collect, and delivery orders for product 1 at time 2 is presented in Figure 2. The figure shows the demand and commutative demand for zone 1 over time.

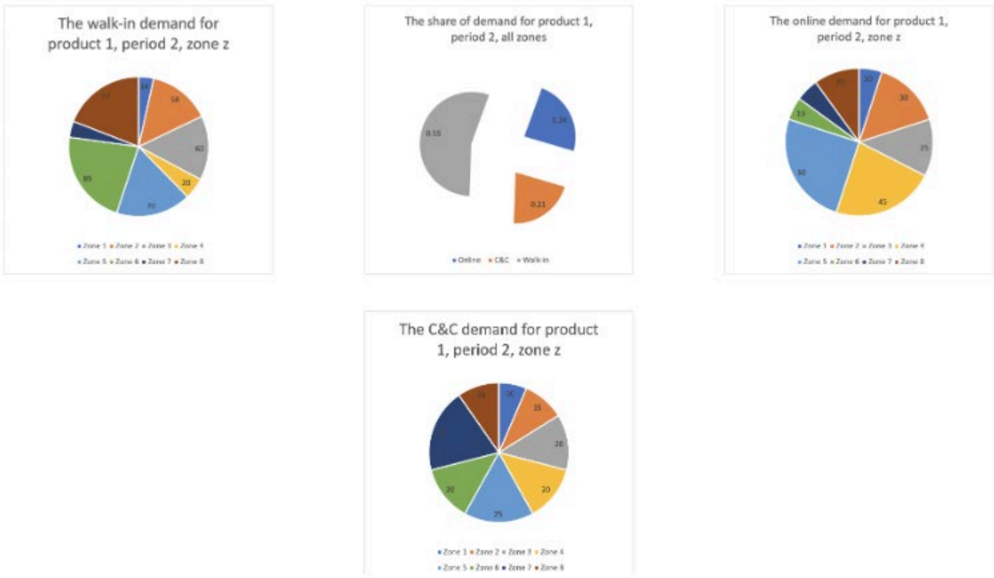

Figure 2: Demand distribution for product 1 at time 2

Solution approach and computation result:

All experiments were carried out on a PC with Intel Corei7, CPU 2.6 GHz, 16 GB of RAM, using a Gurobi solver version 11.5. The maximization problem for the deterministic model was solved in 0.002323 second with 3418 variables and 1204 constraints and the objective value is $636221.5. The most important results are presented as follows.

Start inventory: The start inventory levels of the fulfillment center and store 1 are shown in Figure 3. The beginning inventory levels for the sellers are raised to the highest point at the replenishment date and then continue to fall between two replenishment times. Because here we assume full knowledge of demand, the inventory level drops to zero immediately prior to the second replenishment. In practice, one could set the safety stock to non-zero.

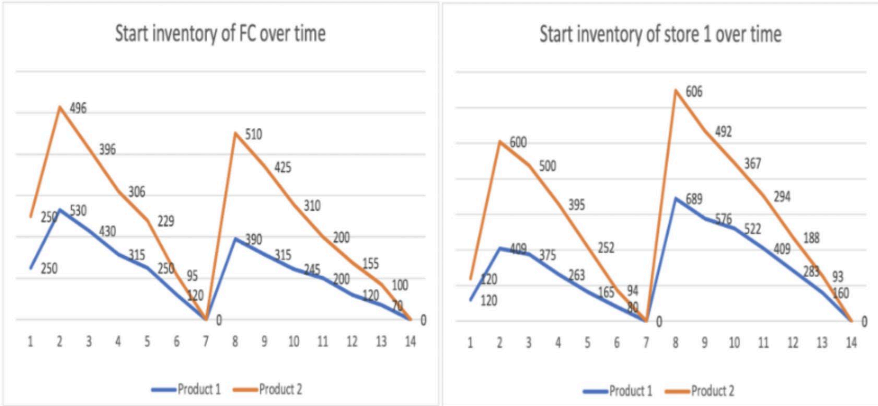

Figure 3: Start inventory for the FC and store 1 over time.

