Accepted Manuscript

Integrating harvesting decisions in the design of agro-food supply chains

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Please cite this article as: Jochem Jonkman, Ana P. Barbosa-Póvoa, Jacqueline M. Bloemhof, Integrating harvesting decisions in the design of agro-food supply chains, *European Journal of Operational Research* (2018), doi: https://doi.org/10.1016/j.ejor.2018.12.024

Highlights

- We present a generic supply chain design model for agro-food industrial supply chains

- The model is applied to the case of a sugar beet processing chain in the Netherlands

- Opportunities exist in the case to improve the economic and environmental performance

- Harvesting decisions affect supply chain design when yields vary largely in time

Integrating harvesting decisions in the design of agro-food supply chains

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Abstract

The inefficiencies observed in current agro-food supply chains, and recent trends in agro-food industry such as consolidation, increase the need for further studies on supply chain management in this field. Models are required for the complex task of determining the optimal supply chain configuration in order to improve their economic and environmental performance, while taking into account the specific characteristics of agro-food supply chains. This paper provides a general description of the supply chain design problem in agro-food industrial chains, considering the role of seasonality and harvesting decisions, perishability, and processing. A general model formulation is presented, which accommodates for these characteristics and for forward and backward flows along the chain. The general model is applied to a case study of the sugar beet processing chain in the Netherlands. The pareto-efficient frontier between maximizing the total gross margin and minimizing the global warming potential in CO_2-eq is explored. Uncertainties in demand and harvest yield are taken into account using a stochastic version of the model. Results show that a supply chain design model tailored to the specific characteristics of an agro-food supply chain with its uncertainties leads to identifying better performing supply chain configurations. In the case study, supply chain configurations can be found in which the performance on both the economic and the environmental objective is better than the modelled current performance. Additionally, we observe that supply chain configurations with decentralized processing or pre-processing are an interesting topic for future research in the context of agro-food industry.

Keywords:
OR in agriculture, Agro-food industry, Supply chain optimization, Food supply chain

1. Introduction

The current set-up of Food Supply Chains (FSCs) is an important cause for inefficiencies in food production (van der Goot et al., 2016). These inefficiencies should be reduced to

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guarantee food security for a growing world population, and improve the future responsible production and consumption of food products (in accordance with the United Nations sustainable development goals, UN General Assembly, 2015). The strategic redesign of FSCs can contribute to meet these challenges.

Inefficiencies in food production result in the creation of waste along the FSC, and a loss of the associated resources, capital, and labour invested. In Europe, the food industry represents almost 13% of the total manufacturing industry turnover (ECSIP Consortium, 2016), and the related FSCs contribute to 31% of the global warming potential (Perrot et al., 2016), while 31% of the food produced is wasted (Gustavsson et al., 2011, Timmermans et al., 2014). Addressing these issues improves the ability of FSCs to meet the demands of the population in a cost effective way while reducing their environmental impact, which is important both from an economic and an environmental perspective (Soysal et al., 2012, Tsolakis et al., 2014, Perrot et al., 2016).

The economic and environmental performance of FSCs is strongly related to their supply chain (SC) configuration, i.e. the number, type, and location of facilities and their interconnecting flows (Akkerman et al., 2010, de Keizer et al., 2017). Hence, reassessing the configuration of FSCs can improve their performance and address inefficiencies in the chain to improve its sustainability (Mota et al., 2018).

However, determining the optimal SC configuration for FSCs is a complex problem, due to the specific characteristics of food products and processes (e.g. de Keizer et al., 2015a, Soto-Silva et al., 2015). Seasonality in production and demand, the perishability of products, and product specific requirements for transportation and storage are a few examples that make the management of FSCs different from other SCs (van der Vorst and Beulens, 2002, Bourlakis and Weightman, 2004, Aramyan et al., 2007). Not every characteristic is however relevant for each FSC. Perishability and seasonality in production are for instance very important in FSCs dealing with fresh fruits, but less important for FSCs in which the products do not spoil that rapidly, as is the case for many pulses. Pulses are generally dried to prevent spoilage, although the weather conditions after harvesting could lead to post-harvest losses for these and other crops. Alternatively, processing plays an important role in for instance dairy SCs, but not in fresh fruit and vegetable SCs such as cabbages.

Due to the wide variety between FSCs, several sub-types are identified and studied in literature. Often, FSCs are categorized based on differences in shelf life (short and perishable, long and non-perishable), origin (animal, plant based), processing (fresh without product conversions, processed), or industry (agro-food, food manufacturing). Each of these subgroups has a specific set of FSC characteristics.

This article investigates decision support modelling for the strategic redesign of SC configurations for agro-food industry, where the main concern of the industry is the conversion of agro-materials into a set of semi-finished and finished products. Recent trends in this industry, such as consolidation, have increased the need for and applicability of models and tools (Ahumada and Villalobos, 2009, Tsolakis et al., 2014). Due to its dependency on agro-materials, seasonal production, harvesting, and processing are important characteristics of these Agro-Food SCs (AFSCs)(Jonkman et al., 2017). Additionally, agro-materials and their derived products are often perishable, and processing can both positively and neg-

atively influence this perishability. Moreover, the natural variability of agro-materials and weather conditions leads to uncertainties in harvest yields (supply), quality, demand and product prices. Due to these specific characteristics and their influence on the management of SCs, standard SC models have to be adapted to include these characteristics (Ahumada and Villalobos, 2009, Rajurkar and Jain, 2011).

These specific characteristics of AFSCs require taking into account harvesting decisions. The seasonal availability of a crop in combination with the perishable harvested agro-material puts restrictions on processing, and therefore affects the optimal SC configuration. Although the need for integrated support for the design and planning of AFSCs was identified (Ahumada and Villalobos, 2009, Tsolakis et al., 2014), the recent literature review of Kusumastuti et al. (2016) observes there is little work done in developing and applying a model that integrates harvesting and processing in this context.

This article contributes to the literature by presenting a Mixed Integer Linear Programming (MILP) model in which tactical decisions at the harvesting stage (area used for cultivation and time of harvesting) are integrated with strategic decisions on the AFSC design (number, location, and capacity of facilities, and the type of processing pathway to operate). It presents an overview of common characteristics of AFSCs and applies the integrated approach to a case study, while accounting for global warming impacts and the presence of uncertainty in harvest yield and demand.

Section 2 gives an overview of specific characteristics of AFSCs. Additionally, the related literature on the strategic and tactical design of AFSCs is presented. In Section 3, the decision problem is further detailed, and a general description of the model requirements and model formulation is developed. This general approach is applied to a case study building on the work of Kolfschoten et al. (2014) and Jonkman et al. (2017) on sugar beet processing in the Netherlands, as described in Section 4. The case study results are presented and discussed in Section 5, and further conclusions are drawn in Section 6.

