Tackling Food Waste: A System Dynamics Approach to Analyzing Food Waste in Wholesale Markets and Developing Targeted Interventions for Sustainable Operations

by

Furqan Khalil Syed
B. Eng. Mechanical Engineering

SUBMITTED TO THE PROGRAM IN SUPPLY CHAIN MANAGEMENT
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE IN SUPPLY CHAIN MANAGEMENT
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 2023

Signature of Author:

Department of Supply Chain Management
May 12, 2023

Certified by:

Dr. Christopher Mejía Argueta
Director, Food and Retail Operations Lab, Center for Transportation and Logistics
Capstone Advisor

Certified by:

Prof. Saartjie Grobbelaar
Department of Industrial Engineering at Stellenbosch University
Capstone Co-Advisor

Accepted by:

Prof. Yossi Sheffi
Director, Center for Transportation and Logistics
Elisha Gray II Professor of Engineering Systems
Professor, Civil and Environmental Engineering

(This page is intentionally left blank)

Tackling Food Waste: A System Dynamics Approach to Analyzing Food Waste in Wholesale Markets and Developing Targeted Interventions for Sustainable Operations

by

Furqan Khalil Syed

Submitted to the Program in Supply Chain Management
on May 12, 2023, in Partial Fulfillment of the
Requirements for the Degree of Master of Applied Science in Supply Chain Management

Abstract

This study addresses the global issue of food waste in wholesale markets, where 1.3 billion tons of food are wasted annually (in the whole value chain) while millions face food insecurity. Our contribution is a preliminary framework to tackle food waste challenges and promote a more sustainable and efficient food supply chain, emphasizing the importance of implementing targeted strategies and recommendations for lasting impact. Partnering with the World Union of Wholesale Markets (WUWM), our goal was to understand food supply chains in wholesale markets and identify opportunities to mitigate food waste. This study uses system dynamics (SD) modeling techniques, including causal loop diagrams and stock and flow diagrams, to analyze supply chain-related food losses and propose potential intervention strategies.

We identified five key supply chain dimensions influencing food losses: Market Strategy, Supply Chain Operations, Infrastructure, Partnerships, and Macro-trends (economic, political, and technological). These dimensions underscore the need to balance commercial objectives and environmental concerns, efficient stock management, adequate storage facilities, collaboration among stakeholders, and consideration of broader food waste trends. Through this study, we demonstrate the utility of SD models in analyzing wholesale supply chains, providing valuable insights into managing and mitigating food waste. In addition, we identified key potential solutions such as timely investment in infrastructure, particularly cold storage, partnerships with food banks, and tracking waste against targets.

Capstone Advisor: Dr. Christopher Mejia Argueta
Title: Director, Food and Retail Operations Lab, MIT Center for Transportation and Logistics

Capstone Co-Advisor: Prof. Saartjie Grobbelaar
Title: Professor, Department of Industrial Engineering at Stellenbosch University

ACKNOWLEDGMENTS

First and foremost, we would like to express our sincere gratitude to all the people from the World Union of Wholesale Markets (WUWM) for their overwhelming support in developing this project and for their invaluable insights. In particular, we are grateful to Eugenia Carrera, General Secretary of WUWM, for her guidance, connections, and insights.

We extend our special thanks to Jordi Valls and the Mercabarna team for their support and insightful contributions to our understanding of the wholesale market dynamics. We would also like to acknowledge Fiona Whitworth from the Melbourne Market, Valerie Vion from Rungis Market, Giannis Triantafyllis from the Greece wholesale market, and Eliane Steinmeyer from the Hamburg wholesale market. We also appreciate Joaquin Perez Martin from the Food and Agricultural Organization for his guidance and insight and Esther Escarzaga, whose expertise on food systems in Mexico has enriched our research.

Next, I would like to convey our heartfelt appreciation to my co-advisors, Dr. Christopher Mejia Argueta and Professor Saartije Grobbelaar, for their exceptional support throughout the project. Their unwavering commitment, guidance, and mentorship have been instrumental in shaping the direction and quality of the research. Their encouragement and constructive feedback have been invaluable in helping us navigate the challenges and celebrate the successes along the way.

Dr. Mejia Argueta's deep understanding of food systems and supply chain management and his ability to inspire creative and critical thinking has significantly enhanced my research. Professor Grobbelaar's expertise in system dynamics and her keen insights into the complexities of food systems have been invaluable in helping us develop a comprehensive and meaningful analysis.

Lastly, I would like to thank our writing coach Toby Gooley for her invaluable guidance, constructive feedback, and support that greatly contributed to the success of this study and my growth as a researcher and writer.

Table of Contents

<u>List of Figures</u>

List of Tables

1 Introduction

1.1 Motivation

About a third of all food produced in the world is wasted. This figure accounts for roughly 1.3 billion tons of food waste yearly (WHO, 2022). At the same time, of the almost 7.8 billion people worldwide, approximately one quarter suffer from food insecurity, i.e., they do not know if they will have anything to eat in the next week (WHO Factsheet, 2022). Of these two billion food-insecure people, 750 million suffer from severe food insecurity, which means their ability to have food on the same day is extremely uncertain (WHO, 2022). Therefore, there is a clear disconnection between the food supply sources and the demand areas, resulting in poor food resource management.

