Design and Planning of Agri-Food Supply Chains

Lourenço Cruz

Centre for Management Studies, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal

Abstract

This paper develops a mixed-integer linear programming (MILP) formulation to support the design and planning of agri-food supply chains (AFSCs). The model focuses on the strategic-tactical decisions of capacity definition, selection of processing technologies, and the establishment of product flows to achieve expected net present value (ENPV) maximisation. Within the model, AFSC-specific characteristics are modelled as is the case of product perishability, flexible storage strategies, and reverse logistics operations. Supply and demand uncertainty is considered using a stochastic scenarios tree. The model is tested via the application of a case study from an existing sugar beet processing chain in The Netherlands.

Keywords: agri-food supply chain, mixed-integer linear programming, modelling, perishability, reverse logistics, uncertainty.

1. Introduction

Agribusiness encompasses all activities related to commercial farming. The USD 5 trillion sector was reported to represent 10 per cent of consumer spending, provide 40 per cent of worldwide employment, and be responsible for 30 per cent of greenhouse-gas emissions, as of 2015 (Goedde et al. 2015). In the European Union (EU), the sector encompasses EUR 117.4 and 137.9 billion in imports and exports, respectively (European Commission 2017). Despite its considerable economic, social, and environmental impact, as well as recently growing productivity, major concerns regarding the sector's future ability to provide food on a worldwide scale are on the rise (Goedde et al. 2015).

These concerns stem from profound shifts in the existing technologies and the consumption habits of end customers. As a consequence of these changes, sector stakeholders are feeling an increasing pressure to adapt their current operating models to ones which better cater to the evolving needs of clients (Goedde et al. 2015).

Within the major drivers for change, sustainability concerns, social concerns, and access to technology should be highlighted. Awareness for sustainability is currently on the rise, with a considerable portion of consumers beginning to adapt their consumption habits to reflect such concerns. It has been reported that consumers are currently willing to spend more on food of organic and sustainable sources, as a way of tackling both environmental sustainability and improving dietary quality. Apart from sustainability, social concerns are also becoming generalised. These concerns, which span from supporting locally-grown products to investing in local job creation, lead customers to preferring a closer proximity to farms and markets, as well as paying more attention to the origin of their products. Naturally, this pushes supply chains (SCs) towards a more local (decentralised) configuration and puts emphasis on product freshness and traceability. Finally, the access to ever-evolving technologies pushes changes and sector improvement at an increasing rate. With computation and better farming, harvesting, and storing capabilities, activities such as precision farming (Boettiger et al. 2017) are no longer a thing of the future, but rather something to which companies need to adapt to in order to remain competitive.

The present paper performs an extensive review of the literature relating to the design and planning of AFSCs making use of quantitative methods and identifies clear knowledge gaps. The paper then aims to solve such gaps by proposing a new modelling approach focused on adapting existing SC models to the unique AFSC context, integrating uncertainty in both supply and demand, flexible storage strategies, as well as reverse logistics activities. This objective is attained via a MILP strategy aimed at maximising the ENPV of an AFSC with five echelons: suppliers, processors, distributors, retailers, and reprocessors.

The model has a strategic-tactical breadth and focuses on defining technology and storage capacity for each facility, processing pathway selection, and definition of product flows between entities.

The paper is structured as follows: Section 2 performs a systematic literature review of papers addressing the design and planning of AFSCs with quantitative methods. In Section 3, the major problem characteristics are introduced and briefly explained. In Section 4, the model formulation is thoroughly described and analysed. Section 5 highlights the details of the case study used to assess model performance. In Section 6, the results of the application of the case study are presented and discussed. Finally, Section 7 uses all previously gathered knowledge to arrive at conclusions and suggest future research directions.

2. Literature review

The number of papers focusing on the design and planning of AFSCs using quantitative models has been steadily increasing (Tsolakis et al. 2014), mostly due to the ever-increasing relevance of the topic on a worldwide scale.

As mentioned, sustainability issues are now at the forefront of concerns, reason for which an increasing number of authors have focused their attention on environmental sustainability objectives and metrics. Although most authors addressing environmental sustainability do so while simultaneously pursuing economic goals, two publications have to be highlighted for their uniquely environmental-directed approach (Banasik et al. 2017; Pipatprapa et al. 2016). These works focus primarily on environmental performance assessment.

Contrasting, a limited amount of work has been conducted on social sustainability, with only a very small number of authors addressing this concern. In light of this context, two papers need to be emphasised for their holistic approaches, in which all three sustainability pillars (economic, environmental, and social) are addressed simultaneously (Allaoui et al. 2018; Izadikhah and Saen 2016). One additional paper focuses exclusively on the social pillar, addressing a distribution-equity problem in a food distribution network for the homeless (Fianu and Davis 2018).

In terms of the decision levels addressed, a large prevalence of studies on the strategic and operational decision levels is verified in contrast to the attention given to tactical decisions. Among these decisions, distribution and location selection are among the most popular topics, while scheduling has seen very little focus (Sel et al. 2015; Bilgen and Çelebi 2013).

Different SC and food product characteristics have also been addressed by most authors, although with considerably differing prevalence. Among SC characteristics, a major focus is verified in centralised SCs, with 24 papers accounting solely for centralised SCs, against 5 which explicitly focus decentralised configurations. This is particularly concerning, as decentralisation strategies may be a solution for current environmental and social challenges. In fact, decentralisation allows for the reduction of transportation costs and emissions, and supports local food production and job creation (Bosona and Gebresenbet 2011; Accorsi et al. 2018). Apart from this, most studies have also addressed forward-oriented SCs exclusively, in which reverse logistics are not considered (25 out of the 34 papers consider forward flows exclusively). With current sustainability and waste reduction concerns on the rise, it is expected that the role of reverse and closed-loop SCs will only increase. In light of this paradigm, the work of Banasik et al. (2017) must be highlighted, as it focuses on closing the loops in AFSCs with the use of multi-objective optimisation.

As mentioned, food product characteristics are also being the focus of attention. Perishability is the most addressed food product characteristic, with 19 models accounting for it. Among these, different approaches can be encountered. In their work, Kanchanasuntorn and Techanitisawad (2006) assess the impact of perishability on costs, net profit, service level, and inventory level; Mejjaouli and Babiceanu (2018) study product shipping and rerouting while including the possibility of product spoilage during transportation; and Bilgen and Çelebi (2013) account for perishability by varying retailing pricing depending on product shelf-life. Food product quality is addressed in 6 papers, with the work of Ge et al. (2015) being a good example of an evaluation of SC agents with a strong quality control component. Apart from this, traceability is another important characteristic, as there is a clear trend in legislation to tighten quality control, often ensured with traceability to ensure accountability in malpractice. Finally, only one publication (Bilgen and Çelebi 2013) addressed product heterogeneity by proposing a model which accounts for multiple products with different production lead times and processes. Product heterogeneity is extremely relevant in AFSCs, as most suppliers and producers operate with a mix of products which should be accounted for. Clearly, there is a need for larger scientific focus on the subject.

AFSCs possess a series of characteristics which render them unlike any other, reason for which specific tools need to be devised for these SCs. Among these, the high level of uncertainty verified in both supply and demand must be highlighted. Naturally, the inclusion of uncertainty modelling is an important trait when evaluating currently-proposed methodologies. The results from this analysis are not ideal. In fact, the number of papers with deterministic problems is far superior to that of papers addressing uncertainty. Disregarding uncertainty drives models away from reality and, consequently, limits their applicability. As far as the sources of uncertainty are considered, one paper (Shabani et al. 2012) created a model to account for input data uncertainty, predicting managerial data input to lack precise information. When accounting for supply and demand uncertainty, it is clear attention has been given to demand uncertainty, which is addressed twice more than supply uncertainty. It must be noted that one publication (Galal and El-Kilany 2016) contributed with both demand and lead time uncertainty considerations. Apart from recognising which authors address AFSCs with uncertainty-encompassing approaches, the analysis of which methods have been used to model uncertainty is also interesting. Stochastic models are the more popular approach towards incorporating uncertainty in models, being three times more frequent than any other option in the literature sampled. Apart from stochastic models, fuzzy programming has been studied and argued as posing several benefits over stochastic approaches (Mohammed and Wang 2017). One paper on demand forecasting (Huber et al. 2017) makes use of an auto regressive integrated moving average (ARIMA) model, while Shabani et al. (2016) use interval data envelopment analysis (IDEA) to account for input data uncertainty. Finally, Fianu and Davis (2018) use a Markov decision process to integrate supply uncertainty in their food distribution-equity problem.