2. Literature survey

There is a growing attention in industry and academia for the management of FSCs (Akkerman et al., 2010, Tsolakis et al., 2014). In this section, the characteristics relevant for the SC design of an agro-food industrial supply chain are presented, and an overview is given of related literature on the design of AFSCs.

2.1. AFSC characteristics

AFSCs are FSCs in which agro-materials are converted into a number of semi-finished and finished products. Although agro-materials can be of both plant and animal origin, AFSCs dealing with products from animal origin are excluded from the scope of this article due to the differences between animal and crop production, slaughtering and harvesting, and processing of the derived products.

Due to the reliance of AFSCs on agro-materials, seasonality and regional differences play an important role when managing such systems (Lucas and Chhajed, 2004, Shukla and Jharkharia, 2013). The crops produced by farmers are only available in a certain region for

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a limited period of time in which they have to be harvested. The yield and quality of the harvested crop depend on its maturity, weather conditions and the naturally varying crop itself. Hence, the supply in AFSCs is time and region dependent, and uncertain in time, quantity, and quality.

The quality of the harvested agro-materials degrades over time, and logistic operations such as transport, storage, and processing influence the quality as well (van der Vorst et al., 2009, Rong et al., 2011). At various points in the supply chain, minimum quality levels are required. Hence, quality decay is linked to the configuration of the SC (de Keizer et al., 2017), and perishability is important to take into account in AFSC design.

Additionally, the processing of agro-materials leads to a range of products. The processing yield and quality of these products is uncertain due to natural variability and the possibilities for processing and storage of products depend on the type of processing pathway operated (i.e. which combination of technologies is used) for the conversion reaction of agro-materials into products. Processing pathways that reduce quality decay could be used close to the supply of agro-materials, to obtain stable products. Pathways that increase quality decay are better located close to the final customers and timed according to demand, in order to avoid unnecessary quality loss (de Keizer et al., 2015a). The interaction with the seasonal, regional, and perishable characteristics therefore makes processing an important feature in the design of AFSCs (Jonkman et al., 2017).

2.2. Strategic AFSC design

In the strategic design and redesign of SCs the number, capacity, and location of processing facilities to operate has to be determined; how to allocate supply and demand; and if relevant which processing pathway to use (Melo et al., 2009). Although these decisions are of great importance, the number of papers dealing with the configuration of AFSCs is limited (Tsolakis et al., 2014). Decision support models used for the design of AFSCs and other FSCs are discussed in the reviews of Lucas and Chhajed (2004), Akkerman et al. (2010) and Soto-Silva et al. (2015), who note that there is a shortage of models that take the specific characteristics of FSCs into account. Additionally, we mention the reviews of Ba et al. (2016) and De Meyer et al. (2014) on methods to optimize biobased SC designs, as these SCs share a number of characteristics with AFSCs due to their dependency on plant-based raw materials. Although harvesting decisions as such received a lot of attention in literature, there is little integration with SC design or decisions in other SC echelons (Tsolakis et al., 2014, Kusumastuti et al., 2016).

Additionally, the seasonality of supply is often left out of scope in AFSC design, and the availability of raw materials in time is generally considered as a given. SC optimization models taking into account seasonality use multiple time periods related to the seasons to allow for the differences between these periods, although the quantities of raw materials available in these periods are assumed to be given (De Meyer et al., 2014, Ba et al., 2016). The availability of raw materials related to harvesting decisions is mostly investigated within a fixed SC configuration (Ba et al., 2016, Kusumastuti et al., 2016), which decouples these decisions from determining the location and capacity of processing facilities. However, the

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perishable nature of the harvested agro-materials in AFSCs requires integration between these decisions (Amorim et al., 2013).

Although perishable products received a lot of attention in production planning and inventory management literature (Ahumada and Villalobos, 2009, Amorim et al., 2013, Pahl and Voß, 2014), there are only few papers that include perishability into SC design models (Akkerman et al., 2010, de Keizer et al., 2015b). In the context of network control, perishability is modelled using fixed shelf lifes (i.e. products expire after a given number of time periods) or decay functions (e.g. every time period a certain percentage of products expires, or the quality degrades based upon an underlying distribution and products below a minimal quality level are considered expired). Notable recent contributions are de Keizer et al. (2015a) and de Keizer et al. (2017), who incorporate perishability into a network design model using a quality decay function within a hybrid optimization-simulation approach and an MILP model, respectively, although seasonality and harvesting are not considered.

In general, the papers that consider processing decisions mainly deal with the selection of technologies or processing pathways, which is especially prominent in the field of biobased SC design (De Meyer et al., 2014, Ba et al., 2016). However, a certain type of network configuration (i.e. fully centralized or with decentral pre-processing) is assumed, with processing happening in a single stage or echelon of the SC. In the case of AFSCs, multi-stage processing could improve the performance of an AFSC due to the effects of transportation and processing on product quality and perishability (Bruins and Sanders, 2012). Pre-determining the type of network configuration might therefore be restrictive on the solutions of the design model. As mentioned, there is little integration between harvesting and processing decisions, and often sequential optimization is implied of first harvesting and subsequently determining the optimal technology selection for processing, SC configuration, and allocation of flows within the SC.

Above, we observe a gap in the integration of harvesting decisions with the design of AFSCs while taking into account the identified specific characteristics of AFSCs. Closing this gap could support agro-food industrial companies with the identification of competitive SC configurations.

3. Problem description and model formulation

In this section we contribute to closing the literature gap by providing a general description of the structure of an AFSC, detailing the design problem, and by presenting a general model formulation.

3.1. Structure of the AFSC

In general, the AFSC is a multi-product SC ranging from the farmers producing the agro-materials to the customers purchasing the processed products (Figure 1). In the production stage, crops (e.g. maize) are grown at farms and yield agro-materials upon harvesting (e.g. maize kernels, corn stover). These agro-materials are processed into semi-finished and finished products in the primary processing stage. The semi-finished products can then be further processed in subsequent processing stages, and all produced products are distributed
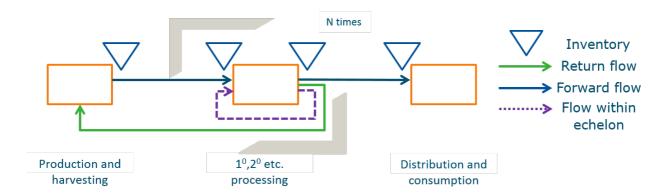
Figure 1: Schematic representation of the general Agro-Food industrial Supply Chain.

to the customers in their respective markets in the final stages of the AFSC. The principal flows of goods are therefore between the echelons of production (farmers), processing (agro-food industry), and downstream distribution and consumption (customers).

Although the literature generally assumes a centralized set-up within the processing echelon (Kusumastuti et al., 2016), alternative set-ups with the flow of goods between locations within the processing echelon are possible. Additionally, recent studies have showed the possibility of reverse flows within FSCs, including AFSCs (Banasik et al., 2017, Jonkman et al., 2017, Kang et al., 2017).

