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Impact of product perishability on agri-food supply chains design

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ABSTRACT

Perishability of agri-food products impacts the economic, environmental, and social aspects of agri-food supply chains (AFSCs). Product perishability is, usually, considered in tactical and operational decisions, but not in strategic ones, such as the design of the AFSC. The contribution of this paper is that it investigates the impact of product perishability on an AFSC design. To do so, first, a novel mixed-integer linear programming model is proposed to design entire AFSCs with multiple-products, which considers capacity, planting, harvesting, transporting and perishability constraints for a multiple-period horizon. A set of scenarios is generated by varying products' shelf life and analysed. The results show that product perishability is relevant when designing AFSCs, especially for products with a short shelf life. The results show that an AFSC's economic performance improves when product perishability is considered. The model can also help in determining the investment needed extend products shelf life while remaining profitable. Other uses could include tactical planning for chains already in place.

1. Introduction

The agri-food sector is the largest manufacturing sector in Europe. It employs more than four million people and produces a revenue of more than one trillion euro [1]. Up to 88 million tons of food are wasted every year in Europe, which accounts for 20% of production [2]. Therefore, the economic and environmental sustainability of European countries is, to some extent, linked to the sustainability of agri-food supply chains (AFSC), which means that any improvement in the economic and environmental efficiency of AFSCs will positively impact Europeans' lives.

Bearing this objective in mind, researchers have proposed mathematical programming models (MPM) to solve agri-food tactical and operational problems in order to optimise AFSC efficiency [3–5]. However, this may not be enough to optimise AFSC efficiency because its configuration influences its performance [6] and limits the decision-making process.

To reduce the AFSC environmental impact, the importance of considering product perishability in AFSC design is highlighted [7–9]. Consumer product perishability perceptions impact the economic, environmental and social aspects of AFSC and waste generation [1]. Additionally, one of the main goals in distributing agri-food products is to guarantee product

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freshness [10], which is related to product perishability. Although some models consider perishability at the tactical and operational levels [11,12], very few design models contemplate this aspect.

This paper proposes an AFSC design MPM by integrating tactical decisions and considering products' shelf life. The model's contribution lies in the joint modelling of design, planting, cultivating, harvest, labouring, packing, inventory, transport, operation, waste and unmet demand decisions by considering the entire supply chain, multiple products, multiple-period horizon, and capacity, perishability and planting constraints.

This model combines strategical (selection and location of facilities to be opened, as well as their role) and tactical (planting, cultivating, harvest, labouring, packing, storage, operation and distribution of products) decisions by considering products' shelf life, which represents the real AFSC characteristics and improves AFSC performance in the long, mid and short terms [1].

To the authors' knowledge, no study, like this paper, in the literature compares optimal AFSC configuration with, or without, product perishability. Our model bridges this research gap by solving a set of scenarios for different shelf lives, which answers the following research question (RQ): Should product perishability be considered when modelling AFSC design?

The rest of the paper is structured as follows. Section 2 analyses previous MPMs to design AFSC and highlights this paper's main contributions. Section 3 describes the problem under study and Section 4 explains the proposed MPM. Section 5 presents the defined experimentation and the main results. Section 6 outlines the managerial insights of this proposal and identifies the main limitations of the paper. Finally, Section 7 draws conclusions and offers future research lines.

2. Related literature analysis and contributions of this study

This section reviews the most relevant MPMs to design AFSCs or generic supply chains (SC) for perishable products. This review does not intend to establish the current state of the art in this area (see [1]), but to analyse the characteristics that are relevant to this work. The last row in each table shows the characteristics of the proposed model, referred to herein as TP.

Table 1 shows the agri-food characteristics of the model. Although research interest in AFSC design has grown, it is still scarce. Most models are for mono-product AFSCs. However, more interest is shown today in multi-product models, as the literature of the last two years indicates.

Product perishability is modelled in AFSC designs by including a product deterioration rate during storage [13–16] or distribution [14–21], a quality decay rate [9,22], a percentage of warehouse storage loss [23], a fixed shelf life for products [7,8,10,24–27] or pallets [28], a limitation to transportation [15,16] or storage [29] duration, and a minimum shelf life [27] or quality [9] required on markets.

Table 2 identifies the characteristics of the design models. Most models have addressed facility location (98%) and market allocation (85%) design decisions. Tactical decisions, such as transport (68%) and inventory (25%), are usually included in design models. Less modelled decisions include the planting (2%) and harvest (9%) of crops, labouring decisions in slaughterhouses (5%), and also waste and unmet demand (2%) Finally, 80% of models consider a single-period horizon to design AFSC, and focus mainly on strategical and tactical decisions (transport).

Regarding constraints, most models limit the transport (34%), production (43%) or inventory (23%) capacity to one facility or more. Jonkman et al. [9] limits the area to be planted per product for legislative or practical reasons. In perishable contexts, [9] limits the maximum age at which products can be sold, while [27] fixes the minimum freshness that products must present on markets.

After the review, it was concluded that the models contemplating the entire AFSC and multiple products are needed, as highlighted in [1]. Product perishability has been modelled, particularly in those models that design partial AFSCs by commercialising one product. To bridge these gaps, the proposed model designs a five-stage AFSC to commercialise multiple products with a limited shelf life.

Most models deal with design decisions combined with one tactical decision or two, such as transport or inventory. AFSC design models that address planting, cultivating or harvest activities are very scarce, although specific AFSC characteristics render it necessary to include harvesting decisions in AFSC designs [9]. Planting should also be addressed to better balance the product flow along the SC, and to reduce production peaks and their impact on AFSC designs. Considering planting, production, storage and distribution decisions and product perishability while designing AFSC ensures adjustments to market requirements and improves SC performance in the short, mid and long terms [1]. The model proposed herein integrates design decisions with planting, cultivation, harvest, labouring, packing, storage, operation, waste, and unmet demand decisions.

Modelled constraints are related mainly to the storage and production capacities of facilities. This paper limits the capacity for managing products in warehouses and DC, which has not been previously considered in the literature. This constraint prevents using cross-docking points to manage an infinite quantity of product per period.

Product perishability-related constraints should be contemplated to ensure the safety of sold products. In the proposed model, minimum freshness on markets is fixed to ensure minimum post-sale product duration so that product properties in consumption terms remain suitable for some time after consumer purchases. Finally, a multiple-period horizon needs to

Table 1
AFSC characteristics.

Ref	SC stages					No. of products		Product perishability
	Supplier	Processor	Distributor	Retailer	Customer	One	Multiple	
Wouda et al. [30]	X	X	X			X		
Apaiah and Hendrix [31]		X				X		
Gong et al. [17]			X	X		X		X
Tang et al. [13]	X		X	X		X		X
Zhi-lin and Dong [18]			X	X		X		X
Xiaohui and Wen [19]			X	X		X		X
Villa-Marulanda et al. [32]		X	X			X		
Boudahri et al. [33]		X		X		X		
Di et al. [14]			X	X		X		X
Ding [34]	X	X				X		
Zhao and Dou [15]	X	X	X				X	X
Zhao and Lv [16]	X	X	X				X	X
Boudahri et al. [35]		X		X		X		
Boudahri et al. [36]		X		X			X	
Nasiri and Davoudpour [37]			X	X			X	
Baghalian et al. [6]		X	X	X			X	
Boudahri et al. [38]		X		X			X	
Ding [39]	X	X		X		X		
Etemadnia et al. [40]		X	X	X		X		
Firoozi et al. [7]	X		X	X		X		X
Jouzdani et al. [41]	X	X					X	
Neungmatcha et al. [42]	X	X				X		
Firoozi et al. [8]			X	X		X		X
Govindan et al. [29]		X	X	X		X		X
Arabzad et al. [20]	X	X		X			X	X
Etemadnia et al. [43]		X	X	X		X		
Accorsi et al. [44]	X	X	X	X		X		
Amorim et al. [24]	X	X		X			X	X
Colicchia et al. [45]			X	X		X		
Rashidi et al. [25]		X	X	X			X	X
De Keizer et al. [22]	X	X	X	X			X	X
Hiassat et al. [26]		X	X	X		X		X
Jonkman dt al. [46]	X	X		X			X	
Mohammed and Wang [47]	X	X		X		X		
Mohammed and Wang [48]	X	X		X		X		
Mohammed and Wang [49]	X	X		X		X		
Musavi and Bozorgi-Amiri [10]			X	X		X		X
Orjuela-Castro et al. [23]	X	X	X	X			X	X
Allaoui et al. [50]	X	X	X	X			X	
Bortolini et al. [28]	X		X	X			X	X
Dai et al. [21]		X	X	X			X	X
Singh et al. [27]			X	X			X	X
Cheraghalipour et al. [51]	X	X	X	X			X	
Jonkman et al. [9]	X	X		X			X	X
TP	X	X	X	X	X		X	X

be contemplated in those cases in which product perishability is included in the model, and when planting and harvest decisions are made, because this can lead to more accurate results [1].

The main contributions to multi-period AFSC design modelling is the joint integration of planting, cultivation, harvest, labouring, packing, inventory, transport, operation, waste, and unmet demand decisions on the design of an entire AFSC that commercialises many perishable products. Cultivation, labouring on farms, packing, and operational decisions have not been previously addressed in AFSC design models. Constraints related to production, storage and product management capacity, the minimum freshness of products when sold, and minimum planting areas, are modelled. The proposed model is used to determine the impact of product perishability on AFSC design, which is another contribution of this paper.