As the literature review is focused on the application of quantitative methods to assist on the design and planning of AFSCs, recognising which methods have been chosen by authors is also important. Optimisation is clearly the most common, with more than half of all reviewed papers using an optimisation approach. It should be noted that a small set of papers make use of multiple methods. The usage of more than one approach is chosen by authors with two possible objectives: 1) utilise two different methods to address different parts of the problem, as performed by Bilgen and Çelebi (2013) who utilise a hybrid optimisation and simulation approach to integrate production scheduling and distribution planning in a dairy SC; 2) utilise two different methods to solve the same problem, thus comparing their performances, as is done by Dellino et al. (2018), who utilise three different microforecasting methods in a fresh food SC. As AFSCs are vastly complex and entail a series of players who must work together to address current challenges, decision analysis is the second most used approach, as analytic hierarchy processes (AHP), analytic network processes (ANP), and data envelopment analysis (DEA) are powerful tools to support managerial decision making, as highlighted by the work of Allaoui et al. (2018) and Huber et al. (2017). Apart from optimisation and decision analysis, simulation is also frequently used. As AFSCs are extremely complex, optimisation methods can be limited by computing power. This is an important note, as simulation can provide a good solution to this limitation, lowering computing requirements considerably. Apart from the most used methods, heuristics and metaheuristics have been proposed by certain authors to decompose larger AFSC problems but are yet to be vastly studied. On the other hand, no papers were found adopting neural networks or queuing theory to an AFSC planning and design context.

To support solving some of the knowledge gaps identified throughout the literature review, this paper develops a generic model to assist decision makers on the design and planning of AFSCs. The model achieves this goal by incorporating underexplored characteristics in the existing literature, such as reverse logistics, integration of both supply and demand uncertainty, as well as perishability and flexible storage strategies.

3. Problem characteristics

The model here described was designed to maximise the ENPV of an AFSC making use of MILP. The generic AFSC to which the model is applied consists of five echelons: **suppliers**, which

ensure the supply of raw materials; **factories/processors**, which use raw materials to manufacture products; **warehouses/ distributors**, which store products for posterior sale and distribute them to retailers; **retailers**, where products are sold to end consumers; and **reprocessors**, which receive wasted products from the remaining SC and produce other valuable products from them, which are then sold to end consumers. The different production processes are represented as technologies, which have associated production costs and bills of materials. To better mimic reality, product inventory is allowed in every echelon (in Cases B and C, please refer to Section 5), although storage capacity is higher in warehouses in comparison to other entities. Furthermore, all entities are allowed to ship their waste to reprocessors, thus effectively modelling reverse logistics and end-of-life product concerns, in line with priorities identified in Section 2. The general structure of the AFSC here discussed is highlighted in Figure 1. Although most authors assume centralised configurations (Kusumastuti et al. 2016), current food-miles concerns and local production awareness are paving the way to alternative (decentralised) set-ups. To account for such possibility, flows can be allowed between farmers and distributors/retailers. The problem can be described as follows:
Given:

- A set of products (raw materials, intermediate products, and final products);
- A set of technologies, which convert raw materials to intermediate and final products,
    - Associated operating costs, material inputs, and outputs;
- A set of entities (suppliers, processors, distributors, markets, and reprocessors),
    - Associated locations and transportation costs,
    - Associated technology capacity,
    - Associated storage capacity,
    - Associated demand;

Select the:

- Technology capacity to use in each entity in each time period;
- Stored quantity in each entity in each time period;
- Product flows between entities in each time period;

Subject to:

- Inventory constraints;
- Technology constraints;
- Storage constraints;
- Transportation constraints;
- Demand constraints;
- Supply constraints;
- Reprocessing constraints;
- Uncertainty-encompassing constraints.

To model supply and demand uncertainty, a stochastic scenarios tree was established. Each tree node is associated to a randomised occurrence probability and has associated supply and demand variation rates. In this specific case, each scenario gives rise to four different scenarios in the next time period, as denoted by Figure 2.

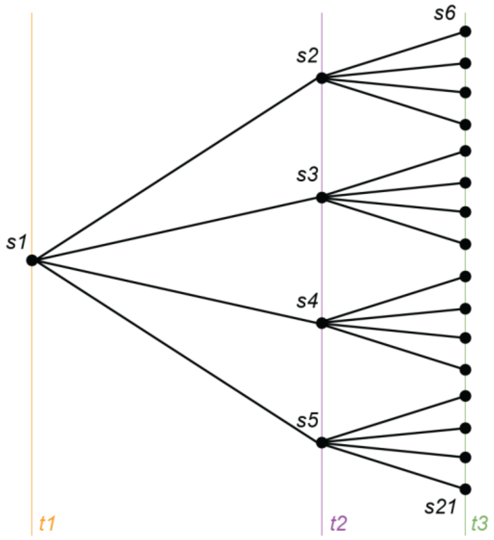

Figure 2 – Stochastic scenarios tree

4. Model formulation

This section informs on the nomenclature of the various indices, sets, parameters, and variables used. Afterwards, it provides a detailed analysis of the objective function and all supporting equations and constraints.

4.1. Indices

v (and *w)* is for SC entities, *p* is for products, *i* is for processing and reprocessing technologies, *t* is for time periods, and *s* is for nodes in the stochastic scenarios tree.

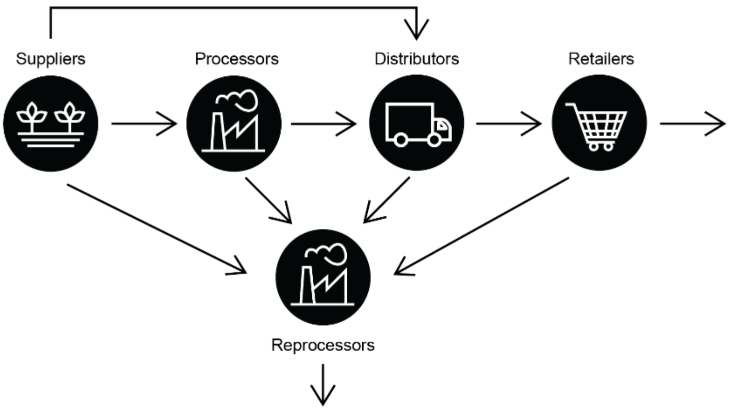

Figure 1 – General structure of the AFSC

4.2. Sets

The set of entities is divided in several subsets, so that $V = \{V_{sto} \cup V_{tra} \cup V_{sup} \cup V_{fac} \cup V_{war} \cup V_{mar} \cup V_{rep} \cup V_{tec}\}$; V_{sto} is entities with storage, V_{tra} is entities with product transformation, V_{sup} is suppliers, V_{fac} is factories, V_{war} is warehouses, V_{mar} is markets, V_{rep} is reprocessors, and V_{tec} is entities with technology. For products, $P = \{P_{was} \cup P_{fin} \cup P_{raw}\}$; P_{was} is waste, P_{fin} is final products, and P_{raw} is raw materials. For technologies, $I = \{I_{pro} \cup I_{rep}\}$; I_{pro} is processing technologies and I_{rep} is reprocessing technologies. It should be noted that, for the particular case study discussed herein, processing and reprocessing entities coincide, as reprocessing technologies are installed in already existing factories. Product flows are represented by set *F*, and the set of nodes from the scenarios tree for each time period is represented by *S*, so that $S = \{(s,t): s \in K \wedge t \in T\}$, with *K* being the set of nodes and *T* the set of time periods. *Q* represents the set of predecessors of each node *s*, and *Z* is the set of two-stage predecessors of node *s*.