Within the AFSC, farmers and processors are mutually dependent, giving rise to SC integration. Organizationally this happens for instance through various cooperative structures in which farmers unite to jointly process their harvest, and large scale processors making use of contract farming. This also provides a platform for integrated SC decision making, and the use of related tools and models.

3.2. AFSC design model description

The integrated AFSC design model has to support selecting the SC configuration that optimizes the harvesting and processing of agro-materials, the transportation and storage of raw, semi-finished and finished products, and the reverse flows (Figure 1), taking into account the specific characteristics of the AFSC. The decision problem can be described as follows:

Given:

- A set of crops, agro-materials, semi-finished and finished products;
  - Maximum age or minimum quality of products;
- A set of processing pathways converting agro-materials into products;
  - Possible conversion reactions for a processing pathway;
  - Required inputs and produced outputs for a processing pathway;

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- A set of production, processing, and market locations;

  - Available land for production;
  - Associated costs to using a location;
  - Feasible connections between these locations;
  - Expected demand;
  - Available capacities;
  - Available transport modes;

- Relevant yield, cost and environmental impact parameters;

Select the:

- Area of land to cultivate with a crop;

- Number, size and location of processing facilities;

- Processing pathways used;

- Quantities of crops to harvest in each time period;

- Quantities of products to produce and demand to cover in each time period;

- Flow and inventory of agro-materials and products;

Subject to:

- Production and harvest constraints;

- Inventory and transportation constraints;

- Location, allocation and processing constraints;

- Quality and perishability constraints;

- Case specific constraints (e.g. legislative, existing infrastructure);

The design objectives can cover different domains of sustainability (see also Mota et al., 2018), such as the maximization of the Total Gross Margin (TGM) or the minimization of Global Warming Potential (GWP) in CO_2 equivalents, related to the previously mentioned economic and environmental impact of AFSCs. Additionally, uncertainties related to the AFSC can be incorporated.

Table 1: General categories used for the definitions of subsets.

Set	Subsets
$\mathcal{P}$	crop, agro, in, out
$\mathcal{L}$	farm, processing, market

3.3. Model formulation

The model formulation based on the description from Section 3.2 is making use of categories of products and locations, and a general way of modelling perishability, as explained in the following paragraphs.

The structure of the AFSC naturally leads to a number of general subsets or categories of products and locations. These categories can be used in the formulation of the model, as constraints may be relevant to some of these categories, but not to the whole set. For instance, harvesting only occurs at farm locations, which makes production and harvest constraints only relevant to locations in that category. Other categories for locations are processing locations and markets for downstream distribution and consumption. At farm locations the relevant product categories considered are the crops grown, and the obtained agro-materials from these crops after harvesting. Additionally there can be the demand for certain semi-finished or finished products which are outputs of processing. A product is not restricted to one category. Products in the agro-material and outputs categories can for instance also be in the processing inputs category. The general category identifiers are shown in Table 1.

There are various ways to model perishability (Pahl and Voß, 2014). In the case that perishability is related to the decline of product quality due to environmental conditions (e.g. temperature, humidity) and time, the perishability of products can be modelled as a number of discrete quality categories, based on a quality decay function (e.g. de Keizer et al., 2017). Alternatively, if the perishability is mainly related to time, it can be incorporated directly or indirectly in the form of shelf life constraints (see also van Elzakker et al., 2014). In the first case, an index is used to represent a discrete quality level, and products will have a lower limit to the quality which is accepted for processing or distribution. In the second case this index can be interpreted as a lifetime counter, and products will have an upper limit to the age at which products are still accepted for processing and distribution. The type of perishability-modelling required is case dependent.

Based on the description above, an MILP model is formulated. The following indices and sets are used:

d	$\in \mathcal{D}$	set of facility designs
j, j'	$\in \mathcal{L}$	set of locations
$\mathcal{L}_i$	$\subset \mathcal{L}$	locations that are of location category $i = \{1 \ldots LI\}$
p, p'	$\in \mathcal{P}$	set of products
$\mathcal{P}_i$	$\subset \mathcal{P}$	products that are of product category $i = \{1 \ldots PI\}$
q, q'	$\in \mathcal{Q}$	quality or age of products
r	$\in \mathcal{R}$	set of conversion reactions
t	$\in \mathcal{T}$	set of time intervals

Parameters used in the model are :

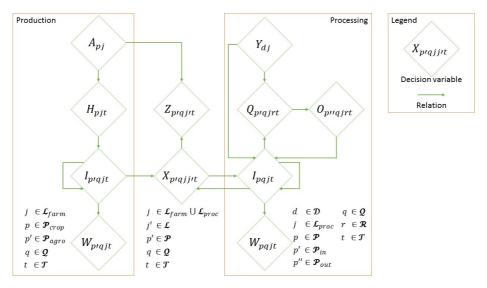|	
al_j	Arable land available at location j
$aq_{p,j}$	Arable production quota for product p at location j
cd_p	Disposal cost of product p
$cf_{d,j}$	Fixed cost of opening facility design d at location j
ch_p	Holding cost of product p
$cp_{p,r}$	Processing cost of p using conversion reaction r
$ct_{p,j,j'}$	Transportation cost for transporting product p from location j to j'
$dem_{p,j,t}$	Demand for product p at location j at time t
$df_{p,t,p',j}$	Demand factor for product p at time t of cultivating crop p' at j
ea_p	Agricultural related CO_2-eq emissions of the production of crop p
ed_p	Disposal related CO_2-eq emissions of product p
$ep_{p,r}$	Processing related CO_2-eq emissions of p using conversion reaction r
$et_{p,j,j'}$	Transportation related CO_2-eq emissions for transporting product p from location j to j'
$mb_{p,q,p',q',r}$	Bill of materials of product p with quality q from product p' with quality q' in conversion reaction r
$pc_{d,r}$	Processing capacity at facility design d for conversion reaction r
$pcl_{p,r}$	Product capacity load of product p in conversion reaction r
pp_p	Price of product p
q_p^{lim}	Quality limit for product p
$qd_{p,q',q}$	Quality decay factor of product p from q' to q per time period
$sc_{p,d}$	Storage capacity for product p at facility design d
$yc_{p,q,p',t}$	Yield of product p with quality q when harvesting crop p' at time t

Figure 2: Inter-dependency between the variables used in the model.

Decision variables used in the model are:

$A_{p,j}$	Area of land allocated to growing crop p at location j
$H_{p,j,t}$	Harvested area of p at location j at time t
$I_{p,q,j,t}$	Inventory of product p with quality q at location j at time t
$O_{p,q,j,r,t}$	Output quantity of product p with quality q at location j from reaction r at time t
$Q_{p,q,j,r,t}$	Processed quantity of product p with quality q at location j in reaction r at time t
$W_{p,q,j,t}$	Wasted product p of quality q at location j at time t
$X_{p,q,j,j',t}$	Flow of product p with quality q from j to j' at time t
$Y_{d,j}$	Facility opened using process design d at location j (binary)
$Z_{p,q,j,t}$	Demand for product p met with quality q at location j at time t

The relations between the different variables of the model are represented in Figure 2. In the following sections, the constraints specifying these relations are sorted per constraint type as described in section 3.2. Constraints are defined using the category identifiers from Table 1.

