A Simulation Study of Sustainable Agri-Food Supply Chain

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Abstract

Agri-food supply chain (ASC) topic has attracted a lot of academics and practitioners in the last decade due to the globally increasing concern of public health and food safety and quality. Fresh produce has special characteristics, which includes perishability, uncertainty of supply and demand, and carbon dioxide equivalent emissions produced throughout the supply chain due to cooling, transportation, and disposal of fresh produce. These factors impose an additional complexity while managing this type of supply chains. This work concentrates on developing a simulation model of a two-echelon real life supply chain. The objective is to study the effect of changing order quantity under uncertain demand and lead time on a set of economic, social and environmental performance measures. Although, in a business environment economic dimension continues to be a top priority, simulation results showed that there is no contradiction between all three dimensions of sustainability. It minimized food wastage, offering higher quality fresh produce, lower emissions; while maintaining highest profit and an acceptable service level.

Keywords
Agri-food supply chain, inventory management, perishable good, simulation modelling

1. Introduction

Globalization, rapid demographic changes and increased concern of public health dictates the increasing demand for high quality agri-food products. According to (FAOSTAT 2017), the production of agri-food has increased globally by more than 20% between 2003 and 2014. Thus, resulting in a striking increase in trading activity during the same period, almost doubling the import transactions between countries. Agricultural produce plays an important role in the world economy and is the raw material for many industries. Among the agricultural produce, agri-food have got the minimum attention in the last decades (Shukla & Jharkharia 2013). The supply chain management of agri-food constitutes the processes from production to delivery of the fresh produce, i.e. from farmer to table. ASC is complex compared to ordinary supply chains due to the perishable nature of the produce, high uncertainty in demand and price, dependence on climate conditions, seasonality in production, meeting the international regulations related to food safety and environment, and maintaining the quality needs dictated by the customer.

A sustainable supply chain can be understood as a supply chain focusing on maintaining environmental, economic, and social stability for long-term sustainable growth; where, the environmental pillar in an ASC can be reflected in the amount of CO_{2eq} emissions produced due to the usage of fertilizers, the energy use in production, transportation, and inventory, add to that the food wastes generated throughout the supply chain due to perishable characteristics (Galal & El-Kilany 2016). However, maintaining high levels of profit while efficiently using the resources achieve the economic pillar of sustainability. Social pillar of sustainability is shown in how ASC affects the consumers and the workers that work within the process. Therefore, planning decisions have to be made while considering the three pillars of sustainability (Prima Dania et al. 2016).

Inventory management is a critical driver in managing ASC operations. Holding inventory levels lower than required will lead to economic losses due to unsatisfied demand. On the contrary, holding excessive inventory levels will increase the holding costs, leading to additional costs due to food losses.

Models for planning ASC needs development, as it mainly ignores the stochastic nature of the supply, demand and lead-time and assume that they are deterministic values (Ahumada & Villalobos 2009). Therefore, simulation is considered a vital tool due to its ability to imitate the real life system while considering stochastic nature of the variables. It further allows for a detailed analysis of system performance, thus giving insights to managerial decisions.

The objective of this work is to identify the order quantity that improves a set of performance measures. This is attained by developing a simulation model for a real ASC that helps in evaluating and analysing its performance. The remainder of this paper is divided as follows: Section 2 presents a literature review of the ASC and identifies the existing gaps in the literature; Section 3 addresses the problem definition and the performance measures. In section 4 the data collection of the case study is presented, while Section 5 delineates the simulation model. Results of the simulation model and proposed solutions are presented and discussed in Section 6. Finally, the paper is concluded in Section 7.

2. Literature Review

As mentioned in the previous section, sustainable supply chain consists of economic, environmental, and social aspects. These aspects are expected to reflect the dynamic environment of ASC that has high food safety expectation, food regulation, and environmental legislation.

The economic pillar is the most addressed pillar in the reviewed papers. It refers to the resource allocation in an appropriate way in order to increase the efficiency and profitability throughout the supply chain. Economic dimensions can be divided into macroeconomic and microeconomic factors. Macroeconomic factors focus on labour productivity, market concentration, and import dependency under economic sustainability to achieve several goals such as promoting the economic growth (Yakovelva et al. 2012). On the other hand, microeconomic factors address revenues, production and transportation costs, and overtime costs as economic indicators (Dwi et al. 2013). A number of papers have been published to cover the economic aspect of ASC. Examples of research conducted in this field are (Validi, S, Bhattacharya, A & Byrne 2014; Tajbakhsh & Hassini 2015; Bourlakis, M, Maglaras, G, Aktas, E, Gallear, D & Fotopoulos 2014).

Environmental aspects of inventory management have been mentioned in literature for non-perishable products. However, considering environmental impact of perishable inventory is rare. A number of papers have been published to cover the environmental footprint of inventory of perishable items. The environmental impact in all of the reviewed work is assessed in quantities of CO_2 only or total greenhouse gases (GHG) expressed as CO_{2eq} emitted throughout the supply chain except (Yakovelva et al. 2012; Bourlakis, M, Maglaras, G, Aktas, E, Gallear, D & Fotopoulos 2014), who reflected the environmental aspect in terms of energy consumption, water consumption, and waste disposal in the supply chain. The common source of emissions considered in all reviewed models is transportation; other sources such as cooling and recycling were also put into consideration. It is concluded that all models combine classical costs elements combined with the environmental impact of the supply chain.