Modern food supply chains are complex entities with food products passing through many intermediaries, from farmers to wholesalers to manufacturers to retailers to consumers. About 30% of preventable food waste stems from a lack of coordination among the different parties, primarily driven by behavioral aspects and ineffective supply chain management (Lum, 2021). For instance, poor demand transparency in a wholesale market can result in producer oversupply, thereby straining storage and enhancing losses downstream in the supply chain (Canali et al. 2017). This suggests that we can move towards more effective and efficient supply chains by understanding and regulating the interactions between the different food supply chain stakeholders in diverse communities. This would help mitigate food losses resulting from problem behaviors and inefficiencies.

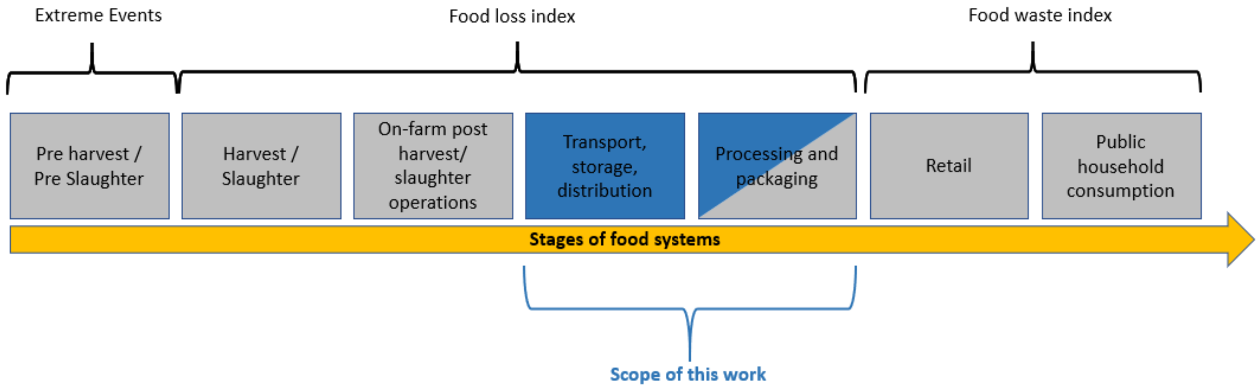
The key partner we work with in building and analyzing these strategies is the World Union of Wholesale Markets (WUWM). WUWM is an international network of fresh food and products organizations with the aim to improve accessibility to healthy food for everyone by delivering more sustainable and inclusive fresh-food supply systems. WUWM operates in over 40 countries worldwide (WUWM, 2022). We conducted semi-structured interviews with various executive members within WUWM, in several cities in diverse countries to understand the differences in their respective markets. These include (but are not limited to) strategy, scale of operations, infrastructure development, alliances, and business model. Their inputs help inform the development of a framework that can explain the dynamics of food supply chains in wholesale markets worldwide and showcase the relevance of the studied dimensions.

1.2 Problem Statement and Research Questions

Food is lost at every stage of the food cycle. Figure 1.1 illustrates different categories of loss and waste along the food supply chain.

Figure 1.1

Sources of Food Loss and Waste Along the Food Value Chain



Adapted from GFN. How food banks mitigate effects of climate change by The Global Food Banking Network (2021). Copyright 2021

In large countries like the United States, wholesale markets and large retailers are responsible for approximately five million metric tons of annual food waste, which translates to an estimated value of $25 billion (ReFED, 2021). This staggering figure underscores the immense potential for waste reduction within wholesale markets. Consequently, our study seeks to address two primary research questions to explore and better understand the opportunities for mitigating food waste in such settings:

1. *What significant supply chain factors may help address overarching challenges like food waste in wholesale markets and their food ecosystems?*
2. *What intervention schemes should be applied to enhance affordability and access to nutritious goods through wholesale markets?*

1.3 Project Goals and Scope

Through our project, we built a high-level framework to better explain the dynamics of food supply chains in wholesale markets and identify the overarching challenges resulting in higher food waste. We focused on the wholesale market supply chain's transport, storage, and distribution stages. We determined that a critical challenge for WUWM is a lack of proper insight into food waste, its causes, and how it propagates across wholesale market operations. Along with developing a framework to explain the food supply chain dynamics, we also identify potential intervention strategies that the World Union of Wholesale Markets can apply in different parts of the world to manage food efficiently and reduce waste.

As part of this study, we examined food supply chains across six diverse cities—Melbourne, Australia; Piraeus, Greece; Mexico City, Mexico; Hamburg, Germany; Paris, France; and Barcelona, Spain—to gain varied insights and compare best practices. The market maturity and development differences in these regions enabled us to construct a comprehensive framework through primary data collection via semi-structured interviews. However, due to limited data availability and reliability, we narrowed our focus to Mercabarna in the Barcelona region to demonstrate the framework's applicability. Our analysis concentrated on two distinct products: potatoes, with a shelf-life of up to a year, and tomatoes, which perish within a week without cold storage. These products are common in the regions where WUWM operates, and their contrasting lifespans allow our findings to be applied to a wide range of food items, practices, and processes.

Regarding the methodological steps, we began our work by reviewing existing literature to identify common problems and causes of food waste and intervention schemes used in the past. This allowed us to establish a preliminary framework for analyzing supply chain food losses. We then conducted semi-structured interviews with various stakeholders to collect qualitative data. This was supplemented with more quantitative data regarding supply chain activities such as wastages, inventory, and shipment volumes. We put together primary and secondary data through causal loop diagrams and stock-flow diagrams. We constructed a comprehensive system dynamics (SD) model that captured the intricate interactions and feedback loops within the wholesale market operations. Causal loop diagrams let us visually represent the relationships between different factors affecting food loss, while stock-flow diagrams facilitate quantitative analysis of these relationships. The SD approach was particularly advantageous due to its ability to work with limited data, making it an appropriate choice for our study. We were further able to use the SD model to effectively simulate the system's behavior, revealing key insights and contributing to a deeper understanding of the dynamics at play.

