Effective sourcing strategies for perishable product supply chains

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Abstract

This paper assesses whether an existing sourcing strategy can effectively supply products of appropriate quality with acceptable levels of product waste if applied to an international perishable product supply chain. We also analyse whether the effectiveness of this sourcing strategy can be improved by including costs for expected shelf life losses while generating order policies. The performance of sourcing strategies is examined in a prototype international strawberry supply chain. Appropriate order policies were determined using parameters both with and without costs for expected shelf life losses. Shelf life losses during transport and storage were predicted using microbiological growth models. The performance of the resulting policies was assessed using a hybrid discrete event chain simulation model that includes continuous quality decay. The studys findings reveal that the order policies obtained with standard cost parameters result in poor product quality and large amounts of product waste. Also, including costs for expected shelf life losses in sourcing strategies significantly reduces product waste and improves product quality, although transportation costs rise. The study shows that in perishable product supply chain design a trade-off should be made between transportation costs, shortage costs, inventory costs, product waste, and expected shelf life losses. By presenting a generically applicable methodology for perishable product supply chain design, we contribute to research and practice efforts

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to reduce food waste. Furthermore, product quality information is included in supply chain network design, a research area that is still in its infancy.

1. Problem description

In the past decades, food supply chains have become globalised and consumers are demanding year-round availability of fresh products in retail outlets. However, seasonal production means that producers must source products from multiple climate regions throughout the year. Sourcing from each of these regions requires a specifically designed supply chain to supply consumers with fresh products of high quality while minimising overall costs and product waste [1, 24]. Despite efforts to optimize perishable product supply chains, recent research indicates that food waste remains unacceptably high; it is estimated that 40-50 % of all root crops, fruits and vegetables are wasted [8]. Food waste can result in hunger, poverty, reduced income generation and reduced economic growth. Food waste is also a waste of production resources such as land, water, energy and other inputs, and affects the sustainability of food production systems [11].

Poor coordination among supply chain actors, along with inefficient retail practices have been identified as important causes of food waste [8]. Recent reports [15] have indicated a need for further assessments that quantify and qualify the scale and value of food waste and identify key constraints, risks and opportunities. Specific strategies that target reduction of food waste must also be developed [16]. The lack of effective food waste reduction strategies was confirmed by a recent literature review on perishable inventory management by Bakker et al. [4], which concluded that few literature contributions take dynamic product quality decay into account while sourcing products. The present paper adds to literature on this topic by assessing the effectiveness of existing sourcing strategies to perishable product supply chains, and proposing a methodology for waste reduction in international perishable product supply chains. The paper proposes the two following hypotheses: (i) existing sourcing strategies may be ineffective at providing appropriate performance in perishable product supply chains; and (ii) robust performance improvements can be achieved in perishable product sup-

ply chains by including costs for expected shelf life losses in logistics decision making.

The remainder of this paper is structured as follows. Section 2 provides an overview of the relevant literature areas, before section 3 gives an overview of the applied research methodology. Section 4 presents the case study that we have used to assess the research methodology, while section 5 offers some conclusions, discussion and recommendations for future research.

2. Position in literature

In this section, we present the findings of several recent literature reviews in areas relevant to this paper; these are supply chain design (section 2.1), sourcing strategies (section 2.2), and perishable inventory management (section 2.3). Section 2.4 discusses the papers contribution to the literature.

2.1. Supply chain design

In both the academic and business worlds, supply chain management and design have received a great deal of attention. There is a general understanding that the design of a supply chain should be based on the combination of the strategic objectives of the involved organizations and specific characteristics of its supply chain [19, 20]. Recent literature reviews [2, 13, 16] have recognised that specific characteristics of perishable product supply chains, such as deteriorating product quality and heterogeneous product supply, complicate the design and management of perishable product supply chains. Therefore, design of perishable product supply chains requires modelling efforts, with the aim to satisfy both logistics goals (such as cost and delivery service requirements) and ensure that products are delivered with the right quality at the right place and time [25]. The growth in consumer attention towards high-quality food products adds to the need for effective design of perishable product supply chains [1]. As a result, it is essential to develop effective supply chain design approaches for perishable products. Several model types can be used to support perishable product supply chain design that often use either simulation or optimization. An example of use of simulation for perishable product supply chain design was that of van der Vorst et al. [24], who introduced a simulation environment for assessing supply chain configurations in perishable product supply chains. An example of optimization models in perishable product supply chain design was given

by Zhang et al. [30], who minimized supply chain storage and transportation costs while penalizing and constraining product quality decay. For an extended review on supply chain management approaches see Rajurkar and Jain [16].