In recent years, there is a great attention toward the theme of social responsibility from the agriculture and agri-food sector. However, compared to other pillars, these aspects are the most difficult ones to measure, since it is correlated to intangible aspects such as culture, social communities, lifestyle and politics (Prima Dania et al. 2016). The social focus in the food industries can be related to the raw material procurement from the local farmer, employees working conditions, and consumer health and safety. However, this paper reflected the social pillar in how it affects the society due to the valuable nature of food especially in a world with areas suffering from hunger, it is essential to reduce any food wastage to a minimum. Moreover, it measured the average remaining life of fresh produce when it is sold to the end customer; the higher the better, due to the perishable nature of fresh produce and importance of good quality products to the health of people. The social pillar was addressed by (Yakovelva et al. 2012) as employment volumes, quality of employment, and gender balance at workplace in U.K. food industries and by (Tajbakhsh & Hassini 2015) as average reputation factor, and average customer satisfaction factor in U.K. food industries. Furthermore, (Turi et al. 2014) established quantitative indicators to measure the social dimensions such as number of employees trained, management levels with specific environment responsibility, and number of improvement suggestions submitted by employees.

A considerable amount of research has been concerned with agri-food supply chains inventory management. Mathematical models for ASC planning are not as developed as the models for manufacturing supply chain. Models for ASC of fresh produce are even more lagging behind due to ASC special characteristics (Galal & El-Kilany 2016). Furthermore, current inventory models focus on consumer satisfaction and revenue maximization and consider environmental aspects and waste minimization as secondary objectives. Consequently, most of the inventory models would be in favour of holding more inventory in face of uncertain demand and lead time. Additionally, they factor demand and transportation lead time as either deterministic values or stochastic with almost no evidence of using real life values for these two factors. According to (Vieira 2004) discrete-event simulation is considered one of the most important tools that is widely used for the analysis and study of supply chains in general due to its ability to handle the challenges imposed by the stochastic nature of demand and other logistical factors such as transportation along with the ability of applying simulation models to real life problems.

From the reviewed literature, it is concluded that there is a scarcity in collectively considering all three pillars of sustainability in ASC. Therefore, it is suggested to consider in this study performance measures reflecting the economic, environmental and social aspects of sustainability. Moreover, there is a need to close the gap between research and implementation by considering real life case studies. Simulation models are suitable tool in this respect due to its capability in capturing details of system structure and operation as well as modelling uncertainty inherent in real life problems.

Therefore, the current research focuses on developing a simulation model for a global two-echelon ASC that can capture the effect of changing the order quantity on performance measures reflecting all three pillars of sustainability. In addition to applying that model to a real-life case study using real values for demand and lead time.

3. Problem Formulation

3.1 Problem Statement

Consider an ASC for a single product consisting of two echelons; producer (i) and distributer (j). The fresh produce considered has a maximum lifetime (M). Quantity (Q_i^t) is sent from the supplier to the producer (i) where processing operations take place including sizing, inspection, and packaging. After inspection fresh produce failing to meet the specifications are sent to the local market at a lower price or disposed of. The fresh produce, which passed the inspection, is stored in a temperature-controlled environment. The quantity transported (q_{ij}^t) is sent to the distributer according to a FIFO queuing policy on daily basis. After items reach the pack house, inspection takes place where the residual lifetime of the product is measured (τ). Items whose residual lifetime is less than τ are disposed of. Figure 1 shows the structure of the supply chain studied together with the information flow from the customer to the supplier and the product flow from the supplier to customer.

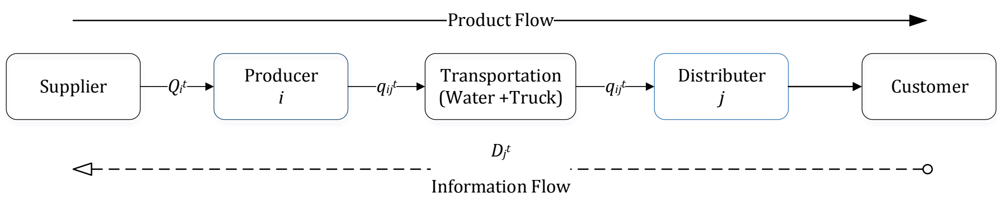

Figure 1. Product and information flow in supply Chain

The problem is to determine the order quantity (Q_i^t) that the producer (i) will order in every time period (t) to meet the uncertain demand of the distributer (D_j^t). The order quantity should be greater than demand (D_j^t) due to losses that occur throughout the supply chain starting from the producer till the distributer and uncertain transportation times. Therefore, the order quantity can be expressed as introduced by (Galal & El-Kilany 2016) in terms of the excess percentage γ ordered (Equation 3.1).

$$Q_i^t = D_j^t(1+\gamma) \tag{3.1}$$

The objective is to study the effect of changing the order quantity on the sustainability of the supply chain. To this end, a number of performance measures representing all three pillars of sustainability are devised as described in the following section.

