Design and Planning of Agri-Food Supply Chains

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Preface

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Abstract

Food products of animal or vegetal origin constitute one of the most important business sectors on a worldwide scale. Providing appropriate nutrition to a growing world population, with ever increasing dietary habits, is one of the major challenges current practitioners are faced with. To ensure the sector can successfully respond to present and future challenges, the appropriate management of agri-food supply chains (AFSCs) is mandatory. This dissertation analyses current scientific knowledge in the area of AFSC design and planning and proposes a new modelling approach to close clearly defined literature gaps. The modelling approach makes use of a mixed-integer linear programming (MILP) strategy to design a quantitative model adapted to the context of AFSCs, exploring product perishability, different storage capacity strategies, and reverse logistics. The model is tested via the application of a case study, mostly drawn from an existing sugar beet supply chain in The Netherlands, and focus is given to the model's behaviour towards specific AFSC characteristics with the objective of economic optimisation. The results of this application are discussed and used to infer on the performance of the model. Finally, future research directions are highlighted to support further investigation in this field.

Keywords: Agri-food supply chain, Mixed-integer linear programming, Modelling, Perishability, Reverse logistics, Uncertainty.

Resumo

Os produtos alimentares de origem animal e vegetal constituem um dos mais importantes setores de atividade a nível mundial. Fornecer nutrição adequada a uma crescente população mundial, com hábitos alimentares cada vez mais exigentes, constitui um dos maiores desafios dos profissionais do setor. Para assegurar que o setor responde satisfatoriamente aos desafios do presente e do futuro, é necessário efetuar uma gestão apropriada das cadeias de abastecimento agroalimentares (CAAs). Esta dissertação analisa o conhecimento científico na área de projeção e planeamento de CAAs e propõe uma nova abordagem de modelação para fechar as falhas encontradas na literatura. A abordagem utiliza uma estratégia de programação linear inteira mista (PLIM) para desenhar um modelo quantitativo adaptado ao contexto das CAAs, explorando a perecibilidade dos produtos, diferentes estratégias de capacidade de armazenamento e logística reversa. O modelo é testado através da aplicação de um caso de estudo, maioritariamente retirado de uma cadeia de processamento de beterraba sacarina dos Países Baixos, com especial atenção a ser dada ao comportamento do modelo relativamente a características específicas das CAAs, tendo em vista a otimização da performance económica da cadeia. Os resultados desta aplicação são discutidos e usados para concluir acerca da prestação do modelo. Por último, são salientados e propostos objetivos para investigação futura de forma a fazer avançar o conhecimento nesta área.

Palavras-chave: Cadeia de abastecimento agroalimentar, Programação linear inteira mista, Modelação, Perecibilidade, Logística reversa, Incerteza.

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List of acronyms

AFSC – Agri-food supply chain

AHP – Analytic hierarchy process

ANP – Analytic network process

ARIMA – Auto-regressive integrated moving average

CODP – Customer order decoupling point

CSCM – Collaborative supply chain management

DEA – Data envelopment analysis

DPP – Demand penetration point

ENE – Expected net earning

ENPV – Expected net present value

EOL – End-of-life

EU – European Union

GAMS – Generic Algebraic Modelling System

GWP – Global warming potential

IDEA – Interval data envelopment analysis

JIT – Just-in-time

LCA – Life-cycle analysis

MILP – Mixed-integer linear programming

MVT – Marginal value of time

OR – Operational Research

ROSA – Recursive optimisation-simulation approach

SC – Supply chain

SCM – Supply chain management

SCP – Supply chain planning

TBL – Triple bottom line

UTP – Unfair trading practice

1. Introduction

Agribusiness activities are of extreme importance to populations, as they not only provide much needed food, but also generate jobs and wealth (European Commission 2017). The sector has existed for a large period of time, but is now facing severe changes due to profound shifts in the existing technologies and the consumption habits of end customers (Kearney 2010). 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. 2017b) are no longer a thing of the future, but rather something to which companies need to adapt to in order to remain competitive.

Despite being clear, the need for adaptation faces a set of unique challenges within agri-food supply chains (AFSCs), as these SCs possess a series of characteristics which render them unlike any other. The uniqueness of AFSCs stems from intrinsic characteristics which make AFSC management vastly different from the management of other SCs. Among these characteristics, three can be highlighted. Firstly, AFSCs deal mostly with highly perishable products (Kusumastuti et al. 2016), which add a series of additional difficulties to the planning of SC activities (for instance, keeping high inventory levels as a means of addressing sudden demand increases is not possible, as products degenerate while in inventory). Secondly, the sector is known for featuring high uncertainty in both supply and demand, which renders planning activities more difficult (Van Der Vorst et al. 2007). Finally, the sector has naturally high lead times (Van Der Vorst et al. 2007), as both products of vegetal and animal origin require considerably more time to develop than most products from typical SCs. This characteristic, associated with the previously mentioned uncertainty, makes AFSCs particularly difficult to manage assertively.

Bearing all these challenges in mind, and knowing the sector is increasingly pushing for change, business decision-makers and academics alike have been focusing on how to better study and plan AFSCs. Naturally, Operational Research (OR) can greatly contribute to this scenario, making use of quantitative models which can become powerful tools to inform managers and other decision-makers on how to better structure and plan their SC activities. The main objective of this work is to propose and test a new modelling approach targeted at solving gaps found within current scientific knowledge in the area of AFSC design and planning using OR methods. The model focuses specifically on the design and planning of AFSCs with a strategic and tactical vision, and aims for economic performance optimisation, via expected net present value (ENPV) maximisation. Ultimately, the improved modelling approach can enable decision-makers to improve their decision capabilities and consolidate appropriate SC planning and configurations. Such improvements may be a stepping stone towards more efficient SCs, in which technological capabilities are put to optimal use and waste is reduced to a minimum, all without damaging the competitiveness of the actors within the SC.

To achieve this goal, and before suggesting a new modelling approach, an extensive analysis of the characteristics of the sector was conducted, aimed at pinpointing the major intrinsic challenges faced by AFSC stakeholders. Following, a systematic review of the literature was conducted to evaluate the efforts of the scientific community on the application of quantitative methods to support the design and planning of AFSCs and, through it, major gaps in the literature were identified. A strategic-tactical model was then formulated with the intent of selecting facility location, technology selection, and distribution planning in an AFSC context. The model is validated via a case study and, finally, conclusions are drawn, and further research steps identified.

1.1. Dissertation methodology

This section provides a comprehensive review of the methodology followed throughout this work. The major steps taken are summarised in Figure 1.1.

Figure 1.1. – Dissertation methodology

1. A theoretical characterisation of the agribusiness sector is performed, aimed at identifying the defining characteristics of AFSCs and the typical behaviour of AFSC stakeholders. These characteristics are then used to draw on the major intrinsic challenges of the sector. This context is fundamental to better understand the major diverging points between the functioning of typical SCs and AFSCs. Current practices are highlighted, and the necessities of stakeholders assessed;
2. Using the information drawn above, a transition towards the scientific community is established. To achieve this, an extensive systematic review of the literature is conducted and the state-of-the-art outlined. The review focuses on quantitative methods used to assist on the design and planning of AFSCs and culminates with the identification of clear gaps in the literature;

3. In the third stage, a new model is proposed, based on that of Cardoso *et al.* (2013). The model is implemented in the Generic Algebraic Modelling System (GAMS) and is designed to assist on the closure of literature gaps identified in the second stage;
4. To test and validate the applicability on the model created in step three, a case study with multiple scenarios is applied, based on that of Jonkman *et al.* (2017, 2018). The results are thoroughly analysed and discussed and major learning points from the model's behaviour are drawn;

Finally, the results obtained from every stage of the work are summarised and analysed. The analysis is used to propose future research steps.

1.2. Objectives

The objectives of this dissertation can be grouped in two categories. Firstly, to gather and deepen an understanding of how AFSCs operate and what are the peculiarities and challenges faced by the sector. Secondly, to evaluate how different concerns and SC characteristics affect the functioning of an AFSC, taking into account the major challenges faced by the sector. In order to achieve these goals, several intermediate goals were defined:

Problem identification

- General analysis of the agribusiness sector;
- Identification of major challenges and stakeholder behaviour;
- Assessment of the functioning of AFSCs.

Literature review

- Analysis of reviews focusing on AFSC design and planning;
- Definition of research questions and material collection;
- Analysis of papers making use of quantitative methods to assist the design and planning of AFSCs.

Model formulation

- Creation of a strategic-tactical model based on that of Cardoso *et al.* (2013);
- Establishment of constraints focusing on underexplored AFSC characteristics.

Model application

- Model testing using a case study with different scenarios, based on that of Jonkman *et al.* (2017, 2018);

Analysis of the obtained results.

1.3. Dissertation outline

This document is organised in six chapters. Chapter 1 corresponds to a brief introduction to the problem, provides a snapshot of the methodology used throughout this work, establishes objectives, and informs on the structure of the work.

Chapter 2 provides an extensive contextualisation of the agribusiness sector. Focus is given to AFSC characteristics and the behaviour of stakeholders, as well as the relevance of the issues addressed along the document.

Chapter 3 contains the systematic review of the literature, conducted in the *Web of Science Database*. The review focuses on establishing the state-of-the-art of the application of quantitative methods in the design and planning of AFSCs, with focus being given to AFSC and food product characteristics, sustainability concerns and metrics, and the deterministic or uncertain nature of the models. This analysis is structured with a set of research questions and permits the clear identification of research gaps which, upon being filled, could greatly contribute to the advance of knowledge in the field. The final part of the chapter uses previously gathered information to propose a future research framework.

Chapter 4 pertains to the model formulation and thoroughly describes the different sets, parameters, and variables used to describe the AFSC modelling problem. The chapter also analyses the ENPV maximisation objective extensively and introduces the different equations used to force constraints upon the model. The chapter highlights the different novelties introduced in the modelling approach.

Chapter 5 describes the case study used to test and validate the model developed in Chapter 4, explaining its context and presenting the data that is used, as well as the different scenarios in which the case study is divided. The scenarios structure the analysis and provide possible comparisons between the performance of the model depending on the characteristics of the AFSC. Additionally, it features the gathering, analysis, and discussion of the results of the application of the different scenarios of the case study.

Finally, Chapter 6 summarises the conclusions of this work and provides future research directions and suggestions.

2. The agribusiness sector

Along this chapter, a brief context of the agribusiness sector will be given, focusing on its importance on a global level. Additionally, an overview of key stakeholders is provided, alongside an introductory analysis of the sector's major challenges and current trends. Finally, main regulatory constraints are identified and discussed.

2.1. What is the agribusiness sector?

2.1.1. Importance

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. Recent estimates suggest that by 2050 caloric and crop demands will have increased by 70 and 100 per cent, respectively (Goedde et al. 2015). This steep rise in consumption needs, alongside water scarcity (Alcamo et al. 2007) and desertification (Bai et al. 2008), clearly indicate a need to improve how the agribusiness sector is preparing for such challenges (Goedde et al. 2015).

Agribusinesses frequently entail vast and complex SCs with international dimensions, making it particularly important to study these chains to reach out for new, innovative methods to improve (Dani 2014). Understanding the roles of farmers, traders, processors, transporters, retailers, and consumers becomes vital, as well as how all these chain participants interact with each other. This exercise led to what is known as Supply Chain Management (SCM) (Oliver and Webber 1982), a field growing in importance which focuses on planning, implementing, and controlling all processes and activities necessary for the correct and appropriate functioning of supply chains. In recent years, SCM has been extensively applied to agribusiness (see section 2.4.2.), further highlighting the sector's importance and the need for improvement.

2.1.2. Typical agribusiness supply chains

Agribusiness SCs have been reported to fall into four types: local, conserved, manufactured, and commodity (Smith 2008).

As the name indicates, local supply chains do not rely on long-distance transportation. Furthermore, local chains frequently support organic farming and can stimulate local farming economies, thus effectively combating established agricultural monopolies.

Conserved SCs make use of conservation techniques such as drying and pasteurisation to preserve food quality and avoid product degradation. The increased longevity permits long-distance transportation, enabling constant access to otherwise seasonal products such as fruits and vegetables (Wu Huang 2004). These SCs are further benefiting from current inexpensive transportation and modern conservation methods.

Manufactured products are those processed with components from different origins, often allowing consumers to avoid any post-acquisition processing. The complexity of manufactured SCs depends on the product, as simple products may involve just a few components, whereas others may require many different elements to be created. This added complexity often undermines ingredient traceability and flows of information within the chain (Smith 2008).

Finally, commodity SCs deal with products manufactured and sold to worldwide uniform specifications. The high standardisation implicates commodities can be sold everywhere. To ensure minimum cost, these products are bulked and transported by sea over great distances. Commodity prices are very dependent on the market and tend to be very low, unstable, and decline over-time (FAO 2004). Although this allows commodity-based products to be accessible to most consumers, farmers can be severely affected by sudden price-drops (Boettiger et al. 2017b).

2.1.3. Products of animal origin

Agribusinesses produce food-stuff of animal or vegetal origin, and it is interesting to explore the characteristics of SCs dealing with each of these types of products. Products of animal origin include, among others, meat and dairy.

Typical meat production includes players such as feed producers, breeders, who are responsible for growing animals to the appropriate size using feed; slaughterhouses, which receive full-grown animals and process them to obtain carcasses; processors, who receive carcasses and process them to originate the final product; retailers, such as butchers and supermarkets; and transporters, who are responsible for linking all other players. Additionally, distribution centres may exist along SCs. The amount of actors within the SC and their relations render meat SCs vast and complex (Nasuelli and Clemente 2013).

Animal breeding has a long-lead time, as animal fattening can only accelerate animal growth to a certain point, which means several weeks may be necessary for the appropriate size to be reached. As discussed in section 2.3.4., these extended lead times may pose a challenge to the SC, which may struggle to fulfil short-notice orders from other operators.

Dairy SCs include feed producers; milk producers, who use feed to grow and maintain their milk-producing herds; processors, who use milk to produce all dairy products; retailers and, naturally, transporters and distributors. Currently, most players within dairy supply chains employ technology to automate labour-intensive tasks which used to be performed manually[1]. Automation leads to more efficiency and frequently ensures higher-quality products, an important aspect considering regulation is only becoming more stringent, for example, in the United States of America[2].

2.1.4. Products of vegetal origin

Products of vegetal origin include all products derived from plants, either being floral products (decorative) or crops aimed at food production for consumption, with the latter being divided in fruits and vegetables (Negi and Anand 2014).

As sustainability and healthy eating habits become more generalised, so too becomes demand for fresh fruit and vegetables, adding pressure to SCs to accommodate for such increase. Additionally, one other challenge rises, as consumers are increasingly aware of social responsibility and tend to search for local products, a trend better discussed in section 2.4.2.4., which means producers can no longer solely rely on high-scale production in a designated location, followed by transportation to retailers such as supermarkets[3]. Contrarily, SCs for products of vegetal origin are now incorporating local producers, who sell products directly to consumers or send their products to retailers or cooperatives. These cooperatives store products from a series of local producers and later sells batches to retailers, frequently through auction (Van Der Vorst et al. 2007). Cooperatives are the preferred business model of many local farmers, who feel their bargaining power increase within SCs if represented by a single and larger entity rather than conducting business individually.

It should be noted that products of vegetal origin are very dependent on seasonality, meaning prices fluctuate considerably throughout the year. In the past, it was not possible to obtain out-of-season products, however, with improvements to transportation and storage technology, seasonality is mostly mitigated. Naturally, out-of-season products are considerably more expensive than their counterparts due to the increased transportation costs or perceived exotic nature (Van Der Vorst et al. 2007).

2.2. Sector stakeholders

Agribusinesses often entail a vast network of stakeholders due to the intrinsic complexity of SCs. The size and multiple stakeholder relations imply truly innovative and efficient solutions must come from a broad range of fully cooperative agents and not from punctual individual action. Hence, understanding who key sector stakeholders are is fundamental, as well as what stakeholders are doing and how they relate and compete. All these aspects are analysed in this section.

2.2.1. Who are they?

AFSC players have been reported to fall into four main categories: suppliers, manufacturers, distributors, and consumers (Lazzarini et al. 2001), as depicted in Figure 2.1.

[1] http://www.inboundlogistics.com/cms/article/the-dairy-supply-chain-from-farm-to-fridge/, accessed on March 2018;
[2] https://www.fda.gov/Food/GuidanceRegulation/FSMA/, accessed on March 2018;
[3] http://ilsirf.org/what-we-do/fruit-vegetable-supply-chains/, accessed on March 2018;

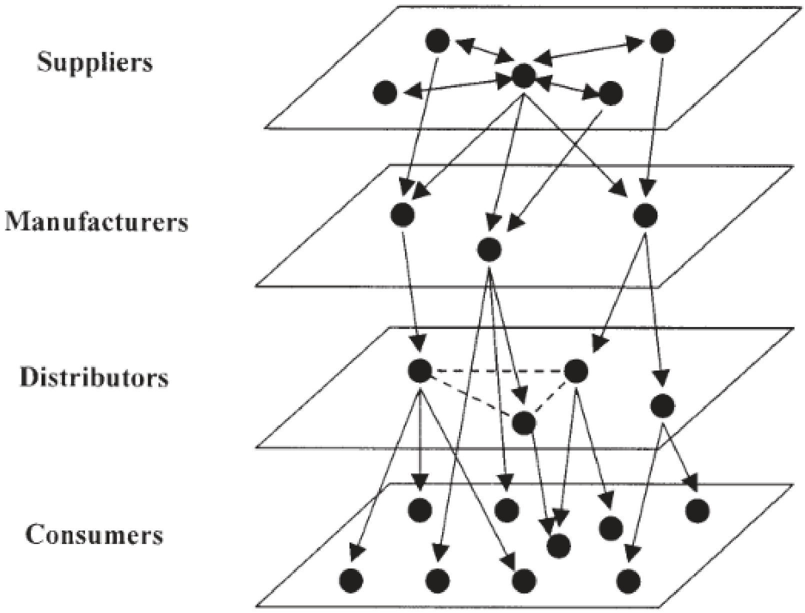

Figure 2.1. – The four categories of AFSC players, with same-level players placed horizontally and players of different levels featuring vertically. Source: (Lazzarini et al. 2001)

Suppliers such as farmers receive input materials such as seeds and fertilisers and produce food-stuff for own and/or commercial consumption. Farmers can operate in small scale (such as in backyard farming), mostly ensuring dietary needs of their own households, or in larger scope, often employing more advanced technology over larger parcels of land. Manufacturers, who are mostly present in manufactured-type SCs, receive inputs from farmers and other producers, and perform added-value activities to produce higher-value goods. These products are increasingly popular in developing economies, as customers gradually adopt rich-country diets with more calories, protein, and processed foods (Goedde et al. 2015). Distributors operate distribution centres which bridge the gap between processors and consumers, focusing primarily on storage and transportation. On the other hand, retailers are all distributors who receive finished products (either fresh or processed) and sell to consumers. Currently, retail is mostly performed via supermarkets or wholesale, although companies such as Amazon are changing this paradigm (see section 2.3.5.). At the end of SCs, consumers are gaining relevance. By changing consumption habits, consumers directly influence which products are successful at any given time. Additionally, food safety and sustainability awareness among consumers dictates how other players within SCs need to adapt to trends. Further analysis of how consumer behaviour challenges agribusiness decision-making is carried out in section 2.3.2.

Finally, remaining stakeholders include legislators and decision-makers, which frequently have a large impact on the functioning of SCs. Among these, emphasis must be given to national governments and international players such as the EU, whose legislative actions must be considered (see section 2.5.).

2.2.2. What are they doing?

Thoroughly understanding current stakeholder behaviour is mandatory to assess the impact of current strategies, evaluate weaknesses, and better design future action plans. This section focuses on farmers and retailers, with greater emphasis being given to regulatory agents in section 2.5.

Farmers are frequently operating at very low-profit margins due to the superior bargaining power of other stakeholders in the value chain, such as large supermarket chains. This trend leads farmers to avoid investing in diversifying their production and drives investment off new technologies. To cope with the current competitive environment, farmers frequently aggregate into cooperatives or join larger farming networks, thus sharing profits and risks with other participants of the same network (Van Der Vorst et al. 2007). Additionally, it is important to note that most farmers adopt one of two strategies. Either investment is made into growing a single crop, one in which the farmer has vast know-how, or a mix of different crops is chosen. Currently, European farmers are trending towards the latter, as the EU's ReMIX[4] initiative encourages crop mixing to ensure agricultural resilience.

On the other hand, retailers (namely, supermarkets) are also responding to the increasingly competitive environment to ensure client retention. The most significant trends among retailers include accepting only high-quality products to improve client satisfaction, performing aggressive promotion campaigns, and putting growing focus on biological and/or Fairtrade goods[5]. In turn, producers and distributors must adjust their productive activities to satisfy supermarket needs, especially regarding quality requirements and SC responsiveness to ensure compliance with short-notice orders (Van Der Vorst et al. 2007).

2.2.3. How do they relate/compete with each other?

As mentioned, AFSCs are vastly complex. To operate successfully, value chain participants must work together to solve problems and improve working methods. Such collaboration is most relevant regarding information sharing (Goedde et al. 2015). Nonetheless, players still mostly choose to share as little information as possible with their partners, fearing greater access to information might improve others' bargaining power within the chain (Van Der Vorst et al. 2007). Naturally, this mentality results in loss of efficiency. Hopefully, as SCM gains momentum, this situation might be reverted.

As mentioned, farmers are mostly operating at low profit margins due to their lower bargaining power within AFSCs. In fact, when dealing with commodity goods, farmers might even operate at a loss when prices drop abruptly, which is not uncommon. However, recent reports (Boettiger et al. 2017b, 2017a; Plaizier et al. 2015) show a more cooperative relationship between farmers and other players is highly beneficial, arguing that successful farming transformations cannot occur without first investing in farmers.

[4] https://www.remix-intercrops.eu/, accessed on February 2018;
[5] https://www.fungglobalretailtech.com/research/uk-organic-fairtrade-markets-strong-demand-reflects-buoyant-consumer-spending/, accessed on March 2018;

2.3. Sector challenges

Most AFSCs face several challenges, which should be addressed by the joint action of players throughout SCs, as only then will solutions be truly impactful due to the vastness and complexity of these networks. To evaluate how decision-makers and managers should face current and future challenges, it is imperative to develop a thorough understanding of what causes them, as well as how AFSCs are impacted. Along this section, the most relevant challenges affecting AFSCs are discussed.

