Agri-food supply chain modelling

Review of the literature

NZIER report to the AgResearch Group of the Bioeconomy Science Institute

August 2025

About NZIER

New Zealand Institute of Economic Research (NZIER) is an independent, not-for-profit economic consultancy that has been informing and encouraging debate on issues affecting Aotearoa New Zealand, for more than 65 years.

Our core values of independence and promoting better outcomes for all New Zealanders are the driving force behind why we exist and how we work today. We aim to help our clients and members make better business and policy decisions and provide valuable insights and leadership on important public issues affecting our future.

We are unique in that we reinvest our returns into public good research for the betterment of Aotearoa New Zealand.

Our expert team is based in Auckland and Wellington and operates across all sectors of the New Zealand economy. They combine their sector knowledge with the application of robust economic logic, models and data and understanding of the linkages between government and business to help our clients and tackle complex issues.

Authorship

This paper was prepared at NZIER by Dr Bill Kaye-Blake.

It was quality approved by Chris Nixon.

The assistance of Sarah Spring is gratefully acknowledged.

How to cite this document:

NZIER. 2025. Agri-food supply chain modelling: review of the literature. A report for the AgResearch Group of the Bioeconomy Science Institute.

Registered office: Level 13, Public Trust Tower, 22–28 Willeston St Wellington
Auckland office: Level 4, 70 Shortland St, Auckland
Postal address: PO Box 3479, Wellington 6140
Tel 0800 220 090 or +64 4 472 1880 | econ@nzier.org.nz | www.nzier.org.nz

Key points

This report creates an information base for our research programme

NZIER is collaborating on a research programme led by the AgResearch Group of the Bioeconomy Science Institute called Plant-Based Food Ingredients (PBFI). The programme's aim is to create opportunities in the emerging plant proteins sector. This report summarises our assessment of the literature through the first phase of the research programme. It will serve as a resource for the later stages.

Our focus is supply chain modelling for the agri-food sector

The agri-food supply chain (AFSC) modelling literature is difficult to summarise. In one sense, the literature is diverse. Models focus on many different topics, such as costs, logistics, production, location, sustainability, perishability, seasonality and labour. They also use a variety of modelling methods, platforms or software, and solution methods. This diversity is discussed throughout the report and is also covered by a few published reviews that we identified.

In another sense, as pointed out by existing literature reviews, the AFSC modelling literature can be considered fragmented and siloed. Modelling exercises in the literature rarely build explicitly on prior models. Each piece of research presents a problem or situation and describes a new modelling solution, usually with a unique configuration of supply chain actors, technologies, products, data and equations.

There are many opportunities to contribute new knowledge

Even with the large variation in the existing literature, the range of issues, products, locations and modelling techniques that could be explore is larger still. Many topics have not been sufficiently explored. This review suggests that the PBFI programme has considerable scope to publish whatever supply chain modelling it decides to conduct.

In addition, there do not appear to be any requirements on methods. The review found many examples that could be built upon, but no mandatory approach that must be followed. This is good for the research programme, which can be guided by the science and curiosity.

We started our modelling work by replicating a model from the literature

We identified a model from the literature that also focused on a plant-based novel protein ingredient and determined that the presentation was complete enough to permit replication. We reprogrammed the model in a different language to test our understanding and tools. The replication was successful. The code ran and the new model solved successfully. The model provides a good framework for future work: it includes several supply chain actors, both primary and secondary processing, and decisions about how or where to conduct processing.

Contents

Appendices

Figures

1 Motivation for this report

1.1 Supporting a multi-year Plant-Based Food Ingredient programme

NZIER is collaborating on a research programme led by AgResearch called Plant-Based Food Ingredients (PBFI): A Systems Approach to Sustainable Design. It is a multi-year programme funded by the Endeavour Fund from the Ministry of Business, Innovation & Employment (MBIE) (programme number C10X2303). The programme aims to:

> *… produce knowledge, technological solutions and IP that lift and support the arable crop processors of NZ and inspire entrepreneurs in the emerging proteins sector to become successful international suppliers of novel, sustainable, nutritious, and high-value plant-based food ingredients.*

For the programme, the key contribution of NZIER is supply chain modelling for the production systems that will be developed.

1.2 Focusing on agri-food supply chain modelling and publication

This report investigates the literature on supply chain modelling for agriculture and food production. At the start of the review, the focus was on understanding both the content of existing agri-food supply chain (AFSC) modelling and the accepted practices in the area. For content, we were interested in modelling of ingredients, concentrates or isolates, and how processing linked up and down the supply chain. We were also interested in how different process and their outputs were modelled, and how they were connected to buyer, distributors and consumers. These content concerns led to some specific topics for the review of the supply chain literature:

- Modelling the whole production array, including co-products and waste products. This focus also connects with other topics, such as waste minimisation, circular production and life-cycle analysis (LCA)
- The kinds of supply chain actors or nodes being modelled
- Optimisation versus other modelling approaches.

NZIER is focused on ensuring that this work connects meaningfully to the existing AFSC literature. This means identifying accepted practices so that we could follow them to the extent necessary. The areas of concern were:

- Modelling techniques
- Solution techniques
- Software or platforms used
- Reporting and publication conventions.

The main role of this report is to summarise our assessment of the literature through the first phase of the research programme. The summary can then serve as a resource for the later stages: information and text that we can draw on later as we conduct our own modelling.

The review has not been conducted as a meta-analysis or as a formally structured systematic literature review (Tranfield et al. 2003), such as following the PRISMA checklist (Ferdous et al. 2023; Moher et al. 2009). There are several reviews in the literature, including formally structured ones. This review is therefore a discussion of what we found and how we understand it, rather than a complete description of the literature. This review is also focused on modelling to enable the present research. The discussion of agri-food supply chains or supply chains in general is only enough to support that focus on modelling.

This report presents summaries and observations of the AFSC literature. Because of the nature of the literature, this report considers a breadth of topics and some of the details of individual pieces of research. It then draws together the observations to consider how the Plant-Based Food Ingredients programme can draw on the literature. It also includes a replication exercise in 0 that re-codes a model from the literature as a demonstration of building on prior work.

2 General state of AFSC modelling

2.1 Literature is varied and fragmented

The AFSC modelling literature is difficult to summarise. Zhao et al. (2024), referring specifically to the AFSC literature on resilience, called it 'sparse, context-dependent and fragmented' (p. 284). The comment echoes an earlier one from Shukla and Jharkharia (2013) about the fresh product supply chain management literature: 'It is revealed from the review that most of the literature is fragmented and is in silos' (p. 114). Certainly, published articles do provide literature reviews as context, and several review articles have been published that provide summaries or descriptions of the literature. However, the comments above reflect that modelling exercises in the literature rarely build on prior models. Each piece of research presents a problem or situation and describes a new modelling solution. In addition, the research presents a lot of variety in tools, focus, technologies studied, and more (Gurrala and Hariga 2022; Alemany et al. 2021).

An explanation for this situation is that there are many decisions to make for each model and many objectives that can be addressed with each analysis (Alemany et al. 2021). Each exercise in industry-specific or product-specific modelling has to contend with the particularities of the supply networks in each industry (Engelseth et al. 2011). The complexity of existing supply chain networks has been linked to product variety: more variety in the products produced entails more information sharing and more complex networks (Huddiniah and Pradana 2023), and thus more options for modelling. Most modelling is focused on one crop or commodity in a single country (Shukla and Jharkharia 2013). With so much conceptual space to explore, each modelling effort is virtually a one-off example. For example, Jaigirdar et al. (2023) compared their modelling to several other publications and found that none of them included their particular combination of multiple products, sustainability, cold storage, waste minimisation, and carbon emissions, with decision variables about total supply chain cost, lead time, and size of distribution centres.[1]

AFSC modelling may also be less developed than modelling for other parts of the economy (Gurrala and Hariga 2022). Galal and El-Kilany (2016) cited Ahumada and Villalobos (2009) on this topic: 'Models for planning ASC in general are still lagging behind compared to manufacturing supply chains; ASC of fresh produce are even more lagging behind due to the logistical complexities added by their limited shelf life'. Those complexities are described by Zhu et al. (2018, no page):

> *The management of food supply chains … are [sic] generally very different from that of industrial supply chain because of food products' unique properties such as perishability, strict governmental regulations on food safety, consumers' high variation on tastes and processes, and consequential operational constraints on their storage, processing, and distribution. Today's FSC faces issues such as high energy consumption, greenhouse gas (GHG) emissions, and other economic and social concerns.*

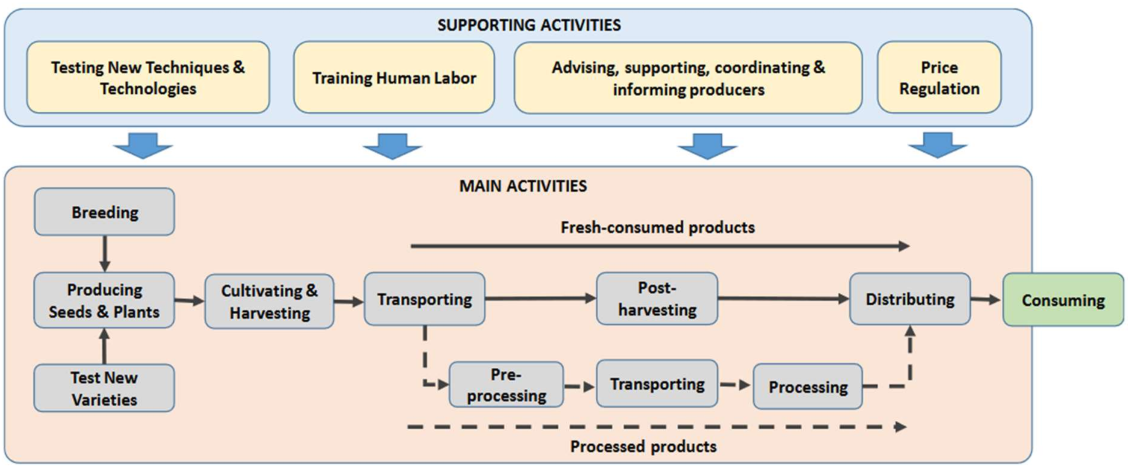
Thus, the state of AFSC modelling may be related to the complexity of agri-food supply chains themselves compared to industrial supply chains.

[1] This approach of tightly defining one's project so that it is unique is described and challenged in Flyvberg and Gardner (2023).

Publication of the literature also seems to have a power law distribution. Zhu et al. (2018) found that four journals accounted for 70 percent of published articles, while the rest of the journal titles had published only one or two such papers. This distribution is likely a good explanation of the result from Shukla and Jharkharia (2013) that each journal most had just one or a few articles per year on AFSC modelling.

Although the modelling for agri-food supply chains is fragmented, the theory is well developed (Esteso et al. 2018; Taşkıner and Bilgen 2021). For example, Alemany et al. (2021) described a framework for AFSCs that recognises different perspectives, including physical, functional, organisational, information and decisional views. Under the functional view, which corresponds well to a standard supply chain view from producer to consumer, they include not just details of the main activities but also a recognition of supporting activities such as training and scientific research. A diagram of this supply chain is shown in Figure 1. Other useful and detailed presentations are available in the literature.

Figure 1 Functional view of crop-based AFSC activities



Source: Alemany et al. (2021)

2.2 Several review articles available

There are several review articles for AFSC modelling. An older article was by Soysal et al. (2012), who focused on how sustainability concerns could be incorporated into food logistics management. They found that food supply chain modelling had not sufficiently taken into account the special characteristics of food – its seasonality and perishability. They also found little material on sustainability in food supply chain modelling. They provided a good overview by summarising common modelling approaches and common metrics from the models, showing both the complexity and the variety of the existing research.

Another older article covered food supply chain management, and modelling examples formed a subset of the 86 papers reviewed (Shukla and Jharkharia 2013). That review found that articles were scattered throughout journals, including operations management, agricultural and other scientific journals. Many journals where the research appeared published only a single food supply chain management article between 1991 and 2011. The review classified research by problem focus and by method. The main problems considered were demand forecasting, production planning, inventory management and transportation.

The methods included modelling and simulation, as well as empirical studies, case studies, action research and other approaches. They found that linear programming and mixed integer linear programming (MILP) were common modelling methods. Interestingly, they noted that the actual models used in the research were not very complex.

A newer article was by Gurrala and Hariga (2022). As a later review, it covered more material. The authors noted that the food supply chain literature contained a lot of variety in the tools, focus, technologies studied, and more topics. For their work, they discussed food waste, traceability, safety and quality, coordination in the supply chain, globalisation, resilience, food security and sustainability. For this last topic, they found that there was increased interest in it, whereas food waste was still a minor topic. They also identified gaps, including research in Africa and South America, empirical validation and multi-product models.

Another newer review considered agri-food supply chain modelling, not just food supply chains (Taşkıner and Bilgen 2021), focusing on harvesting and processing. The authors developed a classification scheme that characterised research by the problem scope, model characteristics and modelling approach. The review again showed the diversity of the research. For example, there were models for each type of decision: operational, tactical or strategic. There were examples of different planning decisions: cultivation, harvesting, production, distribution, and inventory. They considered different constraints, such as the time window, perishability and resource limitation. Although MILP was the most common modelling method, there were examples of several other approaches and therefore different solution methods.

Finally, Zhu et al. (2018) reviewed over 80 publications that used mathematical modelling to assess sustainable food supply chains. They considered whether the papers involved environment, social or economic sustainability in some combination. They also identified which sustainability issues were addressed, such as GHG emission, water, fairness, animal welfare or other issues. They provided details about the models, including the actors or nodes include and the modelling technique. They also finished by identifying future research directions, which included consumer preferences, the global supply chain, farmer and animal welfare, and new methods and technologies.

3 The actors in supply chains

3.1 Supply chains are conceptually well developed

AFSC models start with a concept of the supply chain. The idea of a supply chain and its definition are well developed, both in the general supply chain literature (Stadtler et al. 2015) and in the agri-food area (Shukla and Jharkharia 2013; Apaiah and Hendrix 2005). Here are a couple of definitions:

> *Agri-food supply chains (AFSCs) comprise linked activities from farming to production/processing, testing, packaging, warehousing, transportation, trading/distribution, and marketing/consumption, spanning the process 'from field to fork' (Zhao et al. 2024, 283).*

> *A supply chain network consists of multiple businesses working together to move products or services from their origin to the final customer. Those processes are*

based on the flow of materials, information, and financial transactions from upstream to downstream supply chains (Huddiniah and Pradana 2023, 1059–60).

A key part of supply chains is that they have several links that connect one end to the other. These links may be called nodes, stages or echelons. Each node represents an activity that is homogenous within itself and different from the other nodes in the supply chain, such as processing or transport.

A fairly standard representation of a supply chain recognises five stages: supplier, processor, distributor, retailer and consumer (Esteso et al. 2018). This representation captures the farm-to-fork orientation that is a key part of supply chain thinking for some researchers (Reinhardt 2023) and has ties to food and agriculture policy (Wesseler 2022). Some computer models replicate the whole value chain. For example, Ahumada & Villalobos (2011) included Harvest, Packing, Warehousing, Distribution Centres, and Customers in a model that optimised the harvest activity (timing and amount of harvest) given costs and demand.

Engelseth, et al. (2011) investigated the strawberry supply chain in Norway and included Farmers, Producer cooperative, Wholesaler, Processors, and Retailers including food service. Some models capture the full supply chain with fewer nodes: Ge, Gómez, and Peters (2022) included just Producers, Processors and Consumers.

3.2 Researchers often simplify supply chains for analysis

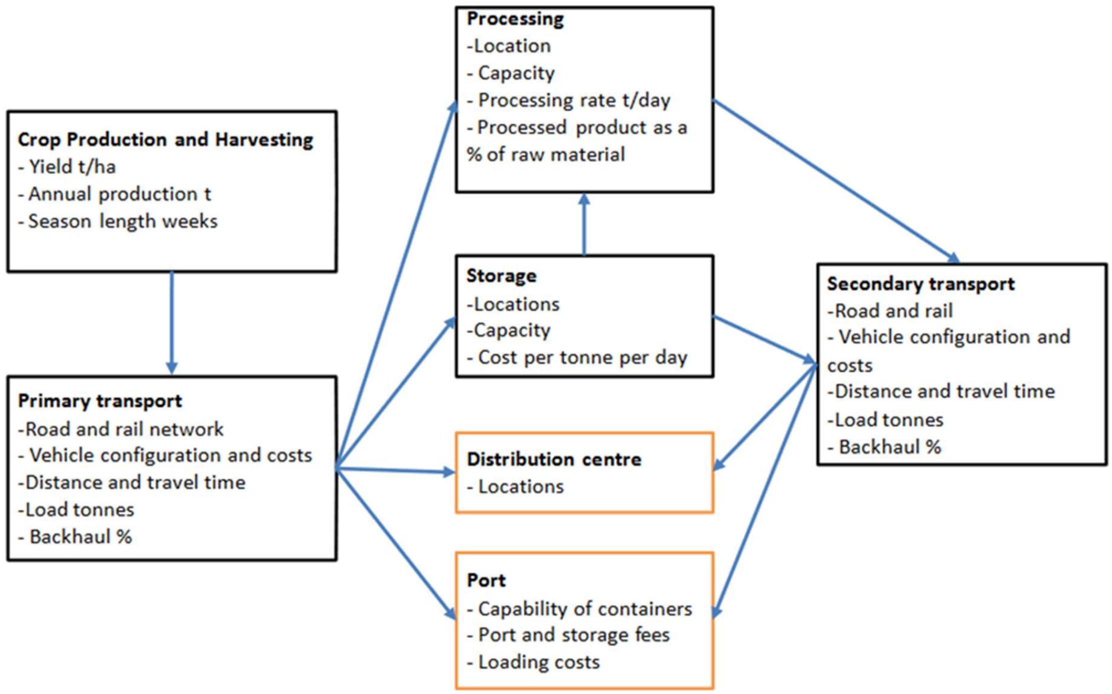
However, several researchers have pointed out that it is more common to include fewer nodes. One review of 30 papers found that none of the models reviewed included the whole supply chain and none included the consumer stage (Esteso et al. 2018). The same researchers later provided a table of 44 examples from the AFSC literature and indicated whether their supply chain nodes included the supplier, processor, distributor, retailer and consumer (Esteso et al. 2021).

None of the reviewed papers included a consumer stage, and only a few included all four of the other stages. Most examples from the literature had just two or three stages. This lack of focus on consumers in supply chains, including issues such as price impacts of changes in consumption or issues with consumer acceptance, has been noted elsewhere (Soto-Silva et al. 2016). The other end of the supply chain can be similarly neglected. A review of literature on modelling sustainable agri-food supply chains found that only 6 of 55 articles included agricultural producers (Zhu et al. 2018). They found that studies on processors and distributors were more common.

In more complex modelling, nodes are sometimes sub-divided. Cheng, Chen, and Chen (2014) created a model of the whole supply chain, but with only three stages: supply, production, and customer. Each stage was further disaggregated: the customer stage was subdivided into retail and customer, for example. Even this relatively simple supply chain was sufficient for the authors to investigate supply chain network complexity.

Some AFSC modelling has tackled more complex supply chains. Figure 2 presents the schematic outline of the supply chain model by Ash et al. (2014). First, it contains seven different nodes, including production, processing, storage, and two types of transport. In addition, it is not a linear presentation. There are four branches off the primary transport mode that represent different possible disposition of the harvested crop. It is also possible to loop back: crops can go directly from Production to Primary Transport to Distribution centres, or they can go from Primary transport to Processing and Secondary transport before reaching a Distribution centre.

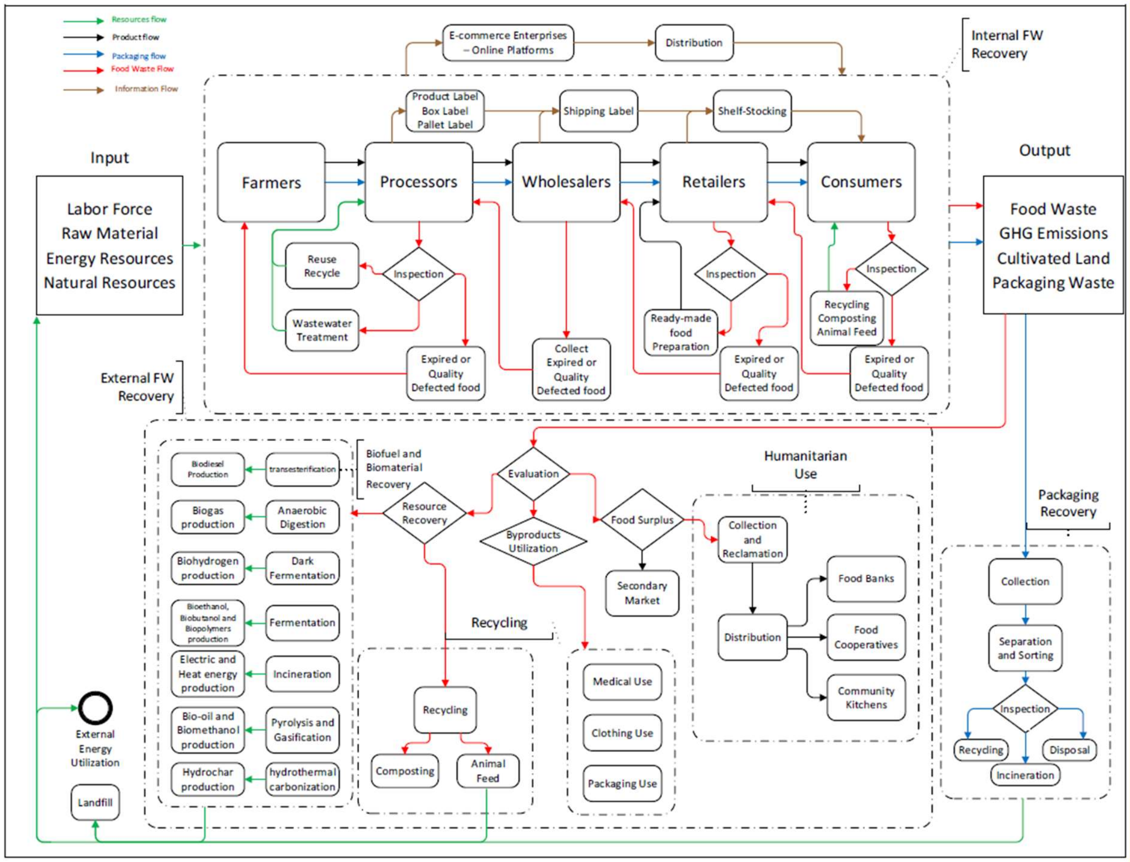
Figure 2 Schematic outline of supply chain model



Source: (Ash et al. 2014)

Even more complex is the framework in Fadhel and Gupta (2020). They traced the production of food waste by actors in the AFSC, and then described the steps required to turn the waste into usable products or recover resources from them. The computer model described in the paper, however, does not appear to have the same level of complexity as the framework.