3.3 Performance Measures

The performance measures considered in this work and used to evaluate the system, are the supply chain costs, profit, service level, carbon dioxide emissions, percentage of food wasted and average remaining life of fresh produce sent to customer. These measures reflect the three pillars of sustainability. Explicitly, supply chain cost and profit represent the economic pillar, while the environmental pillar is represented by carbon dioxide equivalent (CO_{2eq}) emissions. Social pillar is addressed through the service level, remaining life of fresh produce and waste amount. The service level and remaining life present the customer satisfaction in terms of meeting demand and quality level of fresh produce, respectively. Food waste may be considered as social aspect in view of the scarcity of food and hunger existing in areas around the globe. Food losses have a large impact on food security for poor people, on food quality and safety, on economic development, and the environment. Producing food that will not be consumed leads to unnecessary CO_2 emissions in addition to loss of economic value of produced food (Gustavsson et al. 2011).

Economic Pillar

The first economic performance measure is total supply chain cost per period (t), which can be divided into 3 elements according to supply chain stage; producer, transportation and distributer stages. Producers' costs are costs paid in the pack house at the producer's locations and cost of purchasing of raw materials. It is divided into 5 different types of costs. Firstly, purchasing cost of raw material (Cr), processing cost (Cp_i), and holding cost (h_i). Additionally, there is the cost of waste disposed (Cw_i) for fraction β failing to meet quality specifications and cost of local market (Cl) for fraction μ failing to meet quality requirements and sold to the local market. It consists of cost of purchasing raw material and a fraction from processing cost and also subtracted from it the revenue from selling it to local market. The total costs at the producer's stage is shown in Equation 3.2.

Transportation Costs (Equation 3.3), include both truck and water transportation costs (CT_{ij}). The truck costs include transporting container to the origin port and also transporting it from the destination port to the distributer. In addition to transportation between these two ports is by water.

Costs at the distributer (Equation 3.4) can be divided into five cost elements; processing cost (Cp_j), holding cost (h_j) of a quantity ($X^t_{j,r}$) with residual life (r) at the end of period (t) after satisfying demand and perishing outdated items, perished cost (C_z) of perished quantity (O^t_j) whose remaining life time is less than its minimum residual life (τ), where, $r \leq \tau$, disposal cost (Cw_j) for the fraction δ failing to meet quality specifications, and shortage cost (Cs) for shortage quantity (S^t_j) in period t. Finally, total cost (TC^t) is the sum of the three previously mentioned costs and is given by Equation 3.5.

$$TC^t_i = q^t_{ij}(Cr + Cp_i + h_i) + Q^t_i(\beta Cw_i + \mu Cl) \tag{3.2}$$

$$TC^t_{ij} = q^t_{ij} CT_{ij} \tag{3.3}$$

$$TC^t_j = q^t_{ij}\left(Cp_j + \delta Cw_j\right) + \sum_{r=\tau}^{M} X^t_{j,r}\left(h_j\right) + Cs\, S^t_j + O^t_j C_z \tag{3.4}$$

$$TC^t = TC^t_i + TC^t_{ij} + TC^t_j \tag{3.5}$$

The second economic performance measure is the total supply chain profit (P^t). It is expressed by Equation 3.6, and equals to total revenue generated from selling a quantity (q_j) of fresh produce with selling price (S_p) minus the total supply chain costs. It should be noted that sales in local market is subtracted from its cost; hence, there is no need to add revenue from selling to local market to the profit equation as it is already factored in total costs.

$$P^t = S_p\, q_j - TC^t \tag{3.6}$$

Environmental Pillar

The environmental pillar in this work is represented by the amount of CO_{2eq} emissions that are produced throughout the supply chain. Sources of emissions considered are: cooling at the producer, cooling at the distributor, and cooling during transportation as the fresh produce is kept in a controlled temperature environment; disposal of fresh produce that didn't meet specifications required or has perished; and truck and water transportation emissions. Figure 2 shows different sources of emissions in the considered two-echelon supply chain.

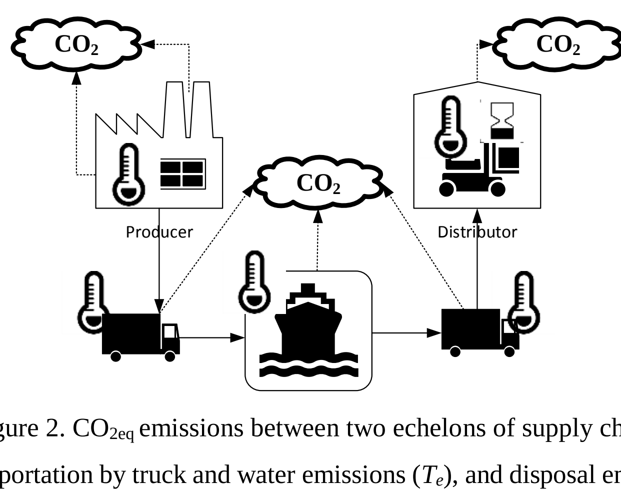

Figure 2. CO_{2eq} emissions between two echelons of supply chain

Cooling emissions (C_e), transportation by truck and water emissions (T_e), and disposal emissions (D_e) are expressed by Equations (3.7), (3.8), and (3.9); respectively, based on the CO_{2eq} emissions per unit product resulting from cooling (e_c), truck transportation (e_t), water transportation (e_w) and disposal (e_d).