2.3.1. Sustainability and waste reduction

Sustainability and waste reduction are the perfect illustration of challenges faced by AFSCs, as current sustainability and environmentally-friendly trends have put them in the spotlight. In 2016, 88 million tons of food were wasted in the EU alone, with estimated costs of up to EUR 183 billion (Stenmark et al. 2016). Moreover, it has been reported that approximately one-third of food is lost or wasted globally, amounting to 1.3 billion tons per year. Overall, waste per-capita is around ten times higher in industrialised countries (Gustavsson et al. 2011). In these countries, food waste occurs mostly at the consumption level, with customers frequently discarding goods which are still appropriate for consumption (see Figure 2.2.). Contrarily, in low-income countries early SC stages are more wasteful, namely due to financial, managerial, and technical limitations (Gustavsson et al. 2011). In industrialised economies, consumer behaviour changes and better coordination between all AFSC participants may be key steps towards waste reduction. On the other hand, improving farmers' businesses and stronger industrialisation could help revert wastefulness in low-income countries.

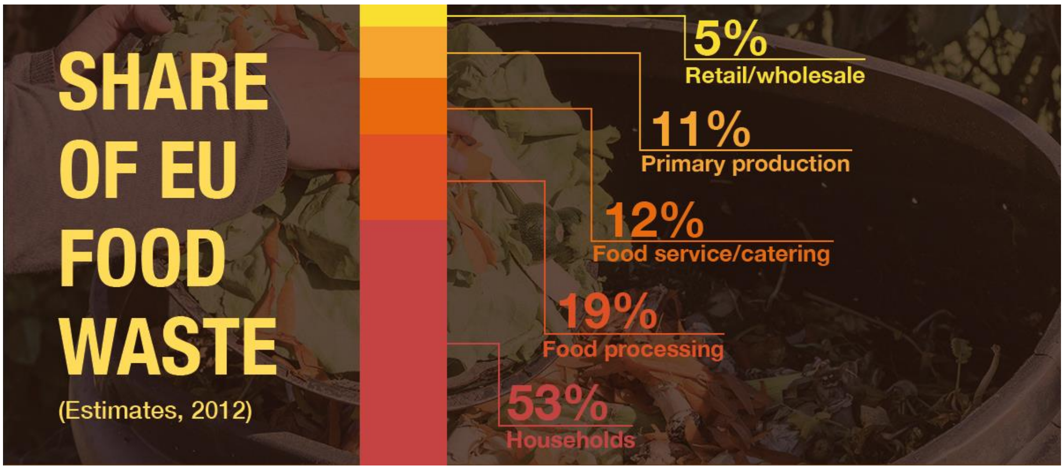

Figure 2.2. – Share of EU food waste; excerpt from a European Parliament infographic. Source: http://www.europarl.europa.eu/news/en/headlines/society/20170505STO73528/food-waste-the-problem-in-the-eu-in-numbers-infographic, accessed on March 2018;

For every wasted ton of food, resources are spent in vain and production activities generate unnecessary emissions. In 2015, McKinsey & Company (Goedde et al. 2015) named productivity as one of the key trends for the future of agribusinesses, as resource depletion will force countries to produce more with less. While genetically modified (GM) crops and other innovative technologies might support additional productivity, food waste reduction is mandatory. Considering this problem, companies are being challenged to improve product shelf-life and innovate in packaging to reduce downstream waste, as part of the efforts to meet customer demand.

Alongside waste reduction, sustainability is a pressing issue. Current AFSCs must be redesigned to ensure that resources will be available to future generations without damaging their ability to provide nutrition to a growing worldwide population. In 2017, the World Economic Forum and Deloitte TTL conducted a scenarios analysis (Schwab 2017) on the future of food security and agriculture, putting forward four different scenarios depending on two factors: market connectivity and resource consumption. It is argued that the only truly positive outcome, named *open-resource sustainability*, results from combining high market connectivity and efficient resource consumption. This scenario further consolidates the necessity for joint action in addressing current problems affecting AFSCs.

2.3.2. Uncertainty and changes in consumer behaviour

The considerable impact of uncertainty on generic SCs is well documented (Chaudhuri and Dukovska-popovska, n.d.), but its impact is even greater in AFSCs. Due to product perishability, weather unpredictability, and long lead times, AFSCs cannot rely on increased inventory to deal with supply uncertainty (Dreyer and Grønhaug 2012). Consequently, supply uncertainty is a challenge AFSCs must be designed to cope with. Among possible solutions, flexibility and adaptation are particularly important and have been extensively analysed, although with modest results (Dreyer and Grønhaug 2012). Furthermore, demand uncertainty also plays a critical role in AFSCs and is increasingly interconnected with consumer behaviour. As mentioned above, dietary habits are changing, with more people following healthy trends and having access to appropriate nutrients and calories. Such possibility stems greatly from recent improvements in productivity and transportation, as well as conservation methods, all the which allow for seasonality mitigation and a fresh supply of quality food-stuff worldwide. Due to the increase in consumer buying-power in developing economies, caloric and protein consumption are on the rise. Furthermore, and as sustainability gains increasing importance on the international stage, so do biological products, which more and more customers are willing to buy even if at a higher price (Kearney 2010).

The agribusiness sector has enormous economic, environmental, and social impact. Local farmers greatly contribute to regional development regarding both economic activity and infrastructure. It has been suggested that local farming investments are an essential driving force of any agricultural transformation and that farming improvement can be a path towards widespread, poverty-reducing growth in rural economies (Boettiger et al. 2017b). As such, it is no surprise that increasingly more consumers look for local or regional produce, in detriment of cheaper internationally-processed ones. Naturally, Fairtrade ingredients have also risen to prominence in recent years (Canada 2012).

In the past, AFSCs focused mostly on aggressive cost reduction to ensure competitive pricing. Currently, large players in the food-stuff business are changing their production habits to satisfy these newly acquired consumption habits[6]. For instance, Nestlé and Häagen-Dazs dropped their synthetic vanillin (the primary component of vanilla extract) consumption entirely for bio-vanillin, a more

[6] https://www.huffingtonpost.com/brian-kennell/healthy-food-trends-drive_b_8222388.html, accessed on March 2018;

expensive, higher quality alternative (Gallage and Møller 2015). Naturally, as players move towards satisfying new trends, so does the need to adapt existing AFSCs.

2.3.3. Product perishability

Unlike other sectors, agribusinesses cannot rely on storage of buffer products as safety stocks to suppress supply uncertainty challenges due to product perishability, that is, several goods have low shelf-life and require quick consumption. Nonetheless, the influence of product perishability is greater than just preventing safety stocking. In fact, perishability issues influence the whole SC, which must be designed to address the issue. Notably, the decrease in product quality over time, which leads to price decrease, makes conventional SC strategies inappropriate for many AFSCs (Blackburn and Scudder 2009), as these products reach peak value at the exact time of harvest, which gradually decreases over time.

Investigation on SCs of perishable products and, most specifically, fresh produce, makes use of the marginal value of time (MVT), the rate at which products lose value over time in the SC. By analysing MVT variation across AFSCs it is possible to identify hybrid strategies as the best-performing. In particular, adopting a responsive model from post-harvest to cooling, followed by an efficient model for the rest of the chain has been highlighted (Blackburn and Scudder 2009). It should be noted that responsiveness and efficiency follow the terms defined by Fisher in 1997, who argued that SCs for *functional* products (with stable, predictable demand) should be designed for cost efficiency, whereas chains for *innovative* products (volatile demand and short life-cycle) should be fast and responsive (Fisher 1997).

Commonly, fresh produce is subject to cooling or other forms of preservation to decelerate the rate at which quality is lost. However, there is a period between harvesting and conservation in which quality is lost at the highest rate, following which quality decline slows down considerably due to preservation (the moment at which goods are cooled, for example). Bearing this scenario in mind, it is comprehensible that the critical time between harvest and conservation should be kept to a minimum to avoid quality decrease (which results in decreased pricing). As such, AFSCs need to be as fast and responsive as possible at this early stage. Contrarily, and as mentioned, after conservation product quality can be maintained for longer periods of time, which means quickness is no longer as impactful and necessary. This means that, after cooling, AFSCs should no longer be designed as fast and responsive, but rather as cost-efficient (Blackburn and Scudder 2009), stressing the need for hybrid strategies.

Despite major advances in managing SCs for perishable produce, several challenges are yet to be successfully addressed. One such example is that of seafood SCs. Seafood is highly perishable, with up to 20 per cent of all seafood spoiling even before the final consumer is reached (Future of Fish 2015), which means proper icing on fishing boats is essential. However, conservation techniques such as icing are known to reduce the perceived quality of a product, which consumers don’t consider as premium as fresh alternatives. This reality implicates considerable price reduction and is yet to be properly avoided.

2.3.4. Lead times and the retail sector

Due to the nature of the productive activities, lead times between placing an order and receiving the product can be considerable in agribusiness SCs, e.g. waiting for crops or animals to grow to the appropriate size before further processing. Although this has always been the case, changes in consumer behaviour, supermarkets, and e-commerce further aggravate the problem.

Demand uncertainty has been covered in section 2.3.2. and is known to affect AFSCs considerably. The inability to accurately predict future demand for food-stuff prevents retail agents or even processors from having full confidence in the amounts to order from their respective suppliers, which can lead to fear of possible stockouts if demand suddenly increases. In sectors with very low lead times between order placement and product receival, this problem is mitigated, as retailers can prevent stockouts by placing orders which are processed fast enough and stock back up. In sectors with high lead times, however, such strategy is not possible, as orders may require considerable time to be delivered (Van Der Vorst et al. 2007). Consequently, when demand for a high-lead time product suddenly rises, retailers feel forced to order more than demand, hoping to fix the problem by placing large orders, which is a valid strategy for most low-lead time SCs. Nonetheless, as high-lead times prevent suppliers from immediately responding to orders placed, retailers grow stressed at impending stockouts, often placing yet larger orders despite having ordered more than enough. This mindset originates serious overstocking which exponentially increases along the SC and has been coined the Forrester or bullwhip effect, which will be better addressed in section 2.4.2.1.

Alongside uncertainty, the rise of supermarkets also poses further concerns towards SCs with higher lead times between order placement and product delivery. Most supermarkets remain competitive by hosting constant promotional events, which frequently revolve around weekly special sales of predetermined products. Due to their small bargaining power, most suppliers are forced to cope with deadlines and decisions imposed by large retailers, which often place short-notice orders that suppliers struggle to fulfil. Whenever promotional events are programmed, supermarkets often order larger-than-usual quantities from their suppliers, further increasing the problem. In some cases, big orders for promotional purposes have been reported to be received only 72 hours before the expected delivery time, which hatcheries and broiler houses, for instance, may not be capable to cope with (van Dijk et al. 2000). Suppliers who do not possess the ability to handle such short-notice order volumes, but cannot afford to deny business opportunities with large retailers, are often forced to buy surplus volume from other suppliers, at greater expense, and fail to make the most efficient use out of their own resources (Van Der Vorst et al. 2007).

2.3.5. New players in the sector – growth and impact

Although major agribusiness companies are expected to continue to consolidate their position in the market, small-niche players, specialised in technical details, are perceived as growing in importance (Goedde et al. 2015). Such importance stems greatly from the ability for market newcomers to bring about change, whether as small-niche players or as large companies. Naturally, change challenges existing firms to adapt their operations to meet new efficiencies, set by the emerging players.

Nonetheless, large organisations can sometimes struggle to find the flexibility to adapt quickly, and may find themselves lagging behind (Page et al. 2016) their smaller and more flexible counterparts.

In a world of rapid change, all things digital are growing to great prominence, and digital marketplaces are no exception to this trend. In this context, Amazon, and more specifically, AmazonFresh, must be highlighted, as it greatly illustrates how sector newcomers can upset and pose challenges to current agribusinesses and corresponding AFSCs. AmazonFresh is Amazon's grocery delivery service subsidiary, currently operating in the United States and some cities in Europe and Japan. The service delivers all products on the same day or the day after and is, consequently, greatly impacting AFSCs.

Despite being an online platform, Amazon still makes use of the same players of more traditional SCs, that is, producers, distributors, transporters, among others, the point of change being how the products are displayed and sold to the public (via the internet and through shipping rather than at physical stores). Naturally, the remaining actors within Amazon's SCs need to deliver according to Amazon's unique necessities.

Traditionally, orders are processed in large batches at the end of the day, but that is no longer the case, as AmazonFresh's fast deliveries require continuous operation from distribution centres, that is, smaller, more frequent shipping. The same holds true for how work is organised inside distribution centres, as orders must be processed almost immediately, and transporters need to ensure constant service. This may not be ideal for transporters, which prefer the more economical approach of operating a single large vehicle rather than multiple, less efficient assets.

Adding to this, producers are also affected and need to adjust to producing smaller batches and the frequent need to change small details in the final product very quickly to meet customised client specifications successfully. Naturally, this necessary flexibility influences how producers and processors acquire the raw materials needed to create their products, which means suppliers also need to adapt to smaller, more frequent orders[7].

Finally, as Amazon's success only seems to accelerate, close attention should be paid to the company's bargaining power within SCs to avoid unfair business-to-business trading practices, which have been briefly mentioned in section 2.3.4. and will be further discussed in section 2.5.1.

2.4. Sector tendencies/What is being done

2.4.1. Agricultural transformations

One of the most efficient ways to improve the lives of people in developing countries is to invest in agriculture (Boettiger et al. 2017b). Agriculture originates jobs, raises incomes, prevents malnutrition, and boosts the economy. Most currently industrialised countries began their development with such kinds of investment, frequently known as agricultural transformations (Boettiger et al. 2017b). These transformations carry so many benefits that many developing countries have performed, are

[7] http://www.scmr.com/article/the_amazon_effect_and_the_global_supply_chain, accessed on February 2018;

performing, or hope to perform them in the near future. Like all long-term, nation-wide policies, agricultural transformations require time and the joint action of several players to be truly effective, and greatly benefit from appropriate planning and correct execution.

In 2017, the McKinsey Centre for Agricultural Transformation issued two reports, which analyse the three drivers of agricultural transformation: transformation readiness, quality of the strategy, and delivery mechanisms (Boettiger et al. 2017a, 2017b).

Transformation readiness comprises 25 factors important or necessary for a country to be considered ready to undertake an effective agricultural transformation. As such, these factors need to be measured before any action is triggered, as attempting any transformational policy without proper readiness often results in wasted resources (Boettiger et al. 2017a). If a country is indeed ready to undergo an agricultural transformation, what to do and how to do it are important questions.

Six core elements are reported to be fundamental for agricultural transformation. Firstly, governments should prioritise strategies based on which objectives will further improve the ability to achieve other future goals. Frequently, transformations fail while trying to tackle every problem at the same time, which prevents proper resolution of each issue and leads to great overload. Secondly, private and public investment must understand that investing in farmers and, more specifically, giving farmers better working conditions and methodologies, is a sure path to long-term profitability. Additionally, appropriate change agents must be identified and mobilised. Change agents are individuals who support farmers with knowledge and insight and help accelerate transformation. Alongside prioritising, governments must understand that priority should be given to issues where know-how is already considerable, which greatly improves the likelihood of success and permits learning, which might be crucial when dealing with other problems. Furthermore, public institutions must stimulate private investors to complement public spending with complementary private investment, as only then can funding be truly impactful. Finally, policy-making should be data-driven to better assess what needs further attention and to conclude on the best possible strategies to achieve desired goals (Boettiger et al. 2017b).

Regarding how transformations should be performed, four elements have been highlighted. First, there must be willingness to change, which goes hand in hand with readiness. If willingness is non-existent, resources are better spent changing that mentality rather than forcing transformation. Adding to this, there must be leadership alignment, that is, heads of government, Chief Executive Officers (CEOs), regional representatives, and regulators must agree on key objectives and contribute effectively to its pursuit. Thirdly, leadership alignment should be complemented with leadership skill-building to ensure leaders are as impactful as possible when fighting for change to occur. At last, managing the transformation continuously is mandatory (Boettiger et al. 2017b).

2.4.2. Supply chain management

Deepening SC understanding has been reported as one of the core elements towards pursuing global opportunities in food and agribusiness (Goedde et al. 2015). The necessity to better understand SCs and, specifically, to study how decisions should be made regarding SCs led to the development of what is now known as SCM, a wide-scope field of study which can be defined as “the process of planning, implementing, and controlling the operations of the supply chain with the purpose to satisfy customer requirements as efficiently as possible. Supply chain management spans all movement and storage of raw materials, work-in-process inventory, and finished goods from point-of-origin to point-of-consumption” (Oliver and Webber 1982). SCM has evolved considerably over the years and has given managers and other SC players powerful tools to assist in decision making. This section will briefly cover important concept and trends within SCM, which will be further analysed in Chapter 3, and their application to AFSCs.

2.4.2.1. The Forrester effect

In traditional SCs, each step of the chain is viewed as an independent process which can be performed without affecting or being affected by the rest of the chain. Consequently, this leads to inventory accumulation after, and before, each step. As processes are independent, information sharing between different chain participants is often lacking and considered unnecessary, an outdated approach which gives rise to considerable problems. One such problem arises when lead times between order placement and product reception are high and is referred to as Forrester or bullwhip effect (Forrester 1961). When suppliers face sudden increases in demand, larger orders are submitted to avoid stockouts. However, due to the large lead time, managers grow concerned of possible stockouts and often place even larger, more numerous orders, disregarding that more than enough has been previously ordered, but is simply not yet at the retailer level in the SC. Naturally, this leads to considerable overstocking. Nonetheless, this is but the root of the problem. As distributors receive large orders from suppliers, and fearing stockouts of their own, even larger orders are placed to ensure a surplus margin exists. This trend continues along the chain, all the way to the early suppliers. Consequently, the earlier the stage within the SC, the greater the overshooting in supply orders (farmers, factories, and growers are the most affected, as depicted by Figure 2.3.).

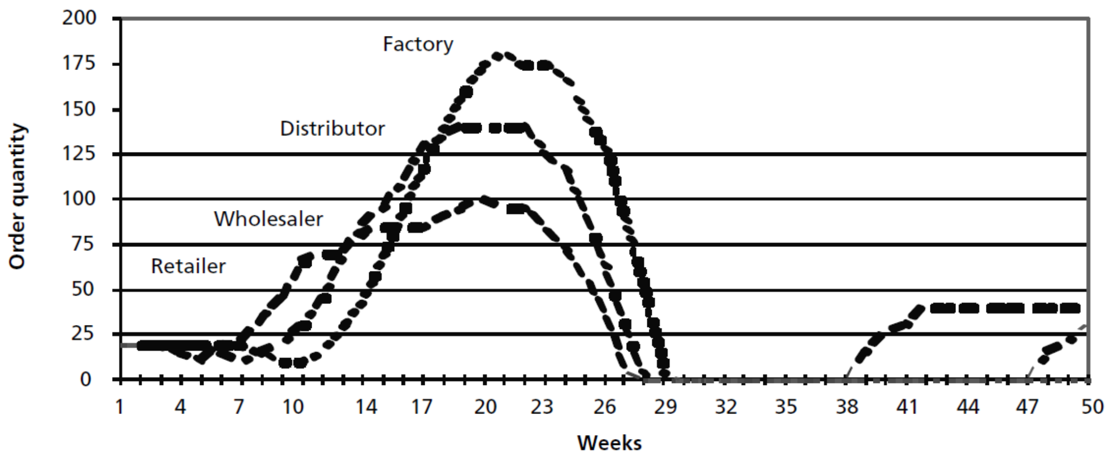

Figure 2.3. – Graphic representation of the Forrester effect. Source: (Van Der Vorst et al. 2007);

To avoid situations such as this, SCM defends SCs must be seen as a series of processes which must be accounted for as a whole, and that appropriate information flows are necessary, in which information and communication technology (ICT) plays an important role. Despite considerable efforts, the bullwhip effect is still seen in most AFSCs, stressing the need for better management of AFSC processes (Van Der Vorst et al. 2007).

The Forrester effect is particularly relevant in AFSCs, as the high-lead times between order placement and product reception increase the effect's likelihood to happen. Despite possible improvements, activities such as crop growth or animal fattening are time-consuming by nature, meaning other strategies need to be employed to deal with this problem.

2.4.2.2. Customer order decoupling point

Traditional SCs operate as a series of independent – decoupled – activities, which do not rely on the remainder of the SC to develop their processes. While this added independence may be attractive to individual operators, which are given the freedom to fully control their processes, there are downsides to the SC as a whole. Independent processes within the SC mean that inventory is kept at the interface of each activity, which increases throughput times, costs, and complicates the ability to analyse the SC. This goes against the Just-In-Time (JIT) philosophy, which argues inventories should be kept to a minimum to improve visibility and optimisation.

Inventory reduction is a less risky strategy than hoarding inventory, as the chance to stock the wrong product is also decreased. Additionally, fewer inventory across the SC allows for much faster throughput times, largely necessary for perishable goods. Finally, inventory reduction also implicates capital can be spent more efficiently.

Nowadays, the concept of fully efficient or fully responsive SCs no longer applies, as customers demand flexible, very responsive chains at very low costs (Van Der Vorst et al. 2007). This trend has led to a revisit of the classic 'push/pull' approach. One central concept of this approach is the Customer Order Decoupling Point (CODP), also referred to as the Demand Penetration Point (DPP) (Van Der Vorst et al. 2007). The CODP separates the SC into two parts: one which operates following customer orders (pull), and other which operates following forecasts (push). Naturally, inventory is kept between the two, but only at that point of the SC (thus respecting the JIT philosophy)[8]. The processes between consumers and the CODP are dependent on client orders and focus on flexibility and responsiveness. On the other hand, upstream towards suppliers, forecasts are followed, and the focus is on cost efficiency (large lots are frequent) (Van Der Vorst et al. 2007).

The CODP is regarded as important for five main reasons: it separates order-driven activities from forecast-driven ones, it is the point where independent demand is converted to dependent demand, it frequently marks the last big stock in the SC, permits upstream activities to be optimised disregarding downstream irregularities, and identifies the point where managerial decisions should move from cost efficiency to responsiveness and flexibility (Olhager 2012).

[8] http://www.toyota-global.com/company/vision_philosophy/toyota_production_system/just-in-time.html, accessed on March 2018;

The definition of the CODP is an important activity in AFSCs, especially those dealing with perishable goods. Due to the nature of products, the CODP can help establish where to keep inventories. If a product has a short-requested delivery lead time, responsiveness is essential, and inventory should be kept closer to the retailer level, that is, the CODP should be closer to the client. Contrarily, if lead time is long, inventory can be kept upstream, making use of centralised inventory management, for which the CODP should be closer to processors. Currently there is a trend to shift the CODP upstream in SCs, but the challenge remains to deliver fast while keeping costs at a low.

2.4.2.3. Centralised vs decentralised supply chains

One of the major aspects of SCM revolves around supply chain planning (SCP) (Pibernik and Sucky 2006), that is, the determination of production or inventory quantities at each stage within the SC as well as transportation quantities between them. Contrarily to the operations of a single firm, in which all decisions regarding inventory, production, and distribution are taken by the same agent, SCP involves several independent actors across the entire chain.