In short, more realistic models are needed to include inherent AFSC characteristics and to study the impact of modelling them. The following sections aim to shed some light on this matter.

3. Problem description

A typical AFSC for fresh fruit and vegetables (short shelf life products) is modelled. It comprises five stages: farmers, packing plants (PP), warehouses, DCs, markets (Fig. 1). Farmers plant, cultivate and harvest crops. Once harvested, products

Table 2
Model characteristics.

	Decisions													Constraints			Horizon	
Ref	FL	SA	FA	MA	P	H	C	Pa	I	T	W	UD	L	P	Ca	Pe	SP	MP
Wouda et al. [30]	X	X	X	X						X							X	
Apaiah and Hendrix [31]	X		X							X							X	
Gong et al. [17]	X			X											X		X	
Tang et al. [13]	X			X					X								X	
Zhi-lin and Dong [18]	X			X											X		X	
Xiaohui and Wen [19]	X			X													X	
Villa-Marulanda et al. [32]	X			X													X	
Boudahri et al. [33]	X			X											X		X	
Di et al. [14]	X			X													X	
Ding [34]	X	X	X							X					X		X	
Zhao and Dou [15]	X	X	X	X		X				X							X	
Zhao and Lv [16]	X	X	X	X		X				X							X	
Boudahri et al. [35]	X			X											X		X	
Boudahri et al. [36]	X			X											X		X	
Nasiri and Davoudpour [37]	X			X											X		X	
Baghalian et al. [6]	X		X	X						X					X		X	
Boudahri et al. [38]	X			X						X					X		X	
Ding [39]	X	X		X						X							X	
Etemadnia et al. [40]	X		X	X						X					X		X	
Firoozi et al. [7]	X			X					X								X	
Jouzdani et al. [41]	X		X							X					X			X
Neungmatcha et al. [42]	X	X													X		X	
Firoozi et al. [8]	X			X					X								X	
Govindan et al. [29]	X		X	X					X	X					X			X
Arabzad et al. [20]	X									X					X			
Etemadnia et al. [43]	X		X	X						X					X		X	
Accorsi et al. [44]	X	X	X	X						X					X		X	
Amorim et al. [24]		X	X	X					X	X					X			X
Colicchia et al. [45]	X			X											X		X	
Rashidi et al. [25]	X			X					X	X							X	
De Keizer et al. [22]	X	X	X	X					X	X							X	
Hiassat et al. [26]	X								X	X					X			X
Jonkman dt al. [46]	X	X	X	X						X					X			X
Mohammed and Wang [47]	X	X		X						X					X		X	
Mohammed and Wang [48]	X	X		X						X			X		X		X	
Mohammed and Wang [49]	X	X		X						X			X		X		X	
Musavi and Bozorgi-Amiri [10]	X			X						X					X		X	
Orjuela-Castro et al. [23]	X	X	X	X						X					X		X	
Allaoui et al. [50]	X	X	X	X						X					X			X
Bortolini et al. [28]	X					X			X	X					X			X
Dai et al. [21]	X									X					X		X	
Singh et al. [27]	X			X						X		X			X		X	
Cheraghalipour et al. [51]	X								X	X					X			X
Jonkman et al. [9]	X				X	X			X	X	X			X	X	X		X
TP	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X

FL: Facility location, SA: Supply allocation, FA: Facility allocation, MA: Market allocation, P: Planting, C: Cultivation, H: Harvest, Pa: Packing, I: Inventory, T: Transport, W: Waste, UD: Unmet demand, L: Labouring; Ca: Capacity, Pe: Perishability, SP: Single period, MP: Multiple period

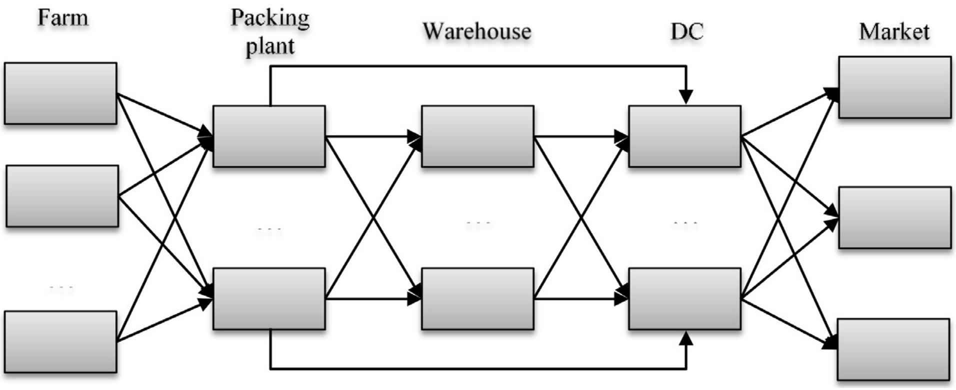

Fig. 1. Fresh fruit and vegetables SC (based on [52]).

are transported to PPs where they are stored and packed. Packed products can be transported to either warehouses or DCs, where they are stored. Warehouses and DCs can also be used as cross-docking points. Finally, products are transported from DCs to markets, which represents end consumers' demand [1].

The assumptions made to define the problem are described below.

- The facilities that can be opened, and their location and role (farm, PP, warehouse, DC), capacity (available area on farms, processing and storage capacity at PPs, operation and storage capacity at warehouses and DCs), and opening costs are known. Facilities and transport can be either refrigerated or non-refrigerated.
- Only crops from annual plants can be planted. Planting can be done with seeds or seedlings, and planting density is known. Planting periods depend on the planted crop. There is a crop-dependent fixed cost related to the planting and cultivation of plants.
- Plants are cultivated from the planting period to the last harvest period. Cultivation activities include irrigation of plants, application of phytosanitary products and plant-related activities like pruning.
- Harvest depends on crop and planting dates. Plants are harvested during all harvest periods, although the harvest frequency (harvest pattern) per period can be chosen.
- Plant yield, which is the quantity of product obtained from a plant, depends on the crop, planting and harvest dates, and on the used harvest pattern. Thus by considering that yield depends on harvest date, the influence that the different seasons in the year may have on plant yield is taken into account.
- Once harvested, products' shelf life is limited according to the crop and harvest period. This shelf life depends not only on the nature of the supply chain to be designed (refrigerated or not), but also on the technologies used (i.e. special packaging) by the chain to prolong the natural product's shelf life.
- Products need to be sold with a minimum remaining shelf life (freshness), otherwise they are wasted.
- Planting, cultivation and harvest activities are performed manually by seasonal and temporary labourers. The time needed to carry out these activities is known as labourers' capacity. The labourers available to be hired are limited. Seasonal labourers have an associated hiring cost in addition to their salary, whereas the only cost for temporary labourers is their salary.
- Products can be stored at PPs until packed. Packing has an associated cost because it involves using materials and energy. Waste is produced when products' shelf life ends before being sold. Penalty costs are associated with waste.
- Packed products are transported to warehouses and DCs to be stored and distributed to markets.
- The unitary transportation costs of vegetables between chain nodes are known and depend on the distance between nodes and the corresponding form of transport.
- Markets and demand are known. Unmet demand is economically penalised.
- Product prices are known and assumed to depend solely on the product, market and time (seasonality in harvest and demand quantities). Product prices are assumed to be independent of product freshness (remaining shelf life) and remain constant during the same time period.

4. MILP model to design AFSC considering products' shelf life

In order to solve the problem described above, a mixed-integer linear programming (MILP) model is proposed which, given its own nature, assumes the linearity of different SC aspects as a widely accepted approach in the existing literature. The validation of the results obtained by experts shows that the assumptions made at the strategical level are sufficiently realistic and, therefore, valid.

4.1. Nomenclature

The nomenclature used to define the model is described in Tables 3 and 4.