4.3. Parameters

qpl^{upper} is the maximum flow of materials allowed between two entities; qpl^{lower} is the minimum flow of materials allowed between two entities; *target* is the minimum allowed percentage of demand satisfaction; *percent* is the minimum allowed percentage of technology capacity usage; *ir* is the interest rate; *sv* is the salvage value of the investment performed; *tr* is the tax rate; fci^{max} *is the* maximum invested fixed capital; tor_v is the inventory turnover ratio in entity *v*; $initialinv_v$ is the initial storage investment for each entity with storage capacity; $centityinit_v$ is the initial storage capacity of each entity; $cesto^{max}_{v,t}$ is the maximum limit for the expansion of storage capacity in entity *v* in time period *t*; $cesto^{min}_{v,t}$ is the minimum limit for the expansion of storage capacity in entity *v* in time period *t*; $nexsto_v$ is the maximum total limit for the expansion of storage capacity in entity *v*; $cinv_v$ is the cost of inventory in entity *v* per stored product unit; $rate_s$ is the product demand variation rate for each node *s*; $suprate_{p,s}$ *is the* supply variation rate for product *p* for each node *s; *$dmk^{upper}_{p,v}$ is the maximum value for the demand of product *p* in entity *v* in the first time period*;* $initinv_{p,v}$ is the initial inventory of product *p* in entity *v;* $avai_{p,v}$ is the availability of raw material *p* in entity *v;* $fpprod_{p,v}$ is the final price of product *p* in entity *v;* $prmat_{p,v}$ is the price of raw material *p* in entity *v;* $qrmat_{p,p'}$ is the quantity of raw material *p* necessary to produce product *p';* $finpro_{p,i}$ is the final product *p* of each technology *i;* $posspur_{p,v}$ is the product *p* which entity *v* has the possibility to purchase; $cdisp_{p,v}$ is the cost of disposal of product *p* in entity *v;* $reprof_{p,v}$ is the fraction of waste *p* which is possible to reprocess in entity *v;* $imwf_{p,v}$ is the fraction of product *p* which immediately turns into waste in entity *v;* $lostsf_{p,v}$ is the fraction of stored product *p* which is lost as waste in entity *v;* $sdmis_{p,v}$ is the fraction of product *p* which is lost due to supply and demand mismatch in entity *v;* $cpl^{init}_{i,v}$ is the initial capacity of technology *i* in entity *v;* $invinit_{i,v}$ is the initial investment in each technology *i* in entity *v;* $operc_{i,v}$ is the operative cost of technology *i* in entity *v* for each produced unit; $pcons_{i,p}$ is the consumption of product *p* by technology *i;* $prodt_{i,p}$ is the technology *i* which produces product *p;* $cepl^{max}_{i,v}$ is the maximum limit for the expansion of technology *i* in entity *v;* $cepl^{min}_{i,v}$ is the minimum limit for the expansion of technology *i* in entity *v;* $nexpl_{i,v}$ is the maximum total limit for the expansion of technology *i* in entity *v;* $alphapl_{i,v,t}$ is the variable investment in technology *i* in entity *v;* $alphawh_{v,t}$ is the variable investment in entity *v* with storage capacity; $transpc_{v,v'}$ is the transportation cost for one unit between entities *v* and *v';* $link_{v,v'}$ is the cost of establishing a transportation contract between entities *v* and *v';* $fipl_{v,v'}$ is the distance between entities *v* and *v';* $prob_s$ is the probability of occurrence of node *s; and* $lvl_{v,s,t}$ is the auxiliary parameter to establish the average inventory level at entity *v* in time period *t*.

4.4. Variables

4.1.1. Continuous variables

$PU_{v,w,p,s,t}$ is the amount of product p purchased by entity *v* from entity *w* at time period *t;* $W^{in}_{i,v,p,s,t}$ is the amount of product *p* consumed by technology *i* at entity *v* in time period *t;* $W^{out}_{i,v,p,s,t}$ is the amount of product *p* produced by technology *i* at entity *v* in time period *t;* $W^{out1}_{v,p,s,t}$ is the amount of product *p* produced at farm *v* in time period *t* after supply variation is applied; $W^{out2}_{v,p,s,t}$ is the amount of product *p* produced at farm *v* in time period *t* after waste fraction is applied; $P^{farm}_{p,v,t}$ is the amount of product *p* lost at farm *v* from supply and demand mismatch in time period *t; *$SQ_{p,v,t}$ *is the* total amount of product *p* lost as waste in farm *v* in time period *t;* $QPL_{v,w,p,s,t}$ is the amount of product *p* shipped from entity *v* to entity *w* in time period *t;* $INV_{v,p,s,t}$ is the inventory level of product *p* kept at entity *v* in time period *t;* $IL_{v,s,t}$ is the average product inventory level kept at entity *v* in time period *t;* $CPL_{i,v,t}$ is the capacity of technology *i* available at entity *v* in time period *t;* $CEPL_{i,v,t}$ is the expansion of capacity of technology *i* in entity *v* undertaken in time period *t;* $C^{sto}_{v,t}$ is the storage capacity of entity *v* in time period *t;* $CE^{sto}_{v,t}$ is the expansion of storage capacity of entity *v* undertaken in time period *t;* $CSer_t$ *is the* customer service level in time period *t;* $Dem_{p,v,s,t}$ is the demand for product *p* in entity *v* in time period *t;* $UnDem_{p,v,s,t}$ is the unmet demand for product *p* in entity *v* in time period *t;* $ENPV_s$ is the ENPV corresponding to node *s;* $SA_{v,p,s,t}$ is the sales value of product *p* at market *v* in time period *t;* $CF_{s,t}$ is the cash flow in time period *t;* $ENE_{s,t}$ is the expected net earnings (ENEs) in time period *t;* $FTDC_t$ is the fraction of the total depreciation capital, which must be paid in time period *t;* *FCI* is the fixed capital investment; DEP_t is the capital depreciation factor in time period *t*.

4.4.2. Binary variables

$XPL_{i,v,t}$ equals 1 if the expansion of capacity of technology *i* at entity *v* occurs in time period *t;* $X^{sto}_{v,t}$ equals 1 if the expansion of storage capacity at entity *v* occurs in time period *t;* $YPL_{v,w,t}$ equals 1 if the flow between entities *v* and *w* is established in time period *t*.

4.5. Objective function and supporting equations

Equation 1 corresponds to the objective of ENPV maximisation, where the ENPV is expressed as a function of the cash flows ($CF_{s,t}$) of each time period (and scenario) and corresponding interest rate (*ir*). This approach was first proposed by Brealey (Brealey et al. 2014).

$$\max ENPV = \sum_{t\in T} \frac{CF_{s,t}}{(1+ir)^t} \tag{1}$$

Equation 2 allows for the calculation of the cash flow parameter for each time period featured on Equation 1. The CF is determined as the difference between the Expected NEs (ENEs) in time period *t* and the fraction of the total depreciable capital which must be paid in said time period. However, the equation for the last modelled time period also encompasses the recoverable fraction of the fixed investment via its salvage value (*sv*).

$$\begin{cases} CF_{s,t} = ENE_{s,t} - FTDC_t & t = 1, \dots, t_{final} - 1 \\ CF_{s,t} = ENE_{s,t} - FTDC_t - sv \times FCI & t = t_{final} \end{cases} \tag{2}$$