Figure 3 Food waste and recovery framework



Source: (Fadhel and Gupta 2020)

Other AFSC research has tailored the choice of actors to the topic of the research:

- A simple model with just farmers and traders in order to analyse price fluctuations, reactivity and time lags (Berg 2017)
- A model of production and processing for olive oil, including processing of a co-product; the model included both groves that were under the control of the processor as well as external farmers' groves, adding complexity to the production node (Bilgen and Taşkıner 2023)
- A three-node supply chain with a large number of farmers whose crops go to four distribution centres, which then sell to five US markets (Flores et al. 2019)
- A model of oranges produced in Egypt and distributed in the Netherlands that modelled just two nodes: producer and distributor (Galal and El-Kilany 2016)
- An end-to-end model with three echelons: production, distribution, customers for guava and lemons in Bangladesh (Jaigirdar et al. 2023)
- A model of tomato harvest decisions with the grower, retailer and manager of the supply chain (Li et al. 2020)

- An AFSC model focused on transportation and storage; the model had five echelons: procurement centres, central warehouses, state warehouses, district warehouses, and fair price shops (Mogale et al. 2020)
- A model of the Philippine vegetable supply chain that included financiers, planters, transporters, kargadors who load the trucks, product brokers, wholesale traders, and retailers/wholesalers (Murray-Prior et al. 2003)
- A model for dragon fruit in Vietnam with four nodes: farmers, traders, wholesale markets and by-product suppliers (Nguyen et al. 2020)
- A model of the broiler chicken supply chain that included breeders, hatcheries, farmers, slaughterhouses and manufacturers, wholesale, and retail and restaurant (Solano-Blanco et al. 2023)
- An end-to-end model that considered conventional and organic wine and included nodes for farmer, winemaker, retailer and consumer (Taghikhah et al. 2021).

One lesson to draw from the diversity of research is that, while there is a standard description of a supply chain (Stadtler et al. 2015), the actual number of actors or nodes modelled is variable. The fraction of the supply chain modelled – whether it is end-to-end or just partial – depends on the question or issue being studied. The number of actors can be larger or smaller and does not appear to show any regularities. The type of actor modelled varies tremendously with the level of detail modelled, the actors and configuration of the actual supply chain being analysed, and the ambition of the researchers.

4 Issues investigated in the AFSC literature

4.1 Introduction

Across the research, many issues are examined. Some of them are practical concerns regarding production, such as costs, labour or scheduling. Some of them are about wider issues, such as sustainability. In this section, we review some issues that could be important for the PBFI programme. However, the reviews already highlighted in section 2.2 contain more thorough descriptions of the issues covered in the literature.

4.2 Perishability

Several pieces of research and modelling investigate the challenges of the perishability of crops and food (Soto-Silva et al. 2016; Esteso et al. 2021). They consider fresh products where perishability is an issue (Sisley et al. 2023) as well as stored products whose quality declines over time and the complications that entails (Li et al. 2020). Some articles have stated that perishability is poorly covered in the literature (Ahumada and Villalobos 2011; Esteso et al. 2018; Jonkman et al. 2019). However, it is recognised as an important aspect of food supply and the supply chain (Engelseth et al. 2011; Esteso et al. 2018; Jonkman et al. 2019; Zhu et al. 2018) and was identified as an important criterion for describing supply chains (Schrobback et al. 2020; Taşkıner and Bilgen 2021). It is also an aspect that differentiates AFSC from other types of supply chains (Shukla and Jharkharia 2013). One reason for supply analysis for AFSC, in fact, is to reduce losses from perishable products or minimise the total cost of the supply chain (Jaigirdar et al. 2023). Nevertheless, the main interests for AFSC research on perishability were in consumer satisfaction and revenue maximisation, while waste reduction was a secondary concern (Shukla and Jharkharia 2013).

The treatment of perishability in modelling varies across the literature. Esteso, Alemany, and Ortiz (2021) optimised a model of the tomato supply chain in Argentina, accounting for the full supply chain and perishability of the product. The model showed the potential benefits of improving shelf life (reducing perishability), which provided information to businesses about the potential returns to investments. Galal and El-Kilany (2016) simulated the impact of supply chain losses on costs, emissions and services levels, which demonstrated the trade-off in costs and emissions from perishability in AFSCs. Nguyan et al. (2020) demonstrated how perishability can add to the complexity of supply chains. They modelled a fresh fruit supply chain in which demand for fruit by traders and wholesalers was met first, and any remaining stock went to by-product processors. Finally, Li et al. (2020) demonstrated a modelling approach for perishability by including an equation for the declining freshness of tomatoes, which they based on prior research.

Perishability connects with other issues in the agri-food sector. Fadhel (2021) and Fadhel and Gupta (2020) focused on modelling waste and the multiple uses of fruit, vegetable and animal waste, grounding the modelling in the food waste hierarchy. Wang, Ghadge and Aktas (2024) described how digital technology can help address the issue of perishability in the food supply chain. Finally, Zhao et al. (2024) described how farmers in France developed cooperative mechanisms to shift competitive pressures from themselves to their customers, to counteract 'malignant competition among farmers' due to the perishability of their products. These examples show that perishability is not just a question of cost or losses, but also connects with technology, incentives and business structures.

4.3 Seasonality

Seasonality is a core feature of agri-food products (Alemany et al. 2021) and contributes to the vulnerability of their supply chains (Vlajic et al. 2012). It affects both demand (G. Wang et al. 2023) – some foods are consumed seasonally or for special occasions (Fischler 1993) – and production (Schrobback et al. 2020). Seasonality affects both the quantity of product or food available (Esteso et al. 2021; Taşkıner and Bilgen 2021) and its price (Shukla and Jharkharia 2013; Esteso et al. 2018; 2021). Seasonal production has further consequences, such as the seasonality of labour (Rodriguez-Sanchez et al. 2019; Esteso et al. 2021). Seasonality of agriculture production is of course related to the seasonality of temperature, water and other factors (Ash et al. 2014; Rodriguez-Sanchez et al. 2019; Ge et al. 2022).

Seasonality is an important aspect of supply chain modelling (Engelseth et al. 2011). Zhao et al. (2024) acknowledged seasonality as a challenge for agri-food SCs that affects their resilience and could be included in modelling. Some AFSC models are explicit about the seasonal variation in production and attempt to optimise subject to known variability (Ahumada and Villalobos 2011). The time window available for operations – when operations can happen – is a common model consideration (e.g., Taşkıner and Bilgen 2021). Other models are models of the production season (e.g., Ge et al. 2022); seasonality is not a variable within the model but a boundary of the model problem.

4.4 Integrated planning

In theory, '[t]here are two broad means for improving the competitiveness of a supply chain. One is a closer integration (or cooperation) of the organizations involved and the other is a better coordination of material, information and financial flows' (Stadtler et al. 2015, 5). Integrated planning in agri-food supply chains may be poorly studied (Jonkman et al. 2019), but integrated planning and collaboration could address the interests of multiple supply chain actors and improve overall supply chain performance (Ge et al. 2022; Simatupang and Sridharan 2002). For example, better management of primary production could benefit processing by reducing peak load and down times. One example considered the trade-off between building additional meat processing plants or transporting animals farther to existing plants (Ge et al. 2022).

Modelling found that transport costs were lower than the savings that could be achieved with new, efficient plants. Jaigirdar et al. (2023) showed that planning across a whole distribution network can lead to minimising the total cost of the supply chain. Modelling is a key part of integration: '[t]he main contributions to multi-period AFSC design modelling is the joint integration of planting, cultivation, harvest, labouring, packing, inventory, transport, operation, waste, and unmet demand decisions on the design of an entire AFSC that commercialises many perishable products.' (Esteso et al., 2021, p. 22). However, integrated planning is not necessarily better for all firms in supply chains (İnkaya et al. 2018).

There are other examples of integrated modelling. Solano-Blanco et al. (2023) undertook complex modelling of the broiler chicken supply chain. They provided an integrated model of the whole supply chain in Colombia, with a two-stage modelling process to account for production planning across farms. Taghikhah et al. (2021) presented an integrated model of wine production and consumption. They included a feedback function in which production is responsive to the sustainability concerns of consumers. The model therefore operationalised the idea that supply chains have a flow of goods in one direction and a flow of information in the other direction (Apaiah and Hendrix 2005; Shukla and Jharkharia 2013).

As Stadtler et al. (2015) indicated, information coordination can be used to improve supply chain performance. Thus, one subtopic of integrated planning is the role and use of data and information sharing systems by supply chain participants (Moysiadis et al. 2023; Nakandala et al. 2017). There are hopes that new technologies (Industry 4.0 technologies) can capture and transmit high-quality and detailed data that allows better integrated planning (S. Wang et al. 2024). This information coordination will have to consider questions of verifiability and digital infrastructure, which can be explored with modelling. Kahmann et al. (2023) found that traceability and auditability were key drivers of integrating information technology into agricultural supply chains. They focused on the architecture of cryptocurrency, arguing that one technology – blockchain – is linear and so it scales poorly.

However, another technology – directed acyclic graphs (DAGs) – offers better scaling, and that technology is also used for modelling in agriculture (Bello et al. 2018) and agri-food supply chains (G. Wang et al. 2023). An AFSC could use a digital system (a distributed ledger technology (DLT)) to allow all the actors in a supply chain from suppliers to final consumers to share and verify relevant information (Moysiadis et al. 2023). These digital systems can also provide the sort of data that supply chain models can use to improve the performance of the agri-food system.

Planning is also relevant for waste reduction (Simatupang and Sridharan 2002). Shukla and Jharkharia (2013, 141) stated 'there is a lack of ownership within the chain. All the players are concerned with their own revenue maximization with limited attention towards the overall profit of the chain. This lack of a holistic view of a supply chain is leading to the post-harvest waste.' Qualitative research has been undertaken (Batista et al. 2021) but that work analysed companies from different parts of the supply in isolation from each other, rather than the flows among them. Food loss and waste remains a minor topic in the agri-food supply chain literature (Gurrala and Hariga 2022; Taşkıner and Bilgen 2021).

4.5 Types of decisions

The literature makes distinctions among the different types of decisions – strategic, tactical or operational decisions – and therefore the use for SC models (Ahumada and Villalobos 2011; Soto-Silva et al. 2016). Shukla and Jharkharia (2013, 119) provided a short description of the typology:

> *Ahumada and Villalobos (2009b) have differentiated the major issues for agri-fresh produce into strategic, tactical and operational issues. They defined that strategic issues includes decisions such as financial planning, supply network design, selection of capacity, and technology, etc. the tactical decisions cover harvest planning, scheduling of crops, selection of labor, capacity and crops, etc. The operational decisions include production scheduling activities, harvesting, storage, etc.*

Some research is explicit about the type of decision being modelled. Tactical decisions are those most often analysed with agri-food supply chain models, at least with fruit supply chains (Soto-Silva et al. 2016). Fadhel and Gupta (2020), by contrast, provided an explicitly strategic model that investigated the food waste strategy in the USA state of Massachusetts. Another strategic model considered the meat industry using a model from the economics of imperfect competition called Stackelberg competition (Rodriguez-Sanchez et al., 2019). It investigated an element of strategy in which the meat processor ('leader') made the first decision and the retailer ('follower') had to react.

Other examples from the literature consider more than one type of decision. They are often explicit about this:

> *There are two levels of decision-making involved in this problem. The first is the strategic selection of the appropriate cut products to produce based on the availability of raw materials, seasonal demands, and customer requirements. The second level is the tactical decision-making which involves allocating the right carcases to the appropriate product. (G. Wang et al. 2023, 1004)*

Similarly:

> *This article contributes to the literature by presenting a Mixed Integer Linear Programming (MILP) model in which tactical decisions at the harvesting stage (area used for cultivation and time of harvesting) are integrated with strategic decisions on the AFSC design (number, location, and capacity of facilities, and the type of processing pathway to operate). (Jonkman et al. 2019, 249)*

In other examples, Flores et al. (2019) put their supply chain planning tool from high-value vegetable markets in the context of both strategic decisions and tactical/operation decisions: growing the right crop using the best technology and then selling to the right market; and Nguyen (2020) included both a tactical phase for planting decisions and an operational phase for harvesting decisions in an optimisation model for dragon fruit in Vietnam.

4.6 Sustainability

The literature on agri-food supply chains has become more interested in sustainability over time. Earlier work found a limited number of models focused on sustainability or the environment (Esteso et al. 2018; Soysal et al. 2012), but later work found that the sustainability focus had grown (Gurrala and Hariga 2022). Zhu et al. (2018) focused specifically on reviewing the modelling of sustainable food supply chains (SFSC) and reported finding 'very few model-oriented papers on SFSC before the year 2000' (Zhu et al. 2018, 5704). Since then, more recent research has considered sustainability of the agri-food supply chain (Jonkman et al. 2019; Schrobback et al. 2020; Taşkıner and Bilgen 2021).

Zhu et al. (2018, 5706) provided a useful description of different dimensions to sustainability:

> *In general, the major environmental issues include GHG emission, energy consumption, ecological issues, and natural resources consumption including water and land, etc…. The main social issues of SFSC include food safety, animal welfare, fairness, and employment/training…which are very different from those of general supply chain,*

citing work by Brandenburg et al. (2014). Overall, they found that only 7 of the 83 studies reviewed included all three domains of social, economic and environmental sustainability, suggesting that the topic of sustainability still had gaps to explore.

The modelling of sustainability raises the issue of how to combine multiple concerns into a mathematical model. Some examples opt for combining multiple goals into a single objective function. An example is the thinking from (Jaigirdar et al. 2023, 16) citing Bloemhof et al. (2015), that 'sustainability can only be realised when it is economically efficient'. That approach subordinates sustainability in a model that optimises an economic metric. In another example, Fadhel and Gupta (2020) designed a model of a sustainable food waste network with a complex flow chart of material flows, but still used a linear model that optimised a simple cost function.

The complexity of sustainability has given rise to other approaches, ones that analyse trade-offs or use multi-objective optimisation – not just optimising the economics but also incorporating sustainability or environmental concerns (Belamkar et al. 2023).

Taghikhah et al. (2021) presented an integrated systems approach for modelling wine production and consumption in which production is responsive to the sustainability concerns of consumers. It combined agent-based modelling and systems dynamic modelling to capture the complexity of the system. They stated that, 'to the best of our knowledge, this is the first study that incorporates the preferences of consumers for organic food as well as farmer decisions regarding organic farming adoption into a model of an agro-food SC' (Taghikhah et al. 2021, 76).

Another example considered both emissions and economic costs in a bi-objective optimisation (Mogale et al. 2020). Yet another approach is simulation modelling. Galal and El-Kilany (2016) took that approach to modelling emissions in a supply chain, which allowed them to explore the trade-offs with costs and service levels. That research put sustainability concerns in a commercial supply chain context.

Another aspect to sustainability research is about drawing connections with other supply chain issues, for example, the circular economy, renewable energy and value chain integration (Reinhardt 2023). Tripti and Shankar (2022) reviewed the literature on food system sustainability using a sustainability triad framework that included economic viability, social progress and environmental preservation. They identified 11 factors from the literature that affect food system sustainability, and then clustered them into three groups:

- Group 1 –integration of the national agriculture market, storage, logistics, government regulations, trust among the partners
- Group 2 – risk, traceability, storage and processing
- Group 3 – food quality, traceability (cross over from group 2).

They stated that 'the government is the biggest actor and its regulation and policy is the most important critical variable that conditions the whole system' (Tripti and Shankar, 2022, p. 18). Other research has connected the issue of sustainability to control and relationships in supply chains (Zhao et al. 2024), which is similar to the trust factor above, and using digital technologies to address supply chain challenges (S. Wang et al. 2024), which is relevant for the traceability factor above.

Sustainability is an issue for grains and seeds, which are the focus of the PBFI programme. Van Der Goot et al. (2016) noted that processing of grains and seeds into highly stable ingredients for global agri-food supply chains was energy-intensive. They linked this resource-intensive processing to two problems: environmental impacts of supply chains and the need to improve nutrition. They proposed that using lower-impact processing to produce less-pure ingredients with better functionality would address both problems. This kind of thinking underpins the PBFI research and supply chain modelling.

4.7 Power relations

Power relations have been studied in the context of supply chains, in particular in the area of enforcement of private standards (Fuchs et al. 2009; 2011; Rossignoli and Moruzzo 2014), and have occasionally been incorporated into agri-food supply chain modelling. The supply chain literature includes analysis of the impact of concentration at specific nodes or echelons and power dynamics (Schrobback et al. 2020).

In the literature, power has positive and negative dimensions. Stadtler et al. (2015) described the situation that can prevail in real-world supply chains: 'In practice, leadership may be executed either by a focal company or a steering committee. A *focal company* is usually a member having the largest (financial) power, the best know-how of products and processes or has the greatest share of values created during order fulfillment' (Stadtler et al. 2015, 10, emphasis in original).

Research in the automotive industry showed that centralised control affects relationships between people and between businesses (Choi and Hong 2002). Roughly, it appeared that exercising greater control could drive short-term cost-cutting but led to more brittle, transactional relationships, with possible implications for long-term supply chain resilience.

Other research has consider the impact on the whole system, and found that coordination or collaboration in one part of a supply chain could hurt firms in another part of the supply chain (İnkaya et al. 2018). Zhu et al. (2018, 5717) were explicit about the role of power:

> *Farmers, especially small farmers usually have weak market power compared to their competitors. Considering farmers' welfare while modeling food supply chain so that small farmers can receive fair treatment from the market and the government is an important social question.*

The counter is that strong control over the supply chain by key firms can be useful for discipline, and that 'Preventing opportunistic behaviour will help maintain healthy, sustainable cooperative relationships' (Zhao et al. 2024, 298).

Zhao et al. (2024) provided a complex analysis of power in supply chains. They divided factors into driving power and dependence power. Driving power related to fundamental factors that are the basis for an agri-food system, whereas dependence power related to factors that link actors together. The researchers identified factors that influenced the agri-food systems, 14 of them for Argentina and 16 for France. They organised the factors in a two-by-two grid with the two dimensions of driving and dependence. That allowed them to classify factors into groups labelled *independent*, *linkage*, *dependent*, and *autonomous*, depending on how power operated. This approach also located power in various characteristics of a system, such as contracting mechanisms or familiarity with each other, rather than in specific companies.

Positive and negative implications of power relations have been studied in the context of several specific supply chains. In a more positive vein, power relations can be harnessed in supply chain relationships. Nasir Uddin et al. (2010, 19) investigated relationships among firms in the Australian beef industry, and concluded that 'The important implication is that firms should build their supply chain as a resource itself by improving the cooperation and relationship structure between primary producers, processors, and retailers, wholesalers or other partners in supply chain'. In a more negative register, Murray-Prior et al. (2003) discussed the power relationship in the Philippines vegetable supply chain, distinguishing between economic information and social information:

> *While the application of transactions costs can identify the various margins extracted by each of the actors along the supply chain and the activities that each perform, an analysis of the relationships themselves will identify the social dimensions of the exchange and in particular, the development of trust and the use of coercive influence strategies so often associated with power dependence* (Murray-Prior et al. 2003, 11).

Power is also dynamic and connected to other concerns, such as policy and the environment. For example, one place where power relations and supply chains connect is the European Union's Green Deal, which aims to rebalance power in agri-food supply chains (Wesseler 2022).

Final, power relations also connect with technology issues. It was noted above that a focal company in a supply chain might have specific know-how or processes (Stadtler et al. 2015). Supply chain power is also an issue in the context of new digital technologies (S. Wang et al. 2024). Larger companies have resources and data that can give them an advantage over small and medium enterprises (SMEs), but they could also be more vulnerable to cyber security issues and trust issues among supply chain actors (S. Wang et al. 2024). SMEs, on the other hand, while they might lack the resources and data, might be more nimble and flexible in adopting new technologies (S. Wang et al. 2024). This issue of resources versus flexibility and innovation is a dynamic in industries with technological change and innovation (Christensen 1997).

4.8 Processing

Processing is part of agri-food supply chains and modelling of it takes several forms. Often, processing is simplified, assumed or omitted. For example, Apaiah and Hendrix (2005) describeed the production scheme for manufacturing novel protein foods (NPF) from peas. The scheme included harvesting, sorting, drying, dehulling, milling, air classification, and then two manufacturing processes including extrusion and food production. The model they developed had just two processing nodes, a first one to produce pea protein and a second one to produce the NPF. In addition, the flow diagram also noted the waste products or co-products, hulls (fibre) and starch. The starch was included in the supply chain model, but the hulls were not.

A more detailed model by Bilgen and Taşkıner (2023) focused on olive oil processing. That model included three types of olive oil (organic extra virgin, extra virgin, and virgin) and one co-product (pomace). Processing has also been considered explicitly in agri-food supply chain models of meat processing (G. Wang et al. 2023; Albornoz et al. 2015). For many other models, processing is not considered. such as for fresh fruit or vegetable supply chains (Li et al. 2020; Engelseth et al. 2011).

Ferdous et al. (2023) considered processing of pulses, which is relevant to the current programme. They presented a framework for integrating life cycle analysis (LCA) with techno-economic analysis (TEA) and process simulation for pulse processing. They also described the state of the art for LCA and TEA studies and noted that dry fractionation and wet fractionation are common processing technologies for extracting protein from pulses. However, the research focused on establishing the framework and so did not provide a model or much of the data that would be required.

5 Technical issues in modelling

5.1 Model presentations are somewhat formulaic

The AFSC modelling literature has, to a greater or lesser extent, a formula for presenting a model. First, the full extent of the supply chain is described. Next, a boundary is drawn around the particular part of the supply chain to be studied. This sub-system is turned into a mathematical problem. The problem is then characterised, often as a Mixed Integer Problem (MIP) or Mixed Integer Linear Problem (MILP), and it is noted (or proved) that the problem is NP-Hard or NP-Complete. The modelling platform or software and solver are noted. Finally, the model is presented mathematically with some level of explanation. This formula is not followed perfectly in every example, but there are enough similarities across papers that it is a useful guide for this section.

5.2 System boundaries

Agri-food supply chains are acknowledged to extend from primary producers or even their suppliers all the way to consumers (Stadtler et al. 2015; Esteso et al. 2018; 2021; Heusala et al. 2020). Typically, however, AFSC models simplify the supply chain. Often, they consider only some of the nodes or echelons. Esteso et al. (2021), for example, reviewed 44 papers and found that 17 included just two nodes and 21 included just three nodes. One-half of the papers included a primary producer node; 73 percent, a processor node; 64 percent, distributor; 82 percent, retailer; and none included a customer node.

In drawing a boundary around the system to be modelled, some researchers are explicit about the process and rationale. For example, Apaiah and Hendrix (2005) presented ex ante modelling on Novel Protein Food (NPF) meant to replace animal meat. Figure 1 in the paper showed a standard supply chain: production, ingredient preparation, product processing, distribution, retail and consumer. They explained that they divided the supply chain into two parts, production planning versus distribution and logistics planning. They focused their study just on the former, including primary production and processing. They did not include the latter inside the system boundary because the novel protein product they modelled was meant to replace chilled pork meat, and the distribution and logistics process would be similar for both products. The model therefore had just three nodes: Primary production, Ingredient preparation and Product processing.

System boundaries are important for modelling (Soysal et al. 2012). In a review of LCA and TEA, Ferdous et al. (2023) included tables of the research reviewed. They noted the system boundaries of each analysis. For example, in the LCA studies of agri-food processing, they noted the system boundaries as ‘cradle to packaging’, ‘cradle to grave’, ‘cradle to gate’, etc. This information helps with comparison across the different analyses. Ferdous et al. (2023) also pointed out the system that is the focus for process simulation is just a subset of a larger system when viewed from the perspective of LCA. This emphasises that the appropriate boundary depends on the type of analysis being undertaken. Similarly with AFSC, explicit recognition of system boundaries helps with classifying research and comparing analyses.

5.3 Modelling approaches

Once a problem is turned into a mathematical model, it can be solved. Common approaches to modelling for AFSC are linear programming, non-linear programming, and mixed integer linear programming (MILP) (Shukla and Jharkharia 2013; Soto-Silva et al. 2016). These types of models involve specifying an objective function, often profit maximisation or cost minimisation (Soto-Silva et al. 2016), and then finding a solution to the model.

There are quite a few MILP models in the literature (Ahumada and Villalobos 2011; Albornoz et al. 2015; Belamkar et al. 2023; Jonkman et al. 2019; Sisley et al. 2023). Reviews suggest that most AFSC models use MILP (Esteso et al. 2018; Taşkıner and Bilgen 2021). An MILP model contains a mix of continuous variables, such as tonnes of production or prices, and integer variables, such as the number of shipments. In the literature, MILP models are shown to be NP Hard (Esteso et al. 2018; Yamchi et al. 2020) or NP-complete (Bayá et al. 2022), that is, it is difficult to find a solution with a reasonable amount of computing resource. One paper noted that these models can become too complex to solve in reasonable times (Albornoz et al. 2015). These MILP models therefore require a heuristic approach to find a solution (Esteso et al. 2018; Soysal et al. 2012; Zhu et al. 2018). Reviews of the literature note that CPLEX is a common solver (Zhu et al. 2018; Shukla and Jharkharia 2013), and it was used for several models reviewed here (Albornoz et al. 2015; Jonkman et al. 2019; Sisley et al. 2023; Soysal et al. 2012; Yamchi et al. 2020; Jaigirdar et al. 2023; Rodriguez-Sanchez et al. 2019; Ahumada and Villalobos 2011; Flores et al. 2019). Some model presentations specify the algorithm, such as branch and bound (Ahumada and Villalobos 2011; Fadhel 2021).

Another approach to modelling is simulation (Ash et al. 2014; Berg 2017; Galal and El-Kilany 2016; Li et al. 2020). Simulation modelling allows researchers to investigate the impact of model parameters on metrics of interest and explore the consequences of changes and decisions. By contrast, LP and MILP models focus on finding optimal solutions. A subset of simulations is agent-based modelling (Miller and Page 2007), and the technique has been used to model AFSCs (Bryceson and Smith 2008; Engelseth et al. 2011). These models investigate the behaviours of the people involved in supply chains, and the resulting effects on system outcomes.

5.4 Platforms

Many software programmes, applications or platforms are used throughout the literature (Soysal et al. 2012; Zhu et al. 2018). Some modellers used general-purpose programmes, such as Microsoft Excel; others used specialised mathematical programmes, such as GAMS or AMPL; and still others used simulation software such as Vensim or Arena.

5.5 Presentation of model equations

Generally, modelling papers present mathematical models well. For example, Jonkman et al. (2019) provided a clear description of the indices and sets for the model, then a list of parameters, and then the decision variables. That was followed by a presentation of the equations, including constraints, with explanatory paragraphs.

An even tidier presentation appeared in Ge et al. (2022): each of the eight terms in the objective function was set on a new line followed by explanatory text ('Shrink loss', ‘Slaughtering costs’, etc.). Apaiah and Hendrix (2005) provided equations and explanation, but also included model computer code in an appendix. There does not appear to be a standard among the articles reviewed, but there are several examples of useful practices.

Prior research was not generally tested for replicability, that is, whether sufficient information was included to replicate each model. However, one test of replicability was carried out on the Apaiah and Hendrix (2005) article; it is presented in 0.

6 Conclusion

The review presented in this report is intended to support the Plant-Based Food Ingredient research programme led by AgResearch. The aim was to get an understanding of the agri-food supply chain modelling research, including the methods used and the issues addressed. This report is not intended to be an exhaustive review of the literature; indeed, several existing reviews were identified that obviated the need for a new one.

There is considerable diversity in the AFSC modelling literature, both in terms of the content studied and method used. As noted here and in the existing literature reviews, the research covers many topics about the AFSC: costs, logistics, production, location, sustainability, perishability, seasonality, labour, and more. Although studies tend to start from a common point – a canonical supply chain from farmers to consumer – they quickly move on to the part of the supply chain, actors and issues of interest. They also use a wide variety of modelling methods, platforms or software, and solution methods. Even with all the variation, the literature also identifies many topics that have not been sufficiently explored.

The results of this review also suggest that the programme has considerable scope to publish whatever supply chain modelling it decides to conduct. There do not appear to be any requirements on methods, any standard approaches that must be used, or a restricted set of journals in which to publish. The review has found that there are many examples that could be built upon, but no mandatory approach that must be followed. This is good for the research programme, which can be guided by the science and curiosity.

Supply chain theory does not by itself give general insights into the optimal approach. Lessons from agricultural supply chains are that institutional arrangements (both formal and informal) in markets determine outcomes. This means it is necessary to understand the unique characteristics, vulnerabilities and context of each supply chain to develop targeted approaches, solutions and models.

7 References

Ahumada, Omar, and J. Rene Villalobos. 2011. 'Operational Model for Planning the Harvest and Distribution of Perishable Agricultural Products'. *International Journal of Production Economics*, Towards High Performance Manufacturing, vol. 133 (2): 677–87. https://doi.org/10.1016/j.ijpe.2011.05.015.

Albornoz, Victor M., Marcela Gonzalez-Araya, Matias C. Gripe, Sara V. Rodriguez, and E. Juventino Treviño. 2015. 'An Optimization Model for Planning Operations in a Meat Packing Plant'. In *Operations Research and Enterprise Systems*, edited by Dominique De Werra, Greg H. Parlier, and Begoña Vitoriano, vol. 577. Communications in Computer and Information Science. Springer International Publishing. https://doi.org/10.1007/978-3-319-27680-9_9.

Alemany, M. M. E., Ana Esteso, A. Ortiz, et al. 2021. 'A Conceptual Framework for Crop-Based Agri-Food Supply Chain Characterization Under Uncertainty'. In *Agriculture Value Chain - Challenges and Trends in Academia and Industry: RUC-APS Volume 1*, edited by Jorge E. Hernández and Janusz Kacprzyk. Studies in Systems, Decision and Control. Springer International Publishing. https://doi.org/10.1007/978-3-030-51047-3_2.

Apaiah, Radhika K., and Eligius M.T. Hendrix. 2005. 'Design of a Supply Chain Network for Pea-Based Novel Protein Foods'. *Journal of Food Engineering* 70 (3): 383–91. https://doi.org/10.1016/j.jfoodeng.2004.02.043.

Ash, Andrew, Trish Gleeson, Hao Cui, et al. 2014. 'Northern Australia: Food & Fibre Supply Chains Study'. *Northern Australia*, August.

Batista, Luciano, Manoj Dora, Jose Arturo Garza-Reyes, and Vikas Kumar. 2021. 'Improving the Sustainability of Food Supply Chains through Circular Economy Practices – a Qualitative Mapping Approach'. *Management of Environmental Quality: An International Journal* 32 (4): 752–67. https://doi.org/10.1108/MEQ-09-2020-0211.