Our study emphasized the significant role of strategically developing infrastructure and capacity in response to market growth to ensure efficiency and waste reduction. However, it is important to note that a short-term focus on procuring more food to sell can detract from infrastructure investment, suggesting that intervention might be necessary to achieve the right balance. If infrastructure and capacity are not adequately developed, sudden shocks to the system, such as demand surges (e.g., panic buying) or supply surges (e.g., early crop harvests), can cause substantial supply chain disruptions. Moreover, forging partnerships with food banks and other redistribution channels, particularly when incentivized by governments through tax schemes, can substantially benefit the market and overall food waste reduction efforts.

Given the limited application of system dynamics models in existing literature concerning wholesale markets, our research helped explore this underdeveloped area by demonstrating the utility of such a model for analyzing wholesale supply chains. By employing an SD approach, our work successfully integrates supply chain dynamics and examines the intricate interactions among factors like infrastructure development and quality. Consequently, we conducted simulations to elucidate the implications of diverse activities and interventions, ultimately identifying strategies that can be applied to manage and mitigate food waste within wholesale markets effectively.

Our study revealed five key supply chain dimensions impacting food losses and proposed we identified some targeted strategies to mitigate waste in the wholesale market. Our recommendations encompass: [1] proactive investments in infrastructure, specifically cold storage, to enhance product shelf life and minimize waste, [2] partnerships with food banks to redistribute excess food, [3] monitoring of waste levels to establish tailored waste reduction plans.

Chapter 2 examines the current state of the art in existing literature, allowing us to construct our framework based on prior research and best practices. Then, Chapter 3 outlines our methodology, encompassing primary and secondary data collection as well as the employment of modeling techniques. Chapter 4 presents key findings derived from our simulations and discusses potential strategies applicable to wholesale markets to address food waste effectively. Finally, Chapter 5 presents the main conclusions and future research opportunities.

2 State of the Art

To build the basis for our work, we reviewed literature in four areas: (1) the dynamics of food value chains, (2) the role of wholesale markets in promoting food accessibility, (3) the impact of various supply chain dimensions on food waste (4) standard methodologies used to model similar systems.

2.1 Dynamics of Food Value Chains

The food value chain is a construct through which one may consider the flow of edible products from conception to consumption. This comprises all activities and actors involved, from farmers who grow the produce to logistics partners involved in transportation to wholesale markets where produce is sold and then to end-consumers (Segre et al., 2014). Food value chains are complex systems with multiple interacting feedback mechanisms across participants, wherein actions and consequences at various stages influence and are influenced by others (Muflikh et al., 2021). A key stakeholder in most food value chains is the wholesale market, which facilitates transactions between numerous other parties like producers, consumers, and logistics companies (Lima et al., 2022).

A major source of complexity in food supply chains is the perishable nature of fresh food products. The fairly short product life cycle and constant degradation of the product from producer to market creates multiple supply chain challenges: [1] A short shelf life means long-term inventory holding is not possible, [2] often specialized infrastructure (e.g., cold storage) is needed to extend product life, [3] distance between market and producer reduces product quality, [4] communication channels between sellers and producers are not always robust. These complex dynamics enhance the risk of food loss (Muriana, 2017).

Other food supply chain issues are the high variability and uncertainty of both demand and supply. Demand is dependent on accessibility, availability, and affordability, which are driven by product perishability and quality. Food supply is seasonal and sensitive to external conditions like weather, yield, and other agriculture-related practices. Thus, a single bad harvest can deliver severe supply shocks to the system. This unpredictable environment exacerbates potential waste in the supply chain and creates a need for closer coordination between actors to manage the system effectively (Kaipia et al., 2013).

A value chain analysis can give a deeper understanding of food supply chains. This essentially involves four key aspects: [1] understanding structures of the value chains; [2] understanding governance and strategy — the depth of relationship and power balance between actors that determines demand, supply, pricing, and other factors; [3] identifying strategic levers — points where minor shifts can lead to significant structural changes across the value chain; and [4] developing interventions schemes for upgrading and refining the whole food ecosystem (Muflikh et al., 2021).

Within the topic of food value chains, prior works exist that explore the dynamics of agricultural production (Muflikh et al., 2021), inter-organizational relationships (Gudbrandsdottir et al., 2021), state policies (Queenan et al., 2022), and inclusiveness of smallholder farmers (Cuevas Garcia-Dorado et al., 2021). However, studies of the dynamics surrounding the role of wholesale markets and interactions among various relevant stakeholder groups are scarce. Our study, therefore, focuses mainly on deconstructing the dynamics around wholesale markets and across their value chains and developing a framework that explains the major causes of food waste and advises mitigation schemes.

2.2 Role of wholesale markets in promoting food accessibility

A high-level approach to investigating food waste should consider five stages along the food supply chain: Production, post-production, processing, distribution, and consumption. (Delgado et al., 2021). Wholesale markets play a role in the post-production and distribution stages of the supply chain. They are an essential component of any agricultural marketing system, acting as an enabler of trade between sources of production (farms) and sources of consumption. In many countries especially developing countries, wholesale markets help provide farmers with effective marketing outlets for their produce. They are fundamental instruments for promoting competition, improving public health, and maintaining food quality control if adequately located, sized, and managed. This thereby lowers and stabilizes consumer prices and enables the reduction of postharvest losses (Yilmaz & Yilmaz, 2008).