2.2. Sourcing strategy

An important consideration in supply chain design is the sourcing and purchasing decision; that is, where to obtain your materials, in what quantities and at what time. The sourcing strategy encompasses a variety of factors, including the number of suppliers that will be contracted, the type of relationship that will be pursued with suppliers, and the type and conditions of contracts that will be negotiated [26]. Extensive attention, both in practice and in research, has been devoted to topics related to product sourcing, such as intermodal transport, globalization, environmental impact, and multimodality [12]. Choosing the most suitable sourcing strategy depends on the organisations strategic objectives and characteristics, as well as its supply chain. Once a sourcing strategy has been chosen, the actual ordering (that is, the placement of purchase orders at previously arranged conditions) can take place. The quantity to be ordered is determined using an order policy, which typically attempts to balance performance objectives such as flexibility against shelf availability and cost. Therefore, the sourcing strategy and order policy may enhance product sourcing in perishable product supply chains that struggle with the sourcing of high-quality products. Despite the potential advantages of advanced sourcing strategies and order policies to perishable product supply chains, their use in this area has been very limited; See Shukla and Jharkharia [18] for an extended review.

2.3. Perishable inventory management

Several recent literature reviews on perishable inventory management have concluded that most literature contributions fail to incorporate realistic stochastic and shelf life property features in order policies [4, 18]. To better represent inventory control in practice, Bakker et al. [4] recommended a stronger focus on stochastic modelling of deteriorating inventory. A key element in the realistic control of perishable product supply chains is the use of real time product quality information. Despite this, the inclusion of deteriorating product quality in management of perishable supply chains still seems to be in its infancy [2]. One of the few examples is Blackburn and Scudder

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[6], who proposed using temperature-dependent loss of product value for perishable products to determine the economic order quantity in a fresh melon chain. The setting of the present paper, however, is very specific and overlooks variation in quality, and its application is limited to the economic order quantity. Therefore, there is still great potential for sourcing strategies that explicitly use product quality predictions while generating order policies.

2.4. Research contribution

As this literature overview shows, integrated product quality influences the design of perishable product supply chains. Despite the impact of quality decay on perishable product supply chains, literature on the use of product quality information in supply chain design, sourcing strategies, and inventory management remains limited. We aim to fill this gap in the literature by presenting a methodology for generating effective sourcing strategies for perishable product supply chains (see section 3). In section 3, we have assessed the effectiveness of this methodology using an illustrative case study.

3. Generating effective sourcing strategies

This section presents a methodology for generating effective sourcing strategies for perishable product supply. Section 3.1 provides a short introduction to the required supply chain analysis. A methodology for generating order policies that are sensitive to expected shelf life losses is presented in section 3.2. The performance of the generated policies is assessed in section 3.3 using a hybrid discretecontinuous event simulation model.

3.1. Supply chain analysis

As noted, the sourcing strategy depends on the specific supply chain characteristics. Therefore, to obtain an overview of these characteristics and obtain the data required for quantitative analysis, we first conduct a supply chain analysis. In this analysis all supply chain processes are described and analysed in detail to get a full understanding of their working, and of the dynamics and objectives of the system. After expert interviews, data gathering and data analysis, the sourcing strategy is determined, for which order policies will be generated. We will also define key performance indicators (KPIs) that reflect the performance of the respective processes or supply chain. These KPIs often include common performance indicators (such as transportation cost, storage cost, shortage costs) and case-specific

performance indicators (such as product waste, quality discounts) [3]. For an overview of supply chain analysis methods in perishable product supply chains, see van der Vorst and Beulens [23].

3.2. Order policy generation for perishable product supply chains

There are numerous sourcing strategies available in literature [26]. In this paper we adopt a commonly used dual-sourcing policy known as the dual index policy (DIP) [14]. DIP provides an easily implementable, robust, and often near-optimal solution, which may bring significant savings when the sourcing options differ substantially in lead times [27]. We apply this sourcing policy to a case in which perishable products are sourced from a single location using two alternative transport routes. The regular transport mode is relatively slow but inexpensive, whereas the expedited transport mode is faster but more expensive. Although the DIP is developed for a specific context (sourcing products from two different locations rather than sourcing from a single location using two different transport modes), the modelling assumptions are identical to the case situation as the two suppliers are assumed to differ only in lead time and shipping costs. Therefore, the DIP order policy is applicable.

The DIP order policy uses a regular and an expedited order-up-to position to control product availability at a reasonable cost. These order-up-to positions denote the number of products that will be ordered minus the number of products in stock and the number of products that will arrive within either the regular or the expedited order lead time. Appropriate DIP order policies are determined using demand data combined with cost parameters for product shortages, regular order cost, expedite order cost, and inventory holding cost. To make DIP sensitive to losses in product shelf life, which would improve product quality and reduce product waste, we introduce alternative cost parameters for processes that involve shelf life losses. In the case of DIP alternative, cost parameters are determined by adding costs for expected shelf life losses during expedited transport, regular transport, and inventory holding.