$$C_e = \left(Q_i^t + q_{ij}^t + X_{j,r}^t\right)e_c \quad (3.7)$$

$$T_e = q_{ij}^t(e_t + e_w) \quad (3.8)$$

$$D_e = (\beta Q_i^t + O_j^t + \delta q_{ij}^t)\, e_d \quad (3.9)$$

Social Pillar

The third and last pillar is the social pillar, which is addressed in this work by three performance measures; namely, service level, percentage of food wasted, and average product remaining life. Service level is expressed by the fill rate given in Equation 3.10 and represents the proportion of the demand satisfied during time period (t). Shortage quantity $\left(S_j^t\right)$ is the maximum of zero and the difference between the retailer's demand and the sum of all quantities on hand at the distributor with a minimum residual life of τ or greater (Equation 3.11).

$$(D_j^t - S_j^t)/D_j^t \geq SL \quad \forall\, i, j \text{ and } t \quad (3.10)$$

$$S_j^t = \left(D_j^t - \sum_{r=\tau}^{M} X_{j,r}^t\right)^+ \quad \forall i, j \text{ and } t \quad (3.11)$$

The percentage food wasted is calculated by dividing the sum of all disposed and perished quantities across the supply chain by the actual quantity ordered (Q_i^t) during period (t), as shown in Equation 3.12.

$$\frac{Qi^t(\beta) + \delta qij^t + O_j^t}{Q_i^t} \times 100\% \quad (3.12)$$

Finally, the last performance measure considered is the average remaining life (Ar) of the fresh produce at the time it is sold to the customer. It is expressed in Equation 3.13 as the difference between the maximum lifetime of fresh produce (M) and the cycle time (C_t), which is the time that the fresh produce took from the beginning of the operations at the producer until it is sold to the customer.

$$Ar = M - C_t \quad (3.13)$$

4. Case Study

The type of fresh produce considered is oranges. The proposed analysis is applied using real life data from Company X operating a supply chain having its production facilities in Egypt while distribution is in Russia. The fresh produce transmitted through the supply chain is oranges. According to FAOSTAT 2014, Egypt is the 8th worldwide exporter of oranges with 3,135,931 tons. Company X runs its ASC as a push supply chain favouring to order excess quantities independent of demand. This results in several problems including food wastage, high carbon dioxide emissions, and high disposal, processing and transportation costs. However, the company ensures high service level using this push policy. Determining an adequate level of inventory is complicated. Holding low levels will decrease service level, while holding excessive inventory will increase holding costs, disposal and waste cost due to product failing to meet quality specification or perished in addition to increase in CO_2 emissions. In order to construct a simulation model for the case under study a set of operational and numerical data have been collected for Company X. These are described in the following subsections.

4.1 Operational Data

Fresh produce arrive daily at the producer stage, where it passes by different operations which includes primary inspection followed by washing, brushing, waxing and spraying. Afterwards, it goes to a sizing machine, which scans it using a micro scan to determine whether it conforms to specifications or not. If it does not pass the inspection, it is disposed of or sold to the local market at a lower price. Consequently, sizing operation takes place where oranges of same sizes are grouped together. Then, labelling and packaging of fresh produce in cartons are performed manually. Subsequently, these cartons are arranged into pallets where they are stored until the container (truck) arrives to the pack house at the end of the day and the transportation process begins. The facility operates 9 hours/day, 5 months/year starting from December ending in April. Multi-modal transportation is used in the current supply chain, where temperature controlled containers are loaded on trucks until the port. Sea freight to the distributor is then used. At the destination port, trucks are again used to transport the containers to the distributor's facility. When arriving at the distributor, pallets are stored in a temperature-controlled warehouse and their quality is checked on daily basis. Products having a remaining shelf life less than 10 days are disposed of.

4.2 Numerical Data

Company X adopts a push policy, producing a minimum daily output of 5 containers (120 tons) and a maximum daily output of 8 containers (192 tons) regardless of the anticipated demand. This results in ordering a quantity ranging from 168 tons to 270 tons (following a discrete uniform distribution). The order quantity is higher than the output due to the conservative policy Company X adopts. It orders 40% more than the required quantities in order to cope with uncertain demand and lead time, and to compensate for the quantity (4%) or sold to local market (34%) of the quantities at the two echelons of producer and distributer. Company X's farms in addition to outsourcing supply the daily order quantities, more specifically 70% from farms and 30% are outsourced.

The distributions of the demand, arrival rate and machine processing times are based on actual historical data collected at the facilities and fitted using Stat::Fit® software. Deterministic values representing the model parameters collected and/or calculated for the case study includes the following. Shortage cost is calculated as lost profit cost, which is the difference between the selling price and unit production cost. Holding cost at both distributor and producer is mainly electricity cost used for cooling. Purchasing cost is the cost of one ton of oranges (unprocessed). Disposal costs at the producer consists of cost of purchasing oranges from the supplier and a percentage of processing cost, while disposal and perished cost at distributer is cost generated due to getting rid of perished and unqualified fresh produce. Transportation cost is due to water and truck transportation. Cooling emissions are calculated by dividing the annual total CO_2 quantity generated by electricity generation in Egypt (85.7 Mton (The World Bank n.d.)) by the total power generated by all thermal power plants in Egypt in the same year of 2011 (129GWh (Ministry of Electricity and Energy n.d.)). This results in an emission factor of $6.648*10^{-4}$ ton of CO_2/kWh. Finally, water and road transportation emissions are adopted from (US Enviromental Protection Agency n.d.) and waste disposal emissions from (Scholz 2013). Table 1 summarizes the deterministic data for the case study.