Wholesale markets worldwide are critical in maintaining food security and accessibility for all. In the case of Nanjing, China, for instance, urban food security has been achieved through a hybrid public-private food provisioning system. Wholesale markets are a vital part of a public-private hybrid food provisioning system. This hybrid model promotes food accessibility by preventing market failures in the food system, ensuring the physical accessibility and affordability of food for urban residents (Zhong et al., 2019).

Similarly, other wholesale markets, like Chennai's Vanagaram, are crucial for addressing urban food security and nutrition. They merge low-priced seafood supplies from various regions, ensuring accessibility for low- and middle-income households. This supports the urban poor by stabilizing and distributing reasonably priced perishable food items (Subramanian et al., 2022).

Next, we investigate the sources of food losses in food supply chains, specifically wholesale markets.

2.3 Strategic and Operational Levers for management of food waste

Food waste and loss are defined as food initially allocated for human consumption but removed from the supply chain even if it is brought to non-food use (Priefer et al., 2016). Food waste and loss can arise at every stage of the food supply chain for multiple reasons, influenced by the actions of many different players (WRAP, 2015). In this section, we have reviewed the common causes of food waste and some potential mitigation strategies and split them into strategic and operational levers. Our findings are summarized in Tables 2.1 and 2.2.

Table 2.1

Strategic Levers and Sources of Waste

	Strategic Levers	Sources
Causes of Loss	Profit prioritized over environmental or social impact	(Chauhan et al., 2021), (Zhang et al., 2019)
	Waste monitoring is unclear or absent	(Chauhan et al., 2021), (Lima et al., 2022)
	The ownership model (public / public-private / private) prioritizes conducive management behaviors	(Priefer et al., 2016)
	Rapidly increasing urbanization puts a strain on existing food networks	(Stangherlin & de Barcellos, 2018)
	High-quality standards lead to the discard of imperfect but edible products	(Diaz-Ruiz et al., 2018)
	Stage of maturity of the wholesale market	
Mitigation Schemes	Legal requirements to redirect potential food waste to recovery modes like food banks	(Chauhan et al., 2021)
	Government incentives for food donation	(Chauhan et al., 2021), (Canali et al., 2017)
	Partnerships between wholesalers and foodbanks/soup kitchens for regular transfers	(Chauhan et al., 2021), (Priefer et al., 2016)
	Digitalization for waste monitoring	(Chauhan et al., 2021), (Lima et al., 2022)
	Taxing Waste	(Priefer et al., 2016)

Table 2.2

Operational Levers and Sources of Waste

	Operational Levers	Sources
Causes of Loss	Low shelf life of perishable products - unsold items will eventually be discarded	(Muriana, 2017), (Muriana, 2016), (Priefer et al., 2016), (Zhang et al., 2019)
	Lack of cold storage infrastructure leads to product degradation	(Muriana, 2017), (Rolker et al., 2022), (Priefer et al., 2016)
	Demand variability and predictability - accuracy of forecasts	(Canali et al., 2017)
	Transportation and packing errors causing damage	(Rolker et al., 2022), (Lima et al., 2022)
	Limited storage space with social enterprises (Food Banks)	(Craig et al., 2013)

	Oversupply when the market is very competitive or during a good season	(Lima et al., 2022)
	Insufficient storage capacity at market	(Muriana, 2017), (Canali et al., 2017), (Rolker et al., 2022)
	Incomplete or improper training of staff handling food	(Canali et al., 2017), (Priefer et al., 2016), (Zhang et al., 2019)
	High travel distance between market and producer	(Diaz-Ruiz et al., 2018)
	Damage or loss during picking and packing	(Rolker et al., 2022)
Mitigation Schemes	Appropriate infrastructure, such as cold chain to elongate shelf life	(Muriana, 2017), (Priefer et al., 2016)
	Price repositioning strategy to encourage consumption of near-expiry products	(Muriana, 2017), (Muriana, 2016)
	Remaining shelf life tracking through RFID	(Muriana, 2010)
	Efficient supply chains aimed at minimizing loss rather than responsive supply chains that try to keep up with fluctuating demand	(Canali et al., 2017)
	Improved SC controls and training	(Rolker et al., 2022), (Priefer et al., 2016)
	Create alternative buying/selling points	(Diaz-Ruiz et al., 2018)

Most wholesale markets operate as private entities or public-private partnerships, often prioritizing profit or revenue over environmental and social impact. Schemes could be developed to help divert potential food waste to areas of consumption. (Chauhan et al., 2021). Moreover, waste monitoring and tracking can be inconsistent or undeveloped in many wholesale markets, thereby hindering the development of corrective measures (Lima et al., 2022).

The short shelf life of products and fluctuating market-driven pricing pose significant challenges for wholesale markets aiming to minimize waste. Seasonal and unpredictable demand and supply patterns further complicate storage and inventory management. A proactive approach to infrastructure investment and the development of waste management practices can help address these challenges effectively. We will thoroughly analyze the literature within these strategic and operational frameworks in the following section. This analysis aims to identify major themes emphasized in prior work, providing a comprehensive understanding of the subject matter and informing future actions.

2.4 Dimensions and Supply Chain Levers to Explain Losses in Food Value Chains

Reviewing the literature, we have identified five supply chain dimensions influencing behaviors and processes resulting in losses: Strategy, Operations, Infrastructure, Partnerships, and Macro-trends. The subsections below discuss these dimensions and their impact on food waste.