Similarly, the ENE parameter required in Equation 2 must also be calculated. Equation 3 makes this calculation by deducting all costs from the total income. The total income is calculated by the product of units sold and respective price in each of the markets. In term, the following costs are considered: cost of raw materials, determined by multiplying the number of units produced by the corresponding costs of the bill of materials; cost of operating technologies, determined by multiplying the cost of production of a single unit by technology *i* by the number of units it produces; cost of inventory, determined by the product of the cost of storage of a single unit by the average storage level at any given entity; cost of transportation, determined by estimating the total amount of transported products, which corresponds to the sum of products sent by entity *v* to other entities and the products bought by entity *v*. This total is then multiplied by the cost of transportation of a single product per distance unit and the total distance between each of the entities between which transportation is carried out at any time period; cost of waste disposal, determined by calculating the total amount of waste which is not prone to being reprocessed and multiplying it by the disposal cost per product unit. The waste amount is the difference between the influx of products to reprocessors and the sales made by them, as the resulting amount corresponds to the waste which was not reprocessed. Apart from the five parameters listed above, a final term in Equation 3 accounts for the depreciation of the fixed capital, to which the tax rate *tr* is applied. Equation 4 accounts for the calculation of this depreciation (DEP_t), which was deemed linear.

$$\begin{aligned} ENE_{s,t} = (1 - ir) \times \Bigg[& \sum_{(v,p) \in mar(v)} \left(fpprod_{p,v} \times SA_{v,p,s,t}\right) \\ & - \sum_{(v,w,p) \in sup(w)} \left(prmat_{p,v} \times PU_{v,w,p,s,t}\right) \\ & - \sum_{(i,v,p) \in Trans(v)} \left(operc_{i,v} \times W^{out}{}_{i,v,p,s,t}\right) \\ & - \sum_{(v) \in sto(v)} \left(cinv_v \times IL_{v,s,t}\right) \\ & - \left(transpc_{v,w} \times \left(qpl_{v,w,p,s,t} \times PU_{w,v,p,s,t}\right) \right. \\ & \left. \times fipl_{v,w}\right) \\ & - \sum_{(v,w,p) \in repro(w)} \left(\left(qpl_{v,w,p,s,t} - SA_{w,p,s,t}\right)\right. \\ & \left. \times cdisp_{p,v,t}\right) \Bigg] + (ir \times DEP_t) \end{aligned} \tag{3}$$

$$DEP_t = \frac{(1 - sv) \times FCI}{t} \tag{4}$$

As mentioned, the cash flow calculation considers the fraction of the depreciable capital that must be paid, in time period *t*, for which such fraction must also be calculated. For this reason, the total fixed capital was simply divided equally by all time periods, as denoted by Equation 5.

$$FTDC_t = \frac{FCI}{t} \tag{5}$$

Finally, to obtain the total fixed capital, Equation 6 encompasses the following investment needs: facility investment, which is translated by the storage capacity of each entity and the corresponding cost per capacity unit, as well as the eventual investments in storage capacity expansion and corresponding variable costs; technology investment, which is translated by the initial capacity of each technology and corresponding cost per capacity unit, as well as the eventual investments in technology capacity expansion and corresponding variable costs; transportation investment, which corresponds to the costs of celebrating transportation agreements with transportation companies for each of the necessary routes. Note the importance of the binary variable $YPL_{v,w,t}$, which ensures only effective routes are considered.

$$\begin{aligned} FCI = & \sum_{v \in sto(v)} \left(centityinit_v \times initialinv_v\right) \\ & + \sum_{v \in sto(v)} \left(alphawh_{v,t} \times CE^{sto}{}_{v,t}\right) \\ & + \sum_{v \in tec(v)} \left(cpl^{init}{}_{i,v} \times invinit_{i,v}\right) \\ & + \sum_{v \in tec(v)} \left(alphapl_{i,v,t} \times CEPL_{i,v,t}\right) \\ & + \sum_{v,w} \left(link_{v,w} \times YPL_{v,w,t}\right) \end{aligned} \tag{6}$$

4.6. Constraints

This section describes the constraints used to define the problem.

Equation 7 corresponds to a continuity condition which ensures there is coherence between the material inflows and outflows in entities where inventory is not allowed. The equation forces the total material inflow to equal the total material outflow. For this, the total inflow includes materials purchased ($PU_{v,w,p,s,t}$), materials produced ($W^{out}_{i,v,p,s,t}$), and materials received from other entities ($QPL_{w,v,p,s,t}$). The total outflow includes materials sent to other entities ($QPL_{v,w,p,s,t}$), material consumption ($W^{in}_{i,v,p,s,t}$), and material turned into waste. Two sources of waste are considered: the first corresponds to a fraction ($imwf_{p,v}$) of the manufactured products ($W^{out}_{i,v,p,s,t}$) which does not meet the required quality standards upon production; the second corresponds to a fraction ($lostsf_{p,v}$) of the average inventory level ($IL_{v,s,t}$) which becomes improper for consumption due to product perishability.

$$\begin{aligned} \sum_{w \in flow(w,v)} QPL_{w,v,p,s,t} + \sum_{w} PU_{v,w,p,s,t} + \sum_{i} W^{out}{}_{i,v,p,s,t} \\ = \sum_{v \in mar(v)} QPL_{v,w,p,s,t} + \sum_{i} W^{in}{}_{i,v,p,s,t} \\ + \sum_{i} \left(W^{out}{}_{i,v,p,s,t} \times imwf_{p,v}\right) \\ + \sum_{w} \left(IL_{v.s.t} \times lostsf_{p,v}\right) \quad \forall p \in P \wedge v \notin V_{sto} \wedge (s,t) \\ \in S \end{aligned} \tag{7}$$

Equations 8 and 9 follow the same rationale behind Equation 7 but are in turn applied to entities where inventory is allowed. As such, apart from all other terms already seen in Equation 7, the inventory levels in time period *t* ($INV_{v,p,s,t}$) and *t-1* ($INV_{v,p,s,t-1}$) are featured. Equation 8 uses the initial inventory ($initinv_{p,v}$) and is thus applied to the first modelled time period. For all remaining time periods, Equation 8 is adapted into Equation 9.

$$\begin{aligned} initinv_{p,v} + \sum_{v \in fac(v)} QPL_{w,v,p,s,t} + \sum_{w} PU_{v,w,p,s,t} + \sum_{i} W^{out}{}_{i,v,p,s,t} \\ = \sum_{v \in mar(v)} QPL_{v,w,p,s,t} + INV_{v,p,s,t} \\ + \sum_{i} W^{in}{}_{i,v,p,s,t} + \sum_{i} \left(W^{out}{}_{i,v,p,s,t} \times imwf_{p,v} \right) \\ + \sum_{w} \left(IL_{v.s.t} \times lostsf_{p,v} \right) \quad \forall p \in P \wedge v \\ \in V_{sto} \wedge s \in S \wedge t = 1 \end{aligned} \tag{8}$$

$$\begin{aligned} INV_{v,p,s,t-1} + \sum_{v \in fac(v)} QPL_{w,v,p,s,t} + \sum_{w} PU_{v,w,p,s,t} + \sum_{i} W^{out}{}_{i,v,p,s,t} \\ = \sum_{v \in mar(v)} QPL_{v,w,p,s,t} + INV_{v,p,s,t} \\ + \sum_{i} W^{in}{}_{i,v,p,s,t} + \sum_{i} \left(W^{out}{}_{i,v,p,s,t} \times imwf_{p,v} \right) \\ + \sum_{w} \left(IL_{v.s.t} \times lostsf_{p,v} \right) \quad \forall p \in P \wedge v \\ \in V_{sto} \wedge s \in S \wedge t = 1 \end{aligned} \tag{9}$$

Equations 10 and 11 focus on establishing the average inventory level at each entity. Equation 10 ensures that the average inventory level at entity *v* does not exceed a certain reasonable fraction of the total storage capacity of the entity, via the parameter $lvl_{v,s,t}$. On the other hand, Equation 11 forces the average inventory level to respect a reasonable inventory turnover ratio (tor_v) to ensure appropriate inventory management, while respecting the limit set by Equation 10.