Very frequently, a centralised approach to SCP is proposed in literature (Pibernik and Sucky 2006) and commercial SC systems, which requires a single decision maker to optimise the network, making use of information from the several actors within the value chain. However, and as previously mentioned, SCs revolve around multiple actors who focus on acting in their own best interests, expecting others to do the same. This mentality will often lead to sub-optimisation in the whole SC, as most high-optimisation strategies can revolve around sacrificed optimisation of individual processes to the benefit of the entire chain (Van Der Vorst et al. 2007). As such, centralised approaches to SCP will often be rejected by the individual players, who are focused on their own individual performances. This further supports the fact that centralised approaches are better for multiple processes within the same firm, whereas entire SCs can often benefit from decentralised strategies, from which stems the popularity of collaborative supply chain management (CSCM) (Pibernik and Sucky 2006).

Appropriate information sharing among actors within the same SC is one of the pillars of CSCM. When information regarding demand forecast is shared among the several players, for example, much can be done to minimise the bullwhip effect, which would most likely be impossible in centralised approaches. Despite its benefits, CSCM is restricted to the SC design currently in use, as it boosts coordination between players but does not question design and, consequently, does not contribute to the implementation of appropriate decentralised strategies. In fact, there is much to be done in correct decentralised approach selection (Pibernik and Sucky 2006).

Decentralised SCs are raising to prominence, especially in the retail sector for locally-grown food-stuff, as customers are increasingly looking for this type of product, as described is section 2.3.2. Retailers currently partner with local farmers and suppliers to ensure a fresh and steady supply of local products, as is the case of Tesco, sector leader in the United Kingdom[9].

[9] https://www.theguardian.com/environment/2006/sep/15/food.supermarkets, accessed on March 2018;

2.4.2.4. Triple bottom line optimisation

There is growing concern towards sustainability across all sectors of human activity, and agribusinesses are no exception. Sustainability has been reported as one of the trends agribusinesses must adapt to in order to benefit from future opportunities within the sector (Goedde et al. 2015). Although sustainability can be characterised in many ways, there is increasing approval towards the triple bottom line (TBL) concept of People, Planet, and Profit. According to Project SCALE, “The concept of a TBL suggests that at the interception of social, environmental and economic performance, there are activities that organisations can engage in which not only positively affect the natural environment and society, but which also result in long-term economic benefits and competitive advantage for the firm” (Platform 2014).

Sustainability is a key issue in agribusiness, namely because the sector is one of the biggest users of road freight, with consequences to road congestion, safety, and emissions. As food demand will increase considerably in future years, according to forecasts (Goedde et al. 2015), so will the reliance on transportation, which carries further usage of fuel and other important resources. Furthermore, excessive emissions resulting from higher transportation requirements will, in turn, have a greater impact on weather and other factors which deeply affect the agricultural sector. Finally, the needs of a growing world population need to be accounted for, as agricultural activities make use of important resources such as water and energy. The dimension of this challenge has led many firms to realise the importance of weighing not just the economic, but also the environmental and social impacts of their activities.

Among this new paradigm, an important challenge is gaining attention: how can companies operate meaningful change in their operations to address environmental and social constraints while retaining their cost-effectiveness and competitiveness? In recent years, answers to this problem have been varied. Some argue that companies are too focused on economic factors and will only operate changes if forced by appropriate legislation, while others believe that true change can only be operated by volunteers who believe a true ‘win-win’ situation can be achieved, in which all elements of the TBL are optimised (Platform 2014). Regardless of which is the way forward, one thing is for sure: the number of agribusinesses which realise sustainability must be a priority is rapidly growing, as pointed by a 2014 McKinsey survey (McKinsey 2014).

In 2014, Project SCALE surveyed agribusinesses regarding which sustainability drivers were considered the most impactful. The results say that expectations of cost reduction and more efficient use of company assets, followed by a “doing things right” type of culture, company reputation and marketing differentiation, compliance with increasing consumer pressure, and legislative pressure are drivers to look out for (Platform 2014).

2.4.3. Reverse logistics

Typical SCs often disregard end-of-life (EOL) products, which are misused or wasted. This situation is incongruent with current sustainability awareness and, consequently, there is a current trend in SC design towards reverse logistics or reverse SCs, which account for EOL products and attempt to deal with them in the most environmentally-friendly way possible. The SCs designed in this manner are seen as 'forward' and 'backwards' oriented and, thus, are referred to as closed-loop SCs. These chains, which are designed and controlled to maximise value creation over the entire life-cycle of products (Xu and Xie 2016), focus on collecting EOL products from customers and performing appropriate processes such as repairing, disassembling, remanufacturing, recycling, and disposing (Kannan Govindan and Soleimani 2017). In fact, EOL product return plays a major role in closed-loop SCs, and many companies such as Zara and H&M are engaging in such efforts[10]. The importance of closing the loop in most SCs has become so striking that many regulatory initiatives have taken place, such as Directive 2002/96/EC of the EU, which became law in 2003 and was later replaced with Directive 2012/19/EU, focusing on closing the loop on waste electrical and electronic equipment (WEEE) (European Parliament and The Council Of The European Union 2012).

Despite growing awareness, there is still much to be done regarding reverse logistics and closed-loop SCs, especially in the area of mathematical optimisation, where mathematical frameworks, simulation studies, and production planning should be the focus of future researchers (Kannan Govindan and Soleimani 2017) Additionally, reverse logistics studies have primarily focused on auto part suppliers, vehicle manufacturers, and electronics and computers, with analysis lacking in areas such as agribusiness. The lack of analysis in agribusiness is striking, as food waste is a generalised problem, especially in the developed world, in which most people discard food which is still appropriate for consumption or simply let product quality expire for carelessness.

2.4.4. Mergers and Acquisitions

It has been argued that the future of agribusinesses relies on consolidated large players or small niche actors (Goedde et al. 2015). Large agribusiness firms have been vertically integrating their SCs to better address cost reductions and solve communication issues among differently-owned players within AFSCs. A large part of this vertical integration consists of large agribusiness firms merging or acquiring seed producers, equipment manufacturers, transporters, among others. Conversely, large firms can also acquire small and very specialised players in order to enrich their company's know-how portfolio, such as BASF's acquisition of Becker Underwood, a seed-treatment technology company, in 2012 (Goedde et al. 2015), or Bayer's acquisition of Monsanto, an agricultural and biotechnological company specialised in seeds, in 2016.

Apart from skill improvement or cost efficiency, information flows are also greatly impacted by vertical integration. As big data gradually rises in importance, all the way up to precision farming, in which variables are monitored and controlled on a square-metre base, there is a pressing need to

[10] https://www.theguardian.com/sustainable-business/2017/may/26/zara-hm-step-up-instore-recycling-tackle-throwaway-culture, accessed on February 2018;

design business models capable of making use of such data. Current inefficiencies can be partly explained by different players capturing data, as communication between them often lacks and prevents appropriate data flows. Better strategic partnerships and acquisitions might be a solution to the problem, as illustrated by Monsanto's acquisition of The Climate Corporation in 2013 (Goedde et al. 2015).

2.5. Regulatory environment

As described before, AFSCs are complex and include several players. Effective transformation requires aligning leaders and appropriate, well-crafted plans, in which regulators can play a particularly important role. Among major regulators, national governments have a preponderant role regarding internal policy and defining how business may be conducted. On a larger level, international organisations such as the EU can overrule national law on certain issues. In this section, a brief overview of what major regulators are doing is conducted.

2.5.1. The European Union

The EU serves as an important regulator for member states, often being able to overrule national policy on specific issues. These, referred to as exclusive competences of the EU, are all affairs in which the EU's policy making must be respected by member states, which need to follow European decisions. One such competence is the establishment of competition rules necessary for the functioning of the European internal market[11], that is, the definition of all rules which dictate how companies may act and compete on the common market.

Competition rules are an important aspect of the market, as well-defined rules prevent abuses of all sorts, a necessary barrier to protect the free market and fairness in business. Along this document, several mentions to bargaining power have been made, and competition rules are particularly important in this regard. Companies with high bargaining power can often subjugate other participants of the SC, forcing them to operate in an unfair or unsustainable manner, which is undesirable. To cope with this problem, the European Commission adopted COM(2014)472 (European Commission 2014), a Communication on tackling unfair trading practices (UTPs) in the business-to-business food SC. While most UTPs do not fall under competition law, as abusers are frequently in a strong, but not dominant position, meaning European rule does not apply (European Commission 2016), the EU has established the Supply Chain Initiative (SCI), a voluntary scheme aimed at improving the existing situation. Naturally, member states can create regulation of their own, as long as it does not go against European rule. Creating national regulation is becoming a trend among European countries. As of 2016, out of the 20 countries which had own regulation, 15 had implemented it in the past five years (European Commission 2016). Along this process, the EU has supported member states in defining what are UTPs, a concept subjective to debate, having identified four main issues: one party should not unfairly shift its own risks and costs to another party, one party should not ask another for benefits or advantages without performing a service related to that advantage, a party should not make unilateral and/or retroactive changes to a contract if allowed conditions are not met, and there should be no termination

[11] http://ec.europa.eu/citizens-initiative/public/competences/faq#q1, accessed on February 2018;

or threat of termination of a contractual relationship without justification. Some member states, such as Slovakia and Hungary, have decided to adopt even more rigid definitions of UTPs, while Germany and Austria assess UTPs on a case-by-case basis.

The abovementioned SCI was launched in 2013 as part of the EU's High-Level Forum for a Better Functioning Food Supply Chain[12], and is aimed at improving business fairness at the European level. Participants agreed on a set of good practices, but have, so far, failed to agree on an enforcement mechanism. Nonetheless, important work is done by the participants who, among other things, ensure complaining businesses are not subject to commercial retaliation (European Commission 2016).

Apart from initiatives such as Forums and the SCI, enforceable European legislation also exists, from which specific Directives and Regulations can be highlighted. Directives are mandatory rules all member states must comply with, although each member is given the freedom to pursue the established goal in its own way. Among relevant Directives, the abovementioned Directive 2012/19/EU on closed-loop SCs can be highlighted. Regulations are similar to Directives but establish the path member states must follow to achieve the final goal. Regulation(EU)1308/2013 is particularly important, as it establishes a common organisation of the markets in agricultural products (European Commission 2013).

2.5.2. China and the United States of America

Alongside the EU, the United States of America (USA) and China deserve recognition as impactful players. In the USA, the Department of Agriculture is the main regulatory entity, responsible for the main legislative documents of the sector, the agriculture bills. Currently, the Agricultural Act of 2014 is in place, to be renovated in 2018. Among others, the bill dictates the USA's agricultural spending, which was fixed in 2014 to USD 956 billion for a ten-year period[13].

On the other hand, China currently faces an immense challenge, especially due to its increasing population and dietary changes, with many consumers changing their eating habits to resemble those of Western countries. To ensure accessible food, China is strongly investing in farming technology, of which fertilisers can be highlighted, with China far surpassing the average fertiliser consumption per hectare of arable land[14]. Under its Ministry of Agriculture, China is currently focused on four major keystones: market control, improving farm efficiencies, curbing land loss, and import strategies.

2.5.3. Portugal

As a member state of the EU, Portugal is subject to most of the EU's abovementioned policies. Specifically, Portugal adopted legislation on UTPs in recent times and is among the group of European countries with the highest number of UTPs reported in recent times (European Commission 2016),

[12] http://ec.europa.eu/growth/sectors/food/competitiveness/supply-chain-forum/, accessed on February 2018;
[13] https://www.congress.gov/bill/113th-congress/house-bill/2642, accessed on March 2018;
[14] https://www.bloomberg.com/graphics/2017-feeding-china/, accessed on March 2018;

highlighting how salient the problem is within the country. Portugal has also received agricultural subsidies from the EU, mostly under its Common Agricultural Policy.

Currently, investment is being made to improve and/or modernise the sector in Portugal. In March 2018, for instance, a EUR 500 million investment was approved to enlarge and reformulate the Portuguese Irrigation Plan[15]. Additionally, and especially after the fires which ravaged the country in 2017, funding is being used to finance and equip teams of professional forest sappers[16].

2.6. Chapter conclusions

Throughout this chapter, brief mention to the agribusiness sector was made, focusing on typical AFSCs, the most pressing current challenges, and what are some of the trends the sector is going through, including regulation. It can be concluded that agribusinesses, and AFSCs in particular, are vastly complex networks spanning large geographic regions and involving a multitude of important players. Increasing customer demands and a much harsher competitive environment, alongside the surface of online marketplaces such as AmazonFresh, are putting pressure on established SCs which, due to their size and multiple decision makers, do not always respond appropriately, falling short on optimisation and efficient strategy.

Much has been made regarding the study of SCs, especially through logistics and SCM, which are increasingly important to cope with larger, more pressing issues that threaten sustainability and effectiveness. However, certain areas are still understudied, and managers often lack tools and established methodologies anchored in literature to deal with ever-changing problems. As such, it is important to note SCM and logistics need to continue evolving towards better frameworks and models, that can give decision makers the means and the confidence to operate significant change in their AFSCs.

To better understand what needs doing, it is paramount to first analyse what has been done, thus identifying areas where major advances have happened and drawing valuable learning points from them. Likewise, such analysis also identifies areas in which knowledge is lacking, which should be the focus of further research. In Chapter 3, a thorough literature review focusing on SCM and OR is conducted, aimed at recognising the most valuable recent developments in the area.

[15] https://www.portugal.gov.pt/pt/gc21/comunicacao/noticia?i=programa-de-regadios-melhora-produtividade-e-cria-emprego, accessed on March 2018;
[16] https://www.portugal.gov.pt/pt/gc21/comunicacao/noticia?i=ministro-da-agricultura-anuncia-conjunto-amplo-de-medidas-para-reequipar-sapadores, accessed on March 2018;

3. Literature review

3.1. Methodology

This section describes the methodology used to develop a systematic review of the literature on AFSCs focused on the usage of OR methods to support the decision process, encompassing all three decision levels, as defined by Ahumada and Villalobos in 2009 (Ahumada and Villalobos 2009). The systematic review here employed provides rigour and quality to the work developed, and ensures the correct treatment of the information obtained and the drawn of appropriate conclusions (Tranfield et al. 2003). The methodology is divided in four steps, covered below.

3.1.1. Step 1: material collection

In this step the characteristics of papers to be selected are specified. The collection was restricted to papers written in English and published in peer-reviewed journals, with no data range restriction being applied. The selection was performed in the *Web of Science Database*, with the final set of papers collected on March 2018. Table 3.1 summarises the keywords selected for the search, as well as the results obtained for each individual search.

Table 3.1. – Keywords used for the search on the Web of Science database and number of papers obtained from each search

AFSC keywords	AND	OR method keywords	Number of papers obtained
Agri-food supply chain Agro-food supply chain Agro supply chain Food supply chain		Data analysis	563
		Decision analysis	304
		Expert systems	96
		Heuristics	39
		Markov decision	4
		Metaheuristics	4
		Neural networks	32
		Optimisation OR optimization	346
		Queueing theory	0
		Simulation	251
		Statistics	41
TOTAL			1,680

To understand if the selected papers comply with the objectives of the present study (to understand how authors support AFSC planning and design using OR methods), the 1,680 publications were subject to a content analysis, being excluded if they did not satisfy all criteria bellow:

1. The paper is written in English and was published in a peer-reviewed journal;
2. The paper has a quantitative approach, applying a formal OR method;
3. The paper is not a review;
4. The paper focuses on AFSCs, thus excluding publications focused on a single operation within a SC, ensuring two or more entities are always considered.

A considerable portion of the retrieved documents was excluded because focus was not on AFSCs or did not include quantitative methodologies. After accounting for paper repetition in multiple searches, a final set of 34 publications was retrieved (a detailed table of all retrieved publications is provided in Annex A). Despite extensive, the material collection here performed was not exhaustive, as other databases such as *Science Direct* were not included. Consequently, it is possible relevant publications were not considered.

3.1.2. Step 2: descriptive analysis

To better position the current chapter within the recently published literature on AFSC planning and design using OR methods, the work here developed is compared to those of recent reviews on the topic. This analysis can be consulted in section 3.2., where the new contribution of the present document is highlighted. Additionally, a factual information analysis was performed, regardless of paper content, focusing on two major details:

1. Where the researchers publishing work on AFSC planning and design using OR methods are located;
2. When the papers on AFSC planning and design using OR methods were published.

The abovementioned information is collected by analysing the country of publishing authors and the year of publication. This analysis can be consulted in section 3.3.

3.1.3. Step 3: category selection

To better grasp how different authors have been addressing the usage of OR methods to support the planning and design of AFSCs, a set of categories was established. Among these, the sustainability pillars are counted, as well as the type of decision level. Additionally, several product and SC characteristics are also considered.

To permit for the appropriate usage of the information given by the different categories considered herein, a set of research questions was established. The answers to these questions map the state-of-the-art in the field, thus giving a good understanding of where to direct future work. Ten research questions were considered:

1. Which decision levels (strategic, tactical, operational) have been addressed when applying OR methods to AFSCs?
2. Which OR methods have been used in modelling AFSCs?
3. Which SC activities have been considered?
4. Which type of problem has been addressed (deterministic or subject to uncertainty)?
5. Which sources of uncertainty have been considered?
6. What kind of food product characteristics have been considered?
7. What kind of AFSC characteristics have been considered?

As the present review also wants to focus on how sustainability concerns have been treated by the authors developing quantitative methodologies to address AFSCs, two new questions were considered:

8. Which sustainability pillars (economic, social, environmental) have been considered when applying OR methods to AFSCs?
9. Which metrics have been used to assess each sustainability pillar?

The analysis and answers to the nine research questions can be found in section 3.5. Adding to this, one other research question was established to make use of the information gathered and analysed.

10. What is still to be done and what are the future directions in research in this area?

The answer to this question can be found in section 3.6.

3.1.4. Step 4: material evaluation

In this step, an evaluation of content is performed for each of the selected papers. The analysis is conducted with the support of the research questions listed above, which help to systematise and structure the information. The content assessment supports the identification of research gaps, from which a future research agenda is proposed, in line with research question 10.

3.2. Previous literature reviews

To identify the areas which have been the focus of scientific attention in recent years, an analysis of previous literature reviews was conducted. The reviews were selected from the *Web of Science Database* using "agro-food supply chain" OR "food supply chain" OR "agro supply chain" AND "review" as keywords, from which 420 results were found. The set of results was subjected to a paper content analysis to select the reviews on AFSC management, from which seven documents were retrieved:

- Fredriksson, Anna and Liljestrand, Kristina (2015), Capturing food logistics: a literature review and research agenda, International Journal of Logistics: Research and Applications, Volume 18, Number 1, Pages 16-34;
- Kusumastuti, Ratih Dyah, van Donk, Dirk Pieter and Teunter, Ruud (2016), Crop-related harvesting and processing planning: a review, International Journal of Production Economics, Volume 174, Pages 76-92;
- Notarnicola, Bruno, Sala, Serenella, Anton, Assumpció, McLaren, Sarah J., Saouter, Erwan and Sonesson, Ulf (2017), The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges, Journal of Cleaner Production, Volume 140, Pages 399-409;
- Routroy, Srikanta and Behera, Astajyoti (2017), Agriculture supply chain: a systematic review of literature and implications for future research, Journal of Agribusiness in Developing and Emerging Economies, Volume 7, Issue 3, Pages 275-302;

- Shukla, Manish and Jharkharia, Sanjay (2013), Agri-fresh produce supply chain management: a state-of-the-art literature review, International Journal of Operations & Production Management, Volume 33, Issue 1-2, Pages 114-158;
- Zhong, Ray, Xu, Xun and Wang, Lihui (2017), Food supply chain management: systems, implementations, and future research, Industrial Management & Data Systems, Volume 117, Issue 9, Pages 2085-2114;
- Esteso, Ana, Alemany, M. M. E. and Ortiz, Angel (2018), Conceptual framework for designing agri-food supply chains under uncertainty by mathematical programming models, International Journal of Production Research, DOI: 10.1080/00207543.2018.1447706.

Finally, three additional articles were considered by cross-referencing the remaining seven documents, thus raising the final set of reviews to ten:

- Ahumada, O. and Villalobos, J. R. (2009), Application of planning models in the agri-food supply chain: a review, European Journal of Operational Research, Volume 196, Number 1, Pages 1-20;
- Soto-Silva, Wladimir E., Nadal-Roig, Esteve, González-Araya, Marcela C. and Pla-Aragones, Lluis M. (2016), Operational research models applied to the fresh fruit supply chain, European Journal of Operational Research, Volume 251, Pages 345-355;
- Tsolakis, N. K., Keramydas, C. A., Toka, A. K., Aidonis, D. A. and Iakovou, E. T. (2014), Agri-food supply chain management: a comprehensive hierarchical decision-making framework and a critical taxonomy, Biosystems Engineering, Volume 120, Pages 47-64.

The papers identified as relevant and listed above were highlighted over all others for their compliance with the following restrictions: 1) papers are written in English, 2) papers were published in peer-reviewed journals, 3) papers deal specifically with AFSC design and management, and 4) papers are classified as reviews. The ten reviews were categorised regarding several important characteristics: research focus, research objective, research methodology, number of papers reviewed, time span of the papers reviewed, and type of decision levels considered. The summarised result of this categorisation can be found in Annex B. The information gathered is a clear snapshot of published reviews focused on AFSCs, thus shedding light on the relevance of this review.

From the information on Annex B, a considerable part of the selected literature is very recent, with 2017 being the most frequently found year of publication, with three out of ten reviews, as can be seen on Figure 3.1a. Such detail translates the increasing relevance of AFSC planning and management and denotes the growing interest of the scientific community towards the topic in recent years. Additionally, when looking at the types of decision levels addressed in the reviews, four out of ten papers include all three decision levels (strategic, tactical, and operational), which makes it possible to infer some emphasis is being given to holistic approaches, as is highlighted in Figure 3.1b. Apart from these, Kusumastuti et al. (Kusumastuti et al. 2016) focus on the operational decision level of integrating harvesting and processing planning, whereas Esteso et al. (Esteso et al. 2018) focus on framework development with a strategic approach. The four remaining reviews do not disclose this kind of information, as focus is put on specific characteristics such as food logistics or Life-Cycle Analysis (LCA) methodologies rather than on the AFSCs themselves.