2.4.1 Strategy – Ownership, specializations, and metrics

The nature of ownership models impacts the strategic operations of the wholesale market. Today, wholesale markets are for-profit entities, public corporations, or public-private partnerships (Densley & Sánchez-Monjo, 1999). The ownership model impacts what gets prioritized by management or how products, information, and cash flows are performed in the wholesale market value chains. Most markets are for-profit entities or at least the sellers within the markets. As such, commercial aspects of the business tend to take priority over environmental and social factors. For many organizations monitoring waste is seen as a secondary metric. Since food waste is not tracked, few actions are taken to rectify behaviors and processes that increase waste (Diaz-Ruiz et al., 2018). While not necessarily oriented towards profits, public wholesale markets face their own challenges. They often lack adequate funding and resources to invest in necessary infrastructure improvements and must navigate complex bureaucratic processes to enact changes (Bilska et al., 2015).

Wholesale markets may specialize in catering to a specific product category, like fruits and vegetables, or they may be more inclined toward domestic sales, imports, or exports (Lima et al., 2022). Differences in the proportion of local production vs. imports within a given market can lead to specific changes in market dynamics and stakeholder behaviors. For instance, the presence of non-costly imports of a certain product may result in local producers shifting to other crops. This, in turn, would lead to an undersupply of one product and an oversupply of another, thus increasing the risk of loss/waste (Queenan et al., 2022).

2.4.2 Operations – Logistics, Inventory, and Price mechanisms

Various operational activities such as transportation, inventory management, and pricing might impact waste generation along the food supply chain. Damage and degradation during transport commonly cause food loss/waste. Additionally, ineffective strategies around inventory management can lead to quality decline and food waste, especially in perishable products (Chauhan et al., 2021). Canali et al. (2017) emphasized the importance of human resource training in enhancing logistics efficiencies to mitigate food loss and waste. Wrong picking and packing practices are identified as common causes of food damage, leading to eventual discard. They concluded that by implementing comprehensive training programs and more efficient stock management practices, wholesale markets could ensure employees handle food products carefully, minimizing damage and subsequent waste.

Muriana et al. (2017) identified a crucial waste cause as the lower shelf life of perishable products. If not consumed within time, many food products degrade quickly and are wasted. This can be mitigated through proper infrastructure such as cold chains, shelf life tracking through RFID technology (Muriana, 2016), and driving pricing strategies that encourage the sale of near-expiry products. Additionally, reverse logistics activities involved in the recovery of food items can significantly allow degrading products to be routed to regions of higher need, thereby preventing waste (Kazancoglu et al., 2021).

2.4.3 Infrastructure – Facilities, equipment, and Capabilities

Infrastructure development within a wholesale market largely determines its ability to serve various stakeholder groups and meet the strategic goal of the business model. Along with the capability to handle incoming and outgoing volumes, a wholesale market needs to have adequate storage, sorting, and handling facilities. Such facilities can prevent waste by reducing cross-contamination, cold chain breaches, and spoilage (Bechoff et al., 2022). In the case of perishable goods (like fresh vegetables), cold storage plays a crucial role in elongating life (Queenan et al., 2022). Storage and processing facilities can help convert ingredients such as fruits and vegetables into processed products (i.e., pulp, cooked food) to extend their lifetime. However, processing units should actively monitor efficiency to determine how much of the product is potentially wasted (Bechoff et al., 2022). The most common facilities the wholesale markets need include cold chambers, which expand the capacity to manage perishable ingredients and increase food safety and quality for the produce items.

2.4.4 Partnerships and Alliances

Partnerships and alliances between key players along the food value chain play a critical role in minimizing waste, especially recovery of poor-grade food that may become waste. Such partnerships could involve the city administration, wholesale markets, food banks, and non-governmental organizations (e.g., charities). In numerous cases, recovering food relies heavily on the responsibility of organizations not very well equipped to handle it effectively (Lai et al., 2022). In their work, Lai et al. (2022) recommended three steps to improve the harnessing of potential food waste: [1] Introduce subsidies and incentives around transportation to prioritize redistribution; [2] Develop strategic partnerships to involve relevant stakeholder groups in the recovery process stably; and [3] Initiate interventions and campaigns that enhance food literacy, engage all relevant participants and frame messages within personal values.

2.4.5 Macro trends – Economical, Political and Social

Over the past few decades, the growing trend of shopping produce items at supermarket chains has shifted investments away from wholesale markets in many countries. The consequence has been a slowdown of infrastructure development, leaving many wholesale markets ill-equipped to manage food supply properly. Obsolete storage facilities, for instance, result in higher waste rates and costs (Ortiz-Gonzalo et al., 2021).

Government regulations often play a significant role in how organizations act. For instance, increasing import tariffs can cause organizations to switch strategies, such as sourcing more produce locally versus internationally. Local sourcing involves shorter, less complex supply chains that generate lower waste (Queenan et al., 2022). The introduction of 'Pay as you throw' schemes (essentially a waste tax) in parts of Europe has played a prominent role in preventing food waste (Priefer et al., 2016).

Lima et al. (2022) in their work discuss strategies to reduce food waste in fruit and vegetable supply chains. They also consider these strategies' social aspects by examining the role of different actors like farmers, wholesalers, and logistics providers. Their study highlights the importance of collaboration and robust partnerships among various actors to develop a more efficient and sustainable food supply chain.

