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Designing a Multiperiod Sustainable Supply Chain Network for Perishable Products

*M. S. Al-Ashhab [1], Omnia M. Nabil [2], Nahid H. Afia [3], Tamer Ismail [4, *]*

[1] *Design and Production Engineering Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt, email:* msashhab@uqu.edu.sa
[2] *Department* of Industrial Automation, *Faculty of Engineering,* German *University* in Cairo, Cairo, Egypt, *email:* omnianabil@gmail.com,
[3] *Design and Production Engineering Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt, email:* nahid_abdelhalim@eng.asu.edu.eg
[4] *Basic and Applied Sciences Department, Faculty of Engineering and Technology, Arab Academy for Science, Technology and Maritime Transport, Cairo, Egypt, email:* tamer.ismail@aast.edu,
**Corresponding author,* *DOI: 10.21608/pserj.2025.331639.1376.*

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ABSTRACT

This study addresses sustainable supply chain network design problem (SSCND) for perishable products which deteriorate or lose their value in a short time period. A mathematical model is presented to design a three-echelon supply network for perishable products that include manufacturers, warehouse, and retailers. The model considers the environmental impacts through considering different costs arising from product expiration. The problem is formulated as mixed-integer nonlinear programming (MINLP). The objective of the proposed model is to maximize the total supply chain profit by determining the optimal supply chain design and the quantities to be produced in each period as well as the quantities to be delivered from manufacturers to warehouse, and from the warehouse to retailers. The developed model is solved using DICOPT solver within GAMS and has achieved the objective of maximizing the profit through the optimum supply chain design together with considering sustainability aspects through minimizing the environmental impact resulting from product expiration. A study for different factors affecting the supply chain profit such as demand at the retailers, manufacturers' capacity and warehouse capacity is conducted.

Keywords: Sustainability, Perishable Products, FIFO, Expiration.

1 INTRODUCTION

Perishable Products Supply Chain Networks is concerned with products with limited shelf-life; after which the product expires and should be disposed of. Perishability is mainly considered in the healthcare and food industries where the products may deteriorate during manufacturing, distribution, or storage. Pharmaceutical products, dairy products and blood are the main examples of perishable products. The expiration of a product results in extra costs related to disposal and other environmental impacts.

Several research addressed the problem of SSCND for perishable products during the past decade; researchers considered different assumptions and tackled different solution approaches according to the nature of the problem under study.

Jiang et al. [1] proposed a bi-objective mathematical model that considers carbon footprint to optimize decisions for selecting, transportation mode, technology in addition to supplies of raw materials and recovery materials. Yakavenka et al. [2] developed a multi-objective SSCND model for perishable food to select facilities locations, transportation mode, routes, and associated flows of goods. Rohmer et al. [3] developed a model that considers cost and environmental aspects in a global food system. Eskandari-Khanghahi et al. [4] proposed a multi-objective model for blood supply chain; considering sustainability. Halim et al. [5] developed a systematic framework for SSCND to select suitable suppliers in the field of pharmaceutics. Tavakkoli-Moghaddam et al. [6] developed a mathematical model for reverse logistics of perishable products. Patidar et al. [7] presented a mathematical model to address the Indian agro-food supply chain design. Zahiri et al. [8] developed a multi-objective sustainable model to achieve optimum design for a pharmaceutical supply chain considering both strategic and tactical decisions. Musavi and Bozorgi-Amiri [9] proposed a multi-objective model that ensures the quality and freshness of food. Diabat et al. [10] proposed a two stage-programming model for supply chain network of humanitarian aids where facilities and routes between them are subject to disruptions and might become inaccessible in the aftermath of disasters. The authors addressed a real case study of blood supply chains. Dutta and Shrivastava [11] developed a non-linear mathematical model for perishable product's supply chain under conditions of demand, supply and process uncertainties. Sinha and Anand [12] developed a holistic model to minimize the total cost which includes set up cost, variable transportation cost, fixed transportation cost, inventory holding cost and ordering costs. The authors used improved bacteria forging algorithm (IBFA) for solving the formulated model. M. Biuki et al. [13] developed multi-objective Mixed-Integer Programming (MIP) model for integrated decision-making on location, routing, and inventory control planning. The model aimed at determining the interrelated decisions concerning location of manufacturing and distributing centers, inventory levels at these two echelons, and flow of materials including routing and volume control. A. Liu et al. [14] developed a multi-objective planning model for an integrated location-inventory-routing problem for perishable products, considering the impact of vehicle speed on economic cost, carbon emissions and product freshness. Chen et al. [15] proposed mathematical model consisting of three objective functions (profit maximization, delivery time minimization, and reduction of lost business days due to workers' injuries). The model considers the disruption in production and distribution capacity and taking into account the uncertainty in customer demand. H. Abbas et al. [16] proposed a multi-objective structure of perishable product supply chain for multiple food products with different attributes such as perishability, cost and weight.