3.3.1. Production and harvest constraints

The first type of constraints encountered are related to the production of agro-materials in the AFSC. These are formulated as follows:

$$\sum_{p \in \mathcal{P}_{crop}} A_{p,j} \quad \leq \quad al_j \quad \forall j \in \mathcal{L}_{farm} \tag{1}$$

$$\sum_{t \in \mathcal{T}} H_{p,j,t} \quad = \quad A_{p,j} \quad \forall p \in \mathcal{P}_{crop}, j \in \mathcal{L}_{farm} \tag{2}$$

Equation (1) limits the total land allocated to crops to the total arable available land at a location. Complete harvest over time of the allocated land is ensured by Equation (2). In

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some cases specific constraints to limit the maximum area of certain crops may be required, for instance to prevent monocropping or allow for crop rotation (see also Mandryk et al., 2014). In this work, only a single year is taken into account. If more than a single year or cropping season is considered, an additional time dimension can be added to these constraints representing the year or season.

The harvested crops remove nutrients and soil from the production location, which can be partially replenished by returning by-products and waste streams from processing to the farms. For example, tare soil and lime fertilizer are produced within the sugar beet processing chain, which can be returned to the farms for fertilization. The demand for these return flows therefore depends on the area under cultivation. Hence, a demand constraint for these return products can be added, as described by Equation (3). In the case there are legislative or practical restrictions for the production of a harvested crop, such as was the case under the European sugar beet quota system, a constraint is applicable to restrict the quantity of a crop produced at a farm, as described by Equation (4).

$$\sum_{q \in \mathcal{Q}} Z_{p,q,j,t} \quad \leq \quad \sum_{p' \in \mathcal{P}_{crop}} df_{p,t,p',j} \times A_{p',j} \qquad \forall p \in \mathcal{P}_{return}, j \in \mathcal{L}_{farm}, t \in \mathcal{T} \tag{3}$$

$$\sum_{q \in \mathcal{Q}} \sum_{p' \in \mathcal{P}_{crop}} \sum_{t \in \mathcal{T}} yc_{p,q,p',t} \times H_{p',j,t} \quad \leq \quad aq_{p,j} \quad \forall p \in \mathcal{P}, j \in \mathcal{L}_{farm} \tag{4}$$

3.3.2. Inventory and transportation constraints

Harvested crops are added to the inventory at farm locations. Since harvesting is not relevant to other locations, the inventory balance equation is split into two parts. The inventory balance at farm locations is described by Equation (5a). For every agro-material, the quantity in stock at the start of a period is determined by the harvest yield of that product at that quality, and the stock that is carried over from the previous period. This is defined as the difference between the inventory of the previous period, the amount of product removed through transportation, waste and demand coverage, multiplied with a decay factor to determine the quality in the next time period.

$$I_{p,q,j,t} \quad = \quad \sum_{p' \in \mathcal{P}_{crop}} yc_{p,q,p',t} \times H_{p',j,t} + \sum_{q' \in \mathcal{Q}} qd_{p,q',q} \times (I_{p,q',j,t\text{-}1} - \sum_{j' \in \mathcal{L}_{proc}} X_{p,q',j,j',t\text{-}1}$$
$$- W_{p,q',j,t\text{-}1} - Z_{p,q',j,t\text{-}1}) \quad \forall p \in \mathcal{P}_{agro}, q \in \mathcal{Q}, j \in \mathcal{L}_{farm}, t \in \mathcal{T} \tag{5a}$$

Similarly, Equation (5b) describes the available quantity of a product with a certain quality at a processing location in time. The inventory at the start of a period again is dependent on the stock carried over from the previous period, subject to a decay factor to determine the quality in the current period. The first two terms refer to the inventory of the previous period and the incoming quantity of products. The third and fourth term represent the quantity of products being consumed and produced through processing, while the last

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three terms refer to the quantity of products being removed through transportation, waste and demand coverage.

$$
\begin{aligned}
I_{p,q,j,t} = & \sum_{q' \in \mathcal{Q}} qd_{p,q',q} \times (I_{p,q',j,t\text{-}1} + \sum_{j' \in \mathcal{L}} X_{p,q',j',j,t\text{-}1} - \sum_{r \in \mathcal{R}} Q_{p,q',j,r,t\text{-}1} \\
& + \sum_{r \in \mathcal{R}} O_{p,q',j,r,t\text{-}1} - \sum_{j' \in \mathcal{L}} X_{p,q',j,j',t\text{-}1} - W_{p,q',j,t\text{-}1} - Z_{p,q',j,t\text{-}1}) \\
& \forall p \in \mathcal{P}, j \in \mathcal{L}_{proc}, t \in \mathcal{T}, q \in \mathcal{Q}
\end{aligned}
\tag{5b}
$$

In both equations, a parameter $i^0_{p,q,j}$ can be added for $t = 1$ to represent any starting inventory of product p with quality q at location j. In the case that perishability is modelled using the index q as an age-counter, the decay parameter will take the value 1 if $q' = q - 1$ and 0 otherwise, which means the constraints of Equation (5a) and Equation (5b) can be reduced to direct shelf life constraints Equation (5c) and Equation (5b), respectively. For a more detailed description of direct shelf life constraints we refer to van Elzakker et al. (2014).

$$
\begin{aligned}
I_{p,q,j,t} = & \sum_{p' \in \mathcal{P}_{crop}} yc_{p,q,p',t} \times H_{p',j,t} + I_{p,q\text{-}1,j,t\text{-}1} - \sum_{j' \in \mathcal{L}_{proc}} X_{p,q\text{-}1,j,j',t\text{-}1} \\
& - W_{p,q\text{-}1,j,t\text{-}1} - Z_{p,q\text{-}1,j,t\text{-}1} \quad \forall p \in \mathcal{P}_{agro}, q \in \mathcal{Q}, j \in \mathcal{L}_{farm}, t \in \mathcal{T}
\end{aligned}
\tag{5c}
$$

$$
\begin{aligned}
I_{p,q,j,t} = & I_{p,q\text{-}1,j,t\text{-}1} + \sum_{j' \in \mathcal{L}} X_{p,q\text{-}1,j',j,t\text{-}1} - \sum_{r \in \mathcal{R}} Q_{p,q\text{-}1,j,r,t\text{-}1} \\
& + \sum_{r \in \mathcal{R}} O_{p,q\text{-}1,j,r,t\text{-}1} - \sum_{j' \in \mathcal{L}} X_{p,q\text{-}1,j,j',t\text{-}1} - W_{p,q\text{-}1,j,t\text{-}1} - Z_{p,q\text{-}1,j,t\text{-}1} \\
& \forall p \in \mathcal{P}, j \in \mathcal{L}_{proc}, t \in \mathcal{T}, q \in \mathcal{Q}
\end{aligned}
\tag{5d}
$$