Table 2.3

Dimensions discussed in prior literature

Prior Work	Dimensions					
	Strategy: Ownership, metrics, specializations, coverage, imports, and exports	**Operations**: Upstream and downstream logistics, Inventory management, Pricing	**Infrastructure**: Capacity, facilities, development	**Partnerships and Alliances**: Established and emerging partnerships, food banks, state, upstream, and downstream actors	**Regulations and macro trends**: Political, economic, social, technological, environmental	**Technology and innovation**: Use of innovative technology, investment in modernization
(Bechoff et al., 2022)			x			
(Lai et al., 2022)				x		
(Ortiz-Gonzalo et al., 2021)					x	
(Allen & de Brauw, 2018)		x				
(Queenan et al., 2022)	x	x			x	x
(Chauhan et al., 2021)		x				
(Muriana, 2017)		x	x			
(Diaz-Ruiz et al., 2018)		x	x			x
(Canali et al. 2017)		x				
(Rolker et al. 2022)		x			x	
(Zhang et. Al 2019)	x		x	x		

Table 2.3 summarizes our literature review and establishes the base framework for us to build upon. The six supply chain dimensions and the relevant works supporting those themes are highlighted above. In the next section, we will discuss possible approaches to further developing this framework and constructing a model to simulate the dynamic behaviors and interactions among supply chain dimensions that impact losses.

2.5 <u>Methodologies to analyze dynamics in food value chains</u>

Agent-based modeling and participatory system dynamics (SD) modeling are two methodologies for studying complex systems like food loss and supply chain dynamics in wholesale markets. Agent-based modeling, a computer simulation method, uses "agents" as basic units representing simplified real-world actors and their interactions to generate the system's emergent behavior (Wu et al., 2018). Although effective in simulating socioeconomic systems like agricultural supply chains, it is data-intensive, requiring a vast set of reliable empirical data (McGarraghy et al., 2022).

Participatory SD modeling, on the other hand, involves engaging stakeholders to improve accuracy, realism, learning, understanding, and collaboration among them (Rieder et al., 2021). Despite its benefits, its adoption has been slow due to time constraints and the need for higher stakeholder involvement, which may not always be feasible. However, its adoption and use have grown drastically in the last decades, given its flexibility to mix qualitative and quantitative data and identify interesting behaviors beyond the traditional simulation.

Discrete event simulation (DES) is a computer-based modeling technique that analyzes complex systems by breaking them into a sequence of individual, discrete events. It is widely employed in various industries to optimize processes, evaluate performance, and make informed decisions. Typical applications of DES include supply chain management, manufacturing, healthcare, transportation, and logistics. The primary advantages of DES are its flexibility and capability to model complex, dynamic systems (De Santis et al., 2023).

Ultimately, we decided to employ system dynamics modeling for three reasons: [1] it requires fewer data, [2] it allows understanding of the dynamics across operations and stakeholders (including behavior), [3] and can produce valuable simulations for policy advisory purposes.

Deepening into system dynamics (SD), it employs stocks, flows, internal feedback loops, functions, and time delays to represent the dynamic interactions between system elements (Rieder et al., 2021). SD simulation models can be run quickly and do not require high computing power, making them particularly useful when quantitative data is scarce. This approach has been applied in food value chains to better capture the various feedback loops, dynamic behaviors, and time delays involved in these systems (Muflikh et al., 2021).

Causal Loop Diagrams (CLDs) are a powerful tool for representing dynamic interrelationships and understanding a system's structure. They provide a visual representation that captures complex systems in a brief form and can support structure-behavior pairs, which describe complex dynamic phenomena. Causal loop diagrams are made of variables connected by arrows, expressing the causal links between the variables. Each causal link is assigned a polarity, either positive (+) or negative (-), to indicate the effect of the independent variable on the dependent variable. Understanding a system's structure makes it possible to ascertain a system's behavior over a specific period (Meadows, 2008).

Additionally, a well-developed CLD allows us to observe emerging System Archetypes. System Archetypes are a set of typical dynamics that occur in many different settings, consisting of various combinations of balancing and reinforcing loops. These archetypes serve as a starting point to build a more precise articulation of a business story or issue. In the case of food supply chains, system archetypes can help expose recurring issues like supply-demand imbalances, resource constraints, or lack of collaboration between actors. Examples of archetypes include "Drifting Goals," "Shifting the Burden," and "Growth and Underinvestment." We can better understand the important levers using System Archetypes in conjunction with the CLD (Kim & Anderson, 1994).

Causal loop diagrams can be transformed into stock and flow diagrams, which help analyze the system quantitatively. Stocks are represented by rectangles, inflows by pipes pointing to the stock, and outflows by lines going out. The valves control the rate of the flow (Sterman, 2000).

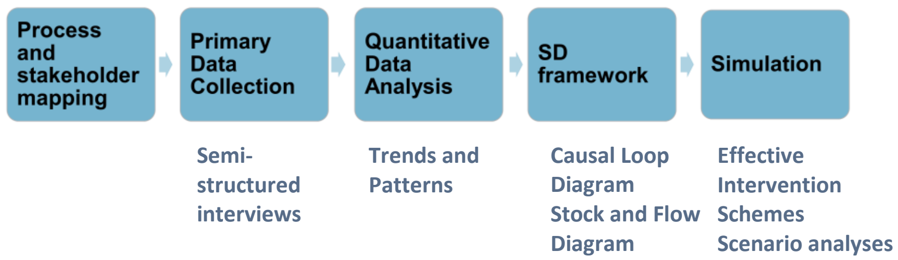
We see examples of work similar to ours in existing literature, where SD models represent food value chains. In their work, Queenan et al. (2022) explain policy issues within the commercial chicken system in South Africa through a qualitative system dynamics model. Using a food systems approach, they provided recommendations to transform food-related policy-making and manage the complex problems associated with food. System dynamics offers a powerful way to analyze and understand complex systems, such as freight procurement. It can calculate stock by formally defining variables, each with its equation and initial value.