In order to reduce the problem size, the model only generates the necessary decision variables related to the flow of products according to their shelf life. In this way, if a product is harvested in week two and its shelf life equals one week, then the model will not create a variable representing the quantity of products harvested in week two, which is transported in week five, as this combination is not possible due to the products' shelf life. On the contrary, if this same product has a shelf life that equals three, the product can be transported in week five and, thus, the model will create a variable for this case. So, in order to model this aspect, the decision variables dependent on indices h and t are created only for cases during which period t is higher than the harvest time of vegetables (h) and lower than $h + sl_v^h - msl_v$. This represents the maximum period during which the product can be sold in markets with the required minimum shelf life (msl_v)

4.2. Agri-food supply chain design considering the products' shelf life model

The model aims to maximise SC profits, calculated as the difference between the sales and costs deriving from opening locations, planting, packing, transport, inventory, operation, workforce, waste and unmet demand (see Tables 3 and 4).

$$\begin{aligned}
Max\,Z_1 = {} & \sum_{v}\sum_{m}\sum_{h\in \mathrm{H_v}}\sum_{t} p_{vm}^{t}\cdot QTS_{vm}^{ht} - \sum_{v}\sum_{f}\sum_{p\in P_v} cf_v\cdot NP_{vf}^{p} - \sum_{v}\sum_{c}\sum_{h\in \mathrm{H_v}}\sum_{t} cpack_v\cdot QP_{vc}^{ht} \\
& - \sum_{f}\sum_{c}\sum_{t} ctfp_{fc}\cdot NTFP_{fc}^{t} - \sum_{c}\sum_{s}\sum_{t} ctpw_{cs}\cdot NTPW_{cs}^{t} - \sum_{c}\sum_{d}\sum_{t} ctpd_{cd}\cdot NTPD_{cd}^{t} - \sum_{s}\sum_{d}\sum_{t} ctwd_{sd}\cdot NTWD_{sd}^{t} \\
& - \sum_{d}\sum_{m}\sum_{t} ctdm_{dm}\cdot NTDM_{dm}^{t} - \sum_{v}\sum_{h\in \mathrm{H_v}}\sum_{t}\left(\sum_{c} chp_{vc}\cdot IP_{vc}^{ht} + \sum_{s} chw_{vs}\cdot IW_{vs}^{ht} + \sum_{d} chd_{vd}\cdot ID_{vd}^{ht}\right) \\
& - \sum_{v}\sum_{h\in \mathrm{H_v}}\sum_{t}\left(\sum_{c}\sum_{s} cow_{vs}\cdot QTPW_{vcs}^{ht} + \sum_{c}\sum_{d} cod_{vd}\cdot QTPD_{vcd}^{ht} + \sum_{s}\sum_{d} cod_{vd}\cdot QTWD_{vsd}^{ht}\right) \\
& - \sum_{f}\sum_{t}\left(chs\cdot HLS_{f}^{t} + cls\cdot LS_{f}^{t} + clt\cdot LT_{f}^{t}\right) - \sum_{v}\sum_{c}\sum_{h\in \mathrm{H_v}}\sum_{t} cwa_v\cdot WAH_{vc}^{ht} \\
& - \sum_{v}\sum_{m}\sum_{t} cud_{vm}\cdot UD_{vm}^{t} - \sum_{f} cff_f\cdot YF_f - \sum_{c} cfp_c\cdot YPA_c - \sum_{s} cfw_s\cdot YW_s - \sum_{d} cfd_d\cdot YD_d \qquad (1)
\end{aligned}$$

The model is subject to the following constraints. At the farm level, the area planted throughout the year cannot exceed the area available on the farm (2). If a decision is made to plant a vegetable on a farm during one period, a minimum and a maximum area must be planted for technical reasons (3). Vegetables can only be planted on one farm if it is open (4).

$$\sum_{v}\sum_{p\in P_v}\frac{NP_{vf}^{p}}{d_v} \le a_f\cdot YF_f \qquad \forall f \qquad (2)$$

$$am_v\cdot YP_{vf}^{p} \le \frac{NP_{vf}^{p}}{d_v} \le a_f\cdot YP_{vf}^{p} \qquad \forall v, f,\ p\in P_v \qquad (3)$$

$$YP_{vf}^{p} \le YF_f \qquad \forall v, f, p\in P_v \qquad (4)$$

Cultivating (5) and harvest (6) activities are done with all the plants that require this during one period. The harvest pattern to be used for each plant can be decided.

$$NC_{vf}^{t} = \sum_{p\in PC_v^t} NP_{vf}^{p} \qquad \forall v, f, t \qquad (5)$$

$$\sum_{w\in W_v} NHW_{vfw}^{ph} = NP_{vf}^{p} \qquad \forall v, f, h\in H_v, p\in HP_v^h \qquad (6)$$

The quantity of vegetables obtained during harvest is in accordance with plant yield (7). Harvested vegetables should be transported to PPs during the harvest period (8).

$$QH_{vf}^{ph} = \sum_{w\in W_v} y_{vw}^{ph}\cdot NHW_{vfw}^{ph} \qquad \forall v, f, p\in P_v, h\in PH_v^p \qquad (7)$$

$$\sum_{p\in HP_v^h} QH_{vf}^{ph} = \sum_{c} QTFP_{vfc}^{ht} \qquad \forall v, f, h\in H_v,\ t=h \qquad (8)$$

When products arrive at PPs, they can be packed, stored or wasted (9). Packing capacity is limited (10). Once products are packed, they are transported to warehouses or DCs during the same period when they are packed (11).

$$IP_{vc}^{ht} = IP_{vc}^{ht-1} + \sum_{f} QTFP_{vfc}^{ht-tfc_{fc}} - QP_{vc}^{ht} - WP_{vc}^{ht} \qquad \forall v, c, h\in H_v, h\le t\le h+sl_v^h - msl_v \qquad (9)$$

$$\sum_{v}\sum_{t-sl_v^h+msl_v\le h\le t} tpa_v\cdot QP_{vc}^{ht} \le capp_c * YPA_c \qquad \forall c, t \qquad (10)$$

$$QP_{vc}^{ht} = \sum_{s} QTPW_{vcs}^{ht} + \sum_{d} QTPD_{vcd}^{ht} \qquad \forall v, c, h\in H_v, h\le t\le h+sl_v^h - msl_v \qquad (11)$$

Vegetables are necessarily transported to markets from DCs. All the vegetables that arrive at markets are sold during the same period (12). If a transported product is not enough to meet demand, unmet demand comes into play (13).

$$QTS_{vm}^{ht} = \sum_{d} QTDM_{vdm}^{ht-tdm_{dm}} \qquad \forall v, m, h\in H_v, h\le t\le h+sl_v^h - msl_v \qquad (12)$$

Table 3
Nomenclature.

Indices			
v	Vegetable	f	Farmer
p	Planting period	c	PP
h	Harvest period	s	Warehouse
t	Time period	d	DC
w	Harvesting patterns	m	Market
Set of indices			
P_v	Set of planting periods p in which vegetables v can be planted	HP_v^h	Set of planting periods p for vegetables v that allow harvesting during period h
H_v	Set of harvest periods h in which vegetables v can be harvested	PC_v^t	Set of periods t during which the vegetables v planted in p need to be cultivated
PH_v^p	Set of periods h during which the vegetable v planted in p can be harvested	W_v	Set of harvest patterns w that can be used with the plants of vegetable v
Parameters			
p_{vm}^t	Sales price for vegetable v in market m during period t	de_{vm}^t	Vegetable v demand in market m during period t
cwa_v	Penalisation cost for wasting one kg of vegetable v	cud_{vm}	Penalisation cost for not meeting one kg of vegetable v demand in market m
cf_v	Cost to plant and cultivate one vegetable v plant	$cpack_v$	Cost to pack one kg of vegetable v
$ctfp_{fc}$	Cost to transport one kg of vegetable from farmer f to PP c	tfc_{fc}	Time needed to transport products from farmer f to PP c
$ctpw_{cs}$	Cost to transport one kg of vegetable from PP c to warehouse s	tcs_{cs}	Time needed to transport products from PP c to warehouse s
$ctpd_{cd}$	Cost to transport one kg of vegetable from PP c to DC d	tcd_{cd}	Time needed to transport products from PP c to DC d
$ctwd_{sd}$	Cost to transport one kg of vegetable from warehouse s to DC d	tsd_{sd}	Time needed to transport products from warehouse s to DC d
$ctdm_{dm}$	Cost to transport one kg of vegetable from DC d to market m	tdm_{dm}	Time needed to transport products from DC d to market m
tpa_v	Time required to pack one kg of vegetable v	$capp_c$	Available packing capacity in PP c during a period
chp_{vc}	Holding cost for vegetable v at PP c for a period	$capip_c$	Available storage capacity in PP c during a period
chw_{vs}	Holding cost for vegetable v at warehouse s for a period	$capw_s$	Available storage capacity at warehouse s during a period
chd_{vd}	Holding cost for vegetable v at DC d for a period	$capd_d$	Available storage capacity at DC d during a period
cow_{vs}	Operation cost for vegetable v at warehouse s for a period	$capow_s$	Available operation capacity at warehouse s during a period
cod_{vd}	Operation cost for vegetable v at DC d for a period	$capod_d$	Available operation capacity at DC d during a period
cff_f	Cost for opening farm f	cfw_s	Cost for opening warehouse s
cfp_c	Cost for opening PP c	cfd_d	Cost for opening DC d
am_v	Minimum area to be planted per period with vegetable v due to technical aspects if it is planted	y_{vw}^{ph}	Yield of a vegetable v plant during period h if planted at p and harvested with pattern w
a_f	Available area on farm f	d_v	Planting density for vegetable v
tp_v	Time needed to plant one vegetable v plant	mls_f	Minimum number of seasonal labourers hired by farmer f
tc_v	Time required to cultivate one plant of vegetable v	Mls	Maximum number of available seasonal labourers to be hired
th_{vw}	Time required to harvest one vegetable v plant with pattern w	Mlt	Maximum number of available temporary labourers to be hired
hw	A labourer's capacity during a period	cls	Weekly cost of a seasonal labourer
chs	Cost for hiring one seasonal labourer	clt	Weekly cost of a temporary labourer
sl_v^h	Shelf life for vegetable v if harvested at h	msl_v	Minimum shelf life that vegetable v needs to have when sold
$capt$	Transportation capacity on one truck		

$$\sum_{t-sl_v^h+msl_v\le h\le t} QTS_{vm}^{ht}+UD_{vm}^t = de_{vm}^t \qquad \forall v,m,t \tag{13}$$

Seasonal and temporary labourers are needed to manually perform activities on farms, which vary according to the plants that require certain operations (14). Striking a balance with labourers when performing hiring and firing actions is deemed necessary for seasonal labourers (15), but not for temporary labourers because their contracts are defined for only one period. A minimum and maximum number of seasonal and temporary labourers must be contemplated (16-18).

$$\sum_{v}\left(\sum_{p=t} tp_v\cdot NP_{vf}^p+tc_v\cdot NC_{vf}^t+\sum_{p\in P_v}\sum_{w}\sum_{h=t} th_{vw}\cdot NHW_{vfw}^{ph}\right)\le hw\cdot\left(LS_f^t+LT_f^t\right) \qquad \forall f,t \tag{14}$$

$$LS_f^t=LS_f^{t-1}+HLS_f^t-FLS_f^t \qquad \forall f,\ t \tag{15}$$

Table 4
Nomenclature.