The flow of products is limited to the available quantity in a time period by Equation (6). This formulation allows a flow of products between locations in the same echelon and locations in different echelons. The return flow of products in the model is therefore enabled in combination with the demand for these products as described by Equation (3).

$$
\sum_{j' \in \mathcal{L}} X_{p,q,j,j',t} \leq I_{p,q,j,t} + \sum_{r \in \mathcal{R}} O_{p,q,j,r,t} - \sum_{r \in \mathcal{R}} Q_{p,q,j,r,t} \quad \forall p \in \mathcal{P}, j \in \mathcal{L}, t \in \mathcal{T}, q \in \mathcal{Q}
\tag{6}
$$

3.3.3. Location, allocation and processing constraints

The location, allocation and processing constraints ensure that allocation of supply and demand and processing can only occur at active locations. Inventory is limited to the available inventory capacity by Equation (7). Similarly, the weighted sum of processed products is limited to the available processing capacity by Equation (8), and the opening of facilities at a single location is restricted by Equation (9). The quantity of processed products is limited by the available quantity of products from the inventory and transportation through Equation (10).

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$$\sum_{q \in \mathcal{Q}} I_{p,q,j,t} \quad \leq \quad \sum_{d \in \mathcal{D}} sc_{p,d} \times Y_{d,j} \qquad \forall p \in \mathcal{P}, j \in \mathcal{L}_{proc}, t \in \mathcal{T} \tag{7}$$

$$\sum_{p \in \mathcal{P}} \sum_{q \in \mathcal{Q}} pcl_{p,r} \times Q_{p,q,j,r,t} \leq \sum_{d \in \mathcal{D}} pc_{d,r} \times Y_{d,j} \qquad \forall r \in \mathcal{R}, j \in \mathcal{L}_{proc}, t \in \mathcal{T} \tag{8}$$

$$\sum_{d \in \mathcal{D}} Y_{d,j} \quad \leq \quad 1 \qquad \forall j \in \mathcal{L}_{proc} \tag{9}$$

$$\sum_{r \in \mathcal{R}} Q_{p,q,j,r,t} \quad \leq \quad I_{p,q,j,t} + \sum_{j' \in \mathcal{L}} X_{p,q,j',j,t} \quad \forall p \in \mathcal{P}, q \in \mathcal{Q}, j \in \mathcal{L}_{proc}, t \in \mathcal{T} \tag{10}$$

In addition, Equation (11) relates the required amount of process inputs to the produced outputs according to the bill of materials of the conversion reaction:

$$O_{p',q',j,r,t} = \sum_{p \in \mathcal{P}} \sum_{q \in \mathcal{Q}} mb_{p,q,p',q',r} \times Q_{p,q,j,r,t} \quad \forall p' \in \mathcal{P}, q' \in \mathcal{Q}, j \in \mathcal{L}_{proc}, r \in \mathcal{R}, t \in \mathcal{T} \tag{11}$$

Allocation of supply to the processing capacity is controlled by the combination of Equation (5b), Equation (6), Equation (8), and Equation (10). Allocation of the demand is accounted for by Equation (12).

$$\sum_{q \in \mathcal{Q}} Z_{p,q,j,t} \quad \leq \quad dem_{p,j,t} \quad \forall p \in \mathcal{P}, j \in \mathcal{L}, t \in \mathcal{T} \tag{12}$$

This constraint works in conjunction with the inventory balance constraints Equation (5a) and Equation (5b). These ensure that demand can only be covered from inventory with acceptable quality levels, as products are counted as waste when the quality level becomes unacceptable. Note that the demand constraint can be substituted with, or extended by, similar formulations indicating a lower bound to demand coverage. Additional case specific constraints for processing can be added, for instance to limit the number of facilities to be opened, or to represent any existing infrastructure.

3.3.4. Quality and perishability constraints

Quality decay of inventories and through processing is accounted for by Equation (5a), Equation (5b), and Equation (11), respectively. When products reach a quality level below their quality limit, or are not used before their maximum age is reached, the products are considered as waste. This is described by Equation (13) for a lower quality limit. If quality is modelled as age, the quality limit turns into an upper bound instead.

$$W_{p,q,j,t} = I_{p,q,j,t} + \sum_{j' \in \mathcal{L}} X_{p,q,j',j,t} - \sum_{j' \in \mathcal{L}} X_{p,q,j,j',t} + \sum_{r \in \mathcal{R}} O_{p,q,j,r,t} - \sum_{r \in R} Q_{p,q,j,r,t}$$
$$\forall p \in \mathcal{P}, j \in \mathcal{L}, t \in \mathcal{T}, q \in \mathcal{Q} | q \leq q_p^{lim} \tag{13}$$

Alternatively, an implicit description of waste is obtained from the inventory balance Equations (5a) and (5b) and the restriction that the inventory equals zero for all products $p \in \mathcal{P}$ for values of $q \in \mathcal{Q}$ below the cutoff value q_p^{lim}.

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3.3.5. Objective functions

Two objective functions are considered. The TGM represents the economic objective to be maximized and the GWP as environmental objective to be minimized.

$$
\begin{aligned}
TGM = & \sum_{p\in\mathcal{P}}\sum_{q\in\mathcal{Q}}\sum_{j\in\mathcal{L}}\sum_{t\in\mathcal{T}} pp_p \times Z_{p,q,j,t} - \sum_{p\in\mathcal{P}}\sum_{q\in\mathcal{Q}}\sum_{j\in\mathcal{L}}\sum_{j'\in\mathcal{L}}\sum_{t\in\mathcal{T}} ct_{p,j,j'} \times X_{p,q,j,j',t} \\
& - \sum_{p\in\mathcal{P}}\sum_{q\in\mathcal{Q}}\sum_{j\in\mathcal{L}}\sum_{t\in\mathcal{T}} ch_p \times I_{p,q,j,t} - \sum_{p\in\mathcal{P}}\sum_{q\in\mathcal{Q}}\sum_{j\in\mathcal{L}}\sum_{t\in\mathcal{T}} cd_p \times W_{p,q,j,t} \\
& - \sum_{p\in\mathcal{P}}\sum_{q\in\mathcal{Q}}\sum_{j\in\mathcal{L}}\sum_{r\in\mathcal{R}}\sum_{t\in\mathcal{T}} cp_{p,r} \times Q_{p,q,j,r,t} - \sum_{d\in\mathcal{D}}\sum_{j\in\mathcal{L}} cf_{d,j} \times Y_{d,j}
\end{aligned}
\tag{14}
$$

$$
\begin{aligned}
GWP = & \sum_{p\in\mathcal{P}}\sum_{j\in\mathcal{L}} ea_p \times A_{p,j} + \sum_{p\in\mathcal{P}}\sum_{q\in\mathcal{Q}}\sum_{j\in\mathcal{L}}\sum_{j'\in\mathcal{L}}\sum_{t\in\mathcal{T}} et_{p,j,j'} \times X_{p,q,j,j',t} \\
& + \sum_{p\in\mathcal{P}}\sum_{q\in\mathcal{Q}}\sum_{j\in\mathcal{L}}\sum_{t\in\mathcal{T}} ed_p \times W_{p,q,j,t} + \sum_{p\in\mathcal{P}}\sum_{q\in\mathcal{Q}}\sum_{j\in\mathcal{L}}\sum_{r\in\mathcal{R}}\sum_{t\in\mathcal{T}} ep_{p,r} \times Q_{p,q,j,r,t}
\end{aligned}
\tag{15}
$$