Bayá, Gabriel, Eduardo Canale, Sergio Nesmachnow, Franco Robledo, and Pablo Sartor. 2022. 'Production Optimization in a Grain Facility through Mixed-Integer Linear Programming'. *Applied Sciences* 12 (16): 16. https://doi.org/10.3390/app12168212.

Belamkar, Prasad, Saptadeep Biswas, Abhijit Baidya, Pinki Majumder, and Uttam Kumar Bera. 2023. 'Multi-Objective Optimization of Agro-Food Supply Chain Networking Problem Integrating Economic Viability and Environmental Sustainability through Type-2 Fuzzy-Based Decision Making'. *Journal of Cleaner Production* 421 (October): 138294. https://doi.org/10.1016/j.jclepro.2023.138294.

Bello, Nora M, Vera C Ferreira, Daniel Gianola, and Guilherme J M Rosa. 2018. 'Conceptual Framework for Investigating Causal Effects from Observational Data in Livestock'. *Journal of Animal Science* 96 (10): 4045–62. https://doi.org/10.1093/jas/sky277.

Berg, Ernst. 2017. *Impacts of Inventory Management on Price Volatility in Agricultural Commodity Markets: Insights from a System Dynamics Model*. https://ageconsearch.umn.edu/record/261281/.

Bilgen, Bilge, and Tuğçe Taşkıner. 2023. 'Optimization of an Integrated Harvest, and Process Planning Model in the Agri-Food Industry'. *Journal of Engineering Research*. https://www.sciencedirect.com/science/article/pii/S2307187723002791.

Bryceson, Kim P., and Carl S. Smith, eds. 2008. 'Abstraction and Modelling of Agri-Food Chains as Complex Decision Making Systems'. Proceedings. https://doi.org/10.22004/ag.econ.49773.

Cheng, Chen-Yang, Tzu-Li Chen, and Yin-Yann Chen. 2014. 'An Analysis of the Structural Complexity of Supply Chain Networks'. *Applied Mathematical Modelling* 38 (9): 2328–44. https://doi.org/10.1016/j.apm.2013.10.016.

Choi, Thomas Y, and Yunsook Hong. 2002. 'Unveiling the Structure of Supply Networks: Case Studies in Honda, Acura, and DaimlerChrysler'. *Journal of Operations Management* 20 (5): 469–93. https://doi.org/10.1016/S0272-6963(02)00025-6.

Christensen, Clayton M. 1997. *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*. The Management of Innovation and Change Series. Harvard Business School Press.

Engelseth, Per, Anniken Karlsen, and Tim Verwaart. 2011. 'Modelling Fresh Strawberry Supply "From-Farm-to-Fork" as a Complex Adaptive Network'. February, 12.

Esteso, Ana, M. M. E. Alemany, and Ángel Ortiz. 2021. 'Impact of Product Perishability on Agri-Food Supply Chains Design'. *Applied Mathematical Modelling* 96 (August): 20–38. https://doi.org/10.1016/j.apm.2021.02.027.

Esteso, Ana, M.M.E. Alemany, and Angel Ortiz. 2018. 'Conceptual Framework for Designing Agri-Food Supply Chains under Uncertainty by Mathematical Programming Models'. *International Journal of Production Research* 56 (13): 4418–46. https://doi.org/10.1080/00207543.2018.1447706.

Fadhel, Adel Waleed. 2021. 'Closed-Loop Sustainable Food Supply Chain Management: Design of Network Models for Efficient Operations.' PhD Thesis, Northeastern University.

Fadhel, Adel Waleed, and Surendra M Gupta. 2020. 'Carbon Emissions and Energy Balance in the Design of a Sustainable Food Waste Network'. *International Journal of Industrial Engineering and Operations Management* 02 (01): 63–77. https://doi.org/10.46254/j.ieom.20200105.

Ferdous, Jannatul, Farid Bensebaa, and Nathan Pelletier. 2023. 'Integration of LCA, TEA, Process Simulation and Optimization: A Systematic Review of Current Practices and Scope to Propose a Framework for Pulse Processing Pathways'. *Journal of Cleaner Production* 402 (May): 136804. https://doi.org/10.1016/j.jclepro.2023.136804.

Fischler, Claude. 1993. *L'homnivore: le goût, la cuisine et le corps*. Nouv. éd. corr. Points 36. Seuil.

Flores, Hector, J. Rene Villalobos, Omar Ahumada, Mark Uchanski, Cesar Meneses, and Octavio Sanchez. 2019. 'Use of Supply Chain Planning Tools for Efficiently Placing Small Farmers into High-Value, Vegetable Markets'. *Computers and Electronics in Agriculture* 157 (February): 205–17. https://doi.org/10.1016/j.compag.2018.12.050.

Flyvbjerg, Bent, and Dan Gardner. 2023. *How Big Things Get Done: The Surprising Factors That Determine the Fate of Every Project, from Home Renovations to Space Exploration and Everything in Between*. First edition. Currency.

Fuchs, Doris, Agni Kalfagianni, and Maarten Arentsen. 2009. 'Retail Power, Private Standards, and Sustainability in the Global Food System'. In *Corporate Power in Global Agrifood Governance*, by Jennifer Clapp and Doris Fuchs. The MIT Press.

Fuchs, Doris, Agni Kalfagianni, and Tetty Havinga. 2011. 'Actors in Private Food Governance: The Legitimacy of Retail Standards and Multistakeholder Initiatives with Civil Society Participation'. *Agriculture and Human Values* 28 (3): 353–67. https://doi.org/10.1007/s10460-009-9236-3.

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

Ge, Houtian, Miguel Gómez, and Christian Peters. 2022. 'Modeling and Optimizing the Beef Supply Chain in the Northeastern U.S.' *Agricultural Economics* 53 (5): 702–18. https://doi.org/10.1111/agec.12708.

Gurrala, Kavitha, and Moncer Hariga. 2022. 'Key Food Supply Chain Challenges: A Review of the Literature and Research Gaps'. *Operations and Supply Chain Management: An International Journal* 15 (4): 441–60. https://doi.org/10.31387/oscm0510358.

Heusala, Hannele, Taija Sinkko, Nesli Sözer, Eemeli Hytönen, Lisbeth Mogensen, and Marie Trydeman Knudsen. 2020. 'Carbon Footprint and Land Use of Oat and Faba Bean Protein Concentrates Using a Life Cycle Assessment Approach'. *Journal of Cleaner Production* 242 (January): 118376. https://doi.org/10.1016/j.jclepro.2019.118376.

Huddiniah, Estu Rizky, and Hilmil Pradana. 2023. 'Impacts of Product Variety and Supply Chain Networks on the Influx of Information Exchange in Industry Applications'. *Smart Cities* 6 (2): 2. https://doi.org/10.3390/smartcities6020051.

İnkaya, Tülin, Dieter Armbruster, Hongmin Li, and Karl G. Kempf. 2018. 'Product Variety Strategies for Vertically Differentiated Products in a Two-Stage Supply Chain'. *International Journal of Production Research* 56 (17): 5930–44. https://doi.org/10.1080/00207543.2018.1461271.

Jaigirdar, Samiha Mustabin, Sudipta Das, Autoshe Ray Chowdhury, Sayem Ahmed, and Ripon Kumar Chakrabortty. 2023. 'Multi-Objective Multi-Echelon Distribution Planning for Perishable Goods Supply Chain: A Case Study'. *International Journal of Systems Science: Operations & Logistics* 10 (1): 2020367. https://doi.org/10.1080/23302674.2021.2020367.

Jonkman, Jochem, Ana P. Barbosa-Póvoa, and Jacqueline M. Bloemhof. 2019. 'Integrating Harvesting Decisions in the Design of Agro-Food Supply Chains'. *European Journal of Operational Research* 276 (1): 247–58. https://doi.org/10.1016/j.ejor.2018.12.024.

Kahmann, Felix, Fabian Honecker, Julian Dreyer, Marten Fischer, and Ralf Tönjes. 2023. 'Performance Comparison of Directed Acyclic Graph-Based Distributed Ledgers and Blockchain Platforms'. *Computers* 12 (12): 12. https://doi.org/10.3390/computers12120257.

Li, Jing, Xinnan Gao, Biao Guo, and Muyuan Wu. 2020. 'Production Plan for Perishable Agricultural Products with Two Types of Harvesting'. *Information Processing in Agriculture* 7 (1): 83–92. https://doi.org/10.1016/j.inpa.2019.05.001.

Miller, John H, and Scott E Page. 2007. *Complex Adaptive Systems: An Introduction to Computational Models of Social Life*. Princeton University Press.

Mogale, D. G., Naoufel Cheikhrouhou, and Manoj Kumar Tiwari. 2020. 'Modelling of Sustainable Food Grain Supply Chain Distribution System: A Bi-Objective Approach'. *International Journal of Production Research* 58 (18): 5521–44. https://doi.org/10.1080/00207543.2019.1669840.

Moher, David, Alessandro Liberati, Jennifer Tetzlaff, and Douglas G. Altman. 2009. 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement'. *Journal of Clinical Epidemiology* 62 (10): 1006–12. https://doi.org/10.1016/j.jclinepi.2009.06.005.

Moysiadis, Theocharis, Konstantina Spanaki, Ayalew Kassahun, et al. 2023. 'AgriFood Supply Chain Traceability: Data Sharing in a Farm-to-Fork Case'. *Benchmarking: An International Journal* 30 (9): 3090–123. https://doi.org/10.1108/BIJ-01-2022-0006.

Murray-Prior, Roy B., Maria Fay Rola-Rubzen, Murray J. McGregor, et al., eds. 2003. 'A Pluralistic Methodology for Analysing Supply Chains'. https://doi.org/10.22004/ag.econ.57926.

Nakandala, Dilupa, Premaratne Samaranayake, Henry Lau, and Krishnamurthy Ramanathan. 2017. 'Modelling Information Flow and Sharing Matrix for Fresh Food Supply Chains'. *Business Process Management Journal* 23 (February): 108–29. https://doi.org/10.1108/BPMJ-09-2015-0130.

Nasir Uddin, Mohammad, Mohammed Quaddus, and Nazrul Islam, eds. 2010. 'Inter-Firm Relationships and Performance Factors in the Australian Beef Supply Chain: Implications for the Stakeholders'. https://doi.org/10.22004/ag.econ.59172.

Nguyen, Tri-Dung, Uday Venkatadri, Tri Nguyen-Quang, Claver Diallo, and Michelle Adams. 2020. 'Optimization Model for Fresh Fruit Supply Chains: Case-Study of Dragon Fruit in Vietnam'. *AgriEngineering* 2 (1): 1. https://doi.org/10.3390/agriengineering2010001.

Reinhardt, Tilman. 2023. 'The Farm to Fork Strategy and the Digital Transformation of the Agrifood Sector—An Assessment from the Perspective of Innovation Systems'. *Applied Economic Perspectives and Policy* 45 (2): 819–38. https://doi.org/10.1002/aepp.13246.

Rodriguez-Sanchez, Sara V., Camila Flores, and Victor Albornoz. 2019. 'Coordination in the Pork Supply Chain through a Bi-Level Formulation'. *III International Conference on Agro BigData and Decision Support Systems in Agriculture* (Valparaíso, Chile), 27–31. https://repositorio.uniandes.edu.co/bitstream/handle/1992/31534/ProceedingsBigDSSagro2019.pdf?sequence=2&isAllowed=y#page=41.

Rossignoli, Cristiano and Moruzzo. 2014. 'Retail Power and Private Standards in the Agri-Food Chain'. *Agroecology and Sustainable Food Systems* 38 (October): 1108–24. https://doi.org/10.1080/21683565.2014.925530.

Schrobback, Peggy, John Rolfe, and Megan Star. 2020. 'An Agri-Food Supply Chain Assessment Framework: Application to Queensland Case Studies'. *Australasian Journal of Regional Studies* 26 (3): 379–410.

Shukla, Manish, and Sanjay Jharkharia. 2013. 'Agri-fresh Produce Supply Chain Management: A State-of-the-art Literature Review'. *International Journal of Operations & Production Management* 33 (2): 114–58. https://doi.org/10.1108/01443571311295608.

Simatupang, Togar M., and R. Sridharan. 2002. 'The Collaborative Supply Chain'. *The International Journal of Logistics Management* 13 (1): 15–30. https://doi.org/10.1108/09574090210806333.

Sisley, Harry, Guvenc Dik, James McGree, and Paul Corry. 2023. 'Multi-Product Multi-Region Supply Chain Optimisation for Seasonal Crops'. *International Journal of Production Research* 61 (16): 5704–22. https://doi.org/10.1080/00207543.2022.2112105.

Solano-Blanco, Alfaima L., Jaime E. González, and Andrés L. Medaglia. 2023. 'Production Planning Decisions in the Broiler Chicken Supply Chain with Growth Uncertainty'. *Operations Research Perspectives* 10 (January): 100273. https://doi.org/10.1016/j.orp.2023.100273.

Soto-Silva, Wladimir E., Esteve Nadal-Roig, Marcela C. González-Araya, and Lluis M. Pla-Aragones. 2016. 'Operational Research Models Applied to the Fresh Fruit Supply Chain'. *European Journal of Operational Research* 251 (2): 345–55. https://doi.org/10.1016/j.ejor.2015.08.046.

Soysal, Mehmet, Jacqueline M. Bloemhof-Ruwaard, Miranda P. M. Meuwissen, and Jack G. A. J. van der Vorst, eds. 2012. 'A Review on Quantitative Models for Sustainable Food Logistics Management'. *International Journal on Food System Dynamics*, ahead of print. https://doi.org/10.22004/ag.econ.144855.

Stadtler, Hartmut, Christoph Kilger, and Herbert Meyr, eds. 2015. *Supply Chain Management and Advanced Planning: Concepts, Models, Software, and Case Studies*. Springer Texts in Business and Economics. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-55309-7.

Taghikhah, Firouzeh, Alexey Voinov, Nagesh Shukla, Tatiana Filatova, and Mikhail Anufriev. 2021. 'Integrated Modeling of Extended Agro-Food Supply Chains: A Systems Approach'. *European Journal of Operational Research* 288 (3): 852–68. https://doi.org/10.1016/j.ejor.2020.06.036.

Taşkıner, Tuğçe, and Bilge Bilgen. 2021. 'Optimization Models for Harvest and Production Planning in Agri-Food Supply Chain: A Systematic Review'. *Logistics* 5 (3): 3. https://doi.org/10.3390/logistics5030052.

Tranfield, David, David Denyer, and Palminder Smart. 2003. 'Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review'. *British Journal of Management* 14 (3): 207–22. https://doi.org/10.1111/1467-8551.00375.

Tripti, and Ravi Shankar. 2022. 'Modelling a Sustainable Agri-Food Supply Chain: A Theoretic System Construct'. *International Journal of Business Performance and Supply Chain Modelling* 13 (1): 1–26. https://doi.org/10.1504/IJBPSCM.2022.122423.

Van Der Goot, Atze Jan, Pascalle J.M. Pelgrom, Jacqueline A.M. Berghout, et al. 2016. 'Concepts for Further Sustainable Production of Foods'. *Journal of Food Engineering* 168 (January): 42–51. https://doi.org/10.1016/j.jfoodeng.2015.07.010.

Vlajic, Jelena V., Jack GAJ Van der Vorst, and René Haijema. 2012. 'A Framework for Designing Robust Food Supply Chains'. *International Journal of Production Economics* 137 (1): 176–89.

Wang, Guangsong, Andre Costa, Wathsala Karunarathne, Matthew Roughan, Sean M. Miller, and Wayne Pitchford. 2023. 'A Strategic Planning Model for the Operation Plan in Lamb Supply Chains'. Paper presented at 25th International Congress on Modelling and Simulation.

MODSIM2023, 25th International Congress on Modelling and Simulation., August 1. https://doi.org/10.36334/modsim.2023.wang57.

Wang, Shiyi, Abhijeet Ghadge, and Emel Aktas. 2024. 'Digital Transformation in Food Supply Chains: An Implementation Framework'. *Supply Chain Management: An International Journal*, ahead of print, January 19. https://doi.org/10.1108/SCM-09-2023-0463.

Wesseler, Justus. 2022. 'The EU's Farm-to-Fork Strategy: An Assessment from the Perspective of Agricultural Economics'. *Applied Economic Perspectives and Policy* 44 (4): 1826–43. https://doi.org/10.1002/aepp.13239.

Yamchi, Hossein Reyhani, Younis Jabarzadeh, Nader Ghaffarinasab, Vikas Kumar, and Jose Arturo Garza-Reyes. 2020. *A Multi-Objective Linear Optimization Model for Designing Sustainable Closed-Loop Agricultural Supply Chain*.

Zhao, Guoqing, Shaofeng Liu, Yi Wang, et al. 2024. 'Modelling Enablers for Building Agri-Food Supply Chain Resilience: Insights from a Comparative Analysis of Argentina and France'. *Production Planning & Control* 35 (3): 283–307. https://doi.org/10.1080/09537287.2022.2078246.

Zhu, Zhanguo, Feng Chu, Alexandre Dolgui, Chengbin Chu, Wei Zhou, and Selwyn Piramuthu. 2018. 'Recent Advances and Opportunities in Sustainable Food Supply Chain: A Model-Oriented Review'. *International Journal of Production Research* 56 (17): 5700–5722. https://doi.org/10.1080/00207543.2018.1425014.

Appendix A Replication of a model from the literature

A.1 Purpose of the exercise

This appendix provides old and new computer code for a model from the literature, one developed by Apaiah and Hendrix (2005). This replication exercise was undertaken for a few reasons:

- To test our understanding of the literature – we wanted to determine whether we could write a programme of a model of an AFSC, working from an example.
- To test our choice of software – we have selected Python as our platform or language for modelling. It is modern and commonly used, and the PBFI programme is using Python for other modelling. Using it for the supply chain modelling may allow the programme to integrate or at least connect different model modules.
- To create a base for future modelling – the Apaiah and Hendrix (2005) model concerned a novel protein food, which is also the focus of the PBFI programme. Once we have a core model that works, we can build on it.

A.2 GAMS model formulation from Apaiah and Hendrix (2005)

The model in Apaiah and Hendrix (2005) is explained well with equations and explanatory text. The article also contains all the necessary data. The model is then presented as a GAMS model formulation in an appendix. The text of the article's appendix is presented below. Note that some of the values required for the model were reported in the body of the article, e.g., the primary production information, and are not in this text.

Sets

I primary production locations/CANADA, FRANCE, UKRAINE, NETHERLANDS/

J Ingredient preparation facilities/CAN, FRA, UKA, NLD/

K NPF production facilities/fran, neth/

N Modes of transportation/sea, rail, barge, truck/;

PARAMETER

wpc(I) cost of production of dry pea at location I in euro per ton/CANADA 160, FRANCE 154, UKRAINE 129, NETHERLANDS 147/

ipc(J) cost of making the pea protein ingredient at location J in euro per ton/CAN 86.7, FRA 145.7, UKA 31.69, NLD 161.9/

ss(J) selling price of starch in euro per ton/CAN 70, FRA 70, UKA 70, NLD 70/

ppc (K) cost of producing the NPF at location K in euro per ton/fran 19.82, neth 17.84/

Table tcdp(I, J, N) transport cost in euro per ton

	Sea	Rail	Barge	Truck
CANADA.CAN				
CANADA.FRA	55.02			
CANADA.UKA	55.02			
CANADA.NLD	55.02			
FRANCE.CAN	55.02			
FRANCE.FRA				
FRANCE.UKA	50.9		21	20
FRANCE.NLD	13.5		16	
UKRAINE.CAN	55.02			
UKRAINE.FRA	50.9		21	20
UKRAINE.UKA				
UKRAINE.NLD	50.9		21	20
NETHERLANDS.CAN	55.02			
NETHERLANDS.FRA	13.5		16	
NETHERLANDS.UKA	50.9		21	37.5
NETHERLANDS.NLD	5		10	

Table tcpp(J,K,N) transport cost in euro per ton

	Sea	Rail	Barge	Truck
CAN.fran	55.02			
CAN.neth	55.02			
FRA.fran				
FRA.neth			13.5	16.0
UKA.fran	50.9		21	20
UKA.neth	50.9		21	20
NLD.fran			13.5	16
NLD.neth			5.0	10.0

Scalar

stpt starch per ton/0.7/

npfp pea protein per ton npf/0.376/

ppdp pea protein per ton of dry transported pea/0.255

pwp percentage of dry pea from total pea produced/0.805/

demand total amount of NPF put into the market/ 30744/

Variables

PP(I)   amount of pea produced at primary production location i

TPI(I, J, N)   amount of dehulled pea transported from location i to facility j

ING(J)   amount of ingredient pea protein concentrate produced at facility j

TIP(J, K, N)   amount of pea protein concentrate transported from facility j to facility k

NPF(K)   amount of NPF produced at facility k

SA(J)   amount of starch produced at J

Z   total costs

Positive variable: PP, TPI, ING, TIP, NPF;