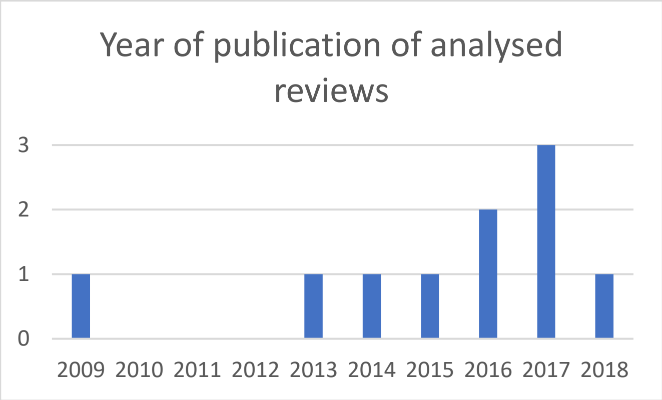

Figure 3.1a – Year of publication of analysed reviews

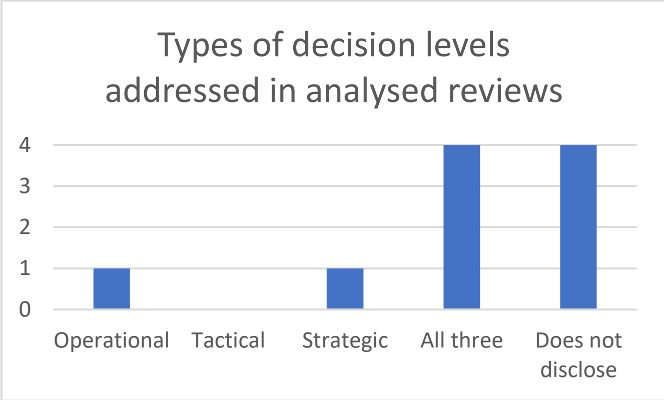

Figure 3.1b – Types of decision levels addressed in analysed reviews

Finally, it can be observed from Annex B that eight out of ten papers utilise systematic review methodologies, which points towards a greater attention to rigour by the authors.

In 2009, Ahumada and Villalobos (Ahumada and Villalobos 2009) performed a systematic review of production and distribution planning in crop-based AFSCs, where 69 papers were reviewed spanning from 1985-2008. In this review, the authors proposed a distinction and definitions for three different decision levels: strategic, tactical, and operational, which are currently being used by several authors. Adding to this, the authors focused their attention on successfully implemented models, highlighting the optimisation methodologies employed as well as the type of crop considered.

On their 2013 systematic review, Shukla and Jharkharia (Shukla and Jharkharia 2013) instead zeroed in on fresh produce SCs, including fruits, flowers, and vegetables, reviewing 86 papers. In their work, the authors highlight most works on fresh produce focus on consumer satisfaction and profit maximisation, while post-harvest waste reduction continues to be a secondary objective despite its clear importance. Additionally, the little attention agriculture has been given in terms of demand forecasting is also criticised.

In one of the two narrative reviews analysed, Tsolakis et al. (Tsolakis et al. 2014) review AFSC design methodologies and propose a comprehensive framework to support decision-making in AFSC design, as well as a critical player taxonomy. It should be noted that the authors support (and make use of) the definition of decision levels suggested by Ahumada and Villalobos.

Fredriksson and Liljestrand (Fredriksson and Liljestrand 2015) reviewed 159 papers focused on food logistics. On their analysis, the authors conclude that there is a lack of a commonly accepted definition of food logistics and proceed to suggest their own. Furthermore, the authors suggest logistics activities can be separated into four categories: procurement, production, distribution, and relationship management. Finally, the systematic review identifies that there is a lack of research on ambient temperature or frozen products, with most of the research focusing on chilled produce.

In their systematic review, Kusumastuti et al. (Kusumastuti et al. 2016) reviewed 76 papers on harvesting and processing planning in crop-based AFSCs, thus focusing solely on an operational decision level. In their work, the authors concluded extensive work has been done either on harvesting or processing planning, but not on their integration. Consequently, it was suggested an integrated approach would be an important step towards post-harvest waste reduction. Furthermore, the authors identified there is much to be done regarding decentralised SCs, as the clear majority of crop-based AFSCs are studied as centralised networks. Finally, it is also important to highlight most of the reviewed papers only incorporated weather uncertainty, thus overlooking demand uncertainty.

In 2016, Soto-Silva et al. (Soto-Silva et al. 2016) reviewed 28 papers on fresh fruit SC management, providing a clear snapshot of the state-of-the-art of the application of optimisation methods to these SCs. It was concluded that most papers make use of linear programming due to its ability to model and solve real problems. Nonetheless, the majority fail to approach fresh fruit SC design holisticaly, often focusing on tactical or operational decisions, while the strategic perspective remains underdeveloped. Additionally, the authors incentivise future work to be developed on emerging topics such as organic fruits.

In their narrative review, Notarnicola et al. (Notarnicola et al. 2017) analyse the challenges concerning the application of LCA tools to support the design of sustainable AFSCs. Among the challenges highlighted, data availability is argued to be particularly relevant, and criticism is pointed towards the lack of inter-comparable databases, which prevent successful data usage by different players within the same SC.

In the same year, Routroy and Behera (Routroy and Behera 2017) performed a systematic review in which 203 papers from 2000-2016 were reviewed regarding AFSCs, although dairy, fisheries and meat SCs were excluded from the study. The conducted analysis focused on assessing several dimensions of AFSCs, such as scope, objectives, wastages, among others. Traceability was deemed of extreme importance, and the review clearly denoted that, despite vast research has been conducted on traceability, there is a lack of research on implementation methodologies. Adding to this, and similarly to the work done by Kusumastuti et al. (Kusumastuti et al. 2016), the authors criticised the lack attention given to post-harvest waste reduction.

Still in 2017, Zhong et al. (Zhong et al. 2017) conducted a systematic review on data-driven AFSCs, spanning 192 articles. Similarly to Routroy and Behera (Routroy and Behera 2017), the authors criticised the lack of food traceability implementation methodologies, arguing that the technology needed to achieve it already exists. Nonetheless, the authors also recognise successful implementation has been performed in the EU, where food safety is a more preponderant issue compared to other markets. Furthermore, it is also highlighted that there is a lack of attention being given to vertical integration.

The most recent review studied was that of Esteso et al. (Esteso et al. 2018), published in 2018, in which a systematic review was conducted on mathematical programming models utilised to design AFSCs. The authors proposed a conceptual framework for AFSC design using the abovementioned models, making use of other frameworks taken from five different papers reviewed. The resulting framework focused solely on the strategic decision level. The review also highlighted no existing model considers uncertainty both in product characteristics and the environment (such as weather conditions), revealing a considerable gap in the literature.

From the reviews listed above, it can be concluded that product and SC characteristics need to be successfully integrated in design models for these to perform adequately. Although existing models have encompassed some characteristics, most focus on specific details and disregard most others, thus failing to satisfy more holistic approaches (Shukla and Jharkharia 2013; Kusumastuti et al. 2016). Nonetheless, it must be noted that models should not be generic enough to the point where these fundamental characteristics are disregarded, as is the case of applying traditional SC design models to AFSCs (Esteso et al. 2018). Adding to this, another important observation is that none of the reviews analysed herein took the social sustainability pillar of the TBL approach into consideration, reason for which the social impact of AFSCs is considerably underdeveloped, thus constituting another important literature gap.

By answering the research questions described in section 3.1.3., the work here presented intends to contribute to the knowledge development in the field. This review provides a quantitative approach perspective, focusing on OR methodologies, while incorporating a wider set of product characteristics when compared to existing studies, as well as encompassing social sustainability. This paper differs from previous reviews by focusing on AFSCs in general, as existing work dedicated to mathematical modelling methods mostly addresses specific SCs or some SC characteristics. The work of Esteso et al. (Esteso et al. 2018), for instance, focuses solely on fresh fruit SCs. By retaining a more holistic approach to the problem, this paper aims at providing a clear snapshot of existing research conducted throughout AFSCs, thus helping establish future work needs and directions.

3.3. Descriptive analysis

To better assess the importance and context of the papers here examined, and before performing a content analysis, a factual analysis was performed, focusing on the year of publication and country of publishing author for each paper. One such analysis can lead to important conclusions, such as the geographical importance of AFSC planning and design, and the temporal relevance of the topic, possible to assess by examining a timeline of number of publications. Answers to these two questions are summarised in Figures 3.2. and 3.3.

As can be seen in Figure 3.2., there is a considerable geographical distribution of papers in Asia, Europe, and North America. Nonetheless, it must be highlighted that some countries put greater emphasis on the topic, as is the case of India and the ASA. It can be argued that the additional focus is justified by the importance of appropriate SC management in such countries.

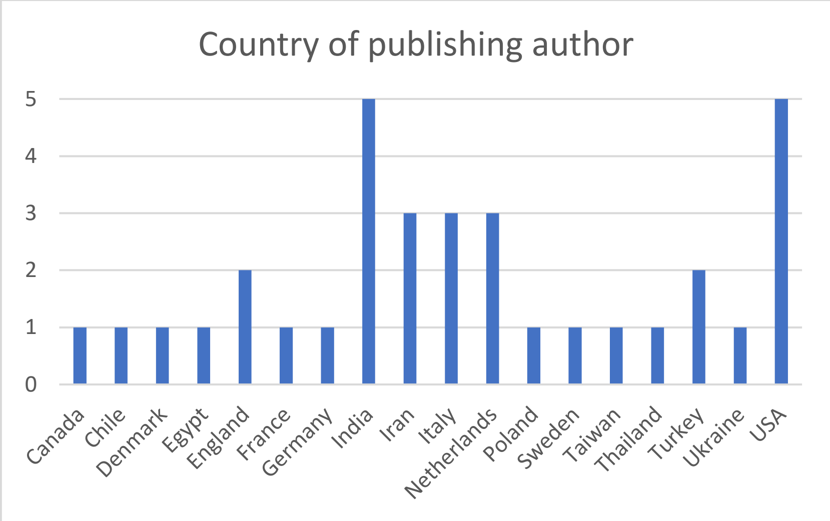

Figure 3.2. – Country of publishing authors of all analysed papers

From the analysis of Figure 3.3., it is clear that the number of publications addressing AFSC planning and design with OR methods is increasing. The trend goes well in line with the increasing awareness towards the benefits and the need for appropriate SC management in the agribusiness sector, with more and more authors publishing work on the subject. The comparatively lower number of papers published in 2018 is justified with the time restriction set during the material collection, as only papers published until March 2018 were included.

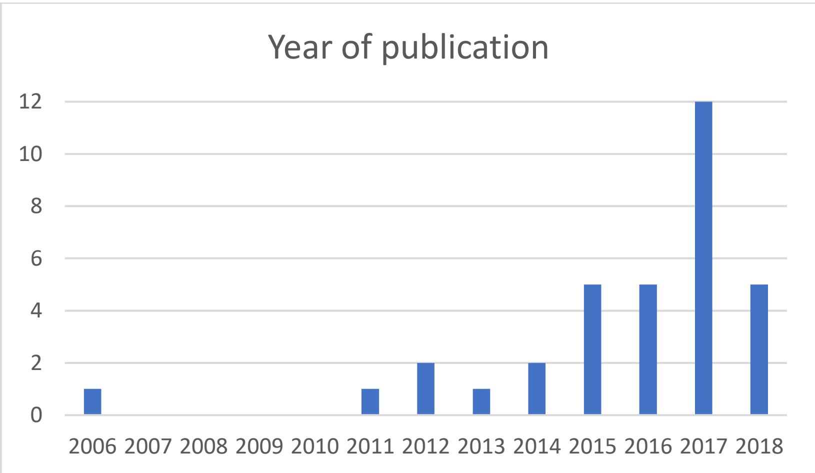

Figure 3.3. – Year of publication of all analysed papers

This descriptive analysis leads to two important conclusions. Firstly, and as previously discussed, planning and design of AFSCs using OR methods are receiving increasing attention from the scientific community, a trend that will likely continue in the future due to the increasing challenges these AFSCs need to accommodate for. Secondly, although certain countries contribute greatly to the number of published papers, the topic shows a wide geographic importance.

3.4. Category selection

As a vast amount of information is handled when reviewing a wide set of publications, ensuring its correct management is critical. To support paper organisation and grouping, a set of categories was established so that papers with similar approaches or topics could be easily grouped or different perspectives identified. As such, the papers were organised according to seven dimensions: decision level type, problem type, modelling approach, product characteristics considered, SC characteristics considered, SC activities considered, and sustainability pillars addressed.

- Decision level: which decision level(s) (strategic, tactical or operational) is(are) considered?
- Problem type: is the problem deterministic or subject to uncertainty?
- Modelling approach: which OR method(s) is(are) used by the authors?
- Product characteristics: quality, perishability, and traceability;
- SC characteristics: centralised, decentralised, forward, reverse, closed-loop, and/or cold chain;
- SC activities: procurement, location selection, distribution/transportation/routing, capacity selection, production, scheduling, and retailing;
- Sustainability pillars: economic, environmental, social, in accordance with the TBL approach.

3.5. Material evaluation

3.5.1. Research question 1: decision levels

When assessing the planning and design of AFSCs using OR methods it is important to understand which kind of problem the model is expected to address. As SCs are vastly complex, there are problems with fundamentally different natures to solve, whether according to the time-span of the solution or its scope. In that sense, a differentiation between strategic, tactical, and operational decision levels has been proposed by several authors (Ahumada and Villalobos 2009; Tsolakis et al. 2014). The first research question aims at understanding which types of decision levels have been the focus of recent work. To ensure consistency in classification, all decisions were categorised according to the framework proposed by Tsolakis et al. in 2014 (Tsolakis et al. 2014). The number of papers addressing each type of decision level is summarised in Figure 3.4. It should be noted that some articles focused more than one decision level, and, in those cases, papers contributed to the final number of multiple levels.

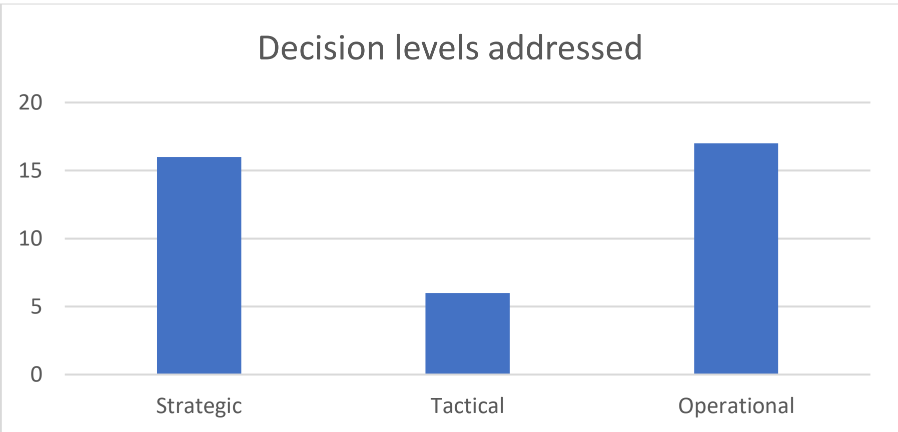

Figure 3.4. – Types of decision levels addressed by the authors

As can be seen, the strategic and operational levels have been the focus of most authors, with 16 and 17 articles focusing on them, respectively. Conversely, the tactical decision level figured in just 6 papers, less than half of that of its counterparts. The accentuated presence of the strategic decision level is justified by the growing importance of environmental concerns. As will be later discussed (research question 3), strategic decisions such as facility location and partner selection are being addressed with environmental objectives in mind. The work of Bosona and Gebresenbet (Bosona and Gebresenbet 2011) is a good example of this focus. Contrasting, the focus on the operational level stems from different AFSC concerns, namely waste reduction, which also goes well in line with environmental concerns. To better address wastage within AFSCs, focus is given to inventory management, scheduling, and demand forecasting. The tactical level is mostly represented by papers on routing and transportation problems, at times paired with strategic location decisions, thus treated as location-routing or location-distribution (Musavi and Bozorgi-Amiri 2017) problems.

3.5.2. Research question 2: OR methods

As this chapter aims at reviewing how the planning and design of AFSCs has been supported by OR methods, identifying which methods authors are selecting to address this complex issue is important and may give a good understanding of the topic's state-of-the-art. Figure 3.5. summarises the OR methods employed in all papers reviewed.

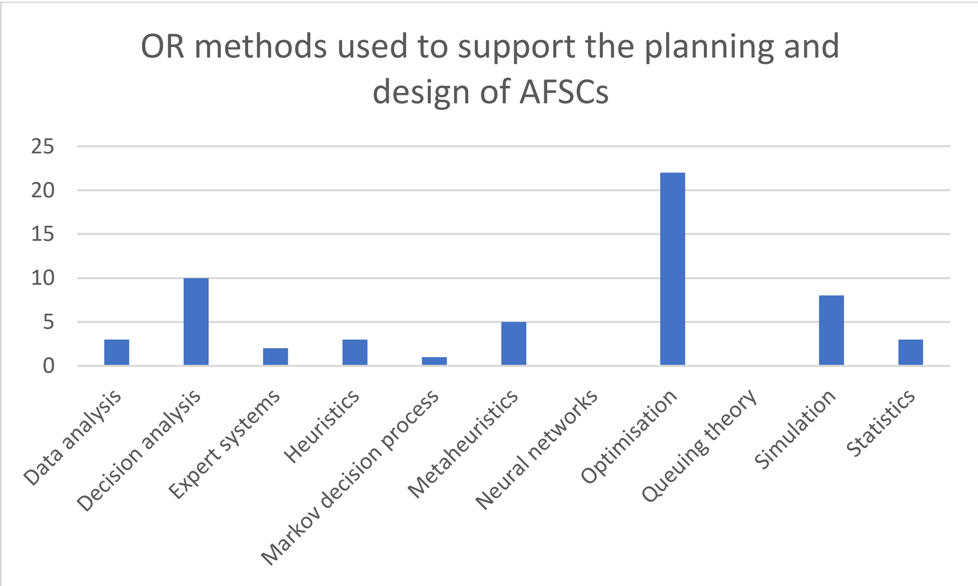

Figure 3.5. – OR methods used by the authors to support the planning and design of AFSCs

Among all OR methods, 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 OR 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 (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. (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. (Allaoui et al. 2018) and Huber et al. (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.

On a final note, only one of the reviewed papers makes use of a Markov decision process (Fianu and Davis 2018). However, this is also the only paper which does not deal specifically with a traditional AFSC. Instead, the paper focuses on the food distribution to people in need, carried out by an existing organisation. As this can be comparable to a scheduling and distribution problem, we decided to include the paper in the reviewed sample.

3.5.3. Research question 3: SC activities

SCs entail a wide range of activities, from raw material production to their transformation and later selling as a finished product. Each type of activity has its own characteristics and, as such, needs to be addressed appropriately. To better understand which SC activities have been the focus of recent work, as well as how authors have addressed those same activities, all reviewed papers were classified in terms of SC activities addressed. The activities were then grouped in a set of seven different activities: procurement (obtention of raw materials), location (establishing facility location), capacity selection (selecting production capacity and inventory levels), scheduling (temporal planning of the necessary production and distribution activities), distribution/transportation/routing (establishing transportation routes and transportation capacities), production (performing the necessary production activities from which results a final product), and retailing (the sale of the final products to the consumer). Figure 3.6. displays the incidence of each category in the papers analysed.

From Figure 3.6., it is clear distribution/transportation/routing problems are the more frequently addressed using OR methods, as more than half (20 out of 34) of the papers analysed reported to this category. As mentioned before, transportation problems are relevant due to the increased environmental awareness, with many authors seeking to optimise routing and distribution to reduce polluting emissions. Furthermore, distribution is focused from the standpoint of supply equity, as previously reported for the work of Fianu and Davis (Fianu and Davis 2018), with wide attention being given to it in countries with historically poor equity, such as India, where a rapidly growing population further accentuates the problem (Mogale et al. 2016; Maiyar and Thakkar 2017).

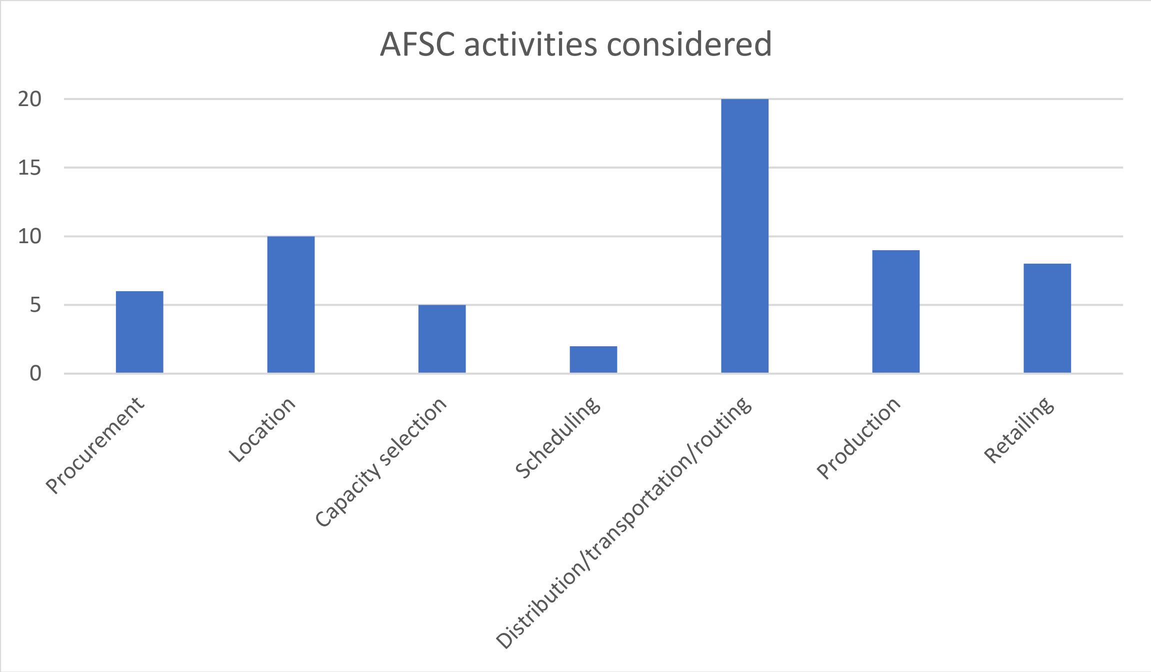

Figure 3.6. – AFSC activities considered by the authors in their publications

In parallel, facility location problems are also popular, with 10 out of 34 publications addressing this strategic issue. It can be noted that some papers contribute to the popularity of distribution/transportation/routing and location simultaneously by focusing on location-routing or location-allocation. On the other end, scheduling is the focus of just 2 publications (Sel et al. 2015; Bilgen and Çelebi 2013).

3.5.4. Research questions 4 and 5: deterministic vs subject to uncertainty

As mentioned in Chapter 2, the uncertainty found in both supply and demand is one of the most defining characteristics of AFSCs, and one of the major reasons why traditional SC models cannot be applied to these SCs. With this in mind, it is important to understand how much attention researchers have given to such a relevant characteristic. To that end, models were classified as deterministic if uncertainty was disregarded, or subject to uncertainty, if one or more sources of uncertainty were considered. The results can be consulted in Figure 3.7a. Furthermore, Figure 3.7b. breaks down the problems where uncertainty is regarded, pinpointing which were the sources of uncertainty.