Equation (14) describes the TGM, and consists of the difference between the value of all products sold and the costs for transportation, inventory holding, waste disposal, processing, and facility depreciation costs. In this formulation, the transportation mode for a product between two locations is considered as a given, hence the transportation cost is dependent on the product, and not explicitly on the transportation mode. The cost parameter for processing includes the cost of sourcing all process inputs and operational costs from energy and labour.

Similarly, Equation (15) describes the GWP of the modelled system and includes the CO_2-eq related to agricultural production, transportation, waste disposal and processing, respectively. Because the transportation mode for a product between two locations is fixed in this formulation, the emissions related to transportation are dependent on the product and not explicitly on the transportation mode. To include modality into the decision variables, an extra index can be added to the flow of goods, and the parameters for transportation cost and transportation emissions should be defined related to this index instead of the product index.

4. Case study description

The general model as presented in Section 3.3 is applied to the sugar beet processing chain in the Netherlands, building on the work of Kolfschoten et al. (2014) and Jonkman et al. (2017). This processing chain is experiencing major changes in the supply of sugar beet and the markets for their final products due to changing legislation of the European Union (Suiker Unie, 2011, EU, 2013). Similar changes in the dairy sector led to substantial changes in that sector, hence there is an urgency to evaluate the current SC configuration in the sugar beet sector, and investigate re-design options. An increase of sugar beet supply of 20% is foreseen, due to growing markets and new uses for sugar beet derived products.

This case study can show the applicability of the model for real life applications, as it integrates harvest and processing decisions in a AFSC design problem with seasonable and
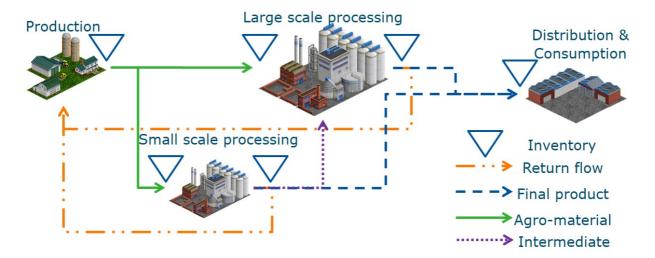
Figure 3: Stages and types of flows of goods considered in the case implementation.

perishable products, forward and return flows, capacity limitations, and allows for product flows within the processing echelon (Figure 3). More information about the implementation of the model and the model run-time is presented in Appendix A.

Every production location has the following decisions:

  i How much land to allocate to produce a crop, given the available land;

  ii In which period to harvest the crop, given the maturation of the crop;

The sugar beet campaign typically lasts for about 3-4 months, and campaign duration and harvest yield depend on uncertain weather conditions. Decision (i) affects the demand of a farm for the return flows of tare soil and lime fertilizer from the processing echelon. Additionally, decision (ii) determines the quantity of crops that is available for transport at a certain time. The existing processing facilities are considered as a given.

Processing locations can receive agro-materials from production locations, and intermediate products from other processing locations. These inputs can be converted into outputs such as intermediate products, return products, and final products. Decisions modeled are:

  iii The facility design type opened and processing pathway operated at location;

  iv The amount of inputs and outputs to receive and dispatch every period.

The quantity of inputs that can be processed into outputs depends on decision (iii), and in turn affects the quantity of products that can be dispatched (iv). The flow of products to downstream distribution and consumption, and the flow of return products back to production locations is limited by the respective demand for these products.

The product and location categories shown in Table 1 are used in the model, with an additional category for products that have a backward flow in the SC as they are returned

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Table 2: Location related parameter values.

Description	Value	Based on
Transport		
ct	*	Jonkman et al. (2017)
et	82.5g CO_2-eq $\times$ ton$^{-1}\times$ km^{-1}	Klenk et al. (2012)
Supply and demand		
al and bq	*	CBS (2014)
yc for sugar beet	80 ton $\times$ ha^{-1}	Kolfschoten et al. (2014)
ea for sugar beet	2.69 ton CO_2-eq$\times$ ha^{-1}	Klenk et al. (2012)
dem	*	Jonkman et al. (2017)

* See the accompaning data file which can be accessed through the website of the journal

Table 3: Products and membership of subsets.

$\mathcal{P}_i$	Members
crop	beetroot
agro	sugar beet, beet leaves
in	sugar beet, beet leaves, raw sugar
out	sugar, raw sugar, ethanol, biogas, lime fertilizer, molasses, beet pulp, tare soil
return	molasses, beet pulp, lime fertilizer, tare soil
final	sugar, raw sugar, ethanol, biogas

from the processing echelon to the farms, according to the description provided above. Values for the location related parameters are presented in Table 2.

The products considered in the case, and their membership of different subsets are presented in Table 3 for clarification. Additionally, values of product related parameters are presented in Table 4. The process designs considered in (iii) are the conventional design used in the existing facilities, and a smaller scale biorefinery design as proposed by Kolfschoten et al. (2014). The conventional design is focused on processing sugar beet into white sugar, with lime fertilizer, beet pulp, molasses and tare soil as additional products. The small scale design is processing sugar beet and beet leaves into raw sugar, ethanol, biogas and tare. The raw sugar can be sold on the market as a final product, but can also be refined by conventional facilities into white sugar.

Parameter values related to the processing are presented in Table 5. The required procurement and shipping of other processing inputs is indirectly accounted for in the processing cost, as is the cost of purchasing the sugar beet from the farmers. Emissions related to the processing are calculated based upon the energy consumption of a conversion. The biogas produced by the biorefinery prevents emissions from other energy sources by the customers. These prevented emissions are subtracted from the emissions related to the conversion reaction in the biorefinery, leading to a negative emission value.

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Table 4: Product related parameter values, based on a) Jonkman et al. (2017); b) Kolfschoten et al. (2014); c) assumption.

Product	pp^a ($€ \times ton^{-1}$)	mb Traditional[b]	Biorefinery[b]	Raw sugar refining[c]
sugar beet	.	1	1	.
beet leaves	.	.	0.5	.
white sugar	500	0.14625	.	0.9
raw sugar	450	.	0.125	1
ethanol	400	.	0.01875	.
biogas	90	.	0.1575	.
molasses	150	0.03375	.	0.1
beet pulp	45	0.1	.	.
lime	6	0.0275	.	.
tare	10	0.125	0.125	.

Table 5: Process related parameter values, based on a) Kolfschoten et al. (2014); b) Jonkman et al. (2017); c) assumption; d) calculated based on Asadi (2006), Klenk et al. (2012).

Facility design[a]	Daily capacity (kton)	Annual fixed cost[b] (M€)	cp Trad.[b]	Bioref.[b]	Refin.[c] ($€ \times ton^{-1}$)	ep Trad.[d]	Bioref.[d]	Refin.[d] (kg CO$_2$-eq$\times ton^{-1}$)
Conventional	25	8.33	62.3	.	12.9			
	15	5	63.36	.	.	60.27	.	29
	10	3.67	65.49	.	.			
Biorefinery	15	5	.	63.36	.			
	10	3.67	.	65.49	.	.	-92.4	.
	6	2.67	.	69.53	.			

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5. Case results and discussion

To validate the model, the base case result of Jonkman et al. (2017) was reproduced. The cost and revenue metrics calculated based on the results were validated using Rosenboom et al. (2013). The calculated carbon footprint of 731 kg CO_2-eq per ton sugar was within the range of 242–748 kg CO_2-eq reported as average for the EU by Klenk et al. (2012).

After validation of the model, constraint Equation (4) was relaxed to represent the disappearing legislative restriction on beet production (EU, 2013), allowing for an increase in beet cultivation to accommodate for the expected growth of 20%. The optimal supply chain configuration was determined without taking the seasonal supply and perishability of the sugar beet into account. Subsequently the presented model was used to determine the optimal supply chain configuration while including harvesting decisions, seasonal supply and the perishability of sugar beet. Twelve time intervals were taken for a year, while harvesting is possible in three of these intervals, each with its expected harvest yield. Sugar beet leaves are only available during the time interval of harvesting due to their perishability, while the age limit of sugar beet was put at the time interval after harvesting.

The sensitivity of the model result was investigated for demand, harvest yield, transport cost, and data aggregation of supply and demand at municipality level or at regional level. The model was solved using different instances of these parameters, and using the two objectives. The optimal configuration did not change upon changes in transportation cost in the tested range of $\pm 10\%$. Similarly, aggregating the supply and demand related parameters at regional level ($\mathcal{L}_{farm}, \mathcal{L}_{market} = \{1, \ldots, 66\}$) did not lead to a different optimal SC configuration compared to the initial aggregation scale at the municipality level ($\mathcal{L}_{farm}, \mathcal{L}_{market} = \{1, \ldots, 403\}$). Changes of the demand parameter in the interval -10% to $+20\%$ did affect the optimal combination of facility designs, their capacities, the location, and the allocation of supply. The obtained optimal SC configurations are discussed in more detail in the following sections.

The optimal SC configuration determined without taking seasonality into account and the configuration determined with the proposed model are the same in those cases in which the TGM is optimized and the harvest yield does not vary much during the harvesting season. Similarly, once perishability is less restrictive the two approaches yield the same result. SC configurations with additional processing capacity are obtained with the proposed model in those cases where crops have a clear peak in the harvest yield, and in those cases where availability of crops is more restricted than assumed in the case where harvesting decisions were not explicitly taken into account.

5.1. Trade-off between objectives

The trade-off between the economic and environmental objective was investigated using the ϵ-constraint method (see for instance Mavrotas, 2009). The TGM was optimized while using ϵ-constraints on the environmental objective represented by the GWP. The obtained trade-off curve is shown in Figure 4, relative to the modelled performance of the currently existing SC configuration. Figure 4 shows that under the new legislative paradigm, opportunities exist to improve on both objectives. Each segment of the Pareto-efficient frontier
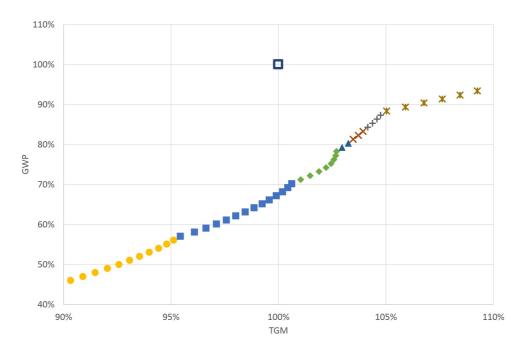
Figure 4: Trade-off curve between the economic and environmental objective. Segments of the frontier correspond to different supply chain configurations. Additional facilities per segment are detailed using their location number, a design type identifier for conventional (C) or biorefinery (B), and the daily processing capacity in kton. ❑ existing infrastructure; ● 1B15,8B15; ■ 8B15; ◆ 1C15,8B15; ▲ 3B15,8C15; ✕ 1B15,8C15; ✛ 1B10,8C15; ✳ 8C15.

corresponds to a SC configuration. The facilities opened in these configurations in addition to the existing facilities are described by indicating their location number (1–14); a design type identifier for conventional (C) or biorefinery (B); and the daily processing capacity in kton. The performance metrics of these configurations at the transition points on the frontier are presented in Table 6. Each optimal SC configuration corresponds to a specific integer solution of the model. The transitions from one configuration to another therefore lead to a non-convex trade-off curve.

Although the locations selected to open new facilities are similar throughout these configurations, there are differences between the type of facilities selected, and in some cases between the capacities. All solutions reduce the GWP by reducing average transportation distances. Additionally, using facilities with the biorefinery design improves on the environmental objective due to its negative contribution through the production of biogas. Part of the raw sugar produced by the biorefineries is refined into white sugar in those cases where the additional transportation and processing cost is offset by the benefit from the added economic value of refining the raw sugar.

The reduction of the GWP by using a biorefinery design is most clearly seen when comparing the configurations in which only a single additional facility is opened, either of the biorefinery design (8B15) or of the conventional design (8C15). The total GWP calculated for these SC configurations is respectively 494kg CO_2-eq and 686kg CO_2-eq per

Table 6: Deterministic performance metrics of the SC configurations at the transition points on the Pareto-efficient frontier, additional facilities are presented using their location number, design type conventional (C) or biorefinery (B), and the daily processing capacity in kton.

Configuration	TGM (M€)	GWP (kg CO_2-eq per ton sugar)	Average transportation distance agro-materials (km)	Average transportation distance products (km)	Sugar beet processed (Mton)	Demand for sugar covered (%)
1B15,8B15	54.7	394	31.0	42.0	6.27	100
8B15	57.9	494	35.8	48.3	6.18	100
1C15,8B15	59.1	551	31.0	43.2	6.13	100
3B15,8C15	59.4	565	30.3	44.9	6.19	100
1B15,8C15	59.8	586	31.8	42.5	6.10	100
1B10,8C15	60.3	615	32.0	44.1	6.08	100
8C15	64.3	686	34.5	48.2	6.01	100

ton sugar, even though the average transportation distances for the configuration with the biorefinery design are longer (35.8km for agro-materials and 48.3km for products versus 34.5km and 48.2km). This indicates that producing by-products with a negative associated footprint has a bigger impact on the GWP of the case study than reducing the average distances. The total product portfolio of the biorefinery design has a lower value however, leading to the trade-off between the GWP and the TGM.