Decision variables	
YF_f	Binary variable with value 1 when farm f is open, and 0 otherwise.
YPA_c	Binary variable with value 1 when PP c is open, and 0 otherwise
YW_s	Binary variable with value 1 when warehouse s is open, and 0 otherwise
YD_d	Binary variable with value 1 when DC d is open, and 0 otherwise
YP_{vf}^{p}	Binary variable with value 1 when vegetable v is planted by farmer f during planting period p, and 0 otherwise.
NP_{vf}^{p}	Number of plants v planted by farmer f during period p
NC_{vf}^{t}	Number of plants v cultivated by farmer f during period t
NHW_{vfw}^{ph}	Number of plants v planted by farmer f at t and harvested at h with harvest pattern w
QH_{vf}^{ph}	Quantity of v planted by farmer f during period p harvested during period h
$QTFP_{vfc}^{ht}$	Quantity of v harvested at h by farmer f transported to PP c during period t, where $t = h$
QP_{vc}^{ht}	Quantity of v harvested at h packed at PP c during period t, where $h \leq t \leq h + sl_v^h - msl_v$
WP_{vc}^{ht}	Quantity of v harvested at h wasted at PP c during period t, where $h \leq t \leq h + sl_v^h - msl_v$
$QTPW_{vcs}^{ht}$	Quantity of v harvested at h transported from PP c to warehouse s during period t, where $h \leq t \leq h + sl_v^h - msl_v$
$QTPD_{vcd}^{ht}$	Quantity of v harvested at h transported from PP c to DC d during period t, where $h \leq t \leq h + sl_v^h - msl_v$
$QTWD_{vsd}^{ht}$	Quantity of v harvested at h transported from warehouse s to DC d during period t, where $h \leq t \leq h + sl_v^h - msl_v$
$QTDM_{vdm}^{ht}$	Quantity of v harvested at h transported from DC d to market m during period t, where $h \leq t \leq h + sl_v^h - msl_v$
IP_{vc}^{ht}	Existing inventory at the end of period t at PP c of vegetable v harvested in h, where $h \leq t \leq h + sl_v^h - msl_v$
IW_{vs}^{ht}	Existing inventory at the end of period t at warehouse s of vegetable v harvested in h, where $h \leq t \leq h + sl_v^h - msl_v$
ID_{vd}^{ht}	Existing inventory at the end of period t at DC d of vegetable v harvested in h, where $h \leq t \leq h + sl_v^h - msl_v$
QTS_{vm}^{ht}	Quantity of v harvested at h and sold in market m during period t, where $h \leq t \leq h + sl_v^h - msl_v$
$NTFP_{fc}^{t}$	Number of trucks that go from farm f to PP c during period t
$NTPW_{cs}^{t}$	Number of trucks that go from PP c to warehouse s during period t
$NTPD_{cd}^{t}$	Number of trucks that go from PP c to warehouse s during period t
$NTWD_{sd}^{t}$	Number of trucks that go from warehouse s to DC d during period t
$NTDM_{dm}^{t}$	Number of trucks that go from DC d to market m during period t
HLS_f^t	Seasonal labourers hired by farmer f during period t
LS_f^t	Seasonal labourers working on farm f during period t
FLS_f^t	Seasonal labourers fired by farmer f during period t
LT_f^t	Temporary labourers working on farm f during period t
UD_{vm}^{t}	Quantity of unmet v demand in market m during period t

$$LS_f^t \geq \ mls_f \cdot YF_f \qquad \forall f,\ t \tag{16}$$

$$\sum_f LS_f^t \leq Mls \qquad \forall t \tag{17}$$

$$\sum_f LT_f^t \leq Mlt \qquad \forall t \tag{18}$$

The number of trucks that cover each route depends on the quantity of vegetables to be transported and truck capacity (19-23). Products can only be transported from and to a location if it is open (24-27).

$$\sum_v \sum_{t - sl_v^h + msl_v \leq h \leq t} QTFP_{vfc}^{ht} \leq NTFP_{fc}^t \cdot capt \qquad \forall f, c, t \tag{19}$$

$$\sum_v \sum_{t - sl_v^h + msl_v \leq h \leq t} QTPW_{vcs}^{ht} \leq NTPW_{cs}^t \cdot capt \qquad \forall c, s, t \tag{20}$$

$$\sum_v \sum_{t - sl_v^h + msl_v \leq h \leq t} QTPD_{vcd}^{ht} \leq NTPD_{cd}^t \cdot capt \qquad \forall c, d, t \tag{21}$$

$$\sum_{v}\sum_{t-sl_v^h+msl_v\le h\le t} QTWD_{vsd}^{ht} \le NTWD_{sd}^{t}\cdot capt \qquad \forall s,d,t \tag{22}$$

$$\sum_{v}\sum_{t-sl_v^h+msl_v\le h\le t} QTDM_{vdm}^{ht} \le NTDM_{dm}^{t}\cdot capt \qquad \forall d,m,t \tag{23}$$

$$\sum_{c}\sum_{t} NTFP_{fc}^{t} \le M\cdot YF_f \qquad \forall f \tag{24}$$

$$\sum_{f}\sum_{t} NTFP_{fc}^{ht} + \sum_{s}\sum_{t} NTPW_{cs}^{t} + \sum_{d}\sum_{t} NTPD_{cd}^{t} \le M\cdot YPA_c \qquad \forall c \tag{25}$$

$$\sum_{c}\sum_{t} NTPW_{cs}^{t} + \sum_{d}\sum_{t} NTWD_{sd}^{t} \le M\cdot YW_s \qquad \forall s \tag{26}$$

$$\sum_{s}\sum_{t} NTWD_{sd}^{t} + \sum_{m}\sum_{t} NTDM_{dm}^{t} \le M\cdot YD_d \qquad \forall d \tag{27}$$

The inventory of a given vegetable at warehouses and DCs equals the inventory during the previous period, plus the product that comes from other locations, less the product transported to other facilities. With warehouses, products come from PPs and are transported to DCs (28). With DCs, products come from both PPs and warehouses, and are transported to markets (29).

$$IW_{vs}^{ht} = IW_{vs}^{ht-1} + \sum_{c} QTPW_{vcs}^{ht-tcs_{cs}} - \sum_{d} QTWD_{vsd}^{ht} \qquad \forall v,s,h\in H_v, h\le t\le h+sl_v^{ph}-msl_v \tag{28}$$

$$\begin{aligned} ID_{vd}^{ht} &= ID_{vd}^{ht-1} + \textstyle\sum_c QTPD_{vcd}^{ht-tcd_{cd}} + \sum_s QTWD_{vsd}^{ht-tsd_{sd}} - \sum_m QTDM_{vdm}^{ht} \\ &\qquad \forall v,d,h\in H_v, h\le t\le h+sl_v^{h}-msl_v \end{aligned} \tag{29}$$

The existing inventory at facilities per period cannot exceed the storage capacity of these facilities (30-32). The total inventory at the end of the horizon should equal zero at all locations (33).

$$\sum_{v}\sum_{t-sl_v^h+msl_v\le h\le t} IP_{vc}^{ht} \le capip_c * YPA_c \qquad \forall c,t \tag{30}$$

$$\sum_{v}\sum_{t-sl_v^h+msl_v\le h\le t} IW_{vs}^{ht} \le capw_s * YW_s \qquad \forall s,t \tag{31}$$

$$\sum_{v}\sum_{t-sl_v^h+msl_v\le h\le t} ID_{vd}^{ht} \le capd_d * YD_d \qquad \forall d,t \tag{32}$$

$$\sum_{v}\sum_{t-sl_v^h+msl_v\le h\le t}\left(\sum_{c} IP_{vc}^{ht} + \sum_{s} IW_{vs}^{ht} + \sum_{d} ID_{vd}^{ht}\right) = 0 \qquad \forall t=52 \tag{33}$$

The quantity of vegetables managed in warehouses and DCs per period is limited (34-35).

$$\sum_{v}\sum_{t-sl_v^h+msl_v\le h\le t}\left(\sum_{c} QTPW_{vcs}^{ht-tcs_{cs}} + \sum_{d} QTWD_{vsd}^{pht}\right) \le capow_s * YW_s \qquad \forall s,t \tag{34}$$

$$\sum_{v}\sum_{t-sl_v^h+msl_v\le h\le t}\left(\sum_{c} QTPD_{vcd}^{ht-tcd_{cd}} + \sum_{s} QTWD_{vsd}^{ht-tsd_{sd}} + \sum_{m} QTDM_{vdm}^{ht}\right) \le capod_d * YD_d \qquad \forall d,t \tag{35}$$

In order to ensure that no products remain on trucks at the end of the horizon, constraint (36) equals the total quantity of sales to the total quantity of product transported to markets.

$$\sum_{v}\sum_{m}\sum_{h\in H_v}\sum_{t} QTS_{vm}^{ht} = \sum_{v}\sum_{d}\sum_{m}\sum_{h\in H_v}\sum_{h\le t\le h+sl_v^h-msl_v} QTDM_{vdm}^{ht} \tag{36}$$

Finally, the nature of decision variables is defined (37).

$$\begin{array}{ll} Continuous: & QH_{vf}^{ph}, QP_{vc}^{ht}, UD_{vm}^{t}, W_{vf}^{ht}, QTFP_{vfc}^{ht}, QTPW_{vcs}^{ht}, QTPD_{vcd}^{ht}, QTWD_{vsd}^{ht} \\ & QTDM_{vdm}^{ht}, IP_{vc}^{ht}, IW_{vs}^{ht}, ID_{vd}^{ht}, QTS_{vm}^{ht} \\ Integer: & NP_{vf}^{p},\ NC_{vf}^{t},\ NHW_{vfw}^{ph},\ HLS_{f}^{t},\ LS_{f}^{t},\ FLS_{f}^{t},\ LT_{f}^{t} \\ & NTFP_{fc}^{t}, NTPW_{cs}^{t}, NTPD_{cd}^{t}, NTWD_{sd}^{t}, NTDM_{dm}^{t} \\ Binary: & YF_f,\ YP_{vf}^{p},\ YPA_c,\ YW_s,\ YD_d \end{array} \tag{37}$$

Table 5
Information about farmers.

Farmer	Available area (ha)	Opening cost (€)
1	110	162,800
2	150	222,000
3	190	281,200
4	230	340,400
5	270	399,600
6	250	370,000
7	210	310,800
8	170	251,600
9	130	192,400
10	290	429,200

4.3. Model extensions

Although the model is formulated to cover the entire AFSC design, it can also be used to design/redesign only one part of the chain. To this end, the binary variables related to the opening of already open locations are set to one by including constraint (38) for farmers, (39) for PPs, (40) for warehouses and (41) for DCs.

$$YF_f = 1 \qquad \forall f \tag{38}$$

$$YPA_c = 1 \qquad \forall c \tag{39}$$

$$YW_s = 1 \qquad \forall s \tag{40}$$

$$YD_d = 1 \qquad \forall d \tag{41}$$

Once AFSCs have been designed, the model can be used to carry out tactical-operative planning by including only those indices that correspond to open locations, and by fixing the binary variables that refer to opening locations to one by including constraints (38-41).

5. Computational experiments

This section aims to validate the proposed model and to determine the impact of product perishability on AFSC design. For this purpose, a set of scenarios, in which products are characterised by different shelf lives, is solved with the model.

5.1. Data

The data used to validate the model and to carry out experimentation are inspired in a realistic case study from the La Plata region of Argentina. An agricultural area composed of ten farmers, grouped into four regions, is considered. The farms belonging to the same region are very close to one another, which means that the distance between them is negligible. The area available on each farm and the related opening costs are detailed in Table 5.

Three crop types can be planted. For technical reasons, a minimum of 200 plants of the same variety are planted, when it is decided to do so during a given period. Planting density is 22,000 plants/ha for crops A and B, and 19,000 plants/ha for crop C. The costs of planting one plant of each variety are 0.095, 0.092 and 0.068 €/plant, respectively.

Crops can be planted during three planting seasons: July, October, January. Cultivation and harvest activities depend on planting dates, as shown in Fig. 2, where week 1 corresponds to the first week of July. Cultivation activities ensure correct plant growth, such as irrigation, application of phytosanitary products, or pruning and staking up of plants. The four harvest patterns defined in [53] can be used during harvest. The times needed to plant, cultivate and harvest crops are defined in Table 6.

These activities are performed manually by labourers, who work 48 h/week. Farmers hire a minimum of one seasonal worker for every ten available hectares on the farm. A maximum of 450 seasonal and 350 temporary labourers is available, who earn a salary of 42.5 and 69 €/week, respectively. Seasonal workers also have an associated hiring cost of 42.5 €.

According to farmers' expertise, plant yield per period falls within the 0.14–0.66 kg/plant range for crop A, 0.13–0.58 kg/plant for crop B and 0.02–0.18 kg/plant for crop C, depending on planting and harvest dates, and also on the harvest pattern used. Once harvested, crops are transported to PPs where 0.15 min are taken to pack one kg of product. Packing and wasting one kg of product costs 6% and 5% of the mean product price, respectively.

Eight PPs, four warehouses and eight DCs can be opened. The costs of opening, and the processing, management and storage capacity for each facility type, are displayed in Table 7. The same data are used for all the facilities of the same nature. Holding costs are calculated as 0.25% of the mean price of each product per week.

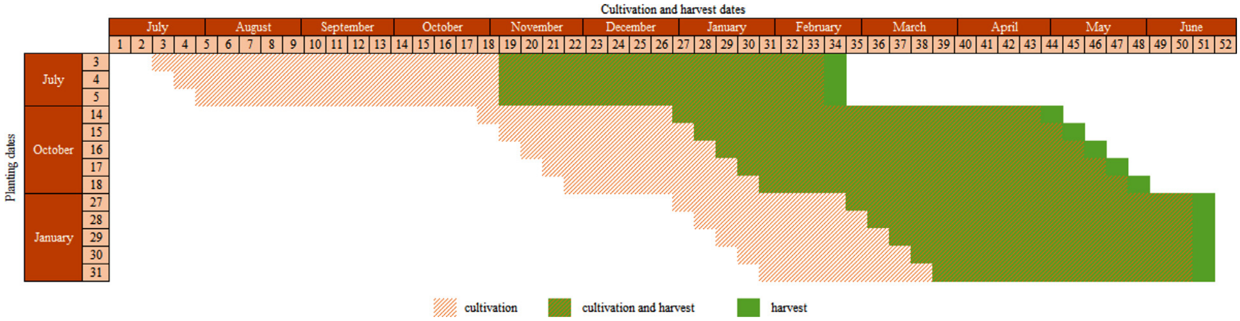

Fig. 2. Planting, cultivation and harvest dates for tomatoes.

Table 6
Time requirements on farms (min/plant).

		Crop		
		A	B	C
Time to plant		0.1309	0.1309	0.1516
Time to cultivate		0.0342	0.0342	0.0396
Time for harvest	Pattern I (harvest every day)	0.0682	0.0682	0.1579
	Pattern II (harvest every two days)	0.0614	0.0614	0.1421
	Pattern III (harvest three times a week)	0.0545	0.0545	0.1263
	Pattern IV (harvest twice a week)	0.0477	0.0477	0.1105

Table 7
Facility-related data.

Facility	Processing capacity (min/week)	Management capacity (kg/week)	Storage capacity (kg)	Opening cost (€)
PP	270,000		36,000	720,000
Warehouse		19,200,000	3,600,000	1,000,000
DC		4,800,000	240,000	4,800,000

Table 8
Transport costs between farms and PPs (€/truck).

Region	Farm	PP							
		1	2	3	4	5	6	7	8
1	1, 2, 3	224	439	525	494	821	754	1,576	866
2	4, 5, 6	238	308	730	692	679	637	1,435	1,030
3	7, 8	431	673	31	108	559	515	1,315	375
4	9, 10	483	789	124	23	658	631	1,403	445

The cost of transporting one truck between two facilities is calculated in accordance with the distances between facilities (Tables 8–11). Each truck can transport a maximum of 24,000 kg of products. The time taken to transport products between facilities ranges between zero and two periods.

The model considers four markets: supply and market prices were obtained from the Buenos Aires Central Market website for different tomato varieties; supplies are used to randomly generate the demand for the model in order to preserve the order of magnitude; unmet demand is penalised with 50% of the mean product price in each market.

5.2. Experimental design and results

In order to determine if product perishability impacts the AFSC configuration to answer our RQ, the model is solved for five scenarios in which shelf life varies from one to five weeks. The results provided by the model were compared by the experts by whom the problem was defined, who also validated the realism, coherence and implementability of the solutions. Fig. 3 displays the objective function value per scenario. The worst values are shown for the AFSCs with very short shelf life products. Values improve as products' shelf life increases, and reach a stable value for those products whose shelf life ranges between three and five weeks.

Fig. 4 displays the economic results. Sales, planting, cultivation, packing, transport, operation, inventory and labouring costs (Fig. 4a–g) increase as shelf life does for the products with shelf lives from one to three weeks. This is because a bigger amount of product is produced to be sold as shelf life increases and, thus, unmet demand lowers (Fig. 4i).

Table 9
Transport costs between PPs and warehouses/DCs (€/truck).

PP	Warehouse				DC							
	1	2	3	4	1	2	3	4	5	6	7	8
1	515	704	665	1,379	65	352	446	434	641	711	1,030	1,017
2	731	521	482	1,200	293	64	596	649	462	528	1,169	1,100
3	52	568	549	1,251	525	768	176	118	473	545	583	514
4	49	654	634	1,337	551	838	246	138	559	631	642	599
5	594	58	23	710	617	554	480	594	92	69	890	670
6	573	69	25	744	576	513	438	554	61	70	897	677
7	1,331	769	766	193	1,363	1,293	1,218	1,341	827	800	1,444	1,224
8	386	675	730	1,325	903	996	417	442	693	637	270	168

Table 10
Transport costs between warehouses and DC (€/truck).

Warehouse	DC							
	1	2	3	4	5	6	7	8
1	577	790	199	90	513	585	623	554
2	645	582	492	609	100	48	863	642
3	604	539	466	582	82	66	887	668
4	1,318	1,258	1,182	1,296	780	755	1,486	1,265

Table 11
Transport costs between DC and markets (€/truck).

DC	Market			
	1	2	3	4
1	69	628	1,461	1,131
2	293	734	1,403	1,215
3	635	141	1,324	641
4	561	155	1,438	663
5	558	428	925	908
6	628	503	897	834
7	1,262	506	1,523	41
8	1,228	441	1,304	228

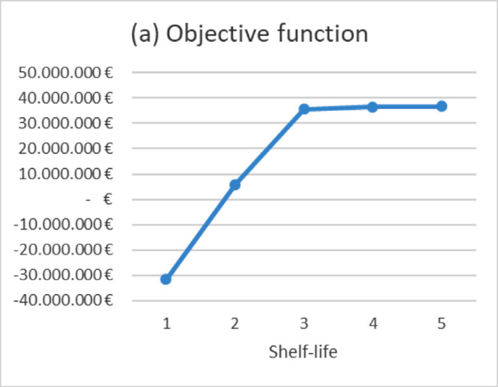

Fig. 3. Objective function.

For the scenarios with a three-week shelf life or longer, sales and packing costs are estabilised, while planting and cultivation, transport, operation and labouring costs remain similar, and their values slightly lower as shelf life increases. The reason for this is that more products are stored as shelf life increases, which means that planting fewer plants, having less production and waste, and the same demand level being met are possible.

This is reinforced in Fig. 5, where the percentage of wasted product and the met demand per scenario and market are shown. The demand from only one market can be met when products have a one-week shelf life, and when wasting the products that cannot be sold during the same period as their harvest. Waste increases for the AFSC with the two-week shelf life products because more product has to be produced to meet the demand of three markets. When shelf life equals or is

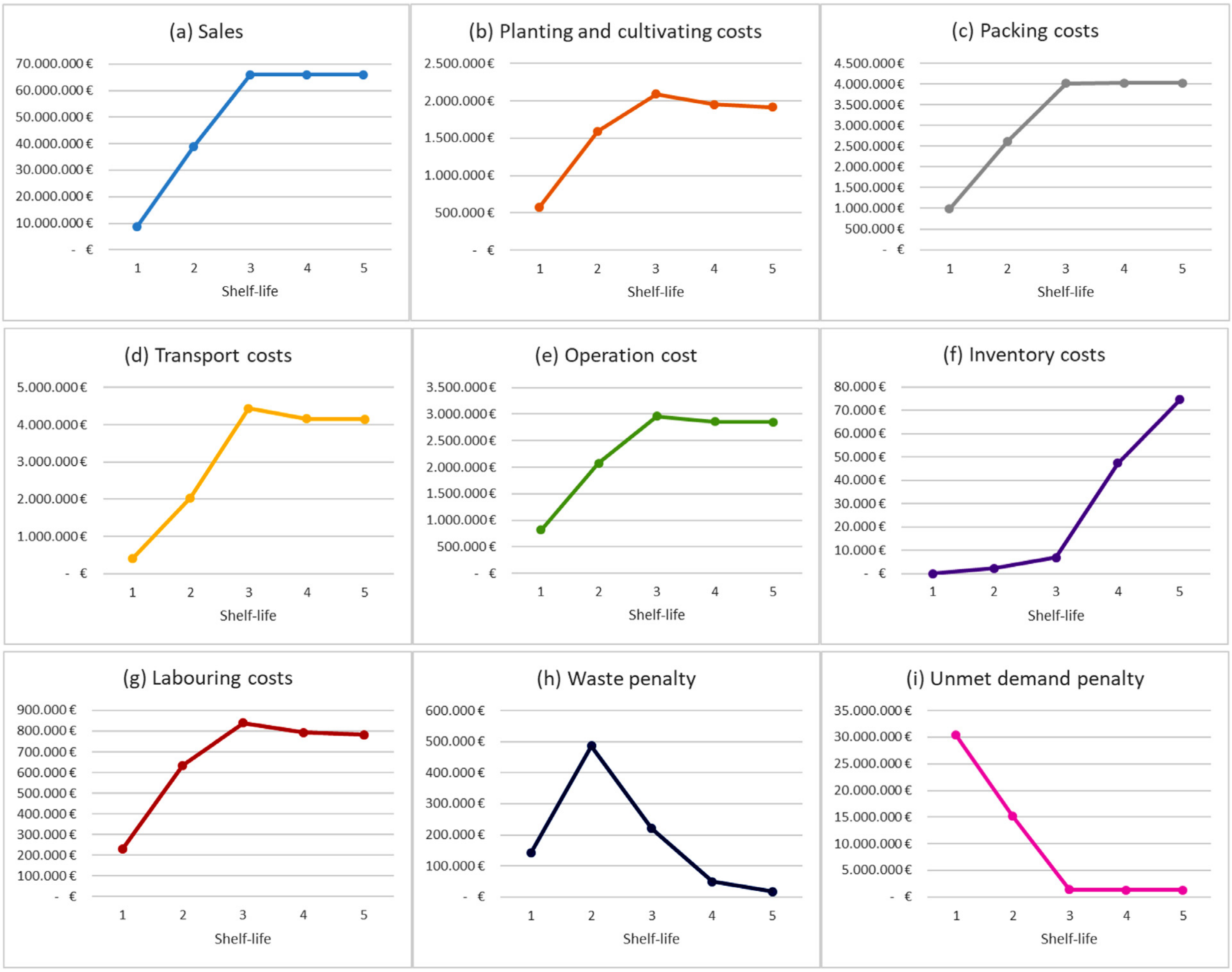

Fig. 4. Economic results.

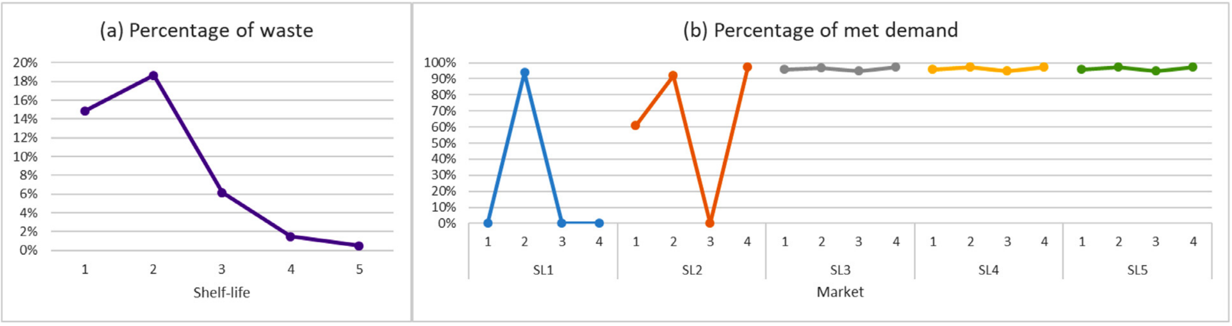

Fig. 5. Percentage of waste and met demand.

longer than three weeks, waste considerably lowers because products can be stored, which reduces the quantity of products to be produced throughout the year. In these cases, almost all the demand from all the markets can be met. In order to improve the environmental and social dimensions of AFSC sustainability, a penalisation for generated waste is included in the objective function.

The use of transport in the five scenarios can be analysed to determine the impact of perishability on the environmental sustainability of the SC under study. Fig. 6 shows the number of trucks and the percentage of cargo used in accordance with products' shelf life. The employed number of trucks increases from a one-week to a three-week shelf life scenario, which is justified by the increased sales in these scenarios. As from the three-week shelf life scenario, the number of used

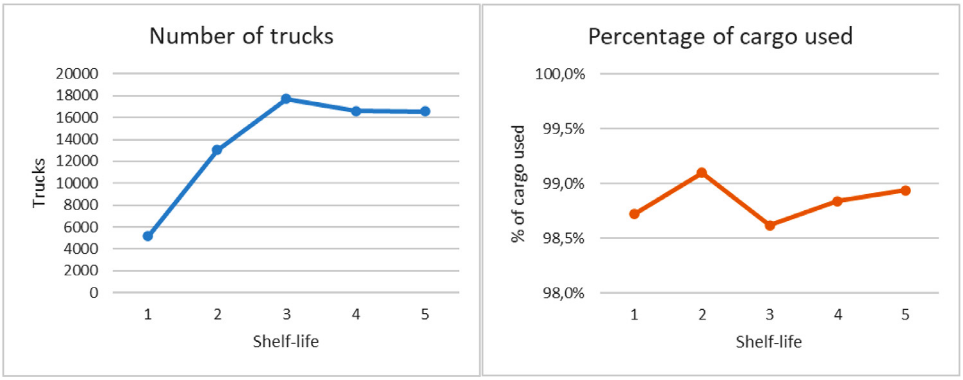

Fig. 6. Transport used.

Table 12
AFSC configuration per scenario.

SL	Farm										PP								Warehouse				DC							
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	1	2	3	4	1	2	3	4	5	6	7	8
1										X				X												X				
2							X	X	X				X	X					X							X				
3						X	X	X	X	X	X		X	X					X				X			X				
4			X				X	X	X	X	X		X	X					X				X			X				
5			X				X	X	X	X	X		X	X					X				X			X				

Table 13
Objective function and margin improvement for considering, vs. not considering, products' shelf life.

Shelf life (sl)	Variation in objective function		Variation in margin	
	(Obj_{sl}-Obj)	(Obj_{sl}-Obj)/ Obj_{sl}	($Marg_{sl}$-Marg)	($Marg_{sl}$-Marg)/ $Marg_{sl}$
1	7,327,352 €	23.09%	7,351,188 €	613.29%
2	1,299,148 €	22.12%	3,216,205 €	14.94%
3	296,725 €	0.83%	144,899 €	0.39%
4	2,994 €	0.01%	5,773 €	0.02%
5	9,742 €	0.03%	8,761 €	0.02%

trucks lowers (Fig. 6), as do transport costs (Fig. 4d). However, a similar quantity of product is transported between the supply chain nodes, and this increases the percentage of used cargo which, in turn, promotes the chain's environmental sustainability. One remarkable finding is that the percentage of cargo used in all the scenarios exceeds 98.5%, which implies sustainable transport.

In order to determine why the solution stabilises for the scenarios with a three-week shelf life or longer, the AFSC configurations are analysed (Table 12). The AFSCs that commercialise products with a one-week shelf life are configured by three facilities that are very close to one another. In this case, only the demand of the market located in the same region as the open farm is partially met, while the demand from other markets is not. For the products with a two-week shelf life, more facilities are open, which allows farmers to meet demand from three markets that are close to the farming region. However, products cannot arrive at one market without losing their properties. This problem is solved for the AFSCs that include products with a three-week shelf life or longer because products' shelf life is long enough to meet the demand on all the markets. In these cases, the same AFSC configuration and similar economic results are obtained.

These results show the impact of products' shelf life on AFSC designs. The proposed model can also be used to determine the cost savings made when considering products' shelf life while designing the chain. To show this, the model is solved without considering the product shelf life by obtaining the corresponding AFSC configuration. Then the resulting AFSC configuration is employed to commercialise the products with short shelf lives by fixing the supply chain configuration to the previous one obtained for the AFSCs without considering product perishability. This is similar to using the model for making tactical decisions once the AFSC is designed. Table 13 displays the improvement made in terms of the objective function and margin when designing AFSCs by taking into account products' shelf life (Obj_{sl} and $Marg_{sl}$, respectively) *versus* not considering it (Obj and Marg, respectively). The results show that better economic results are obtained for the AFSCs designed by taking into account product perishability, especially if products have short shelf lives (less than three weeks for this case study). However, this difference is insignificant for the scenarios in which the perishable AFSC configuration is similar to or equals the AFSC configuration for non-perishable products. Note that margin represents the objective function without

Table 14
Model statistics and computational efficiency.

Shelf life	Continuous variables	Integer variables	Binary variables	Constraints	Iterations	Solution time (seconds)	GAP
1	31,254	19,210	210	190,432	2,513	2	-
2	51,054	19,210	210	190,432	69,452	76	-
3	71,354	19,210	210	190,432	2,335,686	2,344	-
4	88,854	19,210	210	190,432	27,668,979	29,682	-
5	106,854	19,210	210	190,432	85,075,072	86,400	0.32%

considering the economic penalties for either waste or unmet demand. Therefore, considering product perishability when designing AFSC promotes the design of more competitive SCs than those chains designed without contemplating this aspect.

The results show that the optimal AFSC configuration when maximising profits for the Argentinean case study varies according to the product perishability of those products with a short shelf life (one or two weeks). However, a point is reached when product perishability does not influence the AFSC configuration with the cost structure under study. This reveals the importance of considering product perishability while designing AFSCs with short shelf lives, which applies to most crop-based products. However, this importance diminishes as product's shelf life prolongs until a point is reached when the perishable aspect no longer influences AFSC design.

At this point, it is possible to answer our research question (RQ): Should product perishability be considered when modelling AFSC design? Yes, product perishability should be considered when designing AFSCs because distinct products' shelf lives imply several optimal ASFC configurations that perform differently. Therefore, considering product perishability when designing AFSCs is relevant for obtaining configurations that better adjust to the nature of those products to be commercialised.

5.3. Computational efficiency

Intel® Xeon® CPU E5-2640 v2 with two 2.00 GHz processor, and an installed capacity of 32.0 GB and a 64-bit operating system, was used to solve the model. The model was implemented in MPL® 5.0 and solved with the Gurobi 8.0.1 solver. Microsoft Access databases were employed to store the input data and export the values for the decision variables. Model statistics and computational efficiency per execution are presented in Table 14.

The same data instance was employed for the five scenarios. The only difference in them was the value assigned to products' shelf life. It is noteworthy that the number of potential locations for the different nodes of the AFSC employed to solve the model is the same for all scenarios, although the selection of the nodes that would form part of the final AFSC depends on shelf life, as demonstrated in the previous section. Therefore, the model's dimension and the obtained GAP exclusively depend on the number of periods making up products' shelf life: the longer products' shelf life is, the more decision variables there are. For this reason, and as mentioned in Section 4.1, the decision variables that depend on indices h and t are created for only those cases in which period t exceeds the harvest time of vegetables (h) and is shorter than $h + sl_v^h - msl_v$. This represents the maximum period during which the product can be sold in markets with the required minimum shelf life (msl_v). This is because the model only generates the number of continuous and integer variables that are related to the feasible product flow for each scenario depending on shelf life. Accordingly, constraints, integer and binary variables remain the same for all experiments because they are independent of products' shelf life. The number of continuous variables increases as shelf life prolongs because these variables are related mostly to the flow of perishable products along the AFSC. This also increases the model's complexity.

Running the model is limited to 24 h (86,400 s). The time needed to optimally solve the model and the number of iterations increase with the model's complexity. The same happens with the GAP, which represents the difference between the obtained best solution and the investigated best bound. The optimal solution was reached within the limited resolution time for all scenarios, except for the last one. It is important to note that the GAP in Table 14 is expressed as a percentage (0.32%). Therefore, the real discrepancy between the optimal solution and the solution obtained after 24 h equals or is less than 0.0032 of the current value of the best bound reached until that time. This represents 118,803 € in monetary terms, which can be considered a small quantity in strategical terms. As this is a strategical decision-making process, it is also noteworthy that the maximum resolution time can be prolonged to find an optimal solution for the problem in a real situation.

6. Managerial insights

As shown in previous sections, the proposed model is a suitable tool for assisting managers when designing AFSCs with multiple perishable products. The joint modelling of tactical decisions related to the farming of vegetables, the flow of products along the chain with design decisions, and the inclusion of products' shelf life and penalties related to waste and unmet demand in a multi-period horizon, are the novelties of this paper. The application of the model to an Argentinean case study has demonstrated that contemplating product perishability while designing AFSCs can impact the obtained configuration. Thus managers are advised to consider product perishability when defining an AFSC configuration.

This means that the proposed model is a tool that provides solutions for facilities to be opened, and for their role to strike a balance between the supply and demand of vegetables by reducing the over- and underproduction of crops and their negative consequences on the three AFSC sustainability dimensions. Simultaneously taking them into account not only takes the model's behaviour closer to real AFSC behaviour, but also increases the model's number of uses, which are described below.

6.1. AFSC redesign and coordinating its operations

From the managerial point of view, the proposed model can be used mainly by managers to obtain the optimal configuration of entire or part AFSCs (the facilities to be opened in a specific location and their role), with or without the technology to control product perishability in an acceptable time.

The model can also be used to support tactical decisions to plan the planting, cultivation, harvest, transport, storage, operation, waste, unmet demand of vegetables along the supply chain in tactical terms once the AFSC configuration is defined (see Section 4.3): that is, to coordinate its operations.

The model's potential to partly redesign an existing AFSC or to be used at the tactical level can be employed to evaluate the impact on a particular AFSCs of disruptions on the supply or demand side, such as droughts, floods, fire, strikes or global pandemics (i.e. COVID-19), among others. Disruptions can be modelled by the scenarios and the model can be solved with the new input data corresponding to each scenario similarly to simulation models. The solution obtained in each scenario and its comparison made with the normal base scenario will allow managers to assess the impact of potential disruptions. This represents a very valuable information about the priority set to define protection strategies. Some examples of such scenarios are: i) the elimination of some supply chain nodes that become inactive because of disruption; ii) the disablement of transport between some supply chain nodes; iii) different demand patterns etc.; for instance, risks related to the unavailability of specific locations can be modelled by setting the corresponding binary variables related to their opening at zero.