$$lvl_{v,s,t} \times IL_{v,s,t} \leq C^{sto}{}_{v,t} \quad \forall v \in V_{sto} \wedge (s,t) \in S \tag{10}$$

$$IL_{v,s,t} = \frac{\sum_{(w,p) \in flow(v,w)} QPL_{v,w,p,s,t}}{tor_v} \quad \forall v \in V_{sto} \wedge (s,t) \in S \tag{11}$$

Equations 12 and 13 focus on purchases and sales, respectively. Equation 12 ensures entity *v* can only purchase available units from entity *w* (it should be noted that the available quantity – $avai_{p,v}$ – does not vary with the time period, as supply variation is achieved via the strategy explained at a later stage). Equation 13 forces all sales from one entity to another to be considered as a flow of products to be transported between the two, to ensure appropriate transportation costs are considered.

$$\sum_{w} PU_{w,v,p,s,t} \leq avai_{p,v} \quad \forall v \in V \wedge p \in P_{raw} \wedge (s,t) \in S \tag{12}$$

$$SA_{v,p,s,t} = \sum_{w \in flow(w,v)} QPL_{w,v,p,s,t} \quad \forall v \in V \wedge p \in P \wedge (s,t) \in S \tag{13}$$

Equation 14 ensures coherence between the production undertaken by technology *i* in entity *v* ($W^{out}{}_{i,v,p,s,t}$) and its corresponding capacity ($CPL_{i,v,t}$), by forcing production not to overcome the maximum installed capacity.

$$\begin{aligned} \sum_{p \in fin(p)} W^{out}{}_{i,v,p,s,t} \leq CPL_{i,v,t} \quad \forall i \in I \wedge v \in V_{tra} \wedge p \in P \wedge (s,t) \\ \in S \end{aligned} \tag{14}$$

Equation 15 functions similarly but instead addresses product consumption ($W^{in}{}_{i,v,p,s,t}$), by forcing product consumption by technology *i* not to exceed the total installed capacity. Meanwhile, Equation 16 defines $W^{in}{}_{i,v,p,s,t}$ as the product between the production flow ($W^{out}{}_{i,v,p,s,t}$) and the corresponding raw materials necessary to produce each of the manufactured products ($qrmat_{p,p'}$).

$$CPL_{i,v,t} \geq \sum_{i \in ipro(i)} W^{in}{}_{i,v,p,s,t} \quad \forall i \in I \wedge v \in V_{tra} \wedge t \in T \tag{15}$$

$$\begin{aligned} W^{in}{}_{i,v,p,s,t} = \sum_{p \in fin(p)} \left(W^{out}{}_{i,v,p,s,t} \times qrmat_{u,p} \right) \quad \forall i \in I \wedge v \\ \in V_{tra} \wedge p \in P \wedge (s,t) \in S \end{aligned} \tag{16}$$

Equation 17 allows for a minimum acceptable utilisation capacity of technology *i* at entity *v* to be defined for each time period (*percent*), by ensuring the product between *percent* and the technology's capacity ($CPL_{i,v,t}$) does not surpass the produced flow.

$$\begin{aligned} percent \times CPL_{i,v,t} \leq \sum_{p \in fin(p)} W^{out}{}_{i,v,p,s,t} \quad \forall i \in I \wedge v \in V_{tra} \wedge t \\ \in T \end{aligned} \tag{17}$$

Equations 18 and 19 establish the capacity ($CPL_{i,v,t}$) of technology *i* in entity *v* for any given time period *t*. Equation 18 defines such capacity as the capacity installed in the last modelled time period plus an eventual capacity expansion ($CEPL_{i,v,t}$) registered in the present time period. Equation 19 adapts Equation 18 to the first time period by making use of the initial capacity ($cpl^{init}{}_{i,v}$).

$$CPL_{i,v,t} = CPL_{i,v,t-1} + CEPL_{i,v,t} \quad \forall i \in I \wedge v \in V_{tra} \wedge t \in T \tag{18}$$

$$CPL_{i,v,t} = cpl^{init}{}_{i,v} + CEPL_{i,v,t} \quad \forall i \in I \wedge v \in V_{tra} \wedge t \in T \tag{19}$$

As technology capacity expansions ($CEPL_{i,v,t}$) are important inputs for Equations 18 and 19, these must be well defined. The trio of Equations 20, 21, and 22 define the maximum limit for technology capacity expansion in any time period ($cepl^{max}{}_{i,v}$), the minimum limit for technology capacity expansion in any time period ($cepl^{min}{}_{i,v}$), and the maximum sum of all technology capacity expansions which occur during the modelled time span ($nexpl_{i,v}$), respectively. As such, these equations ensure technology capacity expansions stay within reasonable bounds (Equations 20 and 21), and that total facility capacity dictates the maximum technology capacity installed (Equation 22).

$$CEPL_{i,v,t} \leq cepl^{max}{}_{i,v} \quad \forall i \in I \wedge v \in V_{tra} \wedge t \in T \tag{20}$$

$$CEPL_{i,v,t} \geq cepl^{min}{}_{i,v} \quad \forall i \in I \wedge v \in V_{tra} \wedge t \in T \tag{21}$$

$$\sum_{t} CEPL_{i,v,t} \leq nexpl_{i,v} \quad \forall i \in I \wedge v \in V_{tra} \wedge t \in T \tag{22}$$

Equation 23 is applied for the first time period and defines the storage capacity in entity *v* ($C^{sto}{}_{v,t}$) as the initial storage capacity for that same entity ($centityinit_v$) to which an eventual storage capacity expansion in time *t* ($CE^{sto}{}_{v,t}$) is added. Equation

24 functions similarly to Equation 23 but is instead applied to all other time periods, as the initial storage capacity is replaced by the storage capacity in the previous time period ($C^{sto}{}_{v,t-1}$). Equations 25 and 26 ensure that storage capacity expansions stay within maximum ($cesto^{max}{}_{v,t}$) and minimum ($cesto^{min}{}_{v,t}$) realistic boundaries, respectively. Equation 27 ensures the sum of all storage capacity expansions undertaken during the program runtime does not surpass a realistic limit ($nexsto_v$).

$$C^{sto}{}_{v,t} = centityinit_v + CE^{sto}{}_{v,t} \quad \forall v \in V_{sto} \wedge t \in T \tag{23}$$

$$C^{sto}{}_{v,t} = C^{sto}{}_{v,t-1} + CE^{sto}{}_{v,t} \quad \forall v \in V_{sto} \wedge t \in T \tag{24}$$

$$CE^{sto}{}_{v,t} \leq cesto^{max}{}_{v,t} \quad \forall v \in V_{sto} \wedge t \in T \tag{25}$$

$$CE^{sto}{}_{v,t} \geq cesto^{min}{}_{v,t} \quad \forall v \in V_{sto} \wedge t \in T \tag{26}$$

$$\sum_t CE^{sto}{}_{v,t} \leq nexsto_v \quad \forall v \in V_{sto} \wedge t \in T \tag{27}$$

Equation 28 ensures coherence between storage capacity at entity v in time period t ($C^{sto}{}_{v,t}$) and the inventory level for each product p in the same entity and time period ($INV_{v,p,s,t}$), by forcing the sum of all stored products never to exceed total storage capacity.

$$\sum_p INV_{v,p,s,t} \leq C^{sto}{}_{v,t} \quad \forall v \in V_{sto} \wedge p \in P \wedge (s,t) \in S \tag{28}$$

Equation 29 forces the total flow to never surpass the maximum acceptable limit for product flow (qpl^{upper}), and Equation 30 ensures the same flow is never inferior to a minimum value (qpl^{lower}).

$$\sum_p \left(QPL_{v,w,p,s,t} + PU_{v,w,p,s,t}\right) \leq qpl^{upper} \times YPL_{v,w,t} \quad \forall (v,w) \in F \wedge p \in P \wedge (s,t) \in S \tag{29}$$

$$\sum_p \left(QPL_{v,w,p,s,t} + PU_{v,w,p,s,t}\right) \geq qpl^{lower} \times YPL_{v,w,t} \quad \forall (v,w) \in F \wedge p \in P \wedge (s,t) \in S \tag{30}$$