The trade-off curve shows that only a limited number of facility locations are part of the optimal SC configurations. The sensitivity analysis showed however that the optimal SC configuration was affected by the values of the uncertain parameters for demand and harvest yield. Hence, a solution has to be found that performs well given the uncertain parameter values affecting the optimal SC configuration.

5.2. Demand and harvest yield uncertainty

Given the uncertainties related to harvest yield (due to e.g. uncertain weather conditions) and uncertainties in the expected growth of the demand for products, a stochastic version of the model was used to include these uncertainties in the determination of the optimal SC configuration. Scenarios were developed relating to a demand according to the currently expected growth (+20%), no growth in demand, and a small reduction in demand for the products produced (-10%), with expected probabilities of 0.4, 0.45, and 0.15, respectively. Similarly, scenarios were developed representing harvest yields above expectations, according to current expectations, and below expectation, with probabilities of 0.15, 0.60, and 0.25, respectively. In total, this led to 9 scenarios tested with the stochastic version of the model (see the accompanying data file which can be accessed through the website of the journal). An index s was defined to represent the different scenarios, and was added to the variables

Table 7: Weighted sum over all scenarios of the performance metrics of the optimal SC configuration obtained with the deterministic and the stochastic version of the model. Additional facilities are presented using their location number, design type conventional (C) or biorefinery (B), and the daily processing capacity in kton.

	Deterministic	Stochastic
Additional facilities	8C15	1C15,8C15
Expected TGM (M€)	65.7	66.5
Expected GWP (kg CO_2-eq×ton sugar^{-1})	712	704
Average transp. distance agro-materials (km)	37.3	32.6
Average transp. distance products (km)	49.2	43.0
Transp. cost agro-materials (€×ton agro-material^{-1})	3.73	3.26
Transp. cost products (€×ton agro-material^{-1})	2.13	1.86
Acreage of beetroot (kha)	90	90
Sugar beet processed (Mton)	6.26	6.37
Expected demand for sugar covered (%)	98.0	99.5

H, I, O, Q, W, X, Z, and parameters dem, and yc. An additional parameter pr_s was defined to represent the probability of each scenario, and used to formulate the objective function maximizing the expected TGM over all scenarios according to :

$$max \sum_{s \in \mathcal{S}} pr_s \times TGM_s \qquad (16)$$

In which the probability of a scenario is used as a weight to the performance of that scenario. The weighted performance over all scenarios of this configuration is presented in Table 7. For comparison, the performance of the SC configuration obtained with the deterministic approach was calculated for all scenarios used in the stochastic model, and the weighted performance is presented alongside the stochastic results.

Taking into account the uncertainties related to demand and harvest yield leads to an optimal SC configuration with more additional processing capacity than was the case for the deterministic version. The expected performance on both objectives of this configuration for the tested scenarios is better than the performance of the deterministic configuration. Additional capacity gives flexibility to deal with increased product demand, with high harvest yields, and with peaks in harvest yields. However, the stochastic configuration leads to lower performance in scenarios where the demand is lower than currently the case, due to the depreciation on facilities regardless of whether the capacity is used. Since the economic objective was maximized, no facilities with the biorefinery design were selected, although these are expected to appear in cases where a balance is sought between the economic and the environmental objective.

6. General discussion and conclusions

Not much work exists which presents SC design models tailored to applications in the context of AFSCs. There is a gap integrating harvesting decisions with SC design, taking

into account the specific characteristics and uncertainties of the AFSC. Integrating these decisions into strategic AFSC design leads to the identification of SC configuration that are more tailored to the seasonal characteristics of the AFSC. The general problem description and model formulation presented in this work can support decision makers in agro-food industry to identify interesting opportunities for AFSC design and re-design, while the stochastic version supports finding resilient solutions that are capable to perform well given the uncertainties related to the AFSC.

Applicability of the model formulation was shown using the case study of the sugar beet processing chain in the Netherlands. The case study results show that opportunities exist for SC improvement using more decentralized processing, indicating that decentralized processing or decentral pre-processing are potentially interesting SC configurations in the context of agro-food industry. Additionally, the limited sensitivity of the optimal SC configuration to spatial data aggregation at municipality level or regional level is interesting for further analysis. Although limited aggregation leads to more detailed results, the positive effect of aggregation on model run-time and the effort of dealing with the detailed data can justify using aggregated data for strategic SC design studies in agro-food industry.

Explicitly including harvesting decisions into the SC design is mainly important for those AFSCs in which the expected harvest yield shows large differences between time intervals. The importance increases further when these yields are subject to uncertainties due to for instance weather conditions. In AFSCs in which the expected harvest yield is certain and does not vary much between time intervals, a more indirect approach suffices by indirectly taking seasonality into account in parameter values, rather than explicitly modelling harvesting decisions.

The presented model, with its stochastic alternative, allows for SC optimization of a variety of AFSCs. It accommodates for forward and reverse flows of seasonal and perishable goods between and within SC echelons. Perishability can be incorporated in the form of discrete quality categories or in the form of shelf life limitations. In the case of AFSCs dealing with highly perishable goods, more detailed time intervals may be necessary than were used in the current case, and the integrated optimization of inventory and design decisions is called for (Govindan et al., 2017). Alternatively, different uncertainties can play a role, increasing the importance of the stochastic version of the presented model. This could lead to issues regarding model size and run-time. Hence, the monolithic approach used in this work could be extended using other modelling and solution techniques to deal with case studies of larger sizes. Additionally, methods to facilitate the implementation and use of these techniques within agro-food industry deserve attention.

7. Acknowledgements

Appendix A. Computational data

The model presented in Section 3.3 was implemented using GAMS (version 24.5.6) and solved using CPLEX (version 12.6.2) on an 2.60 GHz Intel Xeon E5-2660 computer with 64GB RAM. The model size depends on the data aggregation and the number of time periods considered. The full optimization problem consists of over 18 million variables and about 1.3 million constraints and could take up to 4901 minutes to solve. Aggregation of the supply and demand data at a regional level reduced the model size to about 3.5 million variables and about 0.65 million constraints. Deterministic solutions at this level of data aggregation were typically obtained in a time range of 1–7 minutes with an optimality gap set <5%. It took about 2500 minutes to solve the stochastic version of the model to optimality.

Due to the low frequency with which decision support is needed for strategic questions such as discussed in this article, the occurrence of long model run-time is not considered a major issue. However, a short model run-time facilitates interaction between decision makers and the decision support model, improving the decision making process. Hence, a further investigation into ways to reduce the model size and to improve model run-time will support further implementation and use of the research by practitioners.

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