Table 1. Deterministic values for model parameters

Parameter	Value	Parameter	Value	Parameter	Value
$\boldsymbol{Cr}$	4200 EGP/ton	$\boldsymbol{Cw_j}$	300 EGP/ton	$\boldsymbol{CT_{ij}}$	1870 EGP/ton
$\boldsymbol{Cp_i}$	2100 EGP/ton	$\boldsymbol{Cs}$	1506 EGP/ton	$\boldsymbol{S_p}$	13965 EGP/ton
$\boldsymbol{h_i}$	350 EGP/ton	$\boldsymbol{C_z}$	300 EGP/ton	$\boldsymbol{\tau}$	7 days
$\boldsymbol{\beta}$	4%	$\boldsymbol{h_j}$	150 EGP/ton	$\boldsymbol{Cp_j}$	2900 EGP/ton
$\boldsymbol{\mu}$	32%	$\boldsymbol{e_c}$	0.3273 kg of CO_2/hr/ton	$\boldsymbol{e_d}$	620 kg of CO_2/ton
$\boldsymbol{Cw_i}$	4850 EGP/ton	$\boldsymbol{e_T}$	92.275 kg of CO_2/ton	$\boldsymbol{M}$	6 weeks
$\boldsymbol{Cl}$	2850 EGP/ton	$\boldsymbol{e_w}$	154.32 kg of CO_2/ton	$\boldsymbol{\delta}$	0.1%
$\boldsymbol{F_c}$	10,000 LE/day				

5. Model Development

This section aims at describing the main elements used for developing the simulation model imitating the real life case study. According to (McLean & Shao 2001) a simulation system is composed of a simulator, control logic, user interface, and internal data management. The simulator used to build the simulation model in this paper is the ExtendSim™ Suite v9.2 simulation environment from ImagineThat, Inc. The control logic for the simulation model which manages the execution of the following modules: data input, resource allocation, and calendar and clock are all part of the ExtendSim™ capabilities. As for the user interface, simple 2D animation was used in developing the model for verification purposes only. Finally, all data required to run the model have been represented by different distributions (Section 4.2) in addition to ExtendSim™ built-in database for controlling the random seed values. The model's aim is to study the effect of changing order quantity on a set of performance measures which include, total cost, profit, percentage of food wastage, average remaining life, and service level. Values for these measures are reported daily and are averaged over considerably long simulation runs and for more than one replication.

5.1 Model Assumptions

Due to the complexity of the real life case of the ASC of Company X, a list of assumptions was generated as follows:

- Raw material and labour personnel is always available,
- No breakdowns for machines.
- 32% of raw material is sold to local market, 4% are disposed at producer and 0.1% disposed at distributer.
- The supply chain is between only two echelons supplier in Egypt and distributer in Russia.
- 1 shift of 9 hours per day with no breaks.

- The facility works 7 days per week, 140 days per year (5 seasons).
- No quantities are lost during transportation.
- No backorders are allowed and unsatisfied demand is lost.
- Warehouse capacity is unlimited.
- A container consists of 20 pallets holding 1600 telescopic cartons each of 15 kg.
- Demand follows the same distribution throughout the season.
- 1 USD is equivalent to 18 EGP.
- 1 USD is equivalent to 58 RUB (Russian Rubble).

5.2 Verification and Validation

Verification and validation of computer simulation models is conducted during the development of a simulation model with the ultimate goal of producing an accurate and credible model. Verification is concerned with ensuring that the model is working correctly and that the operational logic is correct (Sargent 2015). Additionally, animation has been used to study the routing of the products and ensuring that it proceeds as intended. Also, the different equation blocks; specifically, the ones for calculating the different costs, has also been checked to make sure that it is reporting the correct values. Validation is concerned with proving that the simulation replicates the real life system; in other words, building the right model. The output results of the base model are compared with the actual system results gathered from the past year records and discussed with the company's supply chain manager. Furthermore, the sensitivity of the outputs to the change in the inputs applied is tested. Finally, the model results are discussed with top management who confirmed the validity of the model.

5.3 Setup Parameters

The setup parameters of the simulation model include the run length, warm-up period, number of replications of each set of parameters and common random numbers used in all experiments. In order to ensure that an enough amount of data has been generated in the experiment, a run length of 5 seasons (equivalent to 750 days) is selected. Below this run length the performance measures didn't reach a steady state and the results are not accurate, while exceeding this value does almost affect no change in the values of the performance measures. To remove any initialization bias, the warm up period has been set to 138 days based on the observation. All the performance indicators mentioned earlier and also throughput rate and cycle time have been investigated and the one requiring the longest time to reach steady state has been used to determine the warm-up period. The number of replications was determined using the confidence interval method based on a confidence interval of 95 % with Robinson method from where 10 replications were considered adequate while considering costs, carbon dioxide emissions, service level, cycle time and throughput. This method involves measuring the error percentage at each number of replications, when the error percentage drops below 5% the number of replications is considered sufficient. Finally, common random numbers are used in all experiments to control the variability in the results and to ensure that the results reflect the effect of changing the order quantity (changing) while reducing the effect of the randomness in the model.