The authors of this research categorized more literature conducted in the field of SSND for perishable products in Nabil et al. [17] as shown in table1. The categories are built according to perishability phenomenon, modelling approaches and characteristics either exact or heuristics/metaheuristics, objective functions; either single objective denoted by (S), bi-objective denoted by (bi) or multi-objective denoted by (M), software tools used in solving the proposed models, the fields of application and sustainability aspects.

Referring to literature, it can be concluded that all research is concerned with the objective of maximizing the profit, without considering minimizing or preventing the expiration cost to minimize the environmental impact that arises due to product expiration as an important pillar of sustainability.

This research is an extension of Al-Ashhab et al. [51]; GAMS is used to solve the developed model instead of Excel to be able to solve large size problems by increasing the number of periods, number of products and the number of goals. This increase in the problem variables will lead to a tremendous increase in the problem size making it too difficult for Excel to solve.

This research considers the design of (SSCN) for perishable goods as well as studying the factors affecting the profit of the designed supply chain. A mathematical model is developed to design a SSCN network with three echelons and multi-period. The supply chain echelons considered in this study are manufacturers, warehouse, and retailers. A mixed-integer nonlinear programming (MINLP) model is formulated and is solved using DICOPT solver in GAMS software v. 25.1.3. A laptop with core (TM) i7 1.8 GHz and 16 GB of RAM is used to perform computational experiments.

This proposed model aims to obtain the optimum supply chain design and the optimum production and transportation plans. The decision regarding the supply chain design and the delivered quantities depends on the demand at the retailers, the perishability of products, and inventory costs. First-in First-Out (FIFO) inventory policy is adopted in the warehouse's store.

2 MATHEMATICAL MODEL

2.1 Model Description

A three-echelon multi-period supply chain for perishable products consisting of manufacturers, warehouse and retailers is considered. Products' shelf-life is priory known after which they will be expired and will need to be disposed. The objective of the model is to achieve maximum total supply chain profit through allocating the manufacturers and specifying the quantities to be delivered from the manufacturers to the warehouse and the quantities to be delivered from the warehouse to the retailers at each period. Figure (1) shows the structure of the proposed supply chain. Figure (2) shows the model flow between the different echelons in the proposed supply chain.