As shelf life reductions reduce the market value of perishable goods [28], shelf life losses during transport and storage periods can be related to losses in market value. Tsiros and Heilman [22] found that consumer willingness to pay for products with a low product quality risk (that is, products that are not commonly associated with food-borne illnesses) decreases linearly as the remaining product shelf life reduces. To the best of our knowledge, there are

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no sources that indicate how shelf life reductions at the distributorretailer interface affect product market value. Therefore, we have assumed a linear cost increase for losses of shelf life in this part of the supply chain as well. By multiplying the rate of shelf life lost (that is, the loss in shelf life relative to the total shelf life) by the value of the perishable product, we obtain costs for expected shelf life losses. Shelf life losses are determined using quality prediction models that are described in the following paragraph.

Quality decay of perishable products is often driven by mould or biochemical processes that depend on environmental conditions such as temperature and gas composition. This quality decay can be predicted for a variety of products using data on time and environmental conditions (for example, temperature and/or gas composition) in combination with microbiological growth models [5]. Many microbiological growth models, such as that proposed by Hertog et al. [9], follow a notation comparable to

$$\frac{dN}{dt} = R^M k^s N\left(\frac{N_{max} - N}{N_{max}}\right), \tag{1}$$

where $\frac{dN}{dt}$ denotes the change in infection level of a spoilage driver over time, R^M is the relative metabolic rate at the specific gas composition and temperature, k^s denotes the growth rate at the specific temperature, N denotes the current infection level, and N_{max} is the maximum achievable infection level (i.e., 1). For normal air, R^M can be set to 1, whereas lower values for R^M can be used for modified atmosphere storage (that is, storage with altered O_2 and CO_2 concentrations to reduce quality decay). The equations and parameters for determining appropriate values for R^M and k^s are specific for the perishable product at hand.

The infection growth rate at constant environmental conditions, approximated using Equation 1, follows a sigmoid curve that ultimately reaches maximum infection level N_{max}. The initial growth of this curve is approximately exponential, slows down as saturation begins, and finally reaches the stage at which all products are infected ($N_{max} = 1$). Since the maximum acceptable infection level at retail outlets is typically low (5 %, following Hertog et al. [9]), the exponential approximate in Equation 2 is a close approximation of the original sigmoid curve (Equation 1).

$$\frac{dN}{dt} = R^M k^s N. \tag{2}$$

A key advantage of Equation 2 is that the growth rate is independent of the infection level at the beginning of the period. Using this notion, the

infection level N_m after m subsequent periods (with $i = 1, \ldots, m$) can be approximated using

$$N_m = N_0 e^{\sum_{i=1}^{m} R_i^M k_i^s t_i},$$ (3)

where N_0 denotes the initial infection level, k_i^s and R_i^M denote the growth rate and the relative metabolic rate in period i, and t_i denotes the length of period i. The period t before a product with infection level N_0 reaches infection level N_c at constant environmental conditions is determined using Equation 4. This equation can therefore be used to approximate the remaining product shelf life.

$$t = \frac{\ln N_c - \ln N_0}{R^M k^s}.$$ (4)

Using the notions in Equations 3 and 4, the rate of shelf life that is lost during consecutive supply chain stages can be approximated based on the initial infection level N_0, the maximum acceptable infection level N_c, and the duration and environmental conditions of the separate stages to which the products are exposed.

3.3. Simulation modelling

We assess the effectiveness of the generated DIP in a supply chain context using a simulation model in combination with the process description generated in the supply chain analysis. We employ a hybrid discretecontinuous simulation tool, which includes both discrete features (that is, individual products moving through a supply chain) and continuous factors (that is, deteriorating product quality). This tool allows for in-depth analysis of supply chain performance, both for standard KPIs (such as inventory levels, transportation costs, shortages) and case-specific KPIs related to dynamic quality features (such as the remaining shelf life at the moment of delivery). For an elaborate overview of hybrid discretecontinuous simulation models, see Zeigler et al. [29].

4. Case study: International strawberry chain

This section presents a case study of a strawberry supply chain to assess the methodology presented in section 3. The structure of this chain is derived from data collected during several company interviews with an international fresh fruit distributor that operates in Belgium. We also obtained company data on a prototype supply chain network for the trade of fresh strawberries from Egypt.

This section is organised as follows. Section 4.1 describes the supply chain, before section 4.2 outlines the appropriate performance indicators for the supply chain. Section 4.3 describes the supply chain scenarios and the generated DIP. Section 4.4 describes the simulated system and chain simulation details and section 4.5 provides the results of the scenario analysis. Section 4.6 provides a sensitivity analysis on several parameters.