6. Experimentation, Results and Analysis

6.1 Base Model Results

The results from running the base model are summarized in Table 2. The results indicate that there are large amounts of fresh produce on hand and perished quantities (reflected in high values of average holding and perished cost per day) revealing the presence of inefficiencies in the current system. Nevertheless, Company X achieves a high service level of 98.8%, which can be seen in the small value of shortage cost. However, due to high total cost per day this results in a loss of 26,175 EGP/day. Base model results fresh produce reaching customers with an average residual life of 23 days and 10.5% of total quantity ordered is wasted. Before proceeding further with the analysis, the results obtained from the base model (Company X model) in terms of quantities sold, perished, transported… etc. were confirmed by the supply chain manager.

6.2 Proposed Scenario Results

Instead of the push supply chain currently applied by Company X, a pull approach in which production is dependent on demand is proposed. To study the effect of varying the order quantity on the different performance measures, the (γ) value is varied from 30% to 80%. The values of (γ) are relatively high as according to supply chain manager of Company X, at the producer stage 34% of the order quantity is sold to local market, which validates the high (γ) range.

However, all the following graphical presentation of the results will focus on (γ) values between 35% and 70%, as it was noticed that the variation in the values of the performance measures appears only in this range.

Table 2. Summary of Base Model Results

Costs Items	**EGP/day**	**Emissions**	**kg of CO_2**
Holding Cost	258,901.90	Cooling Emissions	15,716.18
Disposed and Perished Items Cost	40,099.49	Transportation Emissions	38,342.50
Transportation Cost	289,244.70	Disposal Emissions	8,229.97
Production and Purchasing Cost	1,366,071.60	**Total Emissions**	62,343.30
Shortage Cost	2,803.57	**Profit (LE/day)**	**-26,175.43**
Local Market Cost	155,218.80	**Average Remaining Life (days)**	**23.3**
Total Cost	**2,112,200.00**	**Service Level**	**98.8%**
		% Food wastage	**10.5%**

Food wastage is a critical performance measure addressing the social aspect of the ASC. The daily wasted quantity in tons is investigated at different stages throughout the supply chain. These include the quantities disposed at the distributer and producer and perished quantity having a remaining shelf life less than required. The breakdown of the quantities wasted is shown in Figure 3. It is observed that disposed daily quantity at both producer and distributer is almost constant for (γ) values between 35% and 55%. Starting from a γ value of 55% perished quantities start to appear causing this considerable increase in waste for higher(γ) values. Thus, exceeding a (γ) value of 55% resulted in perished quantity as the fresh produce accumulates in warehouses. Hence, it can be concluded from Figure 3, that for (γ) values below 55% minimized the food wastage compared with (γ) equal to 70%. However, the effect of reducing the (γ) values on service level has to be verified to ensure demand satisfaction.

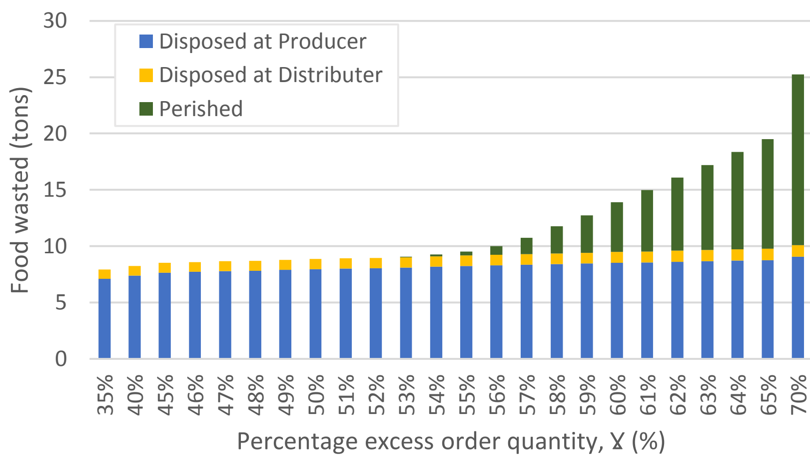

Figure 3. Effect of changing (**γ**) values on wasted daily quantity.

Service level performance is depicted in Figure 4, where the service level increases with the increase of the excess order quantity. A sharp increase is observed for (γ) values ranging from 35% to 60%. After 60%, no major changes occur and a service level of 98% and higher is achieved. It can be deduced that (γ) values below 47% should not be accepted as service level is below 90%. Service level at (γ) values equal to 55% was 95.5%, but at (γ) equals to 70% it reached 100%. Unfortunately, this 4.5% increase in service level maximized the quantities wasted as concluded from Figure 3. Further investigation is needed to identify the effect of reducing the service level on total costs and total profit, in order to find out whether this 4.5% sacrifice in service level will lead to loss or profit.

Figure 5 shows the relationship between total revenue and total cost with changing (γ) values. As (γ) value increases from 35% to 59%; the total revenue exceeds the total cost, therefore profit is achieved. However, exceeding 59% results in loss. As beyond 59% , increasing (γ) has no effect on the total revenues achieved as the daily demand of the consumer is satisfied and the excess quantities produced accumlates in the inventory increasing disposal and holding costs dramtically which is reflected in increasing total costs.

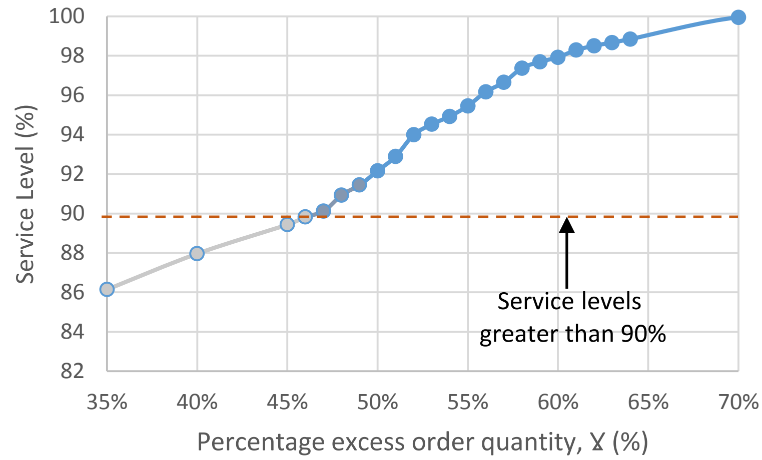

Figure 4. Effect of changing ($\boldsymbol{\gamma}$) values on service level

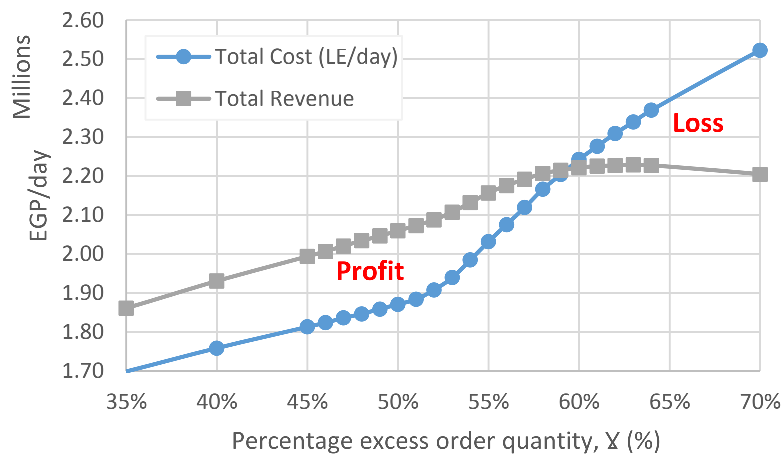

Figure 5. Relationship between total revenue and total cost per day

Figure 6 shows the change in profit at different (γ) values. The profit starts to increase from $(\gamma = 35\%)$ up to $(\gamma = 51\%)$ where it reaches a maximum profit value of 189,256 EGP/day. Beyond $(\gamma = 51\%)$, profit starts to decrease as total revenues start to stabilize and total costs start to increase. Therefore it can be concluded that increasing (γ) values above 51%, increases service level, but leads to loss. So there is no benefit of exceeding (γ) values if loss occurs.

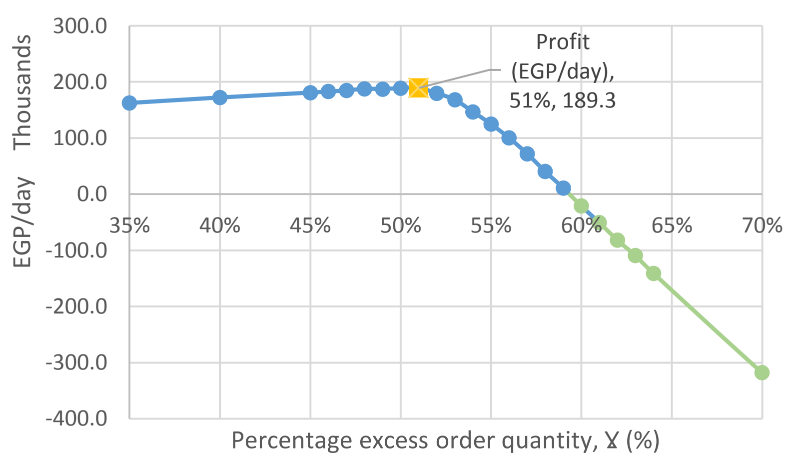

Figure 6. Effect of changing excess percentage ($\boldsymbol{\gamma}$) on daily profit

Finally, the effect of changing (γ) value on the emissions and the average remaining life of items sent to end customer are presented in Figure 7. As (γ) values increase from 35% to 51%, emissions increase at a constant rate due to transportation, cooling and disposal emissions. However, a sharp increase in emissions for (γ) values beyond 51% is observed due to higher cooling emissions and disposal emissions due to higher inventory levels. On the other hand, the average remaining life is almost constant for (γ) values between 30% and 51%. However, beyond 51%, the cycle time of fresh produce increases, resulting in decreasing the average remaining life up to 22 days for a γ value of 59%. Based on the previous results, it may be concluded that increasing (γ) values beyond 51%, decreases average remaining life and increases emissions considerably.

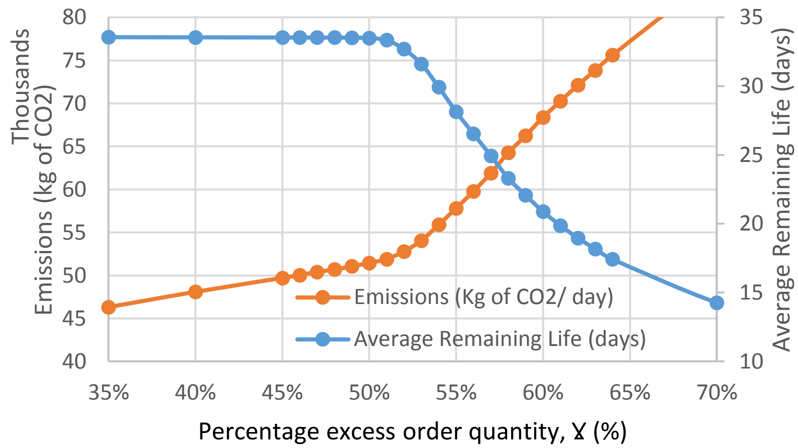

Figure 7. Effect of changing ($\boldsymbol{\gamma}$) values on CO_2 equivalent emissions and average remaining life of fresh produce

6.3 Discussion

Based on the previous analysis, it may be deduced that in order to achieve profit, the (γ) values should be less than 59%, as beyond this value loss occurs. In order to minimize food wastage ordering an excess percentage greater than 55%, increases food wastage considerably due to the increase of perished quantity. Also, to achieve an adequate service level higher than 90%, the (γ) values should be greater than 47%. Additionally, increasing (γ) beyond 51%, results in decreasing the average remaining life and increasing emissions produced by a considerable amount. The effect of changing the excess order quantity on the selected performance indicators are summarized and presented graphically in Figure 8. Hence, it can be concluded that the acceptable (γ) values ranges from 47% to 51. From this range, the recommended (γ) value for Company X is 51%, since all performance indicators are almost constant increasing (γ) values from 47% to 51%. However, at 51% the profit and service level are at their highest values.

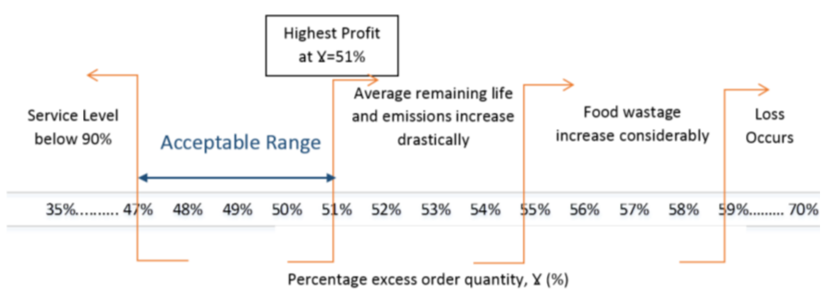

Figure 8. Effect of changing ($\boldsymbol{\gamma}$) values on performance measures

6.4 Comparison between Base Model Results and Proposed Scenarios

When comparing the base model and proposed solution performance measures results it can be concluded that the proposed solution profit is 8 times the base model's profit with a value of 1,833,480 EGP/day. Proposed solution also decreased the percentage of food wastage by 60% from 10.45% to 4.16%, total cost by 11%, and total emissions by 17%. On the other hand, it increased average remaining life time of the fresh produce sent to end customer increased from 23 to 33 days. This overall improvement of the performance indicators is achieved through a sacrifice of 6% in the service level. The base model service level is 98.8% while that of the proposed solution is 92.9%, which is still considered acceptable.

7. Conclusions

This work studied the management of inventory in a sustainable agri-food supply chain with stochastic demand and lead time. It also introduced a real-life case based on data from Company X, which was used to drive a discrete event simulation model and to study the effect of changing the order size on the selected performance measures addressing economic, environmental and social pillars of sustainability. Simulation was used as mathematical models sometimes fail to handle the complexity of real-life situations and due to stochastic nature of the data mentioned. Also due to its ability to replicate and analyse the performance of the real system, as well as suggesting alternatives to improve the overall system efficiency. The suggested inventory model represents a pull system, in which supply depends on demand; it is different from the currently push supply chain model adopted by Company X. The model also considers some of the important features of ASC: product limited life time, product quality, in addition to the stochastic nature of the demand and lead time. Three sources of carbon dioxide equivalent emissions were considered; transportation, cooling, and disposal emissions.

The model has been run for different order quantities and the selected performance measures have been investigated. Based on the results analysis, it was concluded that using a (γ) value of 51% could help in improving overall sustainability of the system when compared with current management practices. Thus, setting adequate order quantity has a considerable effect on the various supply chain performance measures. It was proved that varying order quantities by, as small as, 15% could double food wastage. Furthermore, it may also be concluded that there is no contradiction among the different pillars of sustainability as the present study succeeded in generating a solution which satisfies economic, environmental and social aspects.

Areas to be considered for future research include the study of effect of different transportation modes, whether water, truck, air or multimodal on the sustainability of the supply chain. Furthermore, the effect of different water transportation types whether container shipment or reefer shipment on performance may be investigated.

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