3 Methodology

Building on our literature review, we conducted qualitative research with different representatives from the World Union of Wholesale Markets. We began by examining various food supply chain processes through semi-structured interviews. Based on their industry knowledge, we identified the key factors affecting food loss in wholesale market operations. Many of these confirmed our findings from the literature review, while others provided new information. We then constructed a system dynamics model and conducted sensitivity and scenario analyses to comprehensively capture the system's dynamics. Finally, we derived results and conclusions from our findings. Figure 3.1 provides a summary of our overall methodology.

Figure 3.1

Methodological Steps of our Study



3.1 <u>Primary Qualitative Research on WS Market Dynamics and Food Waste</u>

In collaboration with the World Union of Wholesale Markets (WUWM), we conducted semi-structured interviews with representatives from wholesale markets in Barcelona (Mercabarna), Paris (Rungis Market), Mexico City (Iztapalapa), Melbourne, Hamburg, and Piraeus. In addition, we interviewed the General Secretary of WUWM and an expert from the

Food and Agriculture Organization (FAO), a United Nations Agency. These interviews aimed to identify the most relevant challenges and factors influencing food waste and supply chains in wholesale markets, providing valuable insights into each wholesale market's investment priorities, strategies, metrics, and operations. We highlighted the most pressing issues they face.

The interviews were conducted between October 2022 and March 2023, each lasting from 30 to 60 min. The interviews were then transcribed (auto-generated), and the main repeating themes were extracted. The primary topics that emerged from the discussions included the presence or absence of cold storage facilities, the cost of holding inventory versus the actual returns from sales, a lack of priority or tracking of waste mitigation, partnerships with local food banks and charities, and food loss during transportation. By combining these topics with our earlier literature review, we can develop a causal loop diagram to illustrate the dynamics of wholesale market value chains. Section 3.3 will explore this diagram and its implications in greater detail.

3.2 Collection and Analysis of Secondary Data

The primary research was mainly qualitative and assisted us in constructing an exploratory model of the supply chain dynamics surrounding wholesale markets. As discussed in Section 1.3, secondary data were limited, so we focused on Mercabarna (Barcelona) to develop a generic SD model for our simulation. The data, which were partly provided by the wholesale market and partly collected from publicly available sources, included:

- Location of production areas
- Production history
- Demand history for potatoes and tomatoes
- Wholesale market share

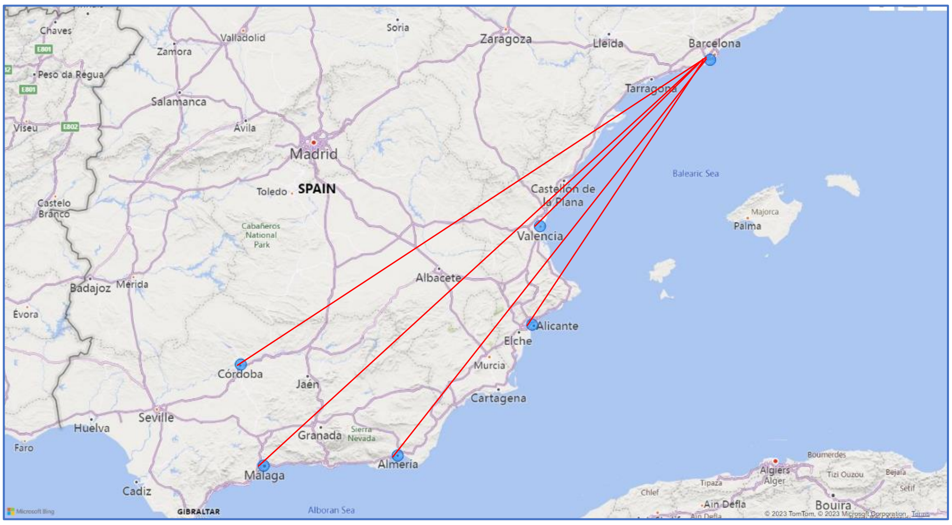
- Costs of infrastructure development
- Product price trends
- Demographic data

These data were then utilized during the simulation to generate results closer to reality.

Figure 3.2 shows some sample data provided by Mercabarna.

Figure 3.2

Sample visual of production location data shared by Mercabarna



3.3 <u>Developing a Causal Loop Diagram</u>

The Causal Loop Diagram (CLD) incorporates all the variables identified through our primary research and their interrelated connections. The complete list of variables, along with their formulations, can be found in Appendix A. In Table 3.1, we emphasize several crucial variables for our model and will delve into them more thoroughly in this section. We will further elaborate on their interactions in the various subsections of the CLD in Section 4.1.