The total online sale: The online sale for stores in comparison to the online sale of the fulfillment center is presented in Figure 4. The figure shows that the total online sale for stores is higher than the fulfillment center. Although the handling cost for the FC is less than a store, this cost increase on the distance and it is more profitable if the online orders are served by the stores at the same zones, however establishing more fulfillment centers and a close distance from customer zones, may improve the objective value.

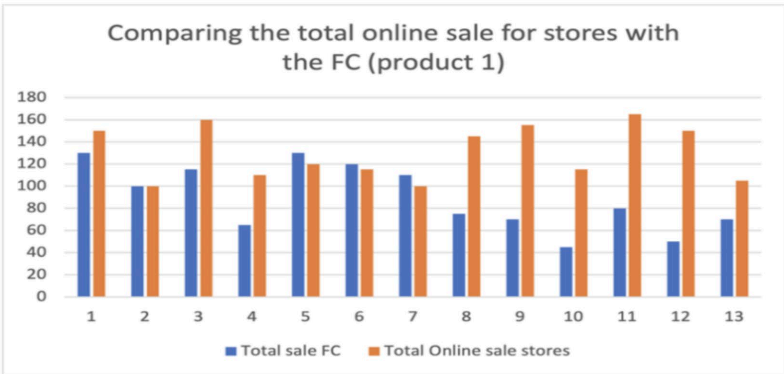

Figure 4: Start inventory for the FC and stores for product 1 over time

The results are also drawn based on changes in demand as depicted in Figure 5. The results shows that the objective function is highly positively correlated with the customer demand. However, we expect when the demand is much higher and hence the penalty of unfulfillment increases, the objective function value will stop increasing eventually.

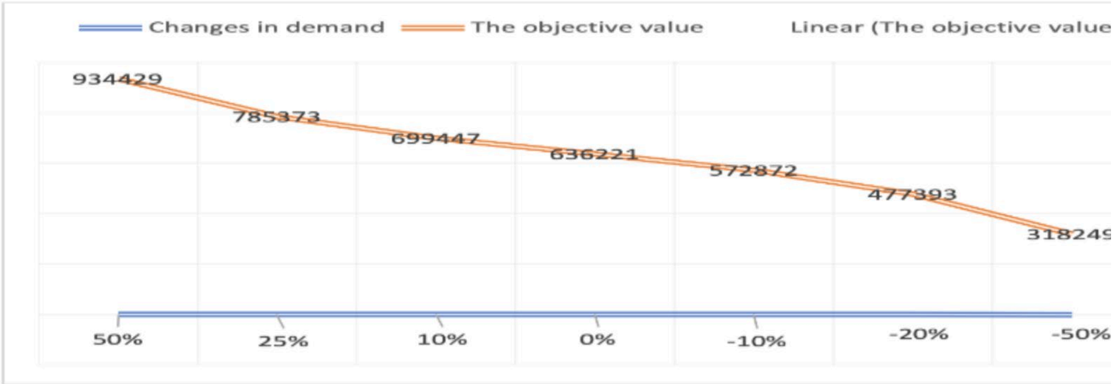

Figure 5: The relationship between demand and objective function

5 Conclusion

This study investigated a capacitated omnichannel retailing problem to integrate tactical and strategic decisions on inventory management and fulfilment optimization. By examining the results, some insights which abide by the market rules and the unique structure of the problem were drawn. This work comes with many limitations and hence offers a large number of future directions. For example, the deterministic setting is not realistic, and the stochastic demand should be considered. Another future direction is to consider a large, connected network with collaboration of partner stores. Partnering with other retailers and leveraging their store location and capacity can provide a great potential for improving delivery efficiency, fulfillment level and customer satisfactory.

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