Equations 31 and 32 establish the connection between demand and sales. Equation 31 forces sales ($SA_{v,p,s,t}$) never to surpass demand ($Dem_{v,p,s,t}$), while Equation 32 ensures sales remain above a minimum acceptable percentage of demand satisfaction ($target$).

$$SA_{v,p,s,t} \leq Dem_{v,p,s,t} \quad \forall v \in V \wedge p \in P \wedge (s,t) \in S \tag{31}$$

$$SA_{v,p,s,t} \geq Dem_{v,p,s,t} \times target \quad \forall v \in V \wedge p \in P \wedge (s,t) \in S \tag{32}$$

Equation 33 defines the demand for product p at entity v in the first time period as equal to a predetermined value ($dmk^{upper}{}_{p,v}$), as this starting point is important to then address demand uncertainty throughout the modelled time span. Having established the stochastic scenarios tree (Figure 2), Equation 34 defines demand for product p in entity v in time period t as the demand in the previous time period, to which $rate_s$ for the current tree node is applied. As such, by selecting a tree node, demand uncertainty is effectively mimicked.

$$Dem_{p,v,s,t} = dmk^{upper}{}_{p,v} \quad \forall v \in V \wedge p \in P \wedge (s,t) \in S \tag{33}$$

$$Dem_{p,v,s,t} = Dem_{p,v,s,t-1} \times rate_s \quad \forall v \in V \wedge p \in P \wedge (s,t) \in S \tag{34}$$

In the literature review, supply uncertainty has been pinpointed as one of the areas in which research is lacking. AFSCs frequently show mismatches between supply and demand due to high lead times. To mimic this condition, the supply is a theoretical value (for instance, the total production from the arable land of a farm), which never truly corresponds to the effective supply that comes from it, due to inevitable loses. From this value are then taken fractions corresponding to the various sources of loss and uncertainty that affect AFSCs, as highlighted by a set of constraints. Equation 35 serves as the starting point for supply modelling and, as mentioned, considers the maximum capacity of production of p in farm v (excluding all loses) as the maximum theoretical availability of p ($avai_{p,v}$). The equation defines variable $W^{out1}{}_{v,p,s,t}$ as the quantity of product p which is effectively produced by deducting $suprate_{p,s}$ from the theoretical availability. The parameter $suprate_{p,s}$ functions similarly to $rate_s$, as it is also an assigned value to each node in the stochastic scenarios tree, but rather corresponds to the variation in supply for each product p.

$$\sum_{\mathrm{p \in raw(p)}} \mathrm{W^{out1}{}_{v,p,s,t}} = \sum_{\mathrm{p \in raw(p)}} \left(\mathrm{avai_{p,v} \times suprate_{p,s}}\right) \quad \mathrm{\forall v \in V_{sup} \wedge p \in P_{raw} \wedge (s,t) \in S} \tag{35}$$

Equation 35 accounts for product growth variability and gives the amount of product which is prone to being harvested. Post-harvesting loses are accounted for as an average loss for the entire time period, that is, fraction $imwf_{p,v}$ (the immediate fraction of product p which turns to waste in entity v). Equation 36 defines auxiliary variable $W^{out2}{}_{v,p,s,t}$ as the total product p produced in farm v after the harvesting operations.

$$\sum_{p \in raw(p)} W^{out2}{}_{v,p,s,t} = \sum_{p \in raw(p)} \left(W^{out1}{}_{v,p,s,t} \times \left(1 - imwf_{p,v}\right)\right) \quad \forall v \in V_{sup} \wedge p \in P_{raw} \wedge (s,t) \in S \tag{36}$$

Equation 37 defines variable $P^{farm}{}_{p,v,t}$ as the total product p which is turned to waste in farm v in time period t due to excessive supply. This variable is calculated as a percentage of the total product after harvest ($W^{out2}{}_{v,p,s,t}$), as an average assumed percentage of product is lost due to this mismatch ($sdmis_{p,v}$).

$$\sum_p P^{farm}{}_{p,v,t} = \sum_{p \in raw(p)} W^{out2}{}_{v,p,s,t} \times sdmis_{p,v} \quad \forall v \in V_{sup} \wedge p \in P_{raw} \wedge t \in T \tag{37}$$

Equation 38 agglomerates all sources of waste in farms to obtain the total spoiled quantity in a given time period ($SQ_{p,v,t}$), including losses in storage due to product perishability. Finally, Equation 39 performs an inventory balance for suppliers.

$$\sum_{p\in raw(p)} SQ_{p,v,t} = \sum_{p\in raw(p)} \left(W^{out1}{}_{v,p,s,t} \times imwf_{p,v}\right) + \sum_{p} P^{farm}{}_{p,v,t} + \sum_{p\in raw(p)} \left(INV_{v,p,s,t} \times lostsf_{p,v,t}\right) \quad \forall v \in V_{sup} \wedge p \in P_{raw} \wedge (s,t) \in S \tag{38}$$

$$\sum_{w,p} PU_{v,w,p,s,t} + \sum_{p\in raw(p)} W^{out1}{}_{v,p,s,t} + \sum_{(w,p)\in flow(w,v)} QPL_{w,v,p,s,t} = \sum_{(w,p)\in flow(v,w)} QPL_{v,w,p,s,t} + \sum_{p\in raw(p)} SQ_{p,v,t} \quad \forall v \in V_{sup} \wedge p \in P_{raw} \wedge (s,t) \in S \tag{39}$$

One final constraint was established to model the functioning of reprocessing facilities. In real scenarios it is never possible to fully reprocess the waste generated alongside SCs and, consequently, only a certain fraction of the waste which reaches reprocessing facilities should generate new commercially-interesting products. This fraction is here incorporated as $reprof_{p,v}$ (the fraction of product *p* which can be reprocessed at entity *v*). Equation 40 defines the total amount of new product generated by reprocessors ($W^{out}_{i,v,p,s,t}$) as a function of the waste input ($W^{in}_{i,v,p,s,t}$) taking into account both the raw material requirements necessary to produce the new product ($qrmat_{p,p'}$) and $reprof_{p,v}$.

$$W^{in}{}_{i,v,u,s,t} \times reprof_{v,u} = \sum_{p\in raw(p)} \left(W^{out}{}_{i,v,p,s,t} \times qrmat_{u,p}\right) \quad \forall i \in I_{rep} \wedge v \in V_{rep} \wedge p \in P_{fin} \wedge u \in P_{was} \wedge (s,t) \in S \tag{40}$$

5. Case study

The case study here described is based on that first published by Jonkman et al. (2017) and later revisited by Jonkman et al. (2018). The case study was divided in three different scenarios, all with specific changes meant to be addressed comparatively to assess the applicability of the model to a realistic context. The different scenarios are structured as follows:

- Case A: the expansion of an existing AFSC is considered, in which storage is allowed solely in warehouses, and under supply and demand uncertainty;
- Case B: the expansion of the same AFSC is considered, but storage is allowed in every echelon, and under supply and demand uncertainty:
- Case C: the expansion of the same AFSC is considered, in which storage is allowed in every echelon, under supply and demand uncertainty, and including a reprocessing echelon where reverse logistics operations are allowed.

The original papers focused on the redesign and expansion of a sugar beet processing AFSC in the Netherlands, stemming from an expected rise in demand due to changing European legislation. The SC includes two processing facilities (factories), located in Dinteloord (F1) and Vierverlaten (F2), and two potential processing facilities, one equipped with conventional technology, located in Puttershoek (F3), and one with a small scale biorefinery technology, located in Roosendaal (F4). The processing echelon is served by 43 suppliers (S1-S43), each with 1000 ha allocated to the plantation of sugar beet. The distribution echelon includes 4 facilities, located in Rotterdam (W1), Eindhoven (W2), Drachten (W3), and Apeldoorn (W4), and serves a total of 17 markets (M1-M17). For the third scenario, the reprocessing echelon corresponds to facilities F1, F2, and eventually F3, in which reprocessing technologies are installed. The locations of these facilities are depicted in Figure 3.

Figure 3 - Location of the facilities within the sugar beet SC. Suppliers are marked in blue, existing processors in red, the potential conventional processor in green, the potential biorefinery processor in purple, warehouses/distributors in brown, and markets/retailers in orange.

The SC uses sugar beet (*p1*) and beet leaves (*p2*) as raw materials, originating in the supplying echelon. Each supplier has a typical sugar beet yield of 80 ton/ha in the first time period (Jonkman et al. 2018) and a beet leaves yield of 30 ton/ha in the first time period (assumed for this work). Alongside the SC the two raw materials are processed into white sugar (*p3*), raw sugar (*p4*), ethanol (*p5*), biogas (*p6*), molasses (*p7*), beet pulp (*p8*), lime fertiliser (*p9*), and tare soil (*p10*). In Case C, tare can be sold to end consumers or sent to the reprocessing echelon, where it can be used as a raw material to produce other agri-products (*p11*). The processing echelon is initially equipped with a conventional processing technology (*i1*) which converts sugar beet into white sugar, generating lime fertiliser, beet pulp, molasses, and tare soil as by-products. However, a small scale biorefinery technology (*i2*) can also be implemented, whereby sugar beet and beet leaves are converted into raw sugar, generating ethanol, biogas, and tare soil as by-products. Additionally, the raw sugar can be sold as is or converted into white sugar and molasses via a sugar refining technology (*i3*). Finally, in Case C, an additional technology (*i4*) is installed, which accounts for the reprocessing of tare soil into other agri-products. The product inputs and outputs for all four technologies are depicted in Figure 4.

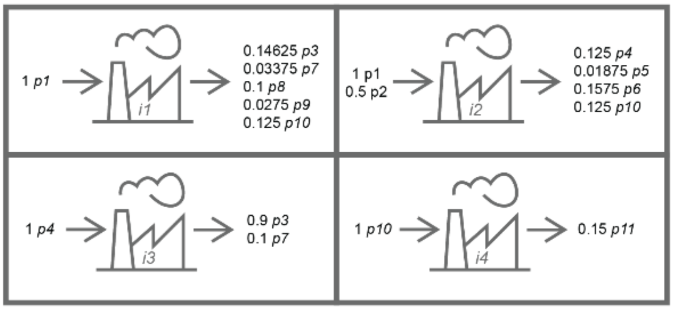

Figure 4 – Product inputs and outputs

All remaining data used to describe the case study can be found in the dissertation accompanying this document(Cruz and

Barbosa-Povoa 2018), which should be consulted for additional details.

6. Results and discussion

ENPVs of EUR 3074961.95, 3080248.23, and 4053404.26 were obtained for Cases A, B, and C, respectively. As can be seen from the presentation of the three cases, each case is similar to the last, except from additional features which would, in theory, improve the sustainability performance of the SC to an agri-food context. Naturally, this leads to an increase in the observed ENPV. The economic performance between Cases A and B is not remarkably different, as the added storage capacity throughout the SC can help prevent product wastage, but only up to a certain level, as product perishability prevents keeping high inventory levels. Still, as can be seen, this added storage capacity does impact the economic performance positively, even if not in a striking manner. However, the same does not hold true for Case C, in which a considerably higher economic performance is achieved due to the additional sales unlocked by the existence of reverse logistics.

Table 1 – Results for major economic variables for Case A

Variable	Value (EUR)
Fixed capital investment (*t1*)	13,981,000.00
Capital investment (*t2*)	437,325.00
Capital investment (*t3*)	0.00
Expected net earnings (*t1*)	6,291,700.00
Expected net earnings (*t2*)	6,972,600.00
Expected net earnings (*t3*)	7,032,200.00
Depreciation costs per time period	3,728,300.00

Table 2 – Results for major economic variables for Case B

Variable	Value (EUR)
Fixed capital investment (*t1*)	13,996,000.00
Capital investment (*t2*)	453,705.00
Capital investment (*t3*)	0.00
Expected net earnings (*t1*)	6,293,600.00
Expected net earnings (*t2*)	6,975,400.00
Expected net earnings (*t3*)	7,035,100.00
Depreciation costs per time period	3,728,600.00

Table 3 – Results for major economic variables for Case C

Variable	Value (EUR)
Fixed capital investment (*t1*)	14,882,000.00
Capital investment (*t2*)	455,240.50
Capital investment (*t3*)	0.00
Expected net earnings (*t1*)	6,994,300.00
Expected net earnings (*t2*)	7,744,200.00
Expected net earnings (*t3*)	7,809,900.00
Depreciation costs per time period	3,968,600.00

As can be seen from Tables 1, 2, and 3, the economic performance of the model improves with the addition of flexible storage strategies and reverse logistics operations. In fact, the addition of reverse logistics does provide a very meaningful increase in the maximum registered ENPV, a finding which goes well in line with what is seen in the literature review. The appropriate response to the subsequent additions of characteristics also translates the correct behaviour of the model when addressing the AFSC context, one of the desired goals of this work.

It can also be seen that the capital investments increase from one case to the next, as the addition of flexible storage capacity and one entire reprocessing echelon do come at a cost. However, and as previously mentioned, the additional investment does bear significant economic compensation.

It is interesting to note that the model behaves similarly for all three cases in terms of storage capacity. In all cases, a capacity expansion of 50 tons/year is registered for the first and second time periods for all warehouses, as this expansion was sufficient to fulfil storage requirements. In cases B and C, four of the non-warehouse entities also undergo 2 ton/year capacity expansions in the first and second time periods.

As far as technology is concerned, it should be highlighted that the model chooses to operate processing capacity increases in already-existing factories rather than opening facility F3, as this approach minimises investment costs. Contrasting, the alternative biorefinery configuration is indeed installed in facility F4 (in all cases) to satisfy demand for products not generated by the standard technology alternative.

Apart from the technologic and storage-related results, it is important to recognise how the improved economic performance of the model impacts customer service, and, most specifically, the percentage of unmet demand. The unmet demand is important for two major reasons. Firstly, the existence of unmet demand implies a potential source of revenue is not being utilised, which in turn lowers the economic performance of the SC as a whole. Secondly, the unmet demand can also be utilised to infer on the perceived customer service of the SC to the client. As customer orders are not fully complied with, the more likely it is for that customer to lose trust in the SC (or a part of its actors) and search for other business opportunities, negatively impacting the SCs' sources of revenue. As such, the lower the percentage of unmet demand, the better. Table 4 summarises the percentages of unmet demand for the three scenarios.

Table 4 – Percentage of unmet demand

Variable	Scenario		
	Case A	Case B	Case C
Unmet demand (%)	9.80	7.60	6.50

Before further analysis, it should be noted that a minimum percentage of demand satisfaction of 90% is imposed to the model as a way of ensuring a minimum acceptable level is achieved at all times. It can be seen that in Case A the minimum percentage is barely achieved (90.20% demand satisfaction). An increase in demand satisfaction is registered between Cases A and B, as the additional scattered storage capacity in Case B reduces waste (Table 5) and improves demand fulfilment. Finally, an additional increase in demand satisfaction is seen between Cases B and C, as the reverse logistics activities provide further waste reduction and generate resources that can be applied to other productive activities, thus positively impacting the available quantities for sale. Again, the unmet demand reduction further consolidates the beneficial impact of the successive improvements made to the SC and tested via Cases A, B, and C.

As mentioned in the literature review, reverse logistics operations are seen as an effective way of tackling environmental sustainability concerns, as the transformation of otherwise waste products into commercially-viable goods reduces waste and increases the levels of stock available for sale. To evaluate this situation, Table 5 displays the costs of disposal obtained for each scenario.

Table 5 – Waste disposal costs

Variable	Scenario		
	Case A	Case B	Case C
Waste disposal cost (EUR)	128,123.41	95,265.41	40,943.48

The decreasing waste disposal costs go well in line with the notion that each scenario improves on the previous. Case B includes more flexible and readily-available storage capacity, thus better addressing perishability and reducing waste. However, a considerably higher difference exists between Case C and the other cases, as reverse logistics activities considerably reduce the final waste, which cannot be subject to reprocessing.

Finally, when addressing optimisation problems, the complexity of the modelling approach is worth studying, as the increased complexity often leads to exponentially higher execution times (Table 6).

Table 6 – Model statistics for each scenario

Scenario	# single equations	# single variables	# discrete variables	Execution time (s)
Case A	94,125	2,303,749	3,921	739.34
Case B	111,397	2,439,415	3,921	1,147.12
Case C	122,928	2,767,073	4,161	2,478.45

As can be seen, the added features of each scenario contribute to the successive increase in complexity of the modelled case.

7. Conclusions

In the present work a quantitative model is proposed to support the design and planning of AFSCs via an optimisation approach, focused on the strategic and tactical decision levels. A MILP strategy is developed, and the exercise of model creation derives from the conduction of an extensive systematic review of the literature, in which a set of literature gaps are thoroughly identified and discussed. The proposed model serves as a solid step towards solving the knowledge gaps, thus providing an additional tool based on which future work can be conducted.

The results discussed in Section 6 confirm the positive response of the model towards the AFSC scenario translated by the case study. As such, it is possible to affirm that the model proposed herein serves as an improved modelling tool for the specific context of AFSCs, in which literature has been documented as scarce (please refer to Section 2). This new improved approach can then serve two major objectives. Firstly, it directly targets existing knowledge gaps. Secondly, it highlights other limitations and lack of research on the specific AFSC context, stimulating other researchers to build upon these findings with further investigative work. Despite providing several improvements when compared to non AFSC-specific models, the current model can still be subject to several improvements. At first, it should be noted that the model here developed incorporates one single economic objective, a trait which fails to meet current triple bottom line optimisation concerns. As such, the addition of an environmental objective could greatly build upon the positive impact of the model. Secondly, more attention can also be given to the stochastic scenarios tree used to model uncertainty. The proposed scenarios tree seems appropriate to the modelled context, but the application of a larger set of possible scenarios could help improve on the model's realism.

It is important to note that both multi-objective optimisation and a wider set of scenarios take a considerable toll on computational requirements and, depending on the scope of the study, optimal solutions may hardly be available. In fact, the usage of optimisation approaches to address such complex problems usually pairs with the exponential increase of the execution time, which may ascend to weeks or more. In the light of this limitation, perhaps simulation approaches may be of value (hybrid approaches). Apart from simulation strategies, the combination of optimisation approaches with heuristics can also be of interest when attempting to solve complexity problems.

To conclude, the current model contributes to the exercise of adapting existing SC management tools to the very unique AFSC context. The research effort produced satisfying results, as the model responded positively and consistently to the various scenarios. As such, a research gap was addressed, and the work here developed can serve as solid ground upon which future research can be conducted.

References

Accorsi, Riccardo, Giulia Baruffaldi, Riccardo Manzini, and Alessandro Tufano. 2018. "On the Design of Cooperative Vendors' Networks in Retail Food Supply Chains: A Logistics-Driven Approach." *International Journal of Logistics Research and Applications* 21 (1). Taylor & Francis: 35–52.

Allaoui, Hamid, Yuhan Guo, Alok Choudhary, and Jacqueline Bloemhof. 2018. "Sustainable Agro-Food Supply Chain Design Using Two-Stage Hybrid Multi-Objective Decision-Making Approach." *Computers and Operations Research* 89. Elsevier Ltd: 369–84.

Banasik, Aleksander, Argyris Kanellopoulos, G. D.H. Claassen, Jacqueline M. Bloemhof-Ruwaard, and Jack G.A.J. van der Vorst. 2017. "Assessing Alternative Production Options for Eco-Efficient Food Supply Chains Using Multi-Objective Optimization." *Annals of Operations Research* 250 (2). Springer US: 341–62.

Bilgen, Bilge, and Yelda Çelebi. 2013. "Integrated Production Scheduling and Distribution Planning in Dairy Supply Chain by Hybrid Modelling." *Annals of Operations Research* 211 (1): 55–82.

r, Sara, Nicolas Denis, and Sunil Sanghvi. 2017. "Successful Agricultural Transformations : Six Core Elements of Planning and Delivery." *McKinsey Quarterly*, no. November.

Bosona, T. G., and G. Gebresenbet. 2011. "Cluster Building and Logistics Network Integration of Local Food Supply Chain." *Biosystems Engineering* 108 (4). IAgrE: 293–302.

Brealey, R., S. Myers, F. Allen, and P. Mohanty. 2014. *Principles of Corporate Finance*. 11th ed.

Cruz, Lourenço, and Ana P. Barbosa-Povoa. 2018. "Design and Planning of Agri-Food Supply Chains."

European Commission. 2017. "Monitoring EU Agri-Food Trade : Development in 2017 2017 : Another Record Year for EU Agri-Food Exports."

Fianu, Sefakor, and Lauren B. Davis. 2018. "A Markov Decision Process Model for Equitable Distribution of Supplies under Uncertainty." *European Journal of Operational Research* 264 (3). Elsevier B.V.: 1101–15.

Galal, N. M., and K. S. El-Kilany. 2016. "Sustainable Agri-Food Supply Chain with Uncertain Demand and Lead Time." *International Journal of Simulation Modelling* 15 (3): 485–96.

Goedde, Lutz, Maya Horil, and Sunil Sanghvi. 2015. "Pursuing the Global Opportunity in Food and Agribusiness." *McKinsey Quarterly*.

Huber, Jakob, Alexander Gossmann, and Heiner Stuckenschmidt. 2017. "Cluster-Based Hierarchical Demand Forecasting for Perishable Goods." *Expert Systems with Applications* 76. Elsevier Ltd: 140–51.

Izadikhah, Mohammad, and Reza Farzipoor Saen. 2016. "A New Preference Voting Method for Sustainable Location Planning Using Geographic Information System and Data Envelopment Analysis." *Journal of Cleaner Production* 137. Elsevier Ltd: 1347–67.

Jonkman, Jochem, Ana P Barbosa-povoa, and Jacqueline M Bloemhof. 2018. "Integrating Harvesting Decisions in the Design of Agro-Food Supply Chains."

Kusumastuti, Ratih Dyah, Dirk Pieter Van Donk, and Ruud Teunter. 2016. "Crop-Related Harvesting and Processing Planning: A Review." *International Journal of Production Economics* 174. Elsevier: 76–92.

Mohammed, Ahmed, and Qian. Wang. 2017. "Developing a Meat Supply Chain Network Design Using a Multi-Objective Possibilistic Programming Approach." *British Food Journal, Vol. 119 Iss 3 Pp.*

Pipatprapa, Anirut, Hsiang-Hsi Huang, and Ching-Hsu Huang. 2016. "A Novel Environmental Performance Evaluation of Thailand's Food Industry Using Structural Equation Modeling and Fuzzy Analytic Hierarchy Techniques." *Sustainability* 8 (3): 246.

Sel, C., B. Bilgen, J. M. Bloemhof-Ruwaard, and J. G.A.J. van der Vorst. 2015. "Multi-Bucket Optimization for Integrated Planning and Scheduling in the Perishable Dairy Supply Chain." *Computers and Chemical Engineering* 77. Elsevier Ltd: 59–73.

Shabani, Amir, Reza Farzipoor Saen, and Seyed Mohammad Reza Torabipour. 2012. "A New Benchmarking Approach in Cold Chain." *Applied Mathematical Modelling* 36 (1). Elsevier Inc.: 212–24.

Tsolakis, Naoum K., Christos A. Keramydas, Agorasti K. Toka, Dimitrios A. Aidonis, and Eleftherios T. Iakovou. 2014. "Agrifood Supply Chain Management: A Comprehensive Hierarchical Decision-Making Framework and a Critical Taxonomy." *Biosystems Engineering* 120. IAgrE: 47–64.