Table 3.1

Extract of the most important variables

Sr. no.	Variable	Type	Model Section	Description	Units	Formula
1	Wholesale Market Stock	Stock	Core	The total volume of available produce	kg	Initial value + Rate of Supply - Rate of Food Recovered - Rate of Food Loss - Rate of Customer Purchases
2	Rate of Food Loss	Flow	Core	The volume of produce lost per month	kg/ month	Rate of spoilage in transit + Rate of spoilage in storage + discarded volume
3	Local Market Demand	Aux	Demand	Total local market demand for the produce that is served by the wholesale market	kg/month	Households * Average per capita consumption * share of WS market * (Baseline Price/Average Product Sale Price)
4	Average Product Sale Price	Aux	Demand	Average price of the produce at a wholesale market level.	$/kg	MIN(Max Price, Baseline Price * Average Product Quality * (1+Import Volume/Yield) * Rate of Customer Purchases/Rate of Supply to WS Market)
5	Average Product Quality	Aux	Cold storage	It determines the percentage of product that is of acceptable quality for sales	kg/kg	Time held in stock *(Ripening rate) / Whole Sale Stock
6	Average time held in Stock	Aux	Cold storage	Represents the average time produce is held in stock	months	Whole Sale Stock / Rate of Customer Purchases
7	Cold Storage Capacity	Stock	Cold storage	Total built capacity of cold storage at the WS market	kg	Initial value + rate of cold storage expansion
8	Investment in infrastructure	Flow	Financial	Amount of cash invested into infrastructure. A subset of total revenue	$ / month	MAX(0,MIN(Wholesale Market Cash-Taxes-Operating expenses,(Cap Investment signal*Cost of capacity expansion + Cold Investment Signal *Cost of cold storage expansion *Whole Sale Market Stock)*Willingness to invest))
9	Operating Expenses	Flow	Financial	Represent the monthly expenditure on holding and replenishing inventory. Salaries of individuals and other overhead expenses would be captured within the inventory holding costs	kg/month	MIN(Wholesale Market Cash*Inventory holding cost+Cost of goods)

Along with the variable name and description, Table 3.1 shows [1] variable type – whether it is a stock, flow, or auxiliary (supporting variables), [2] the part of the model the variable forms, [3] the units, and [4] the formulation used to calculate the variable. Next, we discuss some of the key interactions that exist between these variables. These interactions provide a better understanding of the dynamics at play and help us develop a more realistic model to inform appropriate strategies for wholesale markets.

1. **Wholesale Market Stock**: This stock variable represents the total volume of available produce at a given point in time at the wholesale market, measured in kilograms. The stock is determined as a difference between the incoming supply and the outgoing produce, including sales, waste, and salvage.

$$Wholesale\ Market\ Stock = Initial\ Value + Rate\ of\ Supply$$
$$-Rate\ of\ Customer\ Purchase - Rate\ of\ Food\ Loss - Rate\ of\ food\ recovered$$

2. **Rate of Food Loss**: This flow variable refers to the volume of monthly produce lost, measured in kilograms per month. It comprises the rate of spoilage during transportation, rate of spoilage in storage, and volume discarded due to surplus.

$$Rate\ of\ food\ loss = Rate\ of\ spoilage\ in\ transit\ +\ Rate\ of\ spoilage\ in\ storage\ +$$
$$Discarded\ volume$$

3. **Local Market Demand**: This auxiliary variable represents the total regional market demand for the produce served by the wholesale market, measured in kilograms per month. It is calculated using the number of households, average per capita consumption, the wholesale market share, and the ratio of baseline price to the average product sale price.

$$Local\ Market\ Demand =\ Households\ *\ Avg\ per\ capita\ consumption\ *$$
$$share\ of\ WS\ market\ *\ (Baseline\ Price/Avg\ Product\ Sale\ Price).$$

4. **Average Product Sale Price**: This auxiliary variable indicates the average price of the produce at the wholesale market level, measured in dollars per kilogram. The product sale price in the model is considered elastic, changing depending on the product quality, market equilibrium between demand and supply, and proportion of volume imported.

$$Avg\ Product\ Sale\ Price = MIN(Max\ Price, Baseline\ Price * Avg\ Product\ Quality * (1 + Import\ Volume/Yield) * Rate\ of\ Customer\ Sales/Rate\ of\ Supply\ to\ WS\ Market)$$

5. **Average Product Quality**: This auxiliary variable determines the percentage of the product of optimal quality for sales. Given a defined product shelf life, we model the quality degradation linearly through the product's lifetime. It is calculated using the time held in stock and the ripening rate, where the ripening rate is the inverse of the product shelf life.

$$Avg\ Prod\ Quality = 1 - Avg\ Time\ held\ in\ stock * Ripening\ rate$$

6. **Average time held in Stock**: This auxiliary variable represents the average time produce is kept in stock at the wholesale market – essentially a measure of inventory duration. It is calculated by dividing the stock on hand by the demand.

$$Avg\ Time\ held\ in\ stock = Wholesale\ Stock\ /\ Rate\ of\ Customer\ Purchases$$

7. **Cold Storage Capacity**: This stock variable indicates the total built capacity of cold storage at the wholesale market, measured in kilograms. It starts with an initial value and grows every time an investment is made to expand cold stores.

$$Cold\ storage\ capacity = Initial\ value + rate\ of\ cold\ storage\ expansion$$

8. **Investment in infrastructure**: This flow variable represents the amount of cash invested in infrastructure, a subset of total revenue. Within our model, inventory replenishment and direct operating costs plus taxes take precedence. Once those expenditures are cleared from the revenue, the remaining amount is available for investment. The amount invested then depends on whether a consistent shortage of capacity or cold storage was observed and the willingness of the market to invest.

$$Investment\ in\ infrastructure = MAX(0, MIