A Multi Objective Inventory Model for Short Food Supply Chains

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Abstract: Over the past 50 years, vertically integrated multinationals dominated global food markets by providing huge product diversity at low prices. Such systems are characterized by long supply chains capable of achieving high cost efficiencies resulting from the use of cheap raw materials, high chemical inputs, industrial shelf-life extension processes, economies of scale and mechanization. This dominant position on the market, however, has been achieved at a heavy cost on the global environment, generated by massive food wastage, and by a steady supply of fossil fuels. For such reasons, global supply chains are considered unsustainable and new food systems are being promoted in order to replace them on the long run. It is generally recognized that, in order to be sustainable and competitive a food system must be based on shortened/local supply chains thus reducing the inefficiencies of multiple marginalization. The current market situation, characterized an ever increasing request for higher quality standards, healthy eating, and a lower carbon footprint is an ideal environment for the growth of such systems. In this context, Short food supply chains (SFSCs), as defined in Reg.(EU) n.1305/13, have been recently proposed alternative food systems able to create a direct relationship between producers and consumers and to provide quality products and long-term sustainability. Due to their peculiarities, however, SFSCs require proper methodologies to respond to timely adapt market demand fluctuations and to manage perishable inventories. This paper, in particular, focuses on the logistics of SFSCs and proposes a methodology for optimal inventory management, with the aim to preserve the shelf-life (freshness, safety, nutritional properties etc..) of the products, as well as to ensure supply chain efficiency. A numerical application is proposed in order to prove the effectiveness of the mode.

Keywords: Supply Chain, Multi Objective, shelf-life

1.Introduction

Global food supply chains are the development model adopted by food systems over the past 50 years. The success factors of such systems are mainly related to the low food prices and the high cost efficiencies they provide to business and customers, as a result of industrial shelf-life extension processes economies of scale, cheap raw materials, chemical inputs and mechanization. Such benefits however are achieved at heavy costs on the global environment, generated by massive food wastage, and by a steady supply of fossil fuel. Despite the environmental destruction caused by the global food supply chain, it is failing in its basic goal to 'feed the world', as stated in the United Nations (UN) Food and Agriculture Report (2013), which reports 975 million people in the world today suffering from malnourishment and food insecurity, while a 1 billion individuals are overweight. Recent statistics report that in Europe around 88 million tonnes of food are wasted annually, with associated costs estimated at 143 billion euros and if nothing is done this amount could rise to over 120 million tonnes by 2020 (European Commission, 2016). Further it must be considered that by 2050 the amount of people living on earth is estimated to increase to 9,3 billion, and it will be will be impossible to feed 2 billion more mouths without promoting more efficient and sustainable supply chain models. These examples illustrate the systemic nature of wastage within the global food supply chain, showing that the global food system is struggling with its basic mission of delivering food from producers to consumers. Short food supply chain (SFSCs), as legally defined by (EU) Regulation N. 1305/13, are considered a sustainable model of agricultural productions able to achieve environmental, economic and social benefits, such as the mitigation of marginalization inefficiencies, the reduction of transportation costs, CO2 emissions, etc. The economic sustainability of this model is related to the possibility for farmers to receive a greater share of profit (Sage, 2003) by the elimination of the 'middleman'. Additionally, European customers tend to associate local products with higher quality standards (freshness, nutritional value), healthy eating, and a lower carbon footprint. For such reasons, SFSCs have spread across the European Union, assuming different configurations in order to respond to specific customers' needs. SFSCs thus can be classified into three types: individual direct sales, collective direct sales and partnerships. Direct sales are the simplest form of SFSC and involve a direct transaction between the farmer and the consumer. These transactions can take place on the farm, where the farmer has developed a shop, or outside, for example at farmers' markets. Producers may also cooperate to sell their products collectively to individuals or to consumer groups, on a farm or in local outlets. SFSC can also be found in the form of partnerships between producers and consumers, where partners are bound by a written agreement. Such partnerships result in community-supported agriculture, such as: AMAP (Association pour le Maintien d'une Agriculture Paysanne) in France, GAS (Gruppi di Acquisto Solidale) in Italy, SoLaWi (Solarische Landwirtschaft) in Germany. SFSC can also be classified in in two broad categories: traditional and neo-traditional. Traditional SFSCs tend to be farm-based, in rural areas, and are more likely to take the form of on-farm sales through farm shops, roadside sales and 'pick-yourown' systems, or sales at producer markets. They are usually operated by farming families and often use traditional and artisan methods. Neo-traditional SFSCs are frequently found in the form of collaborative networks of producers, consumers and institutions, sustaining traditional farming practices through new models and social innovation. Examples include: delivery schemes, urban-located farm shops, collectively owned farming systems usually located either in the city or on the urban fringe. They can be seen as local food movements that are often driven and supported primarily by urban residents.

This research is focused on direct sales forms of SFSCs taking place on farmers' markets, outside stores, urban-located farm shops or similar. Across the EU, a growing number of consumers choose to buy food products on local farmers' markets, directly at the farm, through basket/box delivery systems or other community-supported agriculture schemes. The choice of such forms of supply chain by the customers is related to the idea that SFSCs generally deliver higher quality products compared to traditional long chains. The customers are consequently willing to pay more for such products, thus allowing producers to add a price premium (Pearson et al., 2011). Finally SFSCs provide small growers with an opportunity to diversify and add value to their produce that would not usually be marketed otherwise (Alonso, 2011). In order to achieve these objectives, however, the quality of products must be preserved from the production site to the final customer, therefore the management of such supply chains must be properly approached by suitable methodologies. SFSCs business models, as stated before, rely fundamentally on the elimination of the typical intermediaries of the supply chain such as distributors/packagers etc.. These activities however have a significant role in preserving the freshness, quality and safety of the products, therefore, effective logistics methodologies must be established in order to deliver the products, in the right quantity, in the right condition, and at the right cost (Aghazadeh, 2004). The accomplishment of these objectives is a critical element for the success of the partners in the supply chain (Brimer, 1995).

This paper proposes a mathematical model to determine an optimal inventory model to preserve both the quality (freshness, safety, nutritional properties etc..) of the products, as well as to ensure supply chain efficiency. There are this context two main scientific streams, one aims at determining an economic evaluation of the quality loss of perishables through the supply chain, in order to provide an integrated formulation of a lot-sizing policy, while the other focuses on the establishment of valid indicators and mathematical models for measuring the quality decay over keeping separated the two objectives. The first approach has resulted in the body of literature known as "EOQ model for perishable products" which is not a recent topic as the first formulations are dated back in the '60s (see for example Ghare and Schrader, 1963), although it is still object of investigation for recent researchers and a recent review can be foun in Li et al, 2010. The other approach is actually more recent since the phenomena which influence the deterioration rate of perishable products are quite complex and their investigation has traditionally interested chemical and biological scientists, but only recently the application in industrial logistic are being investigated. In this case the quality objective is kept separated from the economical objective, and specific indicators are proposed for measuring the loss of quality over time. In particular, recently, the use of shelf-life models is consolidating in logistics and supply chain management, thanks to the studies conducted by some recent researchers (see for example Taoukis et al, 1997). The interest towards such approach has also risen as a consequence of the technological advances in ICT technologies applied to logistics. The use of electronic devices such as RFID and smart tags, has in fact allowed the real time continuous monitoring of the quality of goods throughout the entire supply chain, thus providing more reliable information about the quality of products delivered (Bertolini et al 2013, Mainetti et al, 2016). The management of Short shelf-life goods is still one of the biggest challenges in supply chain planning, with possible application in many important sectors from agro-industrial to medical, pharmaceutical, etc.

The methodology proposed, in particular, aims at the determination of the optimal inventory management policy (i.e. stock levels) for a SFSC consisting of two warehouses one located close to the producer and the other located in the farmer's market or urban store. Such supply chain is represented as a two-echelon serial system, approached in a bi-objective formulation considering both cost and quality parameters. The model proposed falls in the theoretical framework of optimal inventory management policies for multi-echelon systems and, particularly, refers to the concept of echelon stock, first introduced by Clark and Scarf (1960). In particular, the solution method proposed takes into account the integer-ratio policy proposed by Taha and Skeith (1970), whose optimality for two-echelon systems was proved by Crowston et al. (1973) and Williams (1982). This policy is based on the consideration that an optimal set of lot sizes exists such that the lot size at each facility is a positive integer multiple of the lot size at its successor facility. The solution of this problem is not trivial even in the case of deterministic demand because of the complex interactions between echelons. Additionally, in the multi-objective formulation proposed, the shelf-life parameter is considered as a numerical indicator of the quality of the product referred mainly to its freshness. Several researchers have investigated the reduction of the shelf-life of perishable products in time, considering different storage conditions, and, mainly the effect of temperature. Study of the different deterioration mechanisms that occur in food systems have led to meaningful and objectively measurable ways of evaluating food quality and determining shelf life (Sciortino et al. 2016, La Scalia et al, 2017). In particular, in this research we refer to the Arrhenius model which is one of the most prevalent and widely used model to describe food quality loss reactions in time at different temperatures.

The proposed methodology, hence, allows to evaluate the effects of different Inventory management policies on the cost of the supply chain and on the quality of the products, in order to help the decision maker in evaluating the trade-off between the two objectives. The decision maker can thus determine the best compromise solution once a preference scheme is introduced (La Scalia et al. 2015). Finally, in order to demonstrate the effectiveness of the methodology developed, a numerical application has been proposed. The numerical application aims at determining the set of non-dominated solutions, also known as Pareto-optimal set or efficient solution set, which contains solutions (vectors) where none of the components can be improved without deterioration to the other component in the objective space. Among these solutions, the decision maker can identify the management policy which achieves the best compromise between the quality of delivered products and the cost of Inventory

2. Proposed Model

A SFSC can be modelized as a serial system consisting of two warehouses. The first warehouse (W1) is generally located close to the market and its function is related product sale, while the second warehouse (W2) is located close to the harvesting point, and its function is to store the products harvested until they are transported to the second warehouse. Both warehouses can be equipped with a cold room or a refrigerated area. Despite of its simplicity, the management of this supply chain is generally complicated by the lack of advanced packaging systems and quality preserving processes generally employed to reduce the effects of perishability of products in long supply chains. This issue is extremely relevant since SMFS are intended to deliver fresh un-processed products with a premium quality. The managerial challenge, hence, is to ensure a superior product quality, by employing an inventory management policy which allows to achieve a proper compromise between costs and product quality. The system described above can be represented as a simple two-echelon serial supply chain, as depicted in the following Figure 1, where the only possibility of managing the product flow is to assign appropriate Inventory levels to the warehouses.

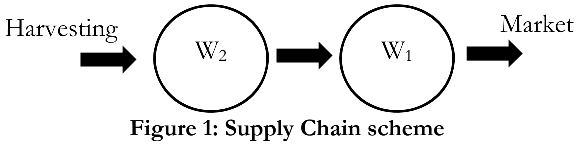

Figure 1: Supply Chain scheme

The overall Inventory Management Cost for the supply chain is related to the quantities (Inventory levels) Q_1 and Q_2 held respectively in warehouse 1 and warehouse 2. In particular, at each echelon, such cost can be expressed as the sum of an order cost, a purchase cost and an inventory holding cost. Coherently with traditional deterministic inventory cost models, the order cost is assumed to be a constant value per order, independent of the quantity on hand or on order, which includes the administrative costs associated with inventory review and order preparation. The inventory holding cost is a function of a unit holding cost (h_i) and of the inventory on hand. In addition, without loss of generality, the order quantity at the upper echelon, Q_2 is assumed to be multiple of the lower echelon order quantity, Q_1. The ratio $k = Q_2 / Q_1$; with $k > 1$ is therefore an integer value. In the model proposed the demand is considered known and deterministic, and the following assumptions are made:

- The lower echelon always replenishes its supply from the upper echelon.
- External customer demand always occurs at the lower echelon.
- The external demand rate is deterministic and constant with a value of d units per year.
- Backorders and lost sales are not allowed.
- Transportation lead time is does not affect the performance of the supply chain.

Also the following notation is employed:

- h_1 , h_2 : unit holding cost for warehouse 1 and 2;
- Q_2 , Q_1 : Order quantities for warehouse 1 and 2;
- d: market demand

In the decentralized approach each warehouse is considered independently, and the optimum order quantity is calculated for the first warehouse, then for the second warehouse it is assumed to be multiple of Q_1

$$C_1=h_1\frac{Q_1}{2}+A_1\frac{d}{Q_1} \tag{1}$$

$$Q_1=\sqrt{\frac{2A_1d}{h_1}} \tag{2}$$

$$C_1=\sqrt{2A_1dh_1} \tag{3}$$

$$Q_2=k_1Q_1 \tag{4}$$

where k is a positive integer.

$$C_2=h_2\frac{(k-1)Q_1}{2}+A_2\frac{d}{kQ_1} \tag{5}$$

The optimum value of k thus obtained is:

$$k^{*}=\frac{1}{Q_1}\sqrt{\frac{2A_2d}{h_2}} \tag{6}$$

If k* < 1 it is optimal to choose k = 1. If k* > 1. Let k´ be the largest integer less or equal to k*, i.e., k´ < k* < k´ + 1, it is optimal to choose k = k´ if k*/k´ □ (k´ + 1)/k*, otherwise k = k´+ 1.

The resulting overall cost of the inventory management policy is:

$$C=(h_1+(k-1)h_2)\frac{Q_1}{2}+\left(A_1+\frac{A_2}{k}\right)\frac{d}{Q_1} \tag{7}$$

Alternatively, the centralized approach, consists employing the echelon holding costs $e_1 = h_1 - h_2$, and $e_2 = h_2$, and in taking into account both the W_1 and W_2 costs in the optimization

$$C_2^e=e_2\frac{kQ_1}{2}+A_2\frac{d}{kQ_1} \tag{8}$$

$$C=C_1^e+C_2^e=(e_1+ke_2)\frac{Q_1}{2}+\left(A_1+\frac{A_2}{k}\right)\frac{d}{Q_1} \tag{9}$$

$$Q_1=\sqrt{\frac{2\left(A_1+\frac{A_2}{k}\right)d}{e_1+ke_2}} \tag{10}$$

$$\mathrm{C}(k)=\sqrt{2\left(A_1+\frac{A_2}{k}\right)d(e_1+ke_2)} \tag{11}$$

$$C^2(k)=2d\left(A_1e_1+A_2e_2+A_1e_2k+\frac{A_2e_1}{k}\right) \tag{12}$$

$$k^{*}=\sqrt{\frac{A_2e_1}{A_1e_2}} \tag{13}$$

If $k^* < 1$ it is optimal to choose k = 1. If $k^* > 1$. Let k´ be the largest integer less or equal to k^*, i.e., $k´ \leq k^* < k´ + 1$, it is optimal to choose k = k´ if $k^*/k´ \leq (k´ + 1)/k^*$, otherwise k = k´+ 1.

Additionally, as stated before, SFSC must be able to deliver premium quality products, therefore reducing the effects of perishability must be considered an additional objective. The loss of quality of a perishable product is generally evaluated by measuring the decay of the attributes which define its sensorial profile and the microbiological contamination level. Generally speaking the loss of quality can be evaluated by means of a measurable parameter related to the reaction that determines the quality loss. Being q such parameter, the variation of q with time can be expressed as:

$$(\pm)\frac{dq}{dt}=kq^{n} \tag{14}$$

Where k is the speed and n is the reaction order of the phenomenon controlling the deterioration of the food. For example n=0 represents a linear decay and n=1 represents an exponential loss of quality. On the basis of these considerations it is possible to develop e kinetic-mathematical model describing the evolution of the quality index as a function of time, when the product us exposed to variable temperatures:

$$k=k_0e^{\left(-\frac{E_a}{RT}\right)} \tag{15}$$

Where k_0 is a constant, E_a is the activation energy of the reaction that controls quality loss, R the universal gas constant (8.31 J/ mol °K) and T is the temperature (in Kelvin). The following equation, known as Arrhenius equation, describes the dependence of the rate constant k of chemical reactions on the temperature T (in Kelvin) and activation energy.

$$\log k_2/k_1=-E_a/\mathrm{R}(1/T_2-1/T_1) \tag{16}$$

In addition, the Q_{10} temperature coefficient is a measure of the rate of change of a biological or chemical system as a consequence of increasing the temperature by 10 °C. This parameter is adopted as the indicator to evaluate the quality change during storage and transportation, describing the relationship between temperature and reaction rate. Q_{10} is an unitless quantity, as it is the factor by which a rate changes, and is a useful way to express the temperature dependence of a process. The Q_{10} is calculated as:

$$Q_{10}=k(T+10)/k(T) \tag{17}$$

These typical Q_{10} values allow us to construct a table showing the effect of different temperatures on the rates of respiration or deterioration and relative shelf life of a typical perishable commodity

The Q_{10} can be calculated by dividing the reaction rate at a higher temperature by the rate at a 10 °C lower temperature, i.e.:

$$Q_{10}=\mathrm{R}_2/\mathrm{R}_1 \tag{18}$$

The temperature ratio is useful because it allows us to calculate the respiration rates at one temperature from a known rate at another temperature by means of the following equation:

$$Q_{\Delta T}=\frac{k_{(t+\Delta T)}}{Q_t}=Q_{10}^{\Delta T/10} \tag{19}$$

On the basis of the Arrhenius equation and knowing the Q_{10} values, it is possible to predict the shelf-life variation corresponding to a ΔT of 10 °K, by means of the following equation:

$$Q_{10}=\frac{\text{Shelf life at } T\ {}^{\circ}C}{\text{Shelf life at}(T+10)\ {}^{\circ}C}=\frac{\theta_{xT}}{\theta_{xT+10}} \tag{20}$$

The loss of quality corresponding to subsequent time intervals at different temperature is given by the following equation:

$$\frac{dq}{q^n} = -\sum (k_i \Delta t_i)_{T_i} \tag{21}$$

It is therefore possible to calculate the fraction of consumed shelf life (fc) and residual shelf-life (ft) as:

$$f_c = -\sum_{i=1}^{n} \left(\frac{\Delta t_i}{SL_i}\right)_{T_i} \tag{22}$$

$$f_t = 1 - f_c \tag{23}$$

The above equations ultimately allow to evaluate the residual shelf-life of a product at each step of the supply chain on the basis of its time/temperature history.

3.Case Study

In this section a numerical application is proposed which shows how above described methodology can be employed in the management of a SFSC. The case presented is referred to the peaches of the variety “elegant lady” grown in Sicily and appreciated as a premium quality product. For such product, we considered a shelf-life of approx. 22 days at the temperature of 0.5 °C, and an activation energy (Ea) of 0.9 kJ/mol, which is coherent with parameters reported in the literature (Testoni et al., 2007). The Q_{10} values and the corresponding shelf-life values of the product considered, at different temperatures are given in the following Tables 1 and 2.

Table 1: Q10 values at different temperatures

	T=10	T=20	T=30
Q10	2.5	2.5	2.0

Table 2: Shelf life (h) at different temperatures

T(°C)	Shelf life (h)
0	528
5	334
7	278
10	211
20	84
25	60
30	30

The following parameters have also been considered: d=50 kg/day, c=0,4 €/kg, A_1=100 €, h_1=0.5 €/kg/year; A_2=600 €, h_2=0.2 €/pc/year. Thus: $e_1 = h_1 - h_2 = 0.6$; $e_2 = h_2 = 0.2$. The order cost (A2)

The considered is referred to a farmer’s market sale in the city of Palermo of peaches harvested in the country. The route’s total distance is approx. 188 km with the truck moving mainly within the national road transport network (90%) and to a smaller extent (10%) within the urban areas. The truck considered for this transport service is a 10 year-old heavy duty vehicle (40 tonnes weight) travelling, on average, 130.000 km per year. The total operating cost that estimated for the specific truck and route, is approx. 600 €, out of which 15% € represents the fixed cost component and 85% the variable cost component. The Fixed costs considered include: cost of vehicle ownership, Cost of license ownership, Road tax, Cargo and vehicle insurance cost, Vehicle parking cost, Cost for the technical inspection of the vehicle, Cost for legal services, Cost for the insurance of road freight transport professionals. The Variable costs include: Fuel cost, Cost for tires, Maintenance cost, Repair cost, Driver wage Driver insurance, Taxes Fines

According to Eq. 13 the value of k can be calculated:

$$k^* = \sqrt{\frac{A_2 e_1}{A_1 e_2}} = 3 \tag{24}$$

Consequently, referring to Eq. 10 and Eq. 4, the optimum order quantities are: Q_1= 290 Q_2=3Q_1=870. Such values represent the quantities that minimize the total inventory cost for the serial 2-echelon supply chain. The corresponding annual inventory costs, considering that the selling season is approx. 15 weeks, are:

$$C_1^e = \frac{e_1 Q_1}{2} + \frac{A_1 d}{Q_1} = 302.12 \text{ €/year} \tag{25}$$

$$C_2^e = e_2 k \frac{Q_1}{2} + A_2 \frac{d}{kQ_1} = 604.24 \text{ €/year} \tag{26}$$

$$C_{TOT} = C_1^e + C_2^e = 906{,}36 \text{ €/year} \tag{27}$$

Finally, the average logistic lead time for the warehouses and for the entire supply chain is:

$$T_1 = \frac{Q_1}{2d} = \frac{290}{100} = 2.9 \text{ g} \tag{28}$$

$$T_2 = \frac{Q_2}{2d} = \frac{870}{100} = 8.7 \text{ g} \tag{29}$$

Total Logistic Leadtime=T_1+T_2=11.6

Once the average stocking periods have been calculated for the two warehouses, the consumed shelf-life can be calculated. In order to demonstrate the importance of a proper stock management policy in the context of SFSCs where due to the absence of packaging solutions, the quality of the product is easy to be depleted. For such purpose, in the proposed multi-objective approach, the total cost of inventory management, and the shelf-life consumed in the supply chain, have been calculated for different values of the inventory levels. Additionally, in order to investigate the influence of the model parameters on the optimality of the solution a sensitivity analysis has been carried out. In the supply chain considered, the first warehouse is equipped with a cold room at 5°C, while the second warehouse is at 20°C.

Table 3: results of the supply chain analysis

Q1	Q2	Ttot	Ctot	%SLtot
290	870	278,4	906,36	267%
200	600	192	1215	184%
150	450	144	1566	138%
100	300	96	2295	92%
50	150	48	4521	46%

The corresponding Pareto-Frontier is given in Fig. 1.

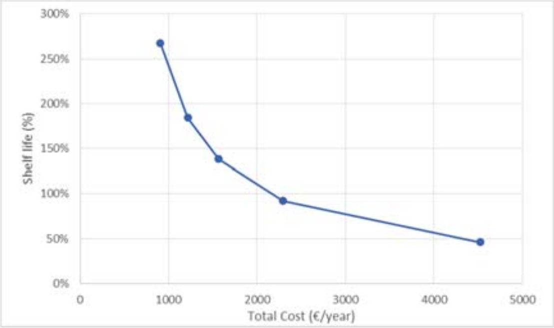

Figure 1: Pareto Frontier for the supply chain analysis

The results obtained show that inventory levels have a significant influence the performance of the entire supply chain, since the shelf life can vary between 46% and 291%, while the corresponding inventory costs range between 380€/year and 1230 €/year. The choice of the best compromise solution is therefore a critical issue for the supply chain management. The proposed approach thus allows to find the set of non-dominated solutions which constitute the pareto-frontier represented in figure 1. A decision maker can finally employ a Multicriteria decision making method (MCDM) in order to determine the best compromise solution among those solutions in the Pareto non-dominated set.

The sensitivity analysis has been performed taking into consideration the effects of a fluctuation in market demand and a variation of the temperature in the farmers market. In particular for a ±10% fluctuation in the market demand, the corresponding optimum values obtained are: Q_1(+10%)= 332; Q_2(+10%)=996; Q_1(-10%)= 300 Q_2(-10%)=900, and the corresponding consumed shelf-life variation and costs change is depicted in figure 2.

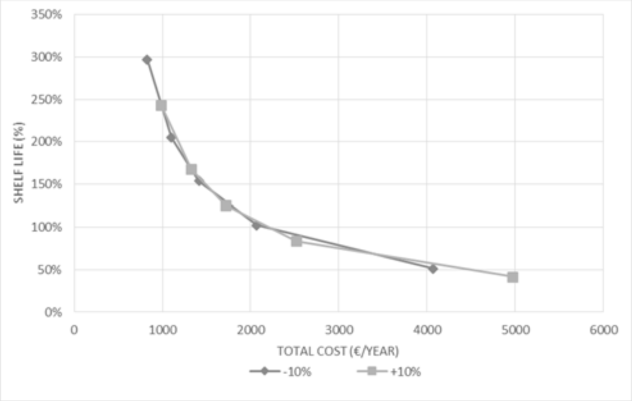

Figure 2: Pareto Frontier for the supply chain corresponding to ±10% demand fluctuations

Similarly, a sensitivity analysis was conducted for the effects of temperature variations, considering a ±2°C (±10%) variation in the farmer's market place temperature.

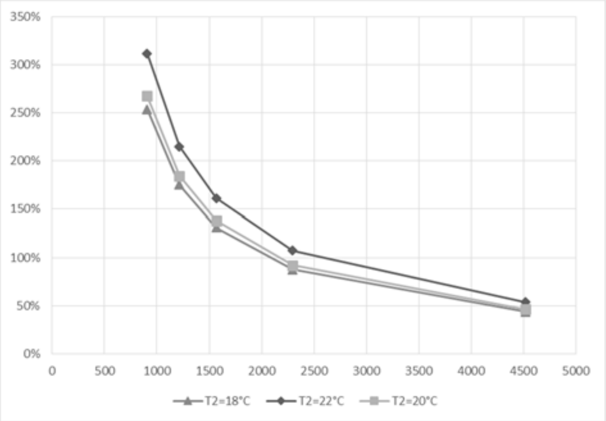

Figure 3: Pareto Frontier for the supply chain corresponding to a variation of ±2°C for T_2

The sensitivity analysis shows a good robustness of the solution towards a fluctuation in market demand, and a higher sensitivity towards variations in the temperature.

4. Conclusions

The research has taken into account the issues related to the management of SFSC, which, in order to be adequately profitable and sustainable, must be able to deliver superior quality products at affordable cost. The Inventory management policies are critically important in this context, since the absence of intermediaries typically hinders the possibility of adopting advanced packing solutions and quality preservation processes. Additionally, modern models of sustainable food systems, such as local SFSCs, must implement specifically optimized supply chain models in order to achieve the right compromise between cost efficiency and product quality. This problem has been approached in a general Multi Objective methodology, taking into account the minimization of the inventory management costs and the maximization of the quality of products.

The effectiveness of this approach has been demonstrated by means of a numerical application, which allowed to calculate the cost/quality tradeoff for different supply chain policies. A sensitivity analysis has also been conducted in order to explore the robustness of the compromise solutions. A limitation in the approach proposed is related to the simplifying assumptions, related for example to the deterministic demand model, which however are coherent with similar approaches in the literature. Further developments may also address the variability of demand and the effects of seasonality in production and demand.

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