4.1. Supply chain details

We have considered the case of a Belgian distributor of fresh fruit. The names of the distributor and supplier in the case analysed in this work are not disclosed, for confidentiality reasons, and we instead use the more generic
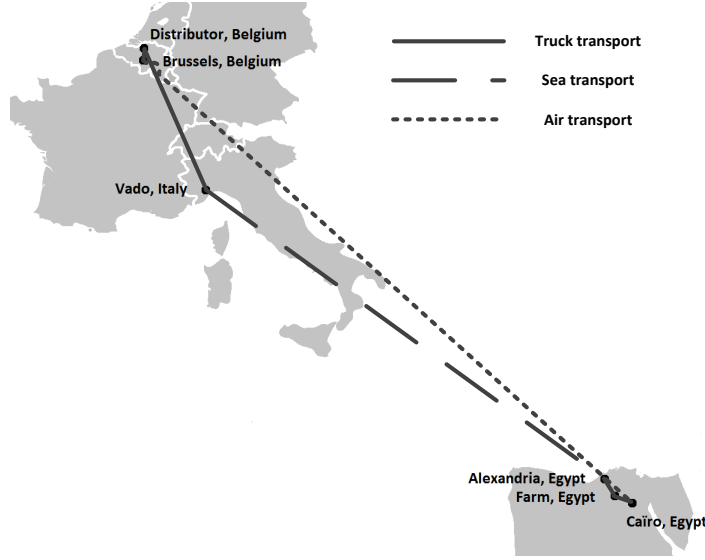
Figure 1: Schematic overview of a strawberry supply chain from Egypt to Belgium.

terms supplier, distributor, and retailer. The distributor imports strawberries from various production regions to provide its customers with fresh strawberries throughout the year. A key problem in international strawberry supply chains is product spoilage and customer complaints, which are mainly caused by a mould called Botrytis cinerea. In this study, the analysis is restricted to the sourcing of strawberries from Egypt, as the distributor does not source strawberries from other regions while strawberries from Egypt are available. We consider a supply chain network that includes a large Egyptian strawberry grower that ships strawberries to the Belgian distributor.

The distributor supplies strawberries to a number of retail outlets that face consumer demand and employs two transport modes to obtain Egyptian strawberries. Figure 1 provides a schematic depiction of the strawberry supply chain from Egypt to Belgium. The individual parts of the supply chain are described below. Table 1 summarizes the data on the environmental conditions throughout the supply chain. *Farm supply*
Strawberries are picked each day between 6.00 a.m. and noon at the strawberry farm. The Belgian distributor has a special arrangement with its supplier, which promises to deliver day-fresh strawberries; strawberries that are not sold on the same day are sold to regional customers. Based on informa-

	Duration (hours)	Temperature (°C)	σ (°C)
Supply chain conditions			
Ambient field conditions	1	15	2
Grower storage room	variable	1	0.25
Distributor storage room	variable	1	0.25
Truck transport to retail outlet	3	2	0.25
Retail outlet	variable	3	0.5
Expedite transport mode			
Truck transport from farm to airport	2	2	0.35
Customs operations	4	10	1.50
Loading, flight and unloading	6	1	0.25
Customs operations + delivery	3	2	0.35
Regular transport mode			
Truck transport from farm to port	4	2	0.35
Customs operations	4	10	1.50
Loading, shipping and unloading	48	1	0.25
Customs operations + delivery	24	2	0.35

Table 1: Consecutive steps during regular and expedite transport mode.

tion provided by the distributor, we assume that the supplier is always able to fulfil the demands of the distributor.

Each strawberry pallet remains on the field, at ambient temperature, for approximately one hour while it is being filled and is then transported to a refrigerated storage room. The average temperature in Cairo between December to February is between 10 and 20 °C, with an average temperature of approximately 15 °C [1]. Based on 5 sigma reasoning, the standard deviation of the ambient temperature is estimated to be 2 °C. Pallets remain in the farmers storage room until a customer order arrives and are then shipped according to the preferred transport route.

Distributor
The distributor orders a number of strawberry punnets every Monday using the regular transport mode, and may order an additional number by expe-

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[1] Based on data obtained from the World Meteorological Organization

dited transport from Monday to Saturday. The distributor places orders each day at noon, based on regular and expedited order-up-to positions. In the regular transport mode, the strawberries are transported by truck from the farmer to the port of Alexandria, Egypt. From Alexandria, the strawberries are shipped to Vado in Italy, where they are loaded on trucks that deliver them to the Belgian distributor. Strawberries that are transported using the expedited transport mode are transported by truck to the airport in Cairo. The strawberries are then flown to an airport in Brussels, from where they are transported to the Belgian distributor by truck. Table 1 summarises the duration and environmental conditions throughout the supply chain. Products that arrive at the distributor are stored in a refrigerated room until retail orders arrive, or until they are thrown away due to spoilage.