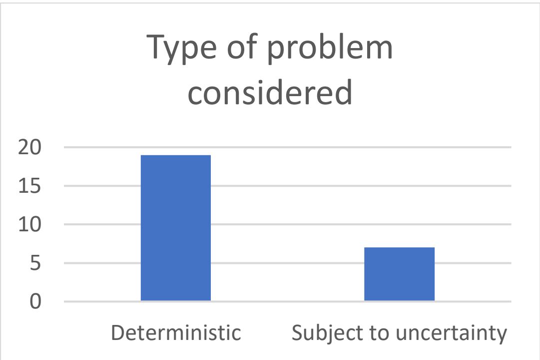

Figure 3.7a. – Type of problem addressed by the authors

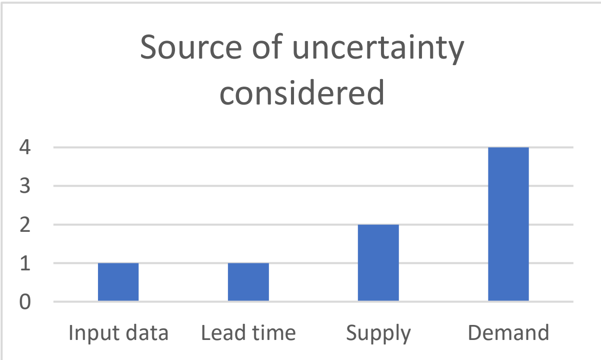

Figure 3.7b. – Sources of uncertainty addressed by the authors

As can be seen, a relatively low amount of papers accounted for uncertainty, given the importance of this characteristic. In fact, the number of papers with deterministic problems is far superior to that of papers addressing uncertainty, which is not ideal, since 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. Figure 3.8. summarises the different methods used to account for uncertainty.

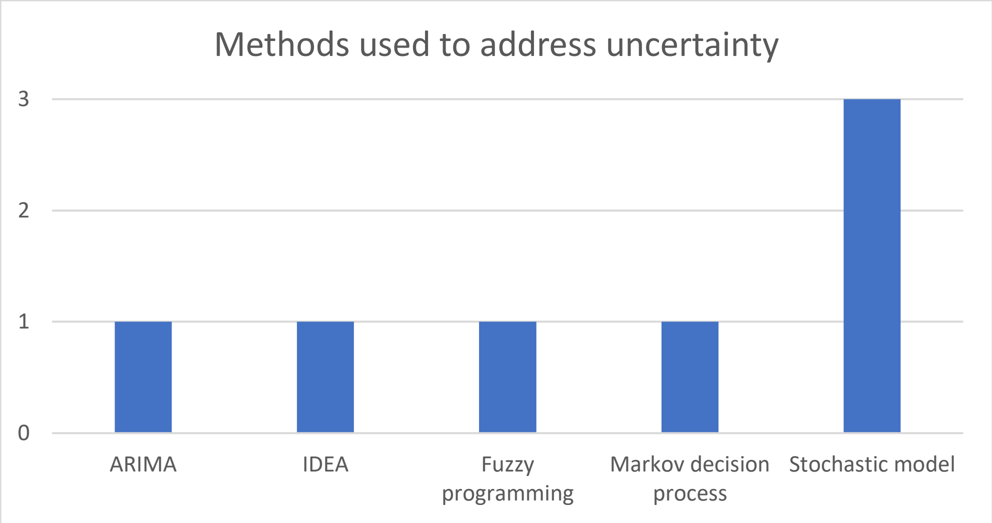

Figure 3.8. – Methods used by the authors to address uncertainty

As can be seen in Figure 3.8., 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. (Shabani et al. 2012) use interval data envelopment analysis (IDEA) to account for input data uncertainty. Finally, Fianu and Davis (Fianu and Davis 2018) use a Markov decision process to integrate supply uncertainty in their food distribution equity problem.

3.5.5. Research questions 6 and 7: product and SC characteristics

Research questions 4 and 5 address uncertainty due to its importance in AFSCs. Alongside uncertainty, and as highlighted in Chapter 2, other characteristics contribute to the uniqueness of AFSCs and impose the need for dedicated methods to be developed. To better organise the assessment of such characteristics in the literature reviewed herein, these were divide regarding whether they report to the products or the SC itself. By recognising which characteristics have been focused, it is possible to identify key aspects of AFSCs which are yet to be accounted for in satisfactory manner. This exercise can be supported by already existing compilations of product and SC characteristics, of which the one performed by Esteso et al. (Esteso et al. 2018) is a prime example. Figures 3.9a. and 3.9b. summarise the food product and SC characteristics considered by authors, respectively.

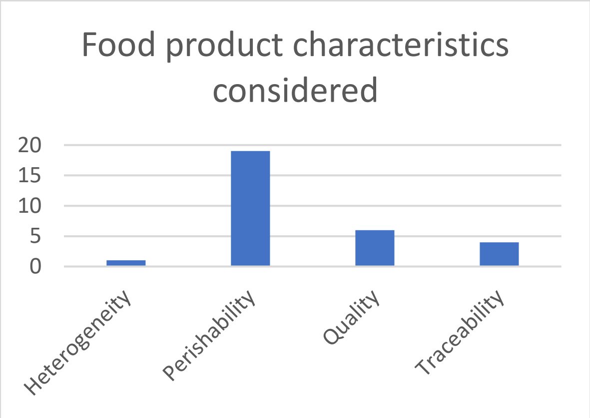

Figure 3.9a. – Food product characteristics considered by the authors

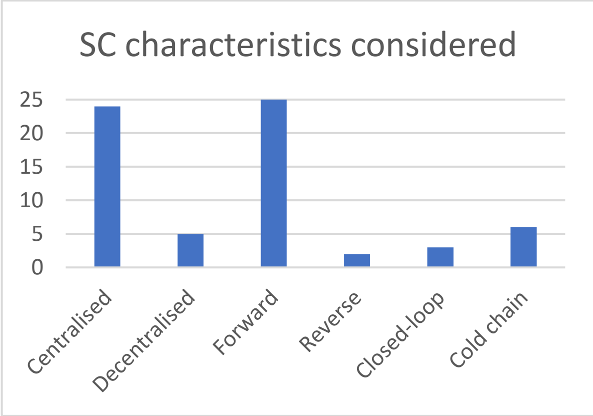

Figure 3.9b. – SC characteristics considered by the authors

From the analysis of Figure 3.9a., 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 (Kanchanasuntorn and Techanitisawad 2006) assess the impact of perishability on costs, net profit, service level, and inventory level; Mejjaouli and Babiceanu (Mejjaouli and Babiceanu 2018) study product shipping and rerouting while including the possibility of product spoilage during transportation; and Bilgen and Çelebi (Bilgen and Çelebi 2013) account for perishability by varying retailing pricing depending on product self-life.

Food product quality is addressed in 6 papers, with the work of Ge et al. (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.

Regarding SC characteristics (Figure 3.9b.), it is clear there is a large prevalence of centralised SCs over decentralised configurations, with only 5 papers accounting for decentralisation in comparison to 24 counterparts which model centralised SCs. Centralised SCs are far more typical, as centralisation and integration (both forward and backwards) often lead to higher competitiveness and cost reduction. Nonetheless, and as discussed in Chapter 2, there is a growing concern with local products and practices, with more and more consumers preferring environmental and socially sustainable options instead of cheaper ones. Naturally, many AFSC operators such as large retailers are changing focus towards local production and supply. In light of this new paradigm, decentralised SCs are and will continue to rise to prominence, a tendency which should help incentivise studies on such configuration. Nonetheless, very little work has been done in modelling decentralised AFSCs.

Simultaneously, the papers have been categorised depending on the SC flows studied. Forward AFSCs encompass the majority of the work reviewed, with 25 papers considering the traditional forward configuration solely. Despite this, and as mentioned, waste reduction is a growing concern, reason for which the importance of reverse logistics is on the rise (see Chapter 2). Still, only five publications address reverse logistics or closed-loop SCs, which means reverse logistics are still greatly underdeveloped in this field. In this regard, the work of Banasik et al. (Banasik et al. 2017b) must be highlighted, as it focuses on closing the loops in AFSCs with the use of multi-objective optimisation.

Finally, one additional category was added: cold chain. As perishability is extremely relevant, it is natural certain authors focus their work on SCs dealing specifically with highly perishable and fresh products. A total of 6 papers proposed models tailored specifically to cold chains.

3.5.6. Research questions 8 and 9: sustainability

As discussed in Chapter 2, sustainability is currently seen in the light of the TBL, which advocates businesses (and agribusinesses, in this case) need to perform their activities with environmental and social concerns alongside their economic sustain. With this concept in mind, the papers were categorised in terms of the sustainability pillars addressed by the authors, to ascertain where attention is being given. Figure 3.10. shows the corresponding results, and it should be noted that several publications addressed more than one sustainability pillar simultaneously, thus contributing to more than one category. Alongside this categorisation, we identify the different metrics authors have been using to address each sustainability pillar to better understand how each of these dimensions is being handled by existing models. This identification is shown in Figure 3.11.

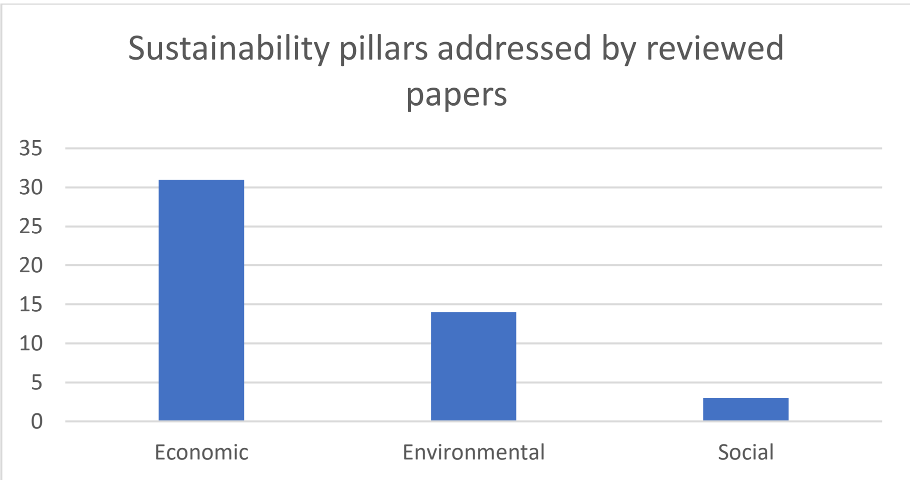

Figure 3.10. – Sustainability pillars addressed by the authors

The first major conclusion is that almost all papers consider at least economic sustainability, with 31 out of 34 publications including this pillar in their models. Despite the increasing importance of the environmental perspective, the economic performance of AFSCs is still the primary focus of most of the papers. Nonetheless, a considerable number of models also include an environmental perspective (14 out of 34), a number expected to increase as environmental concerns remain a top priority. Interestingly, only two papers addressed environmental sustainability exclusively (Banasik et al. 2017a; Pipatprapa et al. 2016), mostly focusing on environmental performance assessment within AFSCs.

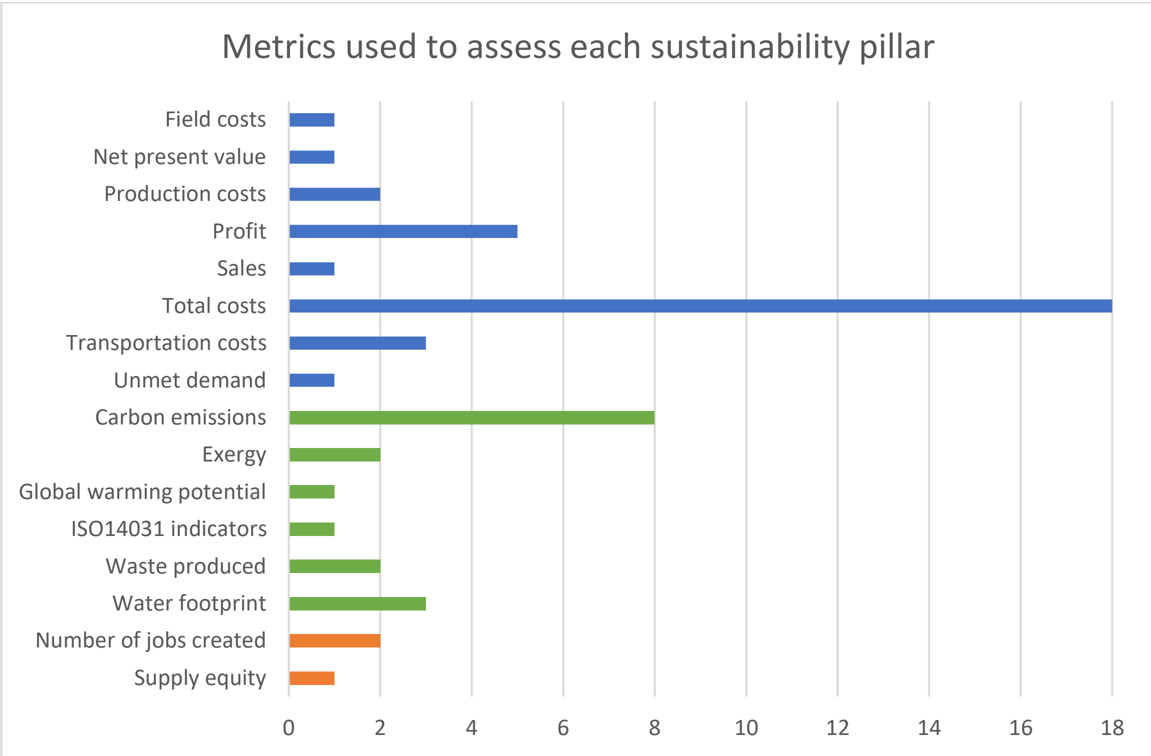

Figure 3.11. – Metrics used by the authors to asses each sustainability pillar: economic pillar in blue; environmental pillar in green; and social pillar in orange.

Contrasting with the economic and environmental pillars, the social dimension has been mostly disregarded, with just 3 out of 34 papers addressing it. What is more, of the 3 papers, the work of Fianu and Davis (Fianu and Davis 2018) does not relate to the traditional understanding of an AFSC (the reason for its inclusion has been previously discussed in this chapter). Apart from this publication, which focuses on distribution equity for people in need, the two remaining papers (Allaoui et al. 2018; Izadikhah and Saen 2016) addressed the social pillar alongside economic and environmental objectives. Hence, these two papers are the only ones among the entire set of reviewed publications to fully account for sustainability under the light of the TBL approach.

As shown on Figure 3.11., most papers focusing on economic sustainability use costs as metrics (24 out of 31 publications), with the most prevalent metric being total costs, which models seek to minimise. The popularity of such metrics is a good indicator of how competitive AFSCs need to be, especially in today's competitive environment. As discussed, new players such as online retailers further increase the competitive environment with new highly efficient business models. Apart from costs, profit is naturally the most common metric, with 5 papers focusing on profit maximisation rather than on cost minimisation. In parallel, one paper (Miranda-Ackerman et al. 2017) performs a combination of both by maximising the NPV. Finally, two papers (Shabani et al. 2012; Huber et al. 2017) make use of alternative metrics, making use of sales maximisation and unmet demand minimisation, respectively.

Looking at environmental sustainability, the minimisation of carbon emissions is the most popular objective. This comes as no surprise, as the agribusiness sector is responsible for 30 per cent of worldwide greenhouse gas emissions (Goedde et al. 2015). As several papers address routing and distribution problems, authors have given major focus to the reduction of pollutant emissions. Apart from carbon emissions, water footprint and waste produced have also been minimised. In more holistic approaches, 4 papers make use of more extensive metrics: Banasik et al. and Linnemann et al. (Banasik et al. 2017a; Linnemann et al. 2015) use indicators based on exergy analysis, which accounts for often disregarded parameters such as energy consumption, fuel consumption, and waste generation (Banasik et al. 2017a); Miranda-Ackerman et al. (Miranda-Ackerman et al. 2017) minimise the global warming potential (GWP), a metric which translates how much heat a greenhouse gas is capable of retaining in the atmosphere; and Pipatprapa et al. (Pipatprapa et al. 2016) develop an environmental performance evaluation method based on ISO14031, which account for both operational performance and environmental condition.

Finally, apart from the work of Fianu and Davis (Fianu and Davis 2018), which focuses on distribution equity, the two papers focusing on the social pillar use the number of jobs created as the metric of choice (Allaoui et al. 2018; Izadikhah and Saen 2016). It can be argued that the social pillar is the most difficult to assess of the three, as there is no clear metric which translates the full impact of AFSCs on society. In light of this, the number of jobs created is one of the simplest, but very relevant, possible metrics. Nonetheless, and as expressed by the minimal attention such metrics have received, there is still a large need for research on the performance of AFSCs regarding social sustainability.

3.6. Research gaps and future research agenda

As previously discussed, more and more attention is being given to the planning and design of AFSCs with the use of OR methods, a reality translated by the increasing number of publications addressing the issue in recent years. Although positive, the increasing focus given to the topic must keep up with the complexity of AFSCs and an ever-evolving competitive environment to which agribusinesses must adapt. With this in mind, more research is needed. Due to the vastness of the problem, the positive impact of future research can be increased if structured research directions are followed. This section makes use of the information gathered from the analysed literature and uses it to identify current research gaps and, simultaneously, propose future research directions to tackle those gaps. Figure 3.12. displays the result of such exercise by presenting a research framework which structures the research agenda proposed herein.

As seen in this chapter, authors have been using several approaches to model and design AFSCs with OR methods, mostly making use of optimisation methodologies. Despite valuable, existing contributions still fail to accurately depict reality, and instead focus on a restricted subset of product and SC characteristics. This reality is explained by the complexity of the problem, which may prove difficult to accurately represent due to computational limitations, especially when looking at optimisation methods. As more characteristics are added to existing models, different methods should be explored to mitigate complexity, such as metaheuristics, which are still considerably unexplored.

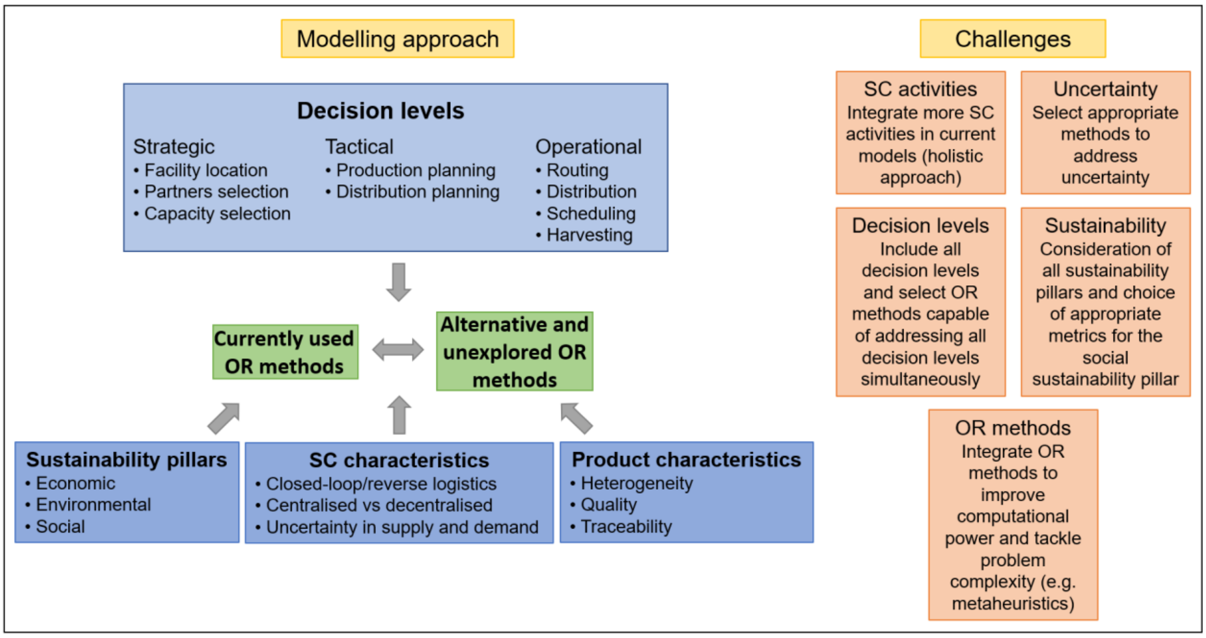

Figure 3.12. – Research framework on the use of OR methods to support the design and planning of AFSCs

The nature of characteristics considered in existing models should also be the focus of future work. Currently, most publications address a limited set of characteristics, with specific characteristics being the focus of a large number of models, while others remain mostly disregarded. Among food product characteristics, perishability is now commonly considered, while product heterogeneity, quality, and traceability require further studying. When accounting for SC characteristics, it should be noted that most models still consider the more traditional centralised and forward SC configuration. Local production contributes to product freshness and reduces food-miles, both aspects valued by consumers, for which future studies on SC decentralisation would be extremely valuable. Similarly, with food waste concerns on the rise, reverse logistics and closed-loop SCs can pave the way to more efficient SC activities. Unfortunately, this area is yet to gain the desired attention from the scientific community. By integrating reverse logistics on future models, researchers could greatly contribute to the applicability of such models to relevant challenges of the present and the future.

To build up on the applicability of existing models to reality, it can be argued much is still to be done regarding uncertainty. Despite being one of the most defining characteristics of AFSCs, uncertainty is still somewhat understudied. The design of models with deterministic supply and/or demand greatly limits the positive impact such models can have on managerial decision making. Consequently, more work on how to address AFSC uncertainty is a necessity.

Additionally, praise must be given to the high volume of work being developed around the concept of sustainability, being it economic or environmental. Nonetheless, it can be argued that social sustainability according to the TBL perspective is still mostly disregarded and constitutes a large gap in the literature. This gap is explained by the complexity it adds to models, a problem mentioned previously, but also by the inexistence of appropriate metrics. In this front, future work should be directed towards exploring a wide variety of social indicators, prone to being quantified, to provide future models with the tools to successfully integrate social sustainability in decision making. Only then will models attain a satisfying holistic approach.

Finally, existing models focus on a subset of decision levels, with papers rarely focusing on all three levels. In the future, the simultaneous integration of all decision levels in models could expand their applicability. Again, this integration implicates larger computational challenges, which require the application of more efficient OR methods.

3.7. Chapter conclusions

In this chapter, a systematic review of the literature was conducted focusing on the use of OR methods to support the planning and design of AFSCs. The popularity of OR methods to support AFSC management is on the rise, as the work of researchers can greatly benefit the tools managers and decision makers alike possess to support their decisions. Still, from the analysis of ten reviews on the topic, it was possible to conclude a more holistic approach is necessary, encompassing all AFSCs and the use of quantitative methods to address their planning and design. This chapter contributes to reducing that gap.

Apart from a review analysis, a content analysis was conducted on a set of 34 publications retrieved from the *Web of Science Database*, focusing exclusively on the use of OR methods to solve AFSC problems. Within this analysis, focus was given to the methods employed, decision levels tackled, nature of the problems, sources of uncertainty considered, product and SC characteristics modelled, SC activities, sustainability pillars addressed, and metrics used to assess those pillars.

The review conducted herein permitted for the identification of clear research gaps and, simultaneously, a research agenda was proposed to solve such gaps and, consequently, help drive forward such an important field of studies.