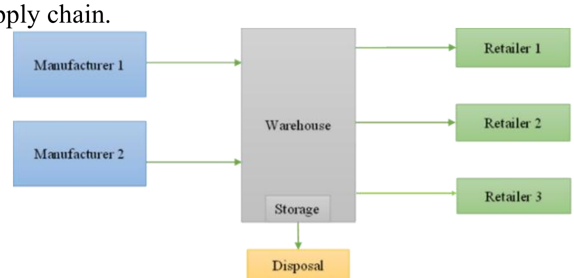

Figure 1: Structure of the proposed supply chain

Table 1. Summary of reviewed Research

No.	Paper	Perishable	Sustainable	Objectives	Economic	Environmental	Social	Mod. approach	Sol. approach	Software	Application
1	[18]	✓	✓	M	✓	✓	✓	*MILP*	*Pareto*	*GAMS*	Pharma
2	[19]	✓	✓	M	✓	✓	✓	*MIP*	*ε-constraint*	*CPLEX*	Wine
3	[20]	✓	✓	S	✓	×	×	__	*piecewise*	_	Deteriorating
4	[21]	✓	✓	Bi	✓	✓	×	*MIP*	*GA*	_	Food
5	[22]	✓	×	S	✓	×	×	_	_	_	avocado
6	[23]	✓	×	M	✓	✓	×	*MILP*	*ε-constraint*	*LINGO*	meat
7	[24]	✓	×	Bi	✓	×	×	*MILP*	*ε-constraint*	*GAMS*	_
8	[25]	✓	×	Bi	✓	✓	×	*MILP*	*Geraeli method*	*GAMS/ CPLEX*	_
9	[26]	✓	×	Bi	✓	✓	×	*MINLP*	*LP-metrics*	_	Dairy
10	[27]	✓	×	S	✓	×	×	MINLP	*Hybrid*	*MATLAB/ LINDO*	_
11	[28]	✓	×	M	✓	✓	✓	MILP	*NSGA-II*	_	_
12	[29]	✓	×	Bi	✓	×	×	_	*Data envelopment*	*GAMS*	Food
13	[30]	✓	×	S	✓	×	×	MIP	_	*LINGO*	Dairy
14	[31]	✓	×	S	✓	×	×	MINLP	*Possibilistic*	*GAMS*	Pharma
15	[32]	✓	×	Bi	✓	×	×	MILP	*Robust*	*GAMS*	Pharma
16	[33]	✓	×	S	✓	×	×	MIP	*GA*	*GAMS*	_
17	[34]	✓	×	Bi	✓	×	×	MIP	_	*Gurobi*	Orange
18	[35]	✓	×	Bi	✓	×	×	_	*Algorithm*	*MATLAB*	_
19	[36]	✓	×	Bi	✓	×	×	MILP	*ε-constraint*	*CPLEX*	Blood
20	[37]	✓	×	Bi	✓	×	×	MILP	*Robust*	*GAMS*	Pharma
21	[38]	✓	×	Bi	✓	✓	×	MIP	*Hybrid*	*MATLAB*	Food
22	[39]	✓	×	Bi	✓	×	×	MIP	*Fuzzy*	*GAMS*	Organ
23	[40]	×	✓	M	✓	✓	✓	_	*Hybrid GA*	*MATLAB*	_
24	[41]	×	✓	Bi	✓	✓	×	MILP	*SA*	*GAMS*	_
25	[42]	×	✓	Bi	✓	✓	×	MILP	*Neighbourhood*	*IBM Ilog*	_
26	[43]	×	✓	M	✓	✓	✓	MIP	*hybrid swarm*	*MATLAB*	_
27	[44]	×	✓	Bi	✓	✓	×	MILP	*GP*	*LINGO*	plastic injection
28	[45]	×	✓	Bi	✓	✓	×	MILP	*Approximation*	*CPLEX*	_
29	[46]	×	✓	M	✓	✓	✓	MILP	*ε-Constraint*	*GAMS*	_
30	[47]	×	✓	M	✓	✓	✓	MILP	*Fuzzy*	*LINGO*	_
31	[48]	×	✓	Bi	✓	✓	×	MINLP	*ε-constraint*	*GAMS*	Biodiesel
32	[49]	×	✓	M	✓	✓	✓	MILP	*ε-constraint*	*GAMS*	_
33	[50]	×	✓	Bi	✓	×	×	MILP	*robust*	*CPLEX*	_
34	[51]	✓	✓	S	✓	✓	×	MINLP	*GP*	*Excel*	General

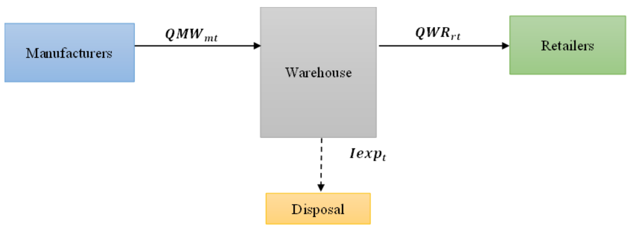

Figure 2: Model flow diagram [51]

2.2 Model Assumptions

The developed mathematical model is based on the following assumptions:

- The demand of the retailers is known and deterministic.
- Capacities of manufacturers and warehouses are predetermined.
- Backlog is allowed.
- The shelf-life of the products is limited and known.
- Products that reach their shelf-life are considered as waste that will be disposed of.
- FIFO inventory management is considered.

Sets

T	Planning periods
A	Ages of products
M	Potential manufactures.
R	Retailers

Parameters

S	Product shelf-life
D_{rt}	Demand at retailer *(r)* for period *(t)*
CM_{mt}	Manufacturer (m) capacity at period *(t)*
CW_t	Warehouse capacity at period *(t)*
p	Unit price
TC	Unit product transportation cost per unit distance
DMW_m	Distance between the warehouse and manufacturer *(m)*
DWR_r	Distance between the warehouse and retailer *(r)*
HC	Unit Inventory holding cost per period
EC	Unit expiry cost
SC	Shortage cost per unit
MC	Material cost per unit
PC	Unit production cost
FC	Fixed cost

Decision variables

QMW_{mt}	Quantity to be delivered from manufacturer *(m)* to the warehouse at time period *(t)*
QWR_{rt}	Quantity to be delivered from the warehouse to retailer *(r)* at time period *(t)*
I_{at}	Inventory of age *(a)* at the end of time period *(t)*
$Iexp_t$	Expired inventory at the end of time period *(t)*
X_m	Binary decision variable which equals 1 if the manufacturer *(m)* exists; 0 otherwise
Z	Total profit

2.3 Objective Function

The objective function of the developed model pursues to maximize the profit of the supply chain network described by Equation (1). The detailed equations for sales revenues and total costs are shown in equations (3) to (9), while the objective function is shown in equation (10).

$$\text{Profit} = \text{Sales Revenues} - \text{Total costs} \tag{1}$$

The sales revenues is calculated using equation (2).

$$\text{Sales revenue} = \sum_r \sum_t \; QWR_{rt} \; p \tag{2}$$

While the total costs include the following cost elements:

- Fixed cost at the manufacturers
- Production cost
- Materials cost
- Transportation cost
- Inventory holding costs
- Expiration cost
- Shortage cost

Where the equations used for calculating each cost element is represented by equations (3) to (9):

$$\text{Fixed cost of the manufacturers} = \sum_M FC \; X_m \tag{3}$$

$$\text{Production cost} = \sum_{m\in M} \sum_{t\in T} \; QMW_{mt} \; PC \tag{4}$$

$$\text{Material cost} = \sum_{m\in M} \sum_{t\in T} QMW_{mt} \; MC \tag{5}$$

$$\text{Transportation cost} = \sum_{m\in M} \sum_{t\in T} \; QMW_{mt}\, TC \; DMW_m + \sum_{r\in R} \sum_{t\in T} \; QWR_{rt}\, TC \; DWR_r \tag{6}$$

$$\text{Inventory holding cost} = \sum_{a\in S} \sum_{t\in T} \; I_{at} \; HC \tag{7}$$

$$\text{Expiration cost} = \sum_{t\in T} \; Iexp_t \; EC \tag{8}$$

$$\text{Shortage cost} = \sum_{r\in R} \sum_{t\in T} \; SC \; \left(\sum_1^t D_{rt} - \sum_1^t QWR_{rt}\right) \tag{9}$$

The objective function for the supply chain is shown in equation 10:

$$\text{Max } Z = \sum_{r\in R} \sum_{t\in T} \; QWR_{rt} \; p \; - \sum_{m\in M} FC \; X_m - \sum_{m\in M} \sum_{t\in T} \; QMW_{mt} \; (PC + MC) - \sum_{m\in M} \sum_{t\in T} \; QMW_{mt} \; TC \; DMW_m - \sum_{r\in R} \sum_{t\in T} \; QWR_{rt} \; TC \; DWR_r - \sum_{a\in S} \sum_{t\in T} \; I_{at} \; HC - \sum_{t\in T} \; Iexp_t \, EC - \sum_{r\in R} \sum_{t\in T} \; SC \; \left(\sum_1^t D_{rt} - \sum_1^t QWR_{rt}\right) \tag{10}$$

2.4 Constraints

The constraints of the proposed model are shown in this section in equations (11) to (20)

$$QMW_{mt} \le CM_{mt} \;\; X_m, \qquad \forall \; m \,\epsilon\, M \,\&\, t \,\epsilon\, T \qquad (11)$$

$$\sum_{m\in M} QMW_{mt} \;\; \le CW_t \;\; , \;\; t = 1 \qquad (12)$$

$$\sum_{m\in M} QMW_{mt} \;\; + \;\; \sum_{a=1}^{S} I_{a,t-1} \le CW_t \;\; , \;\; t \ge 1 \qquad (13)$$

$$I_{at} = \sum_m QMW_{mt} - \sum_r QWR_{rt} \;, \quad \mathrm{t} = 1, \mathrm{a} = 1 \qquad (14)$$

$$I_{at} = \sum_m QMW_{mt} \; - \; max\{(\sum_1^t \sum_r D_{rt} - \sum_1^{t-1} \sum_r QWR_{rt}) - \sum_{a=1}^{S-1} I_{a,t-1}, 0\} \;, t = 2, \dots, T, \;\; a = 1 \qquad (15)$$

$$I_{at} = max\{I_{a-1,t-1} - max\{(\sum_1^t \sum_r D_{rt} - \sum_1^{t-1} \sum_r QWR_{rt}) - \sum_{j=a}^{S-1} I_{j,t-1}, 0\}, 0\}, t = 2, \dots, T, \;\; a = 2, \dots, S \qquad (16)$$

$$\sum_m QMW_{mt} \; + \sum_{a=1}^{t-1} I_{a,t-1} \;\; = \sum_c QWR_{rt} + \sum_{a=1}^{t} I_{at} \;\; + Iexp_t \qquad , \;\; \forall \;\; t \qquad (17)$$

$$Iexp_t = 0 \qquad\qquad , \; 1 \le \; t \le S \qquad (18)$$

$$Iexp_t = max\big(I_{a,t-1} - (\sum_r \sum_1^t D_{rt} - \sum_r \sum_1^{t-1} Qwr_{rt}), 0\big) \,, \quad t > S, a = S \qquad (19)$$

$$Qmw_{mt}, \quad Qwr_{rt}, \quad I_{at}, \;\; Iexp_t \; \ge 0, \;\; \forall \;\; m, r, a, t \qquad (20)$$

The constraint in equation (11) represents the manufacturers' capacity constraint. Equation (12) represents the warehouse capacity constraint for period 1 while the warehouse capacity constraint for the rest of the periods is shown in equation (13). Equations (14), (15) and (16) ensure that the FIFO rule is satisfied for the first period and the rest of the periods respectively. Equation (17) represents the inventory balance constraint, while equations (18) and (19) represent the expired inventory constraint according to the product shelf-life. Equation (20) represents the decision variables non-negativity constraint.

3 RESULTS AND DISCUSSION

3.1 Model verification

The developed model equations has been described where this model has been verified through two stages in Al-Ashhab et al. [51]. The solution of the model using GAMS has been verified by solving the same problems that have been solved in Al-Ashhab et al. [51] and the same results have been achieved. It is observed from the results that the developed model is capable of providing optimum results under the given assumptions and thus can be used efficiently for supply chain optimization and further experimentations.

3.2 Studying the effect of changing in demand on the profit

In this section, the effect of different demand scenarios on profit is studied. Table (2) shows the decision variables' values in studying different demand patterns. It can be observed from the results in scenarios #1 to #8 that the demand at the retailers is below the capacity of manufacturers at each period. Thus, the demand is fulfilled at each period without backlog. It can be observed that in scenario #8, the demand of retailer in each period is 13,000, which exceeds the manufacturer's pre-specified capacity in each period (which equals 12,000 units), so the demand of the retailers will be fulfilled only with the available 12,000 units and there will be a shortage of 1,000 units, that will reduce the profit due to the shortage cost. This happens in any demanding scenario which exceeds the pre-specified manufacturer's capacity (i.e. scenarios #8: #13).

Figure (3) illustrates the effects of demand changes on profit. The expected profit increases, as the demand increases, as long as, the demand of the retailer in all periods is less than or equal to the capacity of the manufacturer. On the other hand, the profit decreases, as the demand increases, in case the demand of the retailer in all periods exceeds the manufacturers' capacity, due to the effect of the shortage cost on the profit. It can be concluded from the previous results that at the given values of supply chain parameters a zero-expiration cost is achieved for all scenarios under study. This is achieved through optimizing the quantity to be delivered from the manufacturers to the warehouses and retailers at each period. This optimization results in maximizing the revenues achieved through fulfilling customer demand at successive periods together with minimizing fixed cost at the manufacturers, material cost, production cost, shortage cost, inventory holding costs, transportation cost in addition to the expiration cost which represents crucial aspect of the supply chain sustainability.

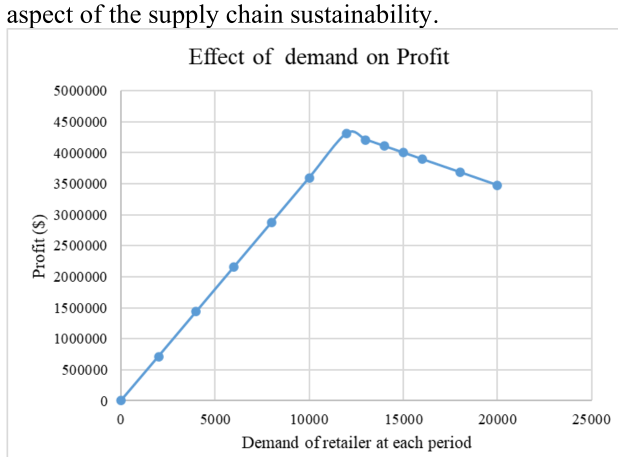

Figure 3: Effect of demand on profit

Table 2. Decision variables values on studying different demand patterns (In thousands)

Scenario #		Decision Variables					Profit ($)
		QMW_{mt}	QWR_{rt}	Shortage quantity	I_{at}	$Iexp_t$	
1	0	0	0	0	0	0	0
2	2	2	2	0	0	0	716
3	4	4	4	0	0	0	1,436
4	6	6	6	0	0	0	2,156
5	8	8	8	0	0	0	3,596
6	10	10	10	0	0	0	3,596
7	12	12	12	0	0	0	4,316
8	13	12	12	1	0	0	4,211
9	14	12	12	2	0	0	4,106
10	15	12	12	3	0	0	4,001
11	16	12	12	4	0	0	3,896
12	18	12	12	6	0	0	3,686
13	20	12	12	8	0	0	3,476

3.3 Studying the effect of warehouse capacity on profit

The effect of warehouse capacity on the profit is studied in this section. This set of experiments considers a supply chain of one manufacturer, one warehouse, and one retailer through six planning periods and a three periods shelf-life. The assumed retailers' demands in each of the six periods are ranging from 1,000 to 18,000 units per period. The experiment was carried out at warehouse capacities 100%, 50%, and 25% of the manufacturer capacity which is 12,000 units each period.

- The relation between the demand of the retailers and the profit at different warehouse capacities is shown in figure (4) from which it can be observed from that:
- In the case of (CW_t=100% of CM_{mt}): the profit increases as the demand at the retailer increases in each period. In point A, there will be an inverse relationship between the profit and the demand due to the shortage costs; as the retailers' demand is greater than the maximum capacity of the manufacturer.
- In the case of (CW_t =50% of CM_{mt}): the profit increases as the demand at the retailer increases in each period. In point B, there will be an inverse relationship between the profit and the demand, as the maximum capacity of the warehouse is reached. Retailers' demand will be only fulfilled with 6,000 and the rest will be considered as shortage quantities. Subsequently, there will be shortage costs that will affect the profit.
- In the case of (CW_t =25% of CM_{mt}): the profit increases as the demand at the retailer increases in each period until point C; after which there will be an inverse relationship between the profit and the demand as the maximum capacity of the warehouse is reached. Consequently, there will be shortage costs that will affect the profit.

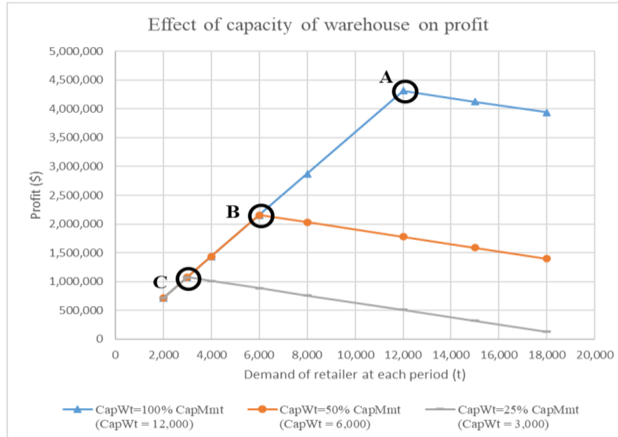

Figure 4: The effect of warehouse capacity on profit

4 CONCLUSION

Sustainable supply chain network design concept for perishable products is presented in this study. The model successfully maximized the profit together with considering sustainability through minimizing the environmental impact resulting from product expiration. Thus, the obtained profit is not affected by the expiration cost as the model minimizes expired quantities. The obtained results showed that as the demand at the retailers increase, the profit increases as long as the demand does not exceed the manufacturer's pre-specified capacity. On the other hand, when the retailers' demand exceeds the manufacturer capacity, the profit decreases due to the impact of shortage costs.

This work can be extended to consider multiple products, addressing uncertainties, and disruptions in facilities. Also, the model can consider the expiry of the products at the retailers. The model can also be extended to consider transportation mode in regard to other aspects such as vehicle routing and CO_2 emissions.

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