Retail demand

The distributor serves a number of retail outlets, each of which places a replenishment order by around midday every day except Sunday. Orders are served by the distributor on a first-come-first-serve basis. Before midday, shop assistants remove spoilt products. Ordered strawberries are delivered to the retailer by truck. The distributor promises that delivered strawberries have an acceptable product quality for at least three days after arrival at the retailer. The retailer distinguishes the three following cases at the moment strawberries are delivered: (i) the product fulfils all retailer quality specifications; (ii) the product is saleable but has less than the desired three days of remaining shelf life, for which claim costs must be paid by the distributor; and (iii) the product is no longer saleable, will be rejected by the retailer, and can be regarded as waste for the distributor. Once the strawberries arrive at the retailer, they are stored in the retail shelves until they are either sold or spoilt. Each of the retail outlets is opened from Monday to Saturday between 8 a.m. and 8 p.m.

4.2. Key performance indicators

Based on a number of performance indicators common in sourcing strategies and in collaboration with an industrial partner, six cost-related KPIs have been defined to assess the sourcing performance in this strawberry supply chain. These KPIs are (i) costs of regular transports (C_r); (ii) costs of expedited transports (C_e); (iii) distributor inventory holding costs (C_h); (iv) shortage costs for failing to deliver products (C_p); (v) costs for products that spoil at the distributor (C_w); and (vi) retailer claim costs for products delivered that do not fulfil the minimum required shelf life (C_i). An overview of

these cost drivers is given in Table 2. The first four KPIs are common cost

Symbol	Costs $€*punnet^{-1}$	Description
C_r	0.10	Regular transport costs
C_e	0.50	Expedite transport costs
C_h	0.05	Holding costs
C_p	0.50	Penalty costs
C_w	1.00	Cost price wasted strawberries
C_i	see Equation 5	Expected customer claim costs

Table 2: KPI Parameters.

drivers in inventory management decisions and are based on actual cost for transportation, product holding, and contractual agreements. In this case, we have assumed a constant cost per unit for transportation and inventory holding, without quantity discounts. KPIs (v) and (vi) relate to the product quality of strawberry punnets. The fifth KPI (C_w) represents the cost of products that spoil at the distributor. The retailer claim costs C_i represent the costs the distributor faces if strawberry punnets delivered to retailers have less than the agreed three days of shelf life ($t_{min} = 3$). The remaining shelf life t is determined using Equation 4, where N_0 represents the Botrytis cinerea infection level at the moment of delivery and k^s is based on the average storage temperature at the retailer. The resulting retailer claim costs C_i for one punnet are obtained using Equation 5.

$$C_i = max(0, C_w \frac{t_{min} - t}{t_{min}}) \tag{5}$$

Equation 5 implies that retailer claim costs increase linearly with a decrease of remaining shelf life t, with a maximum of C_w (that is, the retailer claim equals the product value) and a minimum of 0 (that is, no premium is paid for products whose shelf life exceeds the minimum requirement).

4.3. Generate appropriate policies

As described in section 3.2, the gathered supply chain details will be used to generate the appropriate DIP. The first step in this process is to predict shelf life losses during the transport and storage steps. We do so by modelling the growth of Botrytis cinerea using Equations 3 and 4. The

underlying microbiological growth models and parameter values are obtained from Hertog et al. [9]. Following Hertog et al. [9], we used 0.798 and 5 % for the initial and maximum acceptable Botrytis cinerea infection level. Shelf life losses during the transport and storage steps are predicted using the growth models presented in section 3.2 in combination with the supply chain data presented in Table 1. The appropriate DIP was obtained by including costs for these expected shelf life losses in the cost parameters used for generating order policies. Cost parameters generated using these steps are presented for several scenarios in Table 3.

These cost parameter scenarios differ in terms of the extent to which costs for shelf life losses are included. This allows us to assess the impact of different scenarios on the different KPIs, as this is not a direct relation (i.e. a higher costs for expected shelf life losses will make use of expedite transport more favourable, resulting in lower average inventory levels, which may result in higher product quality and reduced product waste). These scenarios include 0.00 (that is, the standard cost parameters), 0.25, 0.50, 0.75, and 1.00 times the cost of expected shelf life losses. The specific values were chosen since the resulting policies cover the complete spectrum from sourcing only by expedited transport in case of product shortages (0.00) to complete sourcing by expedited transport (1.00). The resulting cost parameters that are used to obtain DIP can be found in Table 3. It is computationally in-

Cost driver	Shortage cost ($€*unit^{-1}$)	Inventory ($€*unit^{-1}*day^{-1}$)	Expedite transport ($€*unit^{-1}$)	Regular transport ($€*unit^{-1}$)
DIP without decay costs	0.500	0.050	0.500	0.100
DIP + 0.25 * decay costs	0.500	0.078	0.523	0.198
DIP + 0.50 * decay costs	0.500	0.105	0.546	0.295
DIP + 0.75 * decay costs	0.500	0.133	0.568	0.393
DIP + 1.00 * decay costs	0.500	0.160	0.591	0.490

Table 3: Cost parameters used to determine dual-index policies.

feasible to obtain globally optimal DIP policies for the considered problem size. However, we obtained near-optimal DIPs for these cost parameters using a heuristic procedure proposed by Veeraraghavan and Scheller-Wolf [27]. These policies were obtained using a set of 50,000 demand observations that were generated following a Poisson distribution with the aggregated average demand of all 10 retail outlets included in the simulation: $\lambda = 6,000$ units per day. A Poisson distribution is widely adopted for modelling discrete

demand at retail outlets, see Jonsson and Mattsson [10]. This distribution is particularly appealing in this context because it models purchases as a memory-less stochastic process. These 50,000 demand observations are sufficient to ensure near-optimal policy outcomes. The resulting DIP in Table 4 reveal that including more cost for shelf life losses will lead to policies that are more sensitive to expected shelf life losses. The - indicates that products will never be ordered using that specific transportation mode, whereas the 0 in Table 4 indicates that products will only be ordered using that transport mode if there is a negative expedited inventory position. The latter may occur if current shortages are higher than the products that will be delivered within the expedited order lead time. The effect of ordering only once a week using regular transport or daily using expedited transport on the inventory level can be observed in Figure 2.

Order up to position	Expedite mode (days of demand)	Regular mode (days of demand)
DIP without decay costs	0	7.017
DIP + 0.25 * decay costs	1.036	4.034
DIP + 0.50 * decay costs	1.039	3.028
DIP + 0.75 * decay costs	1.039	2.018
DIP + 1.00 * decay costs	1.041	-

Table 4: Dual-index order-up-to positions.

4.4. Simulated system

To assess the effectiveness of the DIP presented in Table 4 with respect to performance indicators presented in section 4.2, we developed a hybrid discrete-continuous simulation tool. This model includes 10 retail outlets to simulate a realistic chain. Customer purchases at these retail outlets follow a Poisson distribution with a rate of $\lambda = 600$ units/day at each of the retail outlets; this corresponds to 0.150 tons of expected demand per shop, which is the average quantity supplied by the distributor in this case study. The expected demand is assumed to be constant throughout the week. We assumed that the customer demand rate parameter λ of the Poisson distribution is correctly estimated at each of the retail outlets, and that this information is used for inventory control purposes. Inventory control at the retail outlet is performed by employing a base stock policy targeting a service level of $\alpha =$
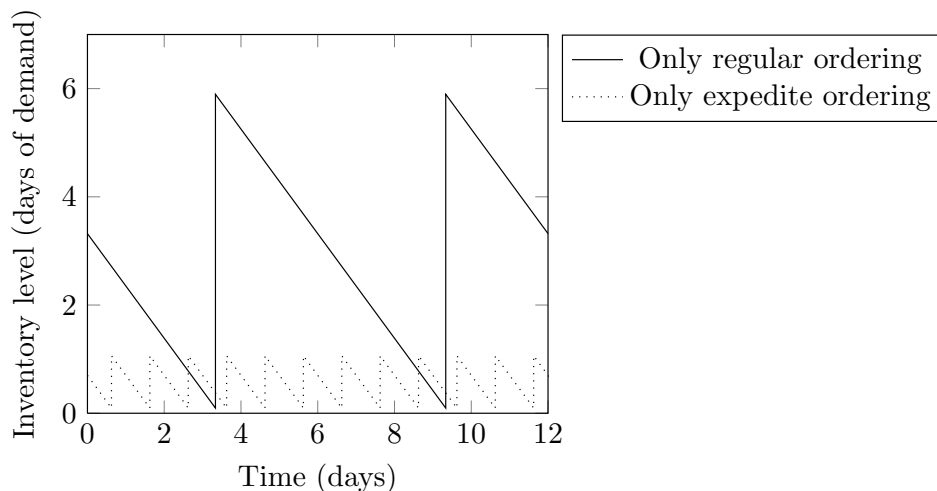
Figure 2: Sawtooth figure of inventory levels.

0.95. Use of base-stock policies is common in retail environments, where the service level most typically used is 95 % [21]. If there are shortages at a retailer, consumer demand is backordered until the next replenishment arrives, so as to comply with the backordering assumptions of the DIP. Due to the high target service level, differences between a situation with and without backordering are limited [7]. The exact time of each retail order is randomized (that is, noon ± 5 minutes, uniformly distributed) to simulate small discrepancies in the automatic ordering system clock and prevent systematic differences between product quality and quantity delivered to the different retail outlets.

We distinguished two consumer groups. Following Rijgersberg et al. [17], 40 % of consumers specifically select the freshest product at the retail shelf (last in, first out), whereas the remaining 60 % simply select the product that appears at the front of the retail shelf (first in, first out). This 40/60 distribution is close to the 42 and 58 % observed by Tsiros and Heilman [22]. The initial quality of strawberry punnets is randomly distributed with an average of 0.798 % and a standard deviation of 0.709 %, based on Hertog et al. [9]. Strawberry quality deteriorates continuously depending on the environmental conditions. The quality integration step is fixed to one hour, since smaller integration steps did not prove to be beneficial. We assumed that once a strawberry punnet enters a given environment, the strawberry is

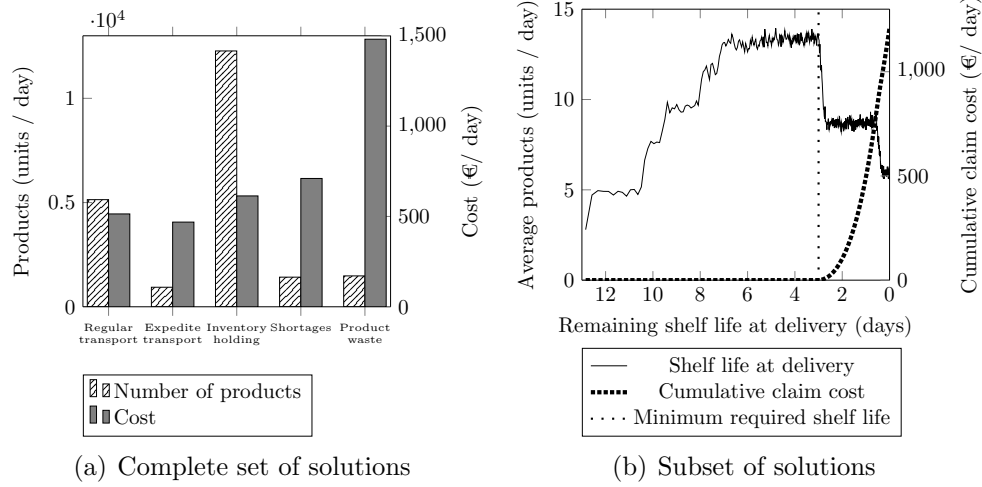(a) Complete set of solutions   (b) Subset of solutions

Figure 3: Performance of the standard scenario with respect to (a) transport, inventory, shortages and waste (b) retailer claim cost and shelf life of delivered products.

immediately at the environmental temperature.

The chain simulation is implemented using the Stochastic Simulation in Java (SSJ) library. For scenario assessment we used a simulation length of 264 days, which proved to be sufficient to obtain stable simulation outcomes. We excluded performance data gathered during the first 14 simulated days from the analysis to ensure a representative filling of the complete supply chain. To ensure comparable results for the different scenarios, random numbers were initialized with the same seed.

4.5. Scenario comparison

The performance of the standard scenario (that is, DIP obtained with normal cost parameters) with respect to the defined KPIs can be seen in Figure 3. The results clearly show that applying DIP with standard cost parameters would result in poor product quality and large amounts of waste. A significant number of products are ordered using expedited transport, despite an expedited order-up-to position of 0. This is caused by products that spoil at the distributor, which results in shortages at the distributor. The aggregated performance data of all five scenarios can be found in Figure 4. The figure shows that including costs for shelf life losses in the DIP has the following six consequences: (1) a reduction in regular transport costs, indicating that fewer strawberries are shipped using the regular transport mode; (2) an

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Figure 4: Performance analysis of dual-index policy.

increase in expedited transport costs, indicating that more strawberries are shipped using the expedited transport mode; (3) a reduction of inventory costs, indicating that the average stock levels are lower; (4) a reduction of shortage costs, indicating that the distributor is able to deliver more reliably; (5) a reduction in distributor waste, indicating that fewer strawberries spoil at the distributor; and (6) a reduction of retailer claim costs, indicating that the strawberries delivered to the retailer have a higher remaining shelf life. Figure 4 reveals that the sum of cost drivers traditionally used in the adopted order policy (that is, regular transport costs, expedited transport costs, inventory holding costs, and shortage costs) increases if costs for shelf life losses are included while determining the DIP. However, this cost increase is cancelled out by reductions in product waste and retailer claim costs, which reduces the overall cost.

4.6. Generalizability of findings

To assess whether the results presented in section 4.5 are generalizable, we generated two alternative sets of scenarios. The first set of scenarios considers a higher initial product quality by reducing both the initial infection level and variation in infection level by 50 % (that is, $N_0 = 0.399 \pm 0.3545$ %). In the second set of scenarios, the quality decay rate during transport and storage steps is reduced by applying modified atmosphere storage with O_2 and CO_2 concentrations of 2.5 and 15 %, respectively (following Zhang et al. [31]). This reduces the microbiological growth rate by approximately 40 %. The resulting DIPs are presented in Table 5 and their performance is assessed using the chain simulation tool. The aggregate performance data

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Table 5: Dual index policies used for robustness analysis.

Order-up-to positions

(days of demand)

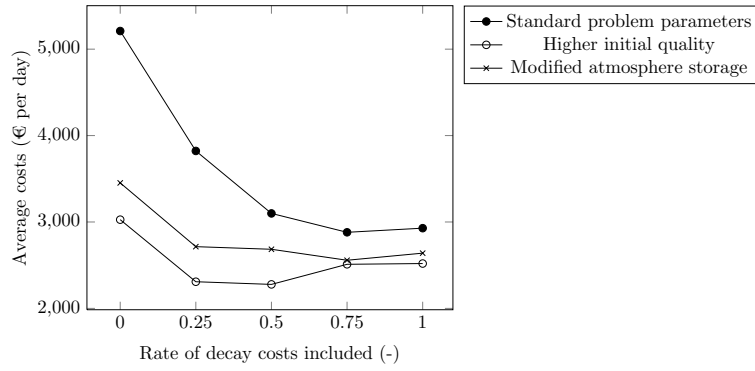| Decay included	Higher initial quality		Modified atmosphere storage	
	Expedite	Regular	Expedite	Regular
no decay	0	7.017		7.017
0.25 * decay	1.035	4.099	1.035	4.103
0.50 * decay	1.040	3.070	1.039	4.005
0.75 * decay	1.039	2.064	1.039	3.006
1.00 * decay	1.039	2.029	1.039	2.033

Figure 5: Performance analysis of DIPs obtained with alternative parameter settings.

presented in Figure 5 shows the effect of changes in initial quality, and modified atmosphere storage on overall costs. The results the figure also show that DIP derived with cost parameters that include costs for expected shelf life losses react effectively to changes in initial product quality, or quality decay rate. The combined results presented in Figure 5 show that the developed method is effective at identifying a trade-off between various cost drivers in perishable product supply chains.

The results presented in Figure 5 only include performance indicators related to logistics, waste and quality decay. The question of whether the benefits of obtaining products with a higher initial quality or use of modified atmosphere outweigh the cost of achieving higher product quality or implementing modified atmosphere storage should be investigated separately.

5. Conclusions and discussion

The results of the presented case study confirm the hypothesis that existing sourcing strategies are ineffective at providing an appropriate performance in international perishable product supply chains, and would actually result in large amounts of product waste and poor delivered product quality. Of course the exact impact depends upon the specific case characteristics. The case results also confirm the hypothesis that performance improvements can be achieved in perishable product supply chains by including costs for expected shelf life losses in logistics decision making. As a result, product waste and retailer claim costs were significantly reduced, which outweighed increases in transportation costs. Analysis of a number of key parameters (that is, the initial product quality, and the rate of quality decay) confirmed the robustness of the presented approach.

The presented methodology shows that decision makers in perishable product supply chains should achieve a trade-off between logistics cost drivers and performance indicators related to product quality. Furthermore, by presenting a method to analyse trade-offs between shelf life losses and logistics cost we provide a method to reduce food waste. The study therefore contributes to worldwide efforts to reduce food waste by presenting a generically applicable methodology to improve the effectiveness of sourcing strategies, thereby addressing one of the research gaps identified by Rajurkar and Jain [16].

Effective use of product quality information is also expected to aid decision makers with the delivery of products of the right quality at the right

place and time. This may lead to more frequent re-stocking and lower inventory levels, thereby changing the design of perishable supply chains; this is a research area that is still in its infancy [2, 25].

The presented methodology is expected to reduce food waste and, consequently, reduce environmental load. However, whether this reduction in environmental load will compensate for the increase in emissions related to expedited (air) transport is an interesting subject for further research. In this paper a linear value decrease of products with reduced shelf life is considered, both while determining DIP and while discounting products delivered to retailers with insufficient shelf life. In future research it would be interesting to assess what effect alternative price discount strategies would have on the effectiveness of the proposed strategy. It might also be interesting to investigate whether including costs for expected shelf life reductions while obtaining policies yields similar results if applied in supply chains with other perishable products or policies.

Acknowledgements

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