4. Model formulation

This chapter performs a thorough characterisation and description of the model developed to assist in the design and planning of AFSCs. To provide a clear snapshot at the novelty introduced by the model contained herein, special attention is given to features found underdeveloped or absent in the literature reviewed throughout Chapter 3.

The model structure consists of sets, scalars, parameters, variables, and equations. This chapter provides a clear explanation on all these entities and is, for convenience, structured accordingly. The model was based on that of Cardoso et al. (2013), although considerable modifications were made to adapt it to an AFSC context.

The model here presented is then implemented using GAMS and tested via a case study, and the results of such application are compiled, analysed, and discussed in Chapter 5.

4.1. Structure of the AFSC

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 Chapter 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 EOL product concerns, in line with priorities identified in Chapter 3. The general structure of the AFSC here discussed is highlighted in Figure 4.1. 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 (see Figure 4.1.).

4.2. Problem description

The model proposed herein supports the design and planning of AFSCs in a tactical-strategic level to optimise the economic performance of the SC, measured by the maximisation of the ENPV. 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 uncertainty constraints;
- Supply uncertainty constraints;
- Reprocessing constraints.

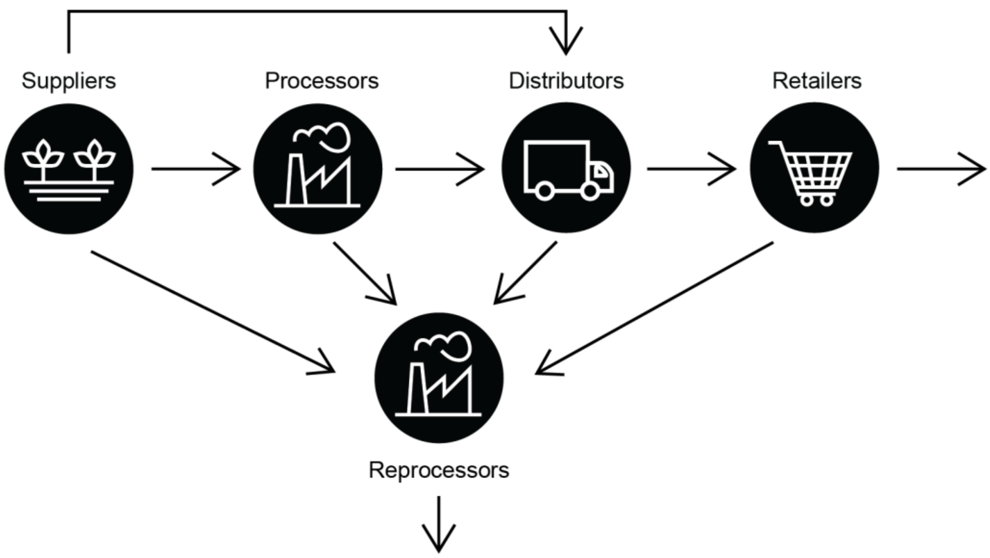

Figure 4.1. – General structure of an AFSC with a reprocessing echelon to mimic reverse logistics, where the arrows represent allowed product flows (arrows after retailers and reprocessors represent sales to end consumers)

4.3. Sets

The different entities, products, and other relevant features were conveniently grouped in sets to both structure the model and ease its utilisation.

V	entities	$V = V_{sto} \cup V_{tra} \cup V_{sup} \cup V_{fac} \cup V_{war} \cup V_{mar} \cup V_{rep} \cup V_{tec}$	
		V_{sto}	Entities with storage
		V_{tra}	Entities with product transformation
		V_{sup}	Suppliers
		V_{fac}	Factories/Processors
		V_{war}	Warehouses/Distributors
		V_{mar}	Markets
		V_{rep}	Reprocessors
		V_{tec}	Entities with technologies
P	products	$P = P_{was} \cup P_{fin} \cup P_{raw}$	
		P_{was}	Products which correspond to waste
		P_{fin}	Final products (to be sold)
		P_{raw}	Raw materials
I	technologies	$I = I_{pro} \cup I_{rep}$	
		I_{pro}	Processing technologies
		I_{rep}	Reprocessing technologies

S nodes for stochastic uncertainty modelling

F allowed flows of products between entities

T time periods

4.4. Scalars

Scalars correspond to fixed values which remain immutable during computation. In this context, scalars are used to force certain conditions into happening or to ensure specific values stay within a reasonable range. The following scalars are employed:

qpl^{upper}	maximum flow of materials allowed between two entities
qpl^{lower}	minimum flow of materials allowed between two entities
$target$	minimum allowed percentage of demand satisfaction
$percent$	minimum allowed percentage of technology capacity usage
ir	interest rate
sv	salvage value of the investment performed
tr	tax rate
fci^{max}	maximum invested fixed capital

4.5. Parameters

Similarly, parameters correspond to pre-defined values used in the model, usually presented in an oriented list that can be related to one or more sets. In this context, parameters vary depending on the entity, product, or even the time period to which they are applied.

As the parameter listing is more extensive than that of scalars, this section is divided considering the sets to which the parameters apply, to easy its interpretation.

4.5.1. Entity-related parameters

tor_v	inventory turnover ratio in entity *v*
$initialinv_v$	initial storage investment for each entity with storage capacity
$centityinit_v$	initial storage capacity of each entity
$cesto^{max}_{v,t}$	maximum limit for the expansion of storage capacity in entity *v* in time period *t*
$cesto^{min}_{v,t}$	minimum limit for the expansion of storage capacity in entity *v* in time period *t*
$nexsto_v$	maximum total limit for the expansion of storage capacity in entity *v*
$cinv_v$	cost of inventory in entity *v* per stored product unit

4.5.2. Product-related parameters

$rate_s$	product demand variation rate for each node *s*
$suprate_{p,s}$	supply variation rate for product *p* for each node *s*
$dmk^{upper}_{p,v}$	maximum value for the demand of product *p* in entity *v* in the first time period
$initinv_{p,v}$	initial inventory of product *p* in entity *v*
$avai_{p,v}$	availability of raw material *p* in entity *v*
$fpprod_{p,v}$	final price of product *p* in entity *v*
$prmat_{p,v}$	price of raw material *p* in entity *v*
$qrmat_{p,p'}$	quantity of raw material *p* necessary to produce product *p'*
$finpro_{p,i}$	final product *p* of each technology *i*
$posspur_{p,v}$	product *p* which entity *v* has the possibility to purchase
$cdisp_{p,v}$	cost of disposal of product *p* in entity *v*
$reprof_{p,v}$	fraction of waste *p* which is possible to reprocess in entity *v*
$imwf_{p,v}$	fraction of product *p* which immediately turns into waste in entity *v*
$lostsf_{p,v}$	fraction of stored product *p* which is lost as waste in entity *v*
$sdmis_{p,v}$	fraction of product *p* which is lost due to supply and demand mismatch in entity *v*

4.5.3. Technology-related parameters

$cpl^{init}_{i,v}$	initial capacity of technology *i* in entity *v*
$invinit_{i,v}$	initial investment in each technology *i* in entity *v*
$operc_{i,v}$	operative cost of technology *i* in entity *v* for each produced unit
$pcons_{i,p}$	consumption of product *p* by technology *i*
$prodt_{i,p}$	technology *i* which produces product *p*

$cepl^{max}_{i,v}$ maximum limit for the expansion of technology *i* in entity *v*

$cepl^{min}_{i,v}$ minimum limit for the expansion of technology *i* in entity *v*

$nexpl_{i,v}$ maximum total limit for the expansion of technology *i* in entity *v*

$alphapl_{i,v,t}$ variable investment in technology *i* in entity *v*

$alphawh_{v,t}$ variable investment in entity *v* with storage capacity

4.5.4. Transportation-related parameters

$transpc_{v,v'}$ transportation cost for one unit between entities *v* and *v'*

$link_{v,v'}$ cost of establishing a transportation contract between entities *v* and *v'*

$fipl_{v,v'}$ distance between entities *v* and *v'*

4.5.5. Other parameters

$prob_s$ probability of occurrence of node *s*

$lvl_{v,s,t}$ auxiliary parameter to establish the average inventory level at entity *v* in time period *t*

4.6. Variables

Variables correspond to the different decisions taken to achieve the final objective. The variables are divided in three groups: continuous variables, the objective function variable and corresponding auxiliary variables, and a smaller set of binary variables.

4.6.1. Continuous variables

$PU_{v,w,p,s,t}$ amount of product p purchased by entity *v* from entity *w* at time period *t*

$W^{in}_{i,v,p,s,t}$ amount of product *p* consumed by technology *i* at entity *v* in time period *t*

$W^{out}_{i,v,p,s,t}$ amount of product *p* produced by technology *i* at entity *v* in time period *t*

$W^{out1}_{v,p,s,t}$ amount of product *p* produced at farm *v* in time period *t* after supply variation is applied

$W^{out2}_{v,p,s,t}$ amount of product *p* produced at farm *v* in time period *t* after waste fraction is applied

$P^{farm}_{p,v,t}$ amount of product *p* lost at farm *v* from supply and demand mismatch in time period *t*

$SQ_{p,v,t}$ total amount of product *p* lost as waste in farm *v* in time period *t*

$QPL_{v,w,p,s,t}$ amount of product *p* shipped from entity *v* to entity *w* in time period *t*

$INV_{v,p,s,t}$ inventory level of product *p* kept at entity *v* in time period *t*

$IL_{v,s,t}$ average product inventory level kept at entity *v* in time period *t*

$CPL_{i,v,t}$ capacity of technology *i* available at entity *v* in time period *t*

$CEPL_{i,v,t}$ expansion of capacity of technology *i* in entity *v* undertaken in time period *t*

$C^{sto}_{v,t}$ storage capacity of entity *v* in time period *t*

$CE^{sto}_{v,t}$ expansion of storage capacity of entity *v* undertaken in time period *t*

$CSer_t$ customer service level in time period *t*

$Dem_{p,v,s,t}$ demand for product *p* in entity *v* in time period *t*

$UnDem_{p,v,s,t}$ unmet demand for product *p* in entity *v* in time period *t*

4.6.2. 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*

4.6.3. Objective variable and corresponding auxiliary variables

$ENPV_s$	expected net present value corresponding to node *s*
$SA_{v,p,s,t}$	sales value of product *p* at market *v* in time period *t* corresponding to node *s*
$CF_{s,t}$	cash flow in time period *t* corresponding to node *s*
$ENE_{s,t}$	expected net earnings in time period *t* corresponding to node *s*
$FTDC_t$	fraction of the total depreciation capital which must be paid in time period *t*
FCI	fixed capital investment
DEP_t	capital depreciation factor in time period *t*

4.7. Objective function

As stated, the model presented herein focuses on the economic objective of ENPV maximisation. This section provides a detailed analysis of the objective function and corresponding auxiliary 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 corresponding interest rate (*ir*). This approach was first proposed by Brealey et al. (Brealey et al. 2014).

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

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 expected net earnings (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.

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

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

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.

$$FTDC_t = \frac{FCI}{t} \quad (5)$$

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.

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

4.8. Constraints

In sections 4.4 and 4.5, the importance of scalars and parameters was discussed, as these allow for specific values to remain within acceptable and/or realistic ranges. In line with this approach, equations must also be established to ensure the model operates at a realistic level, that is, constraints must be applied. These constraints allow for model coherence in terms of mass balance, realistic flows, among others. This section lists and discusses the modelled constraints, which have been categorised depending on where their applicability lies.

4.8.1. Inventory constraints

Inventory constrains ensure that appropriate mass balances are applied to each entity and establish the acceptable inventory levels for warehouses, as well as the maximum and minimum storage capacities deemed realistic for each entity.

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.

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

(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.

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

(8)

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

(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.

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

(10)

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

(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 in section 4.8.6.). 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 (as discussed, transportation flows require corresponding costs, e.g. a contract with a transportation company).

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

(12)

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

(13)

4.8.2. Technology constraints

The model here presented makes use of the set *technologies* (*i*) to define all production (processing) and reprocessing processes. As such, specific constraints need to be established to define the capacity of each technology, as well as the inputs and outputs associated with each process. This section summarises these constraints.

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.

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

(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 ($qrmat_{p,p'}$).

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

(15)

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

(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.

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

(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 ($cpl^{init}_{i,v}$).

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

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

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).

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

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

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

4.8.3. Storage constraints

Apart from technologies, which are used to represent the different production/manufacturing processes within the SC, storage functions as another essential feature of the different entities, as it permits for inventory to be kept at each entity. Storage was modelled in a similar way to technologies, in the sense that storage levels are also regulated by maximum and minimum capacities and capacity expansions. 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 ($nexsto_v$).

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

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

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

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

(26)

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

(27)

Finally, 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.

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

(28)

4.8.4. Transportation constraints

To ensure that material flows remained within appropriate values a set of transportation constraints was introduced. For these, the total flow of materials between two entities *v* and *w* was defined as the sum between the products sent from *v* to *w* ($QPL_{v,w,p,s,t}$) and the products sold by *v* to *w* ($PU_{v,w,p,s,t}$). 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}).

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

(29)

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

(30)

4.8.5. Demand constraints

The literature review (see Chapter 3) presents supply and demand variation in combination with uncertainty as modelling challenges when addressing AFSC planning and design, thus rendering ineffective most design methods created for standard SCs. Appropriate AFSC design models must be capable of effectively addressing demand fluctuations and its corresponding uncertainty, as only then can truly realistic results be obtained. This section focuses on the constraints used to model demand, and section 4.8.6. addresses supply.

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*).

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

(31)

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

(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. In fact, to address demand uncertainty, a stochastic modelling approach was followed, in line with work developed by several authors (Shabani et al. 2012; Huber et al. 2017; K. Govindan et al. 2014; Galal and El-Kilany 2016) (see Chapter 3). To do so, a scenarios tree was established, where each scenario corresponds to a tree node (set *S*). Each node then branches into four possible scenarios in the following time period, and to each node an occurrence probability is attributed ($prob_s$). Each node is then associated to a demand variation rate ($rate_s$). Having established the stochastic scenarios tree, 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.

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

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

4.8.6. Supply constraints

In Chapter 3, supply uncertainty was found to be underdeveloped in existing literature, with larger focus being given to demand uncertainty. To help fill the void in the literature, the model here discussed includes a comprehensive strategy to model supply uncertainty. When addressing supply in AFSCs, two details are of the utmost importance: firstly, it is important to remember supply uncertainty comes from a variety of sources, from variable weather conditions to unpredictable plagues or other causes of crop loss; secondly, it should be noted that agri-food supply will frequently be unable to adapt to demand fluctuations, especially due to the high-lead time characteristic of the sector (better discussed in Chapter 2). As such, the modelling approach must cater for all these characteristics to provide truly realistic results.

As mentioned, AFSCs show reduced flexibility when it comes to adapting supply to demand variation, as lead times are generally too high for production corrections to be undertaken in appropriate time spans. To mimic this condition, the current model defined the supply of each product as a predetermined value with no connection to the demand in the corresponding time period. That is, supply and demand are often mismatched, in accordance with what is seen in reality. Naturally, the predetermined 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 losses. Consequently, several constraints were also incorporated to address such losses, to satisfactorily depict real-life agri-food production. To the best of our knowledge, this supply uncertainty modelling approach is a novelty. Figure 4.2. provides a clear snapshot of the sources of uncertainty/losses in the generic structure of the SC.

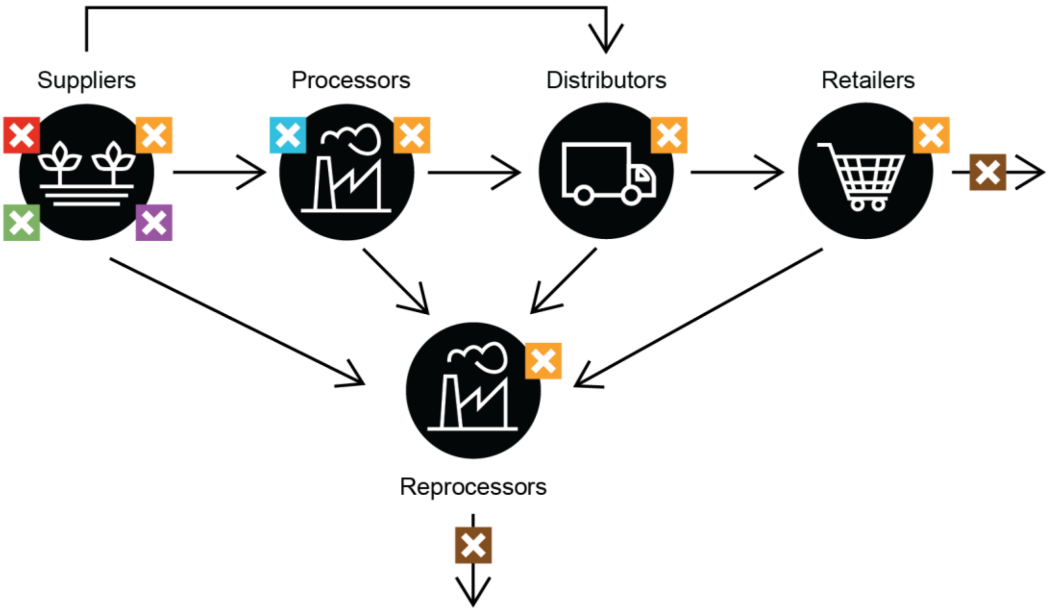

Figure 4.2. – Generic structure of the AFSC with pinpointed sources of uncertainty/losses. Red represents product growth uncertainty in suppliers; green represents harvesting losses; purple represents losses due to supply and demand mismatch; orange represents inventory losses due to product perishability; blue represents losses in processing pathways; brown represents end customers' demand uncertainty

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 losses) 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* (unlike $rate_s$, which reports to demand variation).

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

By immediately deducting a fraction from the theoretical production, Equation 35 effectively mimics uncontrollable factors such as weather changes, soil fertility, occurrence of swarms, and natural disasters (floods and droughts, among others), which cause losses to occur even before the products are harvested. As such, auxiliary variable $W^{out1}_{v,p,s,t}$ corresponds to the quantity of product p which can be harvested in farm *v* in time period *t*.

During and after harvesting the products are handled manually by workers or by machinery. Naturally, the harvesting operation will sometimes feature product mishandling and other accidents which result in additional post-harvest losses. As the current model is of strategic and tactic nature, the modelled time periods are too long for the specific handling of each product to be incorporated. Alternatively, post-harvesting losses 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.

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

(36)

As mentioned in this section's introduction, high-lead times will often result in mismatches between supply and demand. As most food products are highly perishable, such mismatch frequently means excessive supply cannot be kept for long periods of time and is, eventually, wasted. 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 ($sdmis_{p,v}$).

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

(37)

As mentioned in this chapter, the current model allows for storage to be kept in every entity along the SC in Cases B and C (please refer to Chapter 5), condition which better mimics reality in comparison to models which solely allow storage to be kept in warehouses and distribution centres. As food products are highly perishable, and as identified in Chapter 3, perishability must be addressed, especially regarding stored products. As identified by Jonkman et al. (2018), several modelling strategies are available to incorporate product perishability. Nonetheless, most strategies focusing on quality or shelf-life counters require shorter modelling time periods and are, thus, applicable to operational models. As the current model has a strategic and tactical breadth, such strategies are not satisfactory. To circumvent the inconvenience, a more statistical approach was followed by assuming that for each larger time period an average fraction of the stored products eventually becomes inappropriate for consumption as is – the lost stored fraction ($lostsf_{p,v}$). Equation 38 agglomerates all sources of waste in farms to obtain the total spoiled quantity in a given time period ($SQ_{p,v,t}$).

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

(38)

Finally, as the total waste for each farm is calculated, an inventory balance for each farm is possible, derived from Equations 8 and 9, and is given by Equation 39.

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

(39)

4.8.7. Reprocessing constraint

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 $reprof_{p,v}$.

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

4.9. Complementary equations

Apart from the objective function and corresponding constraints necessary for the modelling of AFSCs, two complementary equations were defined to obtain the level of unmet demand of product p at any given entity v in time period t ($UnDem_{p,v,s,t}$) and the level of customer service in time period t ($CSer_t$). Although not strictly necessary, these variables are useful when interpreting results from case studies (see Chapter 5) and are defined by Equations 41 and 42, respectively.

$$UnDem_{p,v,s,t} = Dem_{p,v,s,t} - \sum_{w \in flow(w,v)} QPL_{w,v,p,s,t} \quad \forall v \in V \wedge p \in P \wedge (s,t) \in S \tag{41}$$

$$CSer_t = \sum_{s} \left(prob_s \times \frac{\sum_{(v,p) \in mar(v)} UnDem_{p,v,s,t}}{\sum_{(v,p) \in mar(v)} \left(dmk^{upper}{}_{p,v} \times rate_s \right)} \right) \quad \forall t \in T \tag{42}$$

4.10. Chapter conclusions

Throughout this chapter a detailed description of the model formulation was conducted, focused on the constituting elements of the model and the different constraints imposed. By designing a model with flexible parameters and incorporating AFSC-specific constraints, a generic model was obtained. This approach greatly benefits the applicability of the model to a wide array of AFSCs, thus improving its desired positive impact as a decision-making tool for decision makers and SC managers alike.

By allowing all SC entities to possess a certain degree of storage capacity (please refer to Chapter 5), greater flexibility was given to the SC. This detail is particularly important in AFSCs, as product perishability often undermines keeping inventory for larger periods of time. By equipping all echelons with storage capacity, product inventories can be kept throughout the SC in smaller levels, contributing to faster turnover ratios and minimising the damaging effects of perishability.

Additionally, two other important aspects were incorporated. Firstly, the model was designed considering both supply and demand uncertainty, which renders it more realistic than its deterministic counterparts. This is especially true regarding supply uncertainty, which is modelled here using a novel approach which discriminates a wide set of causes of uncertainty and supply loss. Secondly, the inclusion of reverse logistics via the addition of a reprocessing echelon, in which otherwise wasted products are transformed into other commercially-viable goods. This goes well in line with sustainability concerns and trends identified in Chapter 3.

As previously mentioned, the applicability of the model described herein is put to the test and further discussed throughout Chapter 5, via the application of a multi-scenario case study.

5. Case study, results, and discussion

The model described throughout Chapter 4 was tested via the application of a case study, consisting of several scenarios explained herein. The chapter characterises the specifications of each case in detail and comments on the sources of the data. Furthermore, the present chapter also summarises the results of the application of the three scenarios of the case study. The results presentation is accompanied by a critical discussion of the results, focusing on drawing conclusions regarding the applicability of the model and its behaviour in response to different SC characteristics (mimicked by the different scenarios). Naturally, the results of the three scenarios are analysed comparatively, as only then can truly meaningful conclusions be drawn.

5.1. Case study specifications

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.

It should also be noted that, in all cases, suppliers can send commercially-ready intermediate products directly to distributors, thus suppressing unnecessary routing in which market-ready products are sent from suppliers to distributors via manufacturers (sub-optimal routing).