At this point, it is worth noting that the model not only allows the impact of a disruption to be assessed, but AFSC resilience in three aspects to improve [54]: diminishing time-to-recovery, lost profit and recovery level. Ivanov and Dolgui [55] define SC resilience as supply chains' ability to withstand one disruption or more, and to recover their performance. The importance of designing resilient AFSC relies on products' perishable nature, which means that any disruption more strongly impacts AFSC than other industrial chains [56]. For this particular situation, the option of partially redesigning AFSC provided by the proposed model, along with more operational decisions, can support the rapid definition and assessment of reactive strategies to overcome the negative effects of disruption. Some of these potential strategies include considering potential backup suppliers by introducing new farmer locations for supply-side disruptions or the possibility of re-routing decisions as a reactive strategy using the model at the tactical level [54].

6.2. Assessing technology investment to extend the product shelf life: cold chains

As previously mentioned in Section 5.2., the inclusion of products' shelf life in AFSC designs at the strategic level allows important cost savings to be made compared to not considering it. As shelf life is a parameter of the model, managers should estimate the resulting shelf life of their products with current technology in the AFSC (refrigerated transport, refrigerated storage, new packaging technologies, etc.) and the corresponding costs to be used as input data for the model. This will be considered the base scenario.

Besides, the analysis of the results obtained by the model also provides decision makers with relevant information that can be used to improve AFSC efficiency and competitiveness. For example, the results for the herein examined case study indicates that increasing a product's shelf life means making more AFSC profits, improves the customer service level and reduces waste. Therefore, to quantitatively analyse how these factors improve by prolonging products' shelf life allows decision makers to decide if it is advisable to invest in some technologies to extend products' shelf life, such as refrigerated transport, or investing in either refrigerated product storage or new packing systems to increase product durability. To do this, the model can be solved in different scenarios that correspond to the use of new technologies that result in a new value of products' shelf life, and probably in new inventory holding costs. This means that the model can help to determine the maximum investment to be made to extend products' shelf life based on the increased profits that this investment would make *versus* the base scenario: that is, the difference in the profits made will be the limit of investing in new technology.

For example, during the experimentation described in Section 5.2, an SC profit of 5,874,120€ was obtained when products with a two-period shelf life were commercialised, and this profit increased to 35,687,053€ when commercialised products lasted three periods. In this way, SC members can invest up to 29,812,933€ (this being the difference between 35,687,053€ and 5,874,120€) in extending product's shelf life by one period. In the event of an investment made to increase the products' shelf life by one being less than 29,812,933€, the SC would make more profit than those that would have been obtained without making any investment.

One particular technology type is that related to cold chains (e.g. refrigerated warehouses or transport trucks), which is a relevant AFSC category as different temperatures imply varying product deterioration rates, and the impact on the environment also affecting the design of the chain. In this case, the model would still be valid if the temperature along SCs was previously defined and their associated products' shelf life and inventory holding costs were calculated. This means that the model can be used to decide a specific temperature to be maintained along the AFSC by setting different scenarios that correspond to various temperatures to solve the model in each scenario and to compare the obtained results.

On the contrary, it is not possible to use the model to decide about an optimum temperature to be maintained all along SCs, especially if products' characteristics (e.g. shelf life, deterioration, quality, costs, etc.) depend on the environmental temperature. To model this aspect, it is necessary to introduce a new decision variable as regards the temperature to be maintained and model the function that represents the behaviour of products' shelf life and deterioration with temperature. Temperature, as pointed out before, can also affect holding costs: the higher the temperature, the lower the holding costs, but the worse quality degradation, which would mean more lost value [57]. It is known that AFSCs are major contributors to global warming. Thus temperature decisions will also impact environmental sustainability (CO_2 emissions), as discussed in the next subsection. Including all these characteristics considerably increases the model's resolution complexity given the need to include non-linear equations [57].

6.3. Assessing the environmental impact when designing AFSC: waste and gas emissions

The model herein proposed assesses the environmental impact of AFSC configuration by analysing, on the one hand, the amount of waste generated throughout the SC and, on the other hand, the number of trucks used for transporting and distributing agricultural products.

However, AFSC configuration can present more environmental effects that include direct and indirect emissions from energy and other resource uses, to refrigerant leakages in each AFSC stage, among others. Indeed 31% of greenhouse gas emissions are related to the agri-food sector, which highlights the need to cushion the impact of AFSC on the environment [58]. Besides, the carbon footprint is becoming not only an environmental issue, but also a critical index for many customers, and has become a social aspect. To include these aspects in the proposed model, it would be necessary to firstly determine the emissions released by transport and at each SC location, and to add either a new objective function or a cost term to reduce them.

These emissions become more relevant with cold chains, for which the set point for refrigerated facilities and transport correlates negatively with carbon emissions [59]. Therefore, cold chains consume more energy given the need to control temperature at all the AFSC points. As a result, emissions and other environmental factors involved in using cold chains should also be considered in AFSC designs. Moreover, the social sustainability dimension is also affected by the cold chains, with generated waste (lower temperatures reduce food waste in a world where food scarcity is considered extremely relevant for some customers) and the carbon footprint (lower temperatures increase this index which many customers now believe is critical).

Consequently, it can be concluded that a trade-off should be reached between extending products' shelf life by employing cold chains and economic, environmental and social impacts.

7. Conclusions and future research lines

In this paper, an MPM to design realistic AFSCs is proposed by considering product perishability. This model integrates tactical decisions like planting, cultivating, harvest, labouring, packing, storage, operation and distribution of products into design decisions, which improves AFSC performance in the long, mid and short terms [1]. Regards the contribution, some of these decisions are already included in AFSC design models in the literature, while others, such as labouring, cultivating and operation decisions, are integrated into our AFSC design model for the first time. The consideration of the multiple-time period AFSC design problem allowed us to model product perishability, which is usually considered only in operational terms.

From the theoretical perspective, the relevance of modelling shelf life when strategically designing AFSC is shown for several reasons. Firstly, we analysed the impact of products' shelf life on the optimal AFSCs design by solving our model, which was applied to an Argentinean case study in several scenarios with differences in only products' shelf life. We checked that the optimal AFSC configuration and the resulting profits were quite different when prolonging very short product shelf lives up to a certain value. However after a certain shelf life length value, the same ASFC configuration was obtained, which denotes that the perishability impact on AFSC design diminishes as products' shelf life prolongs. Finally, we revealed that considering product perishability when designing AFSCs improves products' economic competitiveness compared to those chains designed without cotemplating products' shelf life. All this allowed us to answer our main research question about the need to include the operational product perishability characteristic when considering strategical decisions about AFSC design.

From the sustainability point of view, perishability modelling allows the obtained waste to be calculated and its minimisation by its penalisation in the model's objective, which helps to meet the environmental aspect of sustainability. Nonetheless, some waste will always be produced given the demand and plant yield patterns mismatch. This waste can be used for non-food purposes, such as producing fertilisers or alternative fuel, to reduce the negative environmental impact of waste. The quantity of unmet demand is also penalised to balance the supply and demand of vegetables in order to cover human needs and to contribute to the social dimension of sustainability.

From a practical perspective, the proposed model can be used by decision makers to design/redesign an entire or partial AFSC while anticipating tactical decisions about farming and distribution of vegetables, as herein employed. The model can also be employed to plan only tactical decisions once the AFSC configuration is defined. All the above examples improve the three AFSC sustainability dimensions. As previously indicated, the model can also be applied to evaluate the impact of disruptions on ASFC to define different scenarios by changing the input data, and to also assess several strategies to improve AFSC resilience. As AFSCs' commercialising products with longer shelf lives make more profit, the information provided by the model's resolution for different shelf life lengths can be used by decision makers to determine if it is advisable, or not, to invest in certain technology to extend products' shelf life.

Some of the model limitations derive from the assumptions made to simplify different aspects because of the strategic nature of design decisions, such as the independence of product prices in relation to their freshness (remaining shelf life). Although this last aspect has been considered by authors in other studies that address the operational order promising process [12], it is not herein included given the strategic nature of ASFC design decisions.

The model considers the shelf life of different products to be deterministic and constant along the SC. However, as pointed out before, the model can manage the effect of investing in new technologies or different temperatures on the products' shelf life by defining, solving and comparing different scenarios. Nevertheless, the inclusion of temperature as a decision variable in the model during optimisation, its relation with the product's characteristics and costs, and the gas emissions generated along the AFSC, will be interesting future research lines.

It is also advisable to include uncertainty modelling. Whether the uncertainty of product perishability can impact AFSC configurations can be determined. It would be interesting to assess the impact of modelling the dependence of prices on product freshness, and their dependence on other factors like the balance between supply and demand at this strategical decision level. A multi-objective MPM, including the maximisation of product freshness at the time of sales as an objective of the model, is proposed. Finally, the AFSC configuration of commercialising products with several shelf lives should be analysed to determine if perishability impacts this type of chain.

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