Equations

cost   define objective function

supply(K)   observe supply limit at j

demand   satisfy demand at market j

sup(J)   supply from location j

supl(I)   supply from location I

sta(J)   starch limit

deli(J)   delivery to ingredient production

cost .. z E = sum(I,wpc(I)*PP(I)) + sum((I,J,N), tcdp(I,J,N)*TPI(I,J,N)) + sum(J,ipc(J)*ING(J)) + sum((J,K,N), tcpp(J,K,N)*TIP(J,K,N)) + sum(K,ppc(K)*NPF(K)) - sum(J,ss(J)*SA(J));

supply(K) sum((J,N)$(tcpp(J,K,N) gt 0), TIP(J,K,N)) = e = npfp*NPF(K);

demand sum(K, NPF(K)) = e = demand;

sup(J) sum((K,N)$(tcpp(J,K,N) gt 0), TIP(J,K,N)) = l = ING(J);

deli(J) ppdp*sum((I,N)$(tcdp(I,J,N) gt 0), TPI(I,J,N)) = g = ING(J);

supl (I) sum ((J,N)$(tcdp(I,J,N) gt 0), TPI(I,J,N)) = l = pwp*PP(I);

sta(J) SA(J) = e = stpt*sum((I,N)$(tcdp(I,J,N) gt 0), TPI(I,J,N));

Model model1/all/;

Solve model 1 using lp minimizing z;

Display PP.l, pp.m,TPI.L, TPI.M, ING.L, ING.M, TIP.L, TIP.L, NPF.L, NPF.M; Capacitated model:

A.3 Python version of model

```
# Model from Apaiah & Henddrix, 2005, Design of a supply
# chain network for pea-based novel protein foods (NPF).

import pandas as pd
```

```
import numpy as np

# Sets

# Production -- 'prod'
i = ['canada', 'france', 'ukraine', 'netherlands']
# Processing -- 'proc'
j = ['can', 'fra', 'uka','nld']
# NPF production facilities -- 'fac'
k = ['fran', 'neth']
# Transport modes -- 'mode'
n = ['sea', 'rail', 'barge', 'truck']

# Parameters

# Maximum pea production by country i, tonnes
max_pp_data = [1492600, 1700000, 746800, 4000]
max_pp = {}
count = 0
for prod in i:
    max_pp[prod] = max_pp_data[count]
    count = count + 1
#print(max_pp)

# Cost of pea production by country i, euros per tonne
wpc_data = [160, 154, 129, 147]
wpc = {}
count = 0
for prod in i:
    wpc[prod] = wpc_data[count]
    count = count + 1
#print(wpc)

# Dry pea transport costs (TPI), tcdp, euros/tonne
# TPI --> [(prod, proc, mode) for prod in i for proc in j for
mode in n]
tcdp = {}
for prod in i:
    for proc in j:
        for mode in n:
            tcdp[(prod, proc, mode)] = 0
# add tcdp transport costs

tcdp[('canada', 'fra', 'sea')] = 55.02
tcdp[('canada', 'uka', 'sea')] = 55.02
tcdp[('canada', 'nld', 'sea')] = 55.02
tcdp[('france', 'can', 'sea')] = 55.02
tcdp[('france', 'uka', 'sea')] = 50.9
tcdp[('ukraine', 'can', 'sea')] = 55.02
```

```
tcdp[('ukraine', 'fra', 'sea')] = 50.9
tcdp[('ukraine', 'nld', 'sea')] = 50.9
tcdp[('netherlands', 'can', 'sea')] = 55.02
tcdp[('netherlands', 'uka', 'sea')] = 50.9
tcdp[('france', 'uka', 'barge')] = 21
tcdp[('france', 'nld', 'barge')] = 13.5
tcdp[('ukraine', 'fra', 'barge')] = 21
tcdp[('ukraine', 'nld', 'barge')] = 21
tcdp[('netherlands', 'fra', 'barge')] = 13.5
tcdp[('netherlands', 'uka', 'barge')] = 21
tcdp[('netherlands', 'nld', 'barge')] = 5
tcdp[('france', 'uka', 'truck')] = 20
tcdp[('france', 'nld', 'truck')] = 16
tcdp[('ukraine', 'fra', 'truck')] = 20
tcdp[('ukraine', 'nld', 'truck')] = 20
tcdp[('netherlands', 'fra', 'truck')] = 16
tcdp[('netherlands', 'uka', 'truck')] = 37.5
tcdp[('netherlands', 'nld', 'truck')] = 10
#print(tcdp)

# To find the same result as Scenario 1 in Apaiah & Henddrix,
2005
# UKRAINE.UKA by Truck must be feasible (see Table 2)
# Un-comment to do this (assign a small cost as shown)
# tcdp[('ukraine', 'uka', 'truck')] = 10

# Create list to rule out infeasible transport options
tcdp_no = []
for option1 in tcdp:
    if tcdp[option1] == 0:
        tcdp_no.append(option1)
#print(tcdp_no)

# Cost of processing by j, euros per tonne
ipc_data = [86.7, 145.7, 31.69, 161.9]
ipc = {}
count = 0
for proc in j:
    ipc[proc] = ipc_data[count]
    count = count + 1
#print(ipc)

# Concentrate transport costs
tcpp = {}
for proc in j:
    for fac in k:
        for mode in n:
            tcpp[(proc, fac, mode)] = 0
```

```
# add tcpp transport costs
tcpp[('can', 'fran', 'sea')] = 55.02
tcpp[('can', 'neth', 'sea')] = 55.02
tcpp[('uka', 'fran', 'sea')] = 50.9
tcpp[('uka', 'neth', 'sea')] = 50.9
tcpp[('fra', 'neth', 'barge')] = 13.5
tcpp[('uka', 'fran', 'barge')] = 21
tcpp[('uka', 'neth', 'barge')] = 21
tcpp[('nld', 'fran', 'barge')] = 13.5
tcpp[('nld', 'neth', 'barge')] = 5.0
tcpp[('fra', 'neth', 'truck')] = 16.0
tcpp[('uka', 'fran', 'truck')] = 20
tcpp[('uka', 'neth', 'truck')] = 20
tcpp[('nld', 'fran', 'truck')] = 16
tcpp[('nld', 'neth', 'truck')] = 10.0
#print(tcpp)

# Create list to rule out infeasible transport options
tcpp_no = []
for option2 in tcpp:
    if tcpp[option2] == 0:
        tcpp_no.append(option2)
#print(tcpp_no)

# Cost of making NPF by k, euros per tonne
ppc_data = [19.82, 17.84]
ppc = {}
count = 0
for fac in k:
    ppc[fac] = ppc_data[count]
    count = count + 1
#print(ppc)

# Price of starch by j, euros per tonne
ss_data = [70, 70, 70, 70]
ss = {}
count = 0
for proc in j:
    ss[proc] = ss_data[count]
    count = count +1
#print(ss)

# Scalars

# Starch per tonne
stpt = 0.7
# Pea protein per tonne
npfp = 0.376
# Pea protein per tonne of dry transported pea
```

```
ppdp = 0.255
# Percentage of dry pea from total pea produced
pwp = 0.805
# Total amount of npf put into market
demand = 30744

# ---------
#
# LP model
#
# ---------

# Import PuLP solver
from pulp import *

# Step 1 Initialise LP
prob = LpProblem('Problem_1', LpMinimize)

# Step 2 Define decision variables
# dry pea production by country
DPP = LpVariable.dicts("Peas", i, lowBound=0,
cat="Continuous")
#print(DPP)

# concentrate production by facility
ING = LpVariable.dicts("Concentrate", j, lowBound=0,
cat="Continous")
#print(ING)

# new protein food production by facility
NPF = LpVariable.dicts("NPF", k, lowBound=0, cat="Continuous")
#print(NPF)

# transport peas for processing
key1 = [(prod, proc, mode) for prod in i for proc in j for
mode in n]
TPI = LpVariable.dicts("Pea_transport", key1, lowBound=0,
cat="Continuous")
#print(TPI)
#len(TPI)

# transport concentrate for making into npf
key2 = [(proc, fac, mode) for proc in j for fac in k for mode
in n]
TIP = LpVariable.dicts("Conc_transport", key2, lowBound=0,
cat="Continuous")
#print(TIP)
#len(TIP)
```

```
# starch produced at each j
SA = LpVariable.dicts('SA', j, lowBound=0, cat="Continuous")

# Step 3 Objective function
prob += lpSum([
    wpc[prod] * DPP[prod]
    + tcdp[(prod, proc, mode)] * TPI[(prod, proc, mode)]
    + ipc[proc] * ING[proc]
    + tcpp[(proc, fac, mode)] * TIP[(proc, fac, mode)]
    + ppc[fac] * NPF[fac]
    - ss[proc] * SA[proc]
    for prod in i for proc in j for fac in k for mode in n])

# Step 4 Constraints
# constraint 1
prob += lpSum([NPF[fac] for fac in k]) == demand

# constraint 2
for fac in k:
    prob += lpSum([TIP[(proc, fac, mode)]
                   for proc in j for mode in n]) == npfp *
NPF[fac]

# constraint 3
for proc in j:
    prob += lpSum([TIP[(proc, fac, mode)]
                   for fac in k for mode in n]) <= ING[proc]

# constraint 4
for proc in j:
    prob += lpSum([ppdp * TPI[(prod, proc, mode)]
        for prod in i for mode in n]) >= ING[proc]

# constraint 5
for prod in i:
    prob += lpSum([TPI[(prod, proc, mode)]
        for proc in j for mode in n]) <= pwp * DPP[prod]

# constraint 6
for proc in j:
    prob += lpSum([stpt * TPI[(prod, proc, mode)]
        for prod in i for mode in n]) == SA[proc]

# constraint 7
for option1 in tcdp_no:
    prob += TPI[option1] == 0

# constraint 8
for option2 in tcpp_no:
```

```
    prob += TIP[option2] == 0

# Step 5 Solve model
status = prob.solve()
print(LpStatus[status])

# Step 6 Display variables
for var in prob.variables():
    print(f'{var.name} = {var.varValue}')
```

A.4 Discussion of replication

The replication was successful. The code ran and the new model solved successfully. The model provides a good framework for future work: it has several nodes, it includes primary and secondary processing, and it includes decisions about how or where to conduct processing.

One issue was encountered. The solution to the Python code was slightly different from the results reported in Apaiah and Hendrix (2005). The article reported that the solution to the base model (Scenario 1) was:

Primary production of 56,323 metric tonnes in Ukraine

- ➔ *Trucked to Ukraine*
- ➔ *Ingredient processing to produce 11,560 metric tonnes in Ukraine*
- ➔ *Trucked to Netherlands*
- ➔ *Novel protein food production of 30,733 metrics tonnes in Netherlands.*

The new model code found slightly lower production of 56,313 tonnes, and then the primary production (peas) was transported by sea to Canada for processing. The ingredient was then transported by sea to Netherlands, resulting in the same final production of the novel protein food. The differences were the slightly lower primary production, the place where first processing occurred, and the transport methods.

The difference was traced to the inputs. In the article (Table 2), there is no cost listed for transport between Ukraine and Ukraine. The new code treated that lack of cost as a lack of the transport option, similar to lack of a Truck option between Canada and France. If the lack is, instead, a zero-cost option, then the model would solve differently. This was tested in a second scenario that assigned a cost of 10 to transport by Truck within Ukraine. The code for that scenario is commented out in the above code but can be un-commented. With that option made available, the new model produced the same transport route as in the original article.