5.2. Case study data

As mentioned, the different scenarios of the case study here addressed have been taken from works published by Jonkman et al. (2017, 2018). 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 (European Parliament and Council of the European Union 2013; Suiker Unie 2011). To better fit the three scenarios explained in section 5.1., the data was slightly adapted. Nonetheless, as most of the data was drawn from an existing SC, it was mostly kept intact. Additional data was also retrieved from the work published by Cardoso et al. (2013). This section provides a succinct description of the data, which can be found in greater detail in the original papers (Jonkman et al. 2017, 2018; Cardoso et al. 2013).

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 (for specific data on the location of the suppliers, please refer to Figure 5.1.). 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 5.1.

Figure 5.1. – 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 5.2. Furthermore, Table 5.1. introduces the sale prices of all products in final markets in the first time period. For the raw materials, prices of EUR 25.3/ton[17] and EUR 7.67/ton[18] are set for sugar beet and beet leaves for the first time period, respectively.

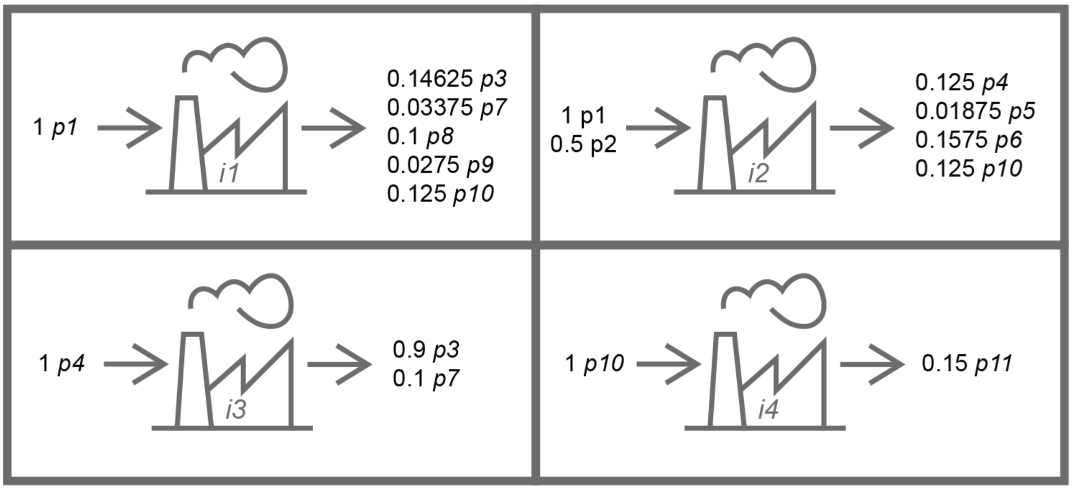

Figure 5.2. – Product inputs and outputs for all processing and reprocessing technologies

Table 5.1. – Sale prices of final products to end consumers

Product	Sale price to end consumer (EUR/ton)
p3	500.00
p4	450.00
p5	400.00
p6	90.00
p7	150.00
p8	45.00
p9	6.00
p10	10.00
p11	84.10

As far as storage capacity is concerned, and as mentioned in Chapter 4, all entities are given the possibility to keep inventory, although storage capacity is much higher in warehouses when comparing to the rest of the SC. Warehouses W1 and W3 begin with a storage capacity of 450 tons per time period, and W2 and W4 with 300 tons per time period. On the other hand, suppliers, processors,

[17] https://www.fwi.co.uk/business/markets-and-trends/crop-prices/price-announced-201819-sugar-beet-crop, accessed in October 2018;
[18] https://www.uvm.edu/vtvegandberry/PriceReports/Price%20Report101910.pdf, accessed in October 2018.

and markets begin with a storage capacity of 2 tons per time period (Cases B and C). Furthermore, in each time period entities are allowed to expand their storage capacity. Again, warehouse capacity expansions can be wider than those of the remaining SC players. Maximum expansions of 50 tons per time period and 2 tons per time period are allowed for warehouses and all remaining SC players, respectively. As capacity expansions should be optional, depending on the conditions of the SC, the minimum capacity expansion was set to zero for all entities.

Similarly, entities with technologies are also dependent on technology capacity (i.e. maximum processing capacity). Entities F1 and F2 operate with processing capacities of 9,125 kton/year and 3,650 kton/year, respectively. F1 and F2 can also expand their *i1* processing capacity by 100 kton/year. Technology expansions should be optional depending on the needs of the SC, for which a minimum expansion capacity of zero was set for all entities. Additionally, F1 is equipped with an initial sugar refining (*i3*) capacity of 1,000 kton/year. It is important to note that the small scale biorefinery design (*i2*) is not initially installed in any entity. As such, the possibility of opening a facility using this design is also explored. In this case, the facility can begin operations with a technology capacity between 500 kton/year and 1,000 kton/year Likewise, the possibility of opening another conventional processing facility is explored. In this case, possible starting technology (*i1*) capacities of 9,125 kton/year, 5,475 kton/year or 3,650 kton/year are considered. Table 5.2. summarises the annual fixed costs associated with each facility design and technology capacity.

Table 5.2. – Summary of annual fixed costs and processing costs depending on facility design and installed capacity

Facility design	Annual capacity (kton)	Annual fixed cost (M EUR)	Processing cost (EUR/ton)			
			i1	*i2*	*i3*	*i4*
Conventional	9,125	8.33	62.3	---	12.9	10.6
	5,475	5	63.36	---	---	10.78
	3,650	3.67	65.49	---	---	10.96
Biorefinery	5,475	5	---	63.36	---	---
	3,650	3.67	---	65.49	---	---
	2,190	2.67	---	69.53	---	---

The case considers three time periods of one year each, thus modelling the SC for a total of three years and a minimum demand satisfaction level of 90 per cent is required for each time period. Additionally, product inventories are set to zero for all entities, the turnover ratio for all entities is set at 20, the parameter $lvl_{v,s,t}$ is set to 2 for all entities, and storage costs of EUR 0.30/ton are assumed for the entirety of the SC. The interest rate, salvage value, and tax rate are fixed at 10 per cent, 20 per cent, and 30 per cent, respectively (Cardoso et al. 2013).

In terms of transportation, contracting costs are set at EUR 200 for each contracted route, and variable costs are set at EUR 0.05/ton.km.

Product spoilage due to perishability, harvesting losses, and supply and demand mismatch losses in farms all set at 5 per cent. In reprocessing entities, 90 per cent of incoming waste is converted to final product.

All costs increase by 1 per cent per time period and, as previously described, supply and demand are subject to uncertainty in all cases. As mentioned in Chapter 4, a stochastic scenarios tree was established to account for demand uncertainty and support the mimicking of supply uncertainty. Figure 5.3. depicts the scenarios tree and Table 5.3. includes reference to the probability of occurrence of each node, as well as associated variation rates in supply and demand. As can be seen, a trending increase in demand was modelled, with 5 per cent and 10 per cent variations occurring depending on the scenario. Similarly, supply variation losses of 5 per cent and 10 per cent have been added, with the final scenarios tree accounting for all combinations of supply losses and demand increase.

Table 5.3. – Information pertaining to the stochastic scenarios tree

Node	Corresponding time period	Occurrence probability (%)	Supply variation rate (%)	Demand variation rate (%)
s1	*t1*	100	0	0
s2	*t2*	12.5	-5	+5
s3	*t2*	50	-5	+10
s4	*t2*	25	-10	+5
s5	*t2*	12.5	-10	+10
s6	*t3*	6.25	-5	+5
s7	*t3*	3.125	-5	+10
s8	*t3*	6.25	-10	+5
s9	*t3*	6.25	-10	+10
s10	*t3*	6.25	-5	+5
s11	*t3*	3.125	-5	+10
s12	*t3*	12.5	-10	+5
s13	*t3*	6.25	-10	+10
s14	*t3*	3.125	-5	+5
s15	*t3*	6.25	-5	+10
s16	*t3*	3.125	-10	+5
s17	*t3*	12.5	-10	+10
s18	*t3*	3.125	-5	+5
s19	*t3*	3.125	-5	+10
s20	*t3*	6.25	-10	+5
s21	*t3*	12.5	-10	+10

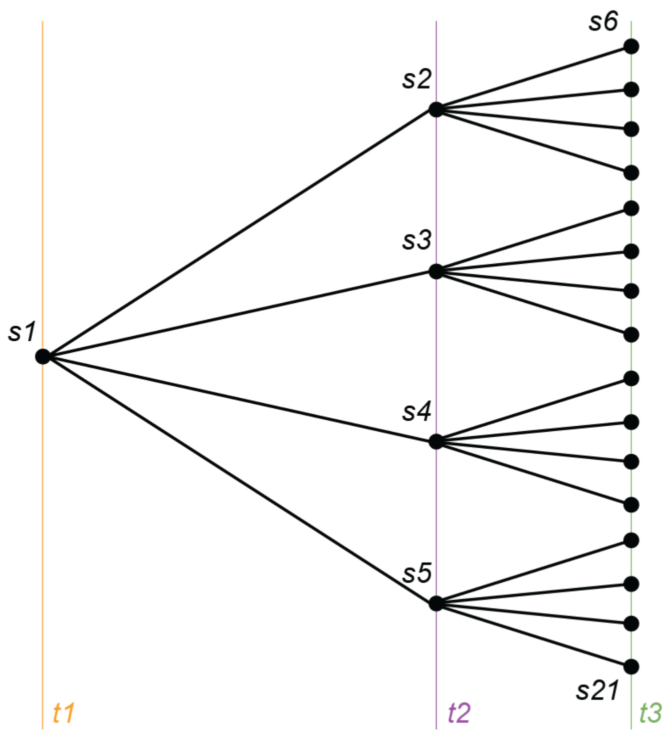

Figure 5.3. – Stochastic scenarios tree. Each scenario(s) branches into four possible scenarios in the following time period. Each scenario is associated to a specific occurrence probability and includes either a 5 per cent or 10 per cent demand increase in comparison to the previous time period, as well as a 5 per cent or 10 per cent decrease in supply due to crop-growth variations

Other important variables for the calculation of the objective function pertain to initial installation costs and variables costs for both storage and technology capacity. Tables 5.4. and 5.5. summarise initial investment and variable costs for storage and technology, respectively.

Table 5.4. – Initial and variable costs pertaining to storage capacity in the first time period

Entity	Initial investment costs (EUR/capacity unit)	Variable costs (EUR/ton)
S1-S43	0.10	1.95
F1-F4	0.10	1.95
W1	1.00	2.10
W2	1.00	2.15
W3	1.00	2.13
W4	1.00	1.95
M1-M17	0.10	1.95

It should be noted that Tables 5.4. and 5.5. only refer to the costs incurred in the first time since costs were assumed to increase by 1 per cent from one time period to the next. Additionally, it is important to mention that the initial investment and variable costs relating to technology *i4* were not available in the consulted literature and have been assumed by force of necessity.

Table 5.5. – Initial and variable costs pertaining to technology capacity in the first time period

Entity	Technology	Initial investment costs (EUR/capacity unit)	Variable costs (EUR/ton)
F1	*i1*	1.00	5.24
	i3	0.90	8.00
	i4	0.60	3.73
F2	*i1*	1.00	7.68
	i3	0.90	8.00
	i4	0.60	3.73
F3	*i1*	1.00	6.28
	i3	0.90	8.00
	i4	0.60	3.70
F4	*i2*	1.30	9.62

Apart from the costs, and returning attention to the scenarios tree, it can be seen that the first scenario (node *s1*) is deterministic. It is upon this node that the remaining variations are applied, giving rise to the stochastic scenarios where uncertainty is indeed considered. As a deterministic node, the initial supply and demand do not suffer variations, as can be seen in Table 5.3., and are then known values. Mention has been given to the state of supply, in the form of arable areas and corresponding product yields. Adding to this, the different sources of loss have also been specified in this chapter. To complement such data, Table 5.6. summarises the deterministic demand values for each product in each retailer.

Table 5.6. – Deterministic demand values for the first time period

Entity	Product	Demand (ton)
M1-M17	*p3*	4,246
	p4	555
	p5	83
	p6	696
	p7	368
	p8	831
	p9	238
	p10	293
	p11	7,650

A brief analysis of Table 5.6. results in the conclusion that product demand was defined as uniform among retailing agents. Although this does not correspond to what is seen in reality, in which consumer habits depend on culture and geographic location, it was deemed an acceptable simplification of the input data.

Finally, it should be noted that the distance between entities was calculated based on Figure 5.1., taking into account its scale to that of The Netherlands.

5.3. Results and discussion

5.3.1. Objective function results

As it has been mentioned, the model developed and discussed throughout Chapter 4 is designed to maximise the ENPV, that is, an economic maximisation objective. Table 5.7. displays the ENPV (final objective value) of each of the three scenarios.

Table 5.7. – ENPV obtained for each scenario

Metric	**Scenario**		
	Case A	Case B	Case C
Expected net present value (EUR)	3,074,961.95	3,080,248.23	4,053,404.26

The results from Table 5.7. seem to agree with what was expected. 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 performance of the SC to an agri-food context. This translates, naturally, 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. Even though further analysis needs to be conducted to confirm this, it may be argued that, at first glance, this fact goes well in line with conclusions from Chapter 3, in which reverse logistics are identified as a promising area in AFSCs. To better understand the causes of such differences in the objective value, an extensive analysis of the remaining model data is conducted.

5.3.2. Data analysis

To improve on the clarity of the information here provided, this section is divided in the three scenarios, that is, the results for each scenario are summarised individually. The individual data is then brought together and discussed in further sections.

5.3.2.1. Case A

Case A corresponds to the scenario in which storage is solely allowed in warehouses/distributors. Hence, this is the simplest of the three scenarios and, naturally, has the lowest registered ENPV (as the features added to Cases B and C are targeted at improving SC performance at the economic level). Table 5.8. highlights the major economic variables used as auxiliary data to obtain the maximum ENPV.

Table 5.8. – 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

As can be seen in Table 5.8., the initial investment is complemented with additional investment in the second time period (expansion of technology capacity and/or expansion of storage capacity). No additional expansions are registered for the third time period. The depreciation costs incurred per time period correspond to the fraction of the fixed investment which does not fall under the salvage value of said investment, divided equally between all existing time periods (linear depreciation is considered).

One other important detail is the increase in ENEs throughout the time periods. This goes well in line with the expected behaviour of the model, as the expansion of the SC derives from an expected increase in demand and, consequently, in supply, which ultimately translates into higher sales (and revenues).

Apart from the economic indicators used to assess the ENPV, other features of interest can be analysed. Namely, technology and storage usage and capacity vary depending on the needs of the SC. Tables 5.9. and 5.10. summarise the major storage and technology-related variables, respectively.

Table 5.9. – Storage-related results for Case A

Entity	Initial storage capacity (ton)	Capacity expansion (ton)			Average inventory level (ton)		
		t1	*t2*	*t3*	*t1*	*t2*	*t3*
W1	450	50	50	0	350	380	510
W2	300	50	50	0	275	300	300
W3	450	50	50	0	350	375	475
W4	300	50	50	0	250	310	310

Storage capacity expansions of 50 tons are registered for all existing warehouses in the two first time periods (this goes well in line with previously discussed economic parameters, in which no investment costs are seen in the final time period). Consequently, warehouses W1 and W3 finish with storage capacities of 550 tons and warehouses W2 and W4 with storage capacities of 400 tons. It has been mentioned that an expected increase in both supply and demand is pushing for the SC expansion, which in turn leads to higher volumes of sales. Naturally, higher sales required both higher production and distribution, which require additional storage. The data follows this trend, with the sum of average inventory levels going up from one time period to the next, even though average levels are kept constant in W2 and W4 from the second to the third time periods.

Table 5.10. – Technology-related results for Case A

Entity	Technology	Initial processing capacity (ton)	Capacity expansion (ton)			Average production (ton)		
			t1	*t2*	*t3*	*t1*	*t2*	*t3*
F1	*i1*	9,125,000	0	125,000	0	58,500	64,350	69,850
	i3	1,000,000	0	0	0	9,550	10,350	10,350
F2	*i1*	3,650,000	0	234,000	0	40,950	46,800	50,800
	i3	0	500,000	123,000	0	5,450	6,800	6,800
F3	*i1*	0	0	0	0	0	0	0
	i3	0	0	0	0	0	0	0
F4	*i2*	0	785,500	0	0	32,500	34,750	36,150

Firstly, it should be noted that the strategic decision not to open facility F3 is taken, and instead capacity expansion is performed in already existing locations F1 and F2, bearing the same technologies as the eventual facility F3. In parallel, the biorefinery technology is installed, here represented by facility F4, which is opened in the first time period and operates unchanged throughout the modelled horizon. Secondly, it can be seen that entity F1 performs a capacity expansion of the conventional technology (*i1*) in the second time period, to cope with increasing production necessities (note that the average production increases steadily throughout). As processing requirements vary only slightly for technology *i3*, one single expansion is registered for entity F2. Again, no investment is performed in the final period.

5.3.2.2. Case B

Case B is very similar to Case A, but storage capacity is allowed in every echelon, although in significantly lower amounts when compared to the warehouse/distribution echelon. The added storage prevents product perishability (up to a certain reasonable level), and slightly improves the economic performance of the model. Table 5.11. highlights the major economic variables used as auxiliary data to obtain the maximum ENPV.

Table 5.11. – 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

In Case B, as in Case A, investment occurs solely in the first and second time periods. The economic variables assume slightly higher values when compared to Case A, specifically due to higher storage costs. This comes, naturally, from the additional storage capacity installed in every entity of every echelon. As mentioned, the improved scattered storage capacity supports the reduction of losses due to product perishability, which allows for larger product quantities to be available at any given time period. In turn, this reality is translated into higher sales and, consequently, higher ENEs (several thousand euros).

Tables 5.12. and 5.13. present storage-related parameters, and Table 5.14. displays technology-related parameters.

Table 5.12. – Storage-related results of warehouses for Case B

Entity	Initial storage capacity (ton)	Capacity expansion (ton)			Average inventory level (ton)		
		t1	*t2*	*t3*	*t1*	*t2*	*t3*
W1	450	50	50	0	315	335	485
W2	300	50	50	0	240	260	260
W3	450	50	50	0	315	330	335
W4	300	50	50	0	215	270	270

The performance of the storage echelon is very similar to that verified in Case A, with the same capacity expansions taking place and average inventory levels behaving in the same manner. Nonetheless, it should be noted that, although average inventory level variation is similar, the observed values are lower when compared to their Case A counterparts. Such reduction stems from the additional storage capacity spread across the remaining SC players.

Table 5.13. – Storage-related results of non-warehouses for Case B

Entity	Initial storage capacity (ton)	Capacity expansion (ton)			Average inventory level (ton)		
		t1	*t2*	*t3*	*t1*	*t2*	*t3*
S1-S39	2	0	0	0	0.71	0.77	0.77
S40-S43	2	2	2	0	2.10	4.30	5.20
F1-F4	2	0	0	0	0.71	0.77	0.77
M1-M17	2	0	0	0	0.71	0.77	0.77

Table 5.13. summarises the storage behaviour for all remaining SC entities, i.e. all SC entities which do not possess storage capacity in Case A. As can be seen, the initial storage level is sufficient for the vast majority of entities to respond positively to storage necessity across all time periods, as capacity expansion is only observed in four locations. Suppliers S40 to S43 suffer expansions of 2 tons in both the first and second time periods, thus increasing their total storage capacity to 6 tons at the end of the modelled horizon. As can be seen, the average inventory levels stay slightly below maximum capacity for all entities. Suppliers S40 to S43 are all located near areas with intense retailer presence, reason for which the expansions take place in these locations, as the higher average inventory requires

additional transportation. By featuring shorter distances between entities, the transportation costs are then minimised.

Table 5.14. – Technology-related results for Case B

Entity	Technology	Initial processing capacity (ton)	Capacity expansion (ton)			Average production (ton)		
			t1	*t2*	*t3*	*t1*	*t2*	*t3*
F1	*i1*	9,125,000	0	125,000	0	58,500	64,350	69,850
	i3	1,000,000	0	0	0	9,550	10,350	10,350
F2	*i1*	3,650,000	0	234,000	0	40,950	46,800	50,800
	i3	0	500,000	123,000	0	5,450	6,800	6,800
F3	*i1*	0	0	0	0	0	0	0
	i3	0	0	0	0	0	0	0
F4	*i2*	0	785,500	0	0	32,500	34,750	36,150

As can be observed, technology-related behaviour is identic for Cases A and B. Such scenario stems from the nature of the additional storage capacity, which occurs mostly at the supplier and retailer levels. Suppliers and retailers are capable of storing products for fixed (short) periods of time, thus better preserving products and minimising the negative impact of perishability. However, since Case B is similar to A in all data except for storage capacity, demand for products is the same and, consequently, product production is identic. However, it should be noted that, by preventing more loss, Case B features a higher met demand percentage when compared to Case A (addressed in section 5.3.3.).

5.3.2.3. Case C

Case C is the most dissimilar to Cases A and B, as it includes one additional echelon in the SC. The additional echelon performs reprocessing operations to transform otherwise wasted products into other commercially-valuable ones. As such, Case C imposes a higher number of products, technologies, and product flows when compared to its counterparts.

As the added echelon provides other commercially beneficial operations, it is natural that the corresponding economic optimisation also bears better results, as can be seen by the maximum ENPV, which is considerably higher than the ones registered for Cases A and B. Table 5.15. highlights the major economic variables used as auxiliary data to obtain the maximum ENPV.

As expected, the initial investment is highest for Case C, as it builds upon Case B by adding a set of reprocessing technologies, with corresponding installation costs. The capital investment for the second time period increases slightly when compared to that of Case B, from which it can be concluded that additional investment was made to expand either storage capacity or technology capacity.

Table 5.15. – 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

Knowing that the reverse logistics activities allow for a certain fraction of existing waste to be turned into other commercially-viable products, it is possible to see that ENEs for Case C are highest among the three scenarios. Such fact is explained by two different factors. Firstly, a fraction of otherwise wasted product (which has no value) is turned into sales, thus increasing revenues. Secondly, due to diminished costs. As can be seen in Equation 3 (please refer to Chapter 4), waste disposal implicates costs which need to be supported by the SC. By reducing the amount of waste, not only do new products become available for retailing, but disposal costs are reduced simultaneously, thus achieving better performance in both revenue maximisation and cost-cutting. To better highlight this situation, Table 5.16 presents the waste disposal costs for all three scenarios.

Table 5.16. – Waste disposal costs for each scenario

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.

Tables 5.17 and 5.18 present storage-related parameters, and Table 5.19 displays technology-related parameters.

The results in Table 5.17. show a very similar storage behaviour to what is observed in the previous scenarios. The major difference is the average inventory level, which is higher due to the additional necessity of storing the reprocessed products (in this case, *p11*).

Table 5.17. – Storage-related results of warehouses for Case C

Entity	Initial storage capacity (ton)	Capacity expansion (ton)			Average inventory level (ton)		
		t1	*t2*	*t3*	*t1*	*t2*	*t3*
W1	450	50	50	0	375	395	545
W2	300	50	50	0	300	320	320
W3	450	50	50	0	375	390	395
W4	300	50	50	0	275	330	330

The results from Table 5.18. shed light on the increased investment made in the second time period. As can be seen, storage capacity for non-warehouse entities behaves similarly to what is seen in Case B, except for the processing echelon, in which capacity expansions are also observed in the first and second time periods. As mentioned in section 5.2., the reprocessing echelon in this case study corresponds to the processing echelon, as the reprocessing technology (*i4*) is installed in entities F1-F3. As such, seeing storage capacity expansions in the entities where additional product is being processed does not come as a surprise. In fact, storing product near its origin helps prevent incurring in further transportation costs. This is further confirmed by entity F4 (the small biorefinery facility), in which the reprocessing technology is not installed, which remains without further storage capacity expansions.

Table 5.18. – Storage-related results of non-warehouses for Case C

Entity	Initial storage capacity (ton)	Capacity expansion (ton)			Average inventory level (ton)		
		t1	*t2*	*t3*	*t1*	*t2*	*t3*
S1-S39	2	0	0	0	0.71	0.77	0.77
S40-S43	2	2	2	0	2.10	4.30	5.20
F1-F3	2	2	2	0	3.60	5.80	5.90
F4	2	0	0	0	0.71	0.77	0.77
M1-M17	2	0	0	0	0.71	0.77	0.77

Again, it can be observed that the model gives preference to expanding the capacity of existing infrastructure rather than installing a new facility (F3). The behaviour of technologies *i1*-*i3* remains unchanged, but the addition of a reprocessing technology (*i4*) gives rise to new observations. It should be noted that the reprocessing technology is installed from the start in entities F1 and F2, and capacity expansions are not necessary throughout the modelled horizon.

At first glance the average production of this new reprocessing technology may seem abnormally high in comparison to the remaining products, as, for instance, in entity F1 it exceeds even the production of white sugar via *i1* (Table 5.19). However, a more careful analysis identifies *p11* (the reprocessed, commercially-viable product) as ‘other agri-products’ (please refer to section 5.2.). Product *p10* corresponds to soil tare, which can be used to produce fertilisers and enrich arable land. Technology *i4* harnesses the fertilising properties of *p10* and allows for other products to be grown making use of it. As such, *p11* corresponds in reality to a myriad of other vegetal crops which can be grown making use of soil tare. As *p11* accounts for a wide set of possible vegetal crops and considering such crops to be the output of technology *i4*, a higher product output is not only acceptable but also natural.

Table 5.19. – Technology-related results for Case C

Entity	Technology	Initial processing capacity (ton)	Capacity expansion (ton)			Average production (ton)		
			t1	*t2*	*t3*	*t1*	*t2*	*t3*
F1	*i1*	9,125,000	0	125,000	0	58,500	64,350	69,850
	i3	1,000,000	0	0	0	9,550	10,350	10,350
	i4	1,000,000	0	0	0	87,000	95,700	95,700
F2	*i1*	3,650,000	0	234,000	0	40,950	46,800	50,800
	i3	0	500,000	123,000	0	5,450	6,800	6,800
	i4	500,000	0	0	0	43,350	54,090	54,090
F3	*i1*	0	0	0	0	0	0	0
	i3	0	0	0	0	0	0	0
	i4	0	0	0	0	0	0	0
F4	*i2*	0	785,500	0	0	32,500	34,750	36,150

5.3.3. Unmet demand results

Throughout section 5.3.2. some results of each scenario have been compared to those from other scenarios in an attempt to better comprehend the behaviour of the model, as well as the influence of the different changes operated within the SC. One other important factor that should be taken into account when assessing the performance of the model in adapting to the different scenarios is the level 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 5.20. summarises the percentages of unmet demand obtained for each scenario.

Table 5.20. – Percentage of unmet demand obtained for each scenario

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 per cent is imposed to the model (as mentioned in section 5.2.), 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 per cent 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 (see Table 5.16.) 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 variation further consolidates the beneficial impact of the successive improvements made to the SC and tested via Cases A, B, and C.

5.3.4. Model statistics

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 5.21. shows the main model statistics for each of the three scenarios.

Table 5.21. – Model statistics for each scenario

Scenario	# non-zero elements	# single equations	# single variables	# discrete variables	Execution time (s)
Case A	4,188,720	94,125	2,303,749	3,921	739.34
Case B	5,448,124	111,397	2,439,415	3,921	1,147.12
Case C	6,190,425	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. A gradual increase is observed in each column of Table 5.21., especially regarding the execution time of each scenario. In fact, while the number of variables and equations does increase, the execution time differences are even more striking. This observation goes well in line with the idea that additional complexity often leads to exponentially higher processing times. While execution times remained within reasonable boundaries, it is natural to assume such might not have been the case were the different scenarios to be larger in terms of data quantity. Ultimately, the exponentially-increasing execution times could be a barrier to appropriately solving this type of optimisation problems.

Nonetheless, and using the results presented throughout this chapter as justification, the added complexity stemming from the different improvements made from one scenario to the next does come with a considerable performance improvement in terms of the final results to which the modelling effort arrives. As such, it could be argued that, in an extreme case, a trade-off between appropriate model response and acceptable execution time would have to be reached.

5.3.5. Results summary

This section provides a summary of the major differences between the three scenarios and uses such differences to make the case for the improved performance provided by the modelling approach. Table 5.22. provides a snapshot at the major differences between the three scenarios.

Table 5.22. Differences between the three scenarios

Scenario	Technology-related approach	Storage-related approach
Case A	Three processing technologies, without reprocessing possibility	Storage is allowed at the warehouses/distributors echelon
Case B	Three processing technologies, without reprocessing possibility	Storage in warehouses is complemented with minor and flexible storage in every single echelon
Case C	Four processing technologies, including a reprocessing technology to incorporate reverse logistics	Storage in warehouses is complemented with minor and flexible storage in every single echelon

As seen in Table 5.22., each scenario builds upon the previous one by the addition of an improvement to either the technologic or storage-related approach. By adding more flexible storage options, Case B mitigates part of the product perishability issues to which Case A cannot respond positively, thus improving both the environmental and economic performance of the model. Similarly, Case C improves on the performance of Case B by incorporating reverse logistics, further reducing the amount of wasted product and improving on the economic performance by transforming non-valuable waste into commercially-viable goods. Although improvement between Cases A and B is undeniable, the improvement caused by the addition of reverse logistics activities is considerably more impactful, a finding which goes well in line with conclusions drawn from Chapters 2 and 3.

5.4. Chapter conclusions

This chapter clearly depicts the different performance behaviours of the model when additional SC features are incorporated via the application of various scenarios of the same case study. It can be concluded that the addition of features such as more widely available storage capacity and reverse logistics positively contribute to the objective of economic performance optimisation.

As discussed previously, especially throughout Chapter 3, reverse logistics are now among the most prominent responses to increasing environmental concerns, as well as on the forefront of sustainability objectives and waste reduction. Here, the superior economic performance of Case C brings new light into this paradigm, as it clearly shows reverse logistics are not only a powerful tool to improve the environmental performance of AFSCs (waste reduction), but also serve as a meaningful contributor to better economic performance.

The three scenarios analysed herein are mostly taken from an existing sugar beet SC in The Netherlands, for which a considerable portion of the data is realistic. Even though some of the data was assumed or derived from other publications, and the three scenarios designed to fit the intent of the study, the results can be seen as considerably realistic, a trait which further improves their relevance.

Finally, and as always, additional work can be performed to further advance and consolidate the findings here discussed, a topic which is analysed in detail in Chapter 6.

6. Conclusion and future research steps

The work presented throughout this document is centred on the development of a quantitative model to support the design and planning of AFSCs via an optimisation approach, focused on the strategic and tactical decision levels. A MILP strategy is proposed, and the exercise of model creation derives from the conduction of an extensive systematic review of the literature (Chapter 3), in which a set of literature gaps are thoroughly identified and discussed. The proposed model (presented in Chapter 4) 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 and discussion of a case study carried out in Chapter 5 confirm the positive behaviour of the model in response to specific AFSC characteristics, identified via theoretical analysis (Chapter 2) and practical application (Chapter 3). 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 Chapter 3). 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.

The satisfactory performance of the model in an AFSC context solves a set of clearly identified knowledge gaps. Firstly, the model is an important step towards encompassing both supply and demand uncertainty in the AFSC sector, traits deemed essential for the appropriate applicability of the model to real-world cases. Secondly, the model incorporates reverse logistics, which have been identified as powerful tools in the optimisation of both the economic and environmental performance of AFSCs and that, so far, had been understudied. Finally, the model includes specific under-explored AFSC characteristics such as product heterogeneity and a flexible storage strategy.

Despite providing several improvements when compared to non AFSC-specific models, the current model can still be subject to several improvements. The major limitations of the current approach are summarised here, and a brief suggestion of future research steps provided in order to support mitigating such limitations.

At first, it should be noted that the model here developed incorporates one single economic objective, a trait which fails to meet current TBL optimisation concerns. In reality, the literature review highlights the importance of developing work based, at least, on both economic and environmental concerns. Even though, as discussed, the addition of reverse logistics and more flexible storage can support waste reduction, 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 (Zeballos et al. 2014). 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. Instead of developing a model solely based on optimisation, a hybrid strategy such as a recursive optimisation-simulation approach (ROSA), using the optimisation as master and the simulation as slave, could help solve computational demands. This would allow for the exact optimised solution of the optimisation step to be paired with the lighter, more realistic solution of the simulation step. Again, it should be noted that solution convergence may still be a problem for larger case studies. Apart from simulation strategies, the combination of optimisation approaches with heuristics can also be of interest when attempting to solve complexity problems. Heuristics can greatly contribute to the simplification of otherwise impossible or difficult problems, which can positively impact the execution times of modelling approaches. However, it should be noted that the application of appropriate heuristics requires solid background knowledge and a critical approach towards its influence on the final results.

One other possible improvement consists in studying other AFSC-specific characteristics, such as comparing the performance of centralised and decentralised SC configurations, adding specific cold chain features, inserting product traceability concerns, among others. Again, it is important to remember that each additional feature further increases the complexity of the problem which then needs to be modelled, incurring in the same problems described in the paragraph above.

One final improvement could also be conducted in the formulation of case studies with which to test the models. In this work, despite most of the data being taken from an existing SC, there was still a necessity to adapt data from other publications or assume specific parameters, a situation which inevitably adds another layer of uncertainty to the modelling exercise. A closer collaboration with existing industrial players can prove valuable, especially if that implicates obtaining the full set of required data from a single operating source.

To conclude, the current model contributes primarily 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, previous literature gaps are now closer to being solved, and it is my hope that this work serves as the solid ground upon which future research in conducted.

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Annex A: table of reviewed papers

Table A.1. – Summary of the major characteristics of reviewed papers

Author	Title	Journal	Year	Decision Level	Problem type	Modelling approach	Sustainability pillars addressed
Allaoui, Hamid; Guo, Yuhan; Choudhary, Alok; Bloemhof, Jacqueline	Sustainable agro-food supply chain design using two-stage hybrid multi-objective decision-making approach	Computers & Operations Research	2018	Strategic	Deterministic case study	Decision analysis	Economic, environmental, and social
Izadikhah, Mohammad; Saen, Reza Farzipoor	A new preference voting method for sustainable location planning using geographic information system and data envelopment analysis	Journal of Cleaner Production	2016	Strategic	Deterministic case study	Decision analysis	Economic, environmental, and social
Dellino, G.; Laudadio, T.; Mari, R.; Mastronardi, N.; Meloni, C.;	Microforecasting methods for fresh food supply chain management: A computational study	Mathematics and Computers in Simulation	2018	Operational	Deterministic case study	Optimisation, data analysis, and statistics	Economic
Joshi, Rohit; Banwet, D. K.; Shankar, Ravi; Gandhi, Jimmy	Performance improvement of cold chain in an emerging economy	Production Planning & Control	2012	Operational	Application	Optimisation	Economic and environmental
Shabani, Amir; Saen, Reza Farzipoor; Torabipour, Seyed Mohammad Reza	A new benchmarking approach in Cold Chain	Applied Mathematical Modelling	2012	Strategic	Stochastic case study	Simulation and optimisation	Economic
Bosona, T. G.; Gebresenbet, G.	Cluster building and logistics network integration of local food supply chain	Biosystems Engineering	2011	Strategic and operational	Deterministic case study	Optimisation	Economic and environmental
Miranda-Ackerman, Marco A.; Azzaro-Pantel, Catherine; Aguilar-Lasserre, Alberto A.	A green supply chain network design framework for the processed food industry: Application to the orange juice agrofood cluster	Computers & Industrial Engineering	2017	Strategic	Deterministic case study	Optimisation and decision analysis	Economic and environmental

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Table A.1. – continued from previous page

Author	Title	Journal	Year	Decision Level	Problem type	Modelling approach	Sustainability pillars addressed
Accorsi, Riccardo; Baruffaldi, Giulia; Manzini, Riccardo; Tufano, Alessandro	On the design of cooperative vendors' networks in retail food supply chains: a logistics-driven approach	International Journal of Logistics-Research and Applications	2017	Strategic	Deterministic case study	Data analysis and decision analysis	Economic
Huber, Jakob; Gossmann, Alexander; Stuckenschmidt, Heiner	Cluster-based hierarchical demand forecasting for perishable goods	Expert Systems with Applications	2017	Operational	Stochastic case study	Expert systems and decision analysis	Economic
Banasik, Aleksander; Kanellopoulos, Argyris; Claassen, G. D. H.; Bloemhof-Ruwaard, Jacqueline M.; van der Vorst, Jack G. A. J.	Assessing alternative production options for eco-efficient food supply chains using multi-objective optimization	Annals of Operations Research	2017	Operational	Deterministic case study and application	Optimisation	Environmental
Linnemann, Anita R.; Hendrix, Eligius M. T.; Apaiah, Radhika; van Boekel, Tiny A. J. S.	Food chain design using multi criteria decision making, an approach to complex design issues	NJAS-Wageningen Journal of Life Sciences	2015	Strategic	Deterministic case study	Decision analysis	Economic and environmental
Ge, Houtian; Gray, Richard; Nolan, James	Agricultural supply chain optimization and complexity: A comparison of analytic vs simulated solutions and policies	International Journal of Production Economics	2015	Operational	Deterministic case study	Simulation, optimisation, and decision analysis	Economic
Bortolini, Marco; Faccio, Maurizio; Ferrari, Emilio; Gamberi, Mauro; Pilati, Francesco	Fresh food sustainable distribution: cost, delivery time and carbon footprint three-objective optimization	Journal of Food Engineering	2016	Tactical	Deterministic case study	Optimisation and expert systems	Economic and environmental
Pipatprapa, Anirut; Huang, Hsiang-Hsi; Huang, Ching-Hsu	A Novel Environmental Performance Evaluation of Thailand's Food Industry Using Structural Equation Modeling and Fuzzy Analytic Hierarchy Techniques	Sustainability	2016	Operational	Deterministic case study	Decision analysis	Environmental

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Table A.1. – continued from previous page

Author	Title	Journal	Year	Decision Level	Problem type	Modelling approach	Sustainability pillars addressed
Kanchanasuntorn, K; Techanitisawad, A	An approximate periodic model for fixed-life perishable products in a two-echelon inventory-distribution system	International Journal of Production Economics	2006	Operational	Deterministic case study	Simulation	Economic
Mogale, D. G.; Kumar, Mukesh; Kumar, Sri Krishna; Tiwari, Manoj Kumar	Grain silo location-allocation problem with dwell time for optimization of food grain supply chain network	Transportation Research Part E-Logistics and Transportation Review	2018	Strategic	Deterministic case study	Optimisation, heuristics, and metaheuristics	Economic
Musavi, MirMohammad; Bozorgi-Amiri, Ali	A multi-objective sustainable hub location-scheduling problem for perishable food supply chain	Computers & Industrial Engineering	2017	Strategic and tactical	Deterministic case study	Optimisation and metaheuristics	Economic and environmental
Kuznietsov, Kostiantyn A.; Gromov, Vasilii A.; Skorohod, Valery A.	Cluster-based supply chain logistics: a case study of a Ukrainian food distributor	IMA Journal of Management Mathematics	2017	Strategic	Deterministic case study	Optimisation and heuristics	Economic
Mogale, D. G.; Dolgui, Alexandre; Kandhway, Rishabh; Kumar, Krishna; Tiwari, Manoj Kumar	A multi-period inventory transportation model for tactical planning of food grain supply chain	Computers & Industrial Engineering	2017	Tactical	Application	Optimisation, metaheuristics and statistics	Economic
Etemadnia, Hamideh; Goetz, Stephan J.; Canning, Patrick; Tavallali, Mohammad Sadegh	Optimal wholesale facilities location within the fruit and vegetables supply chain with bimodal transportation options: An LP-MIP heuristic approach	European Journal of Operational Research	2015	Tactical	Application	Optimisation	Economic
Sel, C.; Bilgen, B.; Bloemhof-Ruwaard, J. M.; van der Vorst, J. G. A. J.	Multi-bucket optimization for integrated planning and scheduling in the perishable dairy supply chain	Computers & Chemical Engineering	2015	Tactical and operational	Deterministic case study	Optimisation and heuristics	Economic
Sitek, Pawel; Wikarek, Jaroslaw; Nielsen, Peter	A constraint-driven approach to food supply chain management	Industrial Management & Data Systems	2017	Strategic	Deterministic case study	Decision analysis	Economic and environmental

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Table A.1. – continued from previous page

Author	Title	Journal	Year	Decision Level	Problem type	Modelling approach	Sustainability pillars addressed
Mogale, D. G.; Kumar, Sri Krishna; Tiwari, Manoj Kumar	Two Stage Indian Food Grain Supply Chain Network Transportation-Allocation Model	IFAC Papers online	2016	Operational	Deterministic case study	Optimisation and metaheuristics	Economic
Govindan, K.; Jafarian, A.; Khodaverdi, R.; Devika, K.	Two-echelon multiple-vehicle location-routing problem with time windows for optimization of sustainable supply chain network of perishable food	International Journal of Production Economics	2014	Strategic	Stochastic case study	Optimisation and metaheuristics	Economic and environmental
Banasik, Aleksander; Kanellopoulos, Argyris; Claassen, G. D. H.; Bloemhof-Ruwaard, Jacqueline M.; van der Vorst, Jack G. A. J.	Closing loops in agricultural supply chains using multi-objective optimization: A case study of an industrial mushroom supply chain	International Journal of Production Economics	2017	Strategic and operational	Deterministic case study	Optimisation	Economic and environmental
Mejjaouli, Sobhi; Babiceanu, Radu F.	Cold supply chain logistics: System optimization for real-time rerouting transportation solutions	Computers in Industry	2018	Operational	Deterministic case study and application	Simulation and optimisation	Economic
Maiyar, Lohithaksha M.; Thakkar, Jitesh J.	A combined tactical and operational deterministic food grain transportation model: Particle swarm-based optimization approach	Computers & Industrial Engineering	2017	Tactical and operational	Deterministic case study	Optimisation, data analysis, and statistics	Economic
Soto-Silva, Wladimir E.; Gonzalez-Araya, Marcela C.; Oliva-Fernandez, Marcos A.; Pla-Aragones, Lluis M.	Optimizing fresh food logistics for processing: Application for a large Chilean apple supply chain	Computers and Electronics in Agriculture	2017	Operational	Deterministic case study	Optimisation	Economic
Mohammed, Ahmed; Wang, Qian	Developing a meat supply chain network design using a multi-objective possibilistic programming approach	British Food Journal	2017	Strategic	Stochastic case study	Optimisation and decision analysis	Economic

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Table A.1. – continued from previous page

Author	Title	Journal	Year	Decision Level	Problem type	Modelling approach	Sustainability pillars addressed
Bilgen, Bilge; Celebi, Yelda	Integrated production scheduling and distribution planning in dairy supply chain by hybrid modelling	Annals of Operations Research	2013	Operational	Deterministic case study	Simulation and optimisation	Economic
Galal, N. M.; El-Kilany, K. S.	Sustainable agri-food supply chain with uncertain demand and lead time	International Journal of Simulation Modelling	2016	Operational	Stochastic case study	Simulation	Economic and environmental
Krejci, Caroline; Beamon, Benita	Impacts of Farmer Coordination Decisions on Food Supply Chain Structure	The Journal of Artificial Societies and Social Simulation	2015	Strategic	Stochastic case study	Simulation	Economic
Atallah, Shady S.; Gomez, Miguel I.; Bjoerkman, Thomas	Localization effects for a fresh vegetable product supply chain: Broccoli in the eastern United States	Food Policy	2014	Strategic	Deterministic case study	Simulation	Economic
Fianu, Sefakor; Davis, Lauren B.	A Markov decision process model for equitable distribution of supplies under uncertainty	European Journal of Operational Research	2018	Operational	Stochastic case study and application	Markov decision	Social

Annex B: table of analysed reviews

Table B.1. – Summary of the major characteristics of analysed reviews

Paper	Research focus	Research objective	Research methodology	Number of papers reviewed	Time span of the papers reviewed	Types of decision levels addressed
Ahumada and Villalobos (2009)	Production and distribution planning in crop-based AFSCs	Analyse research development	Systematic review	69	1985-2008	Strategic, tactical, and operational
Shukla and Jharkharia (2013)	Fresh produce SC (fruits, flowers, and vegetables)	Analyse research development and proposing a framework for fresh produce SCM	Systematic review	86	1989-2009	Strategic, tactical, and operational
Tsolakis *et al.* (2014)	Design of AFSCs	Provide a comprehensive hierarchical decision-making framework and a critical taxonomy to design and manage AFSCs	Narrative review	---	---	Strategic, tactical, and operational
Fredriksson and Liljestrand (2015)	Impact of food characteristics on logistics	Analyse research development and proposing a common definition for food logistics	Systematic review	159	1980-2012	---
Kusumastuti *et al*. (2016)	Integration of harvesting and processing planning	Analyse research development	Systematic review	76	1983-2013	Operational
Soto-Silva *et al.* (2016)	Application of OR methods to fresh fruit SCs	Analyse research development	Systematic review	28	1976-2015	Strategic, tactical, and operational
Notarnicola *et al.* (2017)	Life cycle assessment in AFSCs	Analyse research development and priority establishment	Narrative review	---	---	---
Routroy and Behera (2017)	AFSCs excluding dairy, fisheries and meat SCs	Analyse research development	Systematic review	203	2000-2016	---
Zhong *et al.* (2017)	Data-driven AFSCs	Analyse research development	Systematic review	192	1993-2017	---
Esteso *et al.* (2018)	Mathematical programming models to design AFSCs	Analyse research development and proposing a framework to design AFSCs using mathematical programming models	Systematic review	5	2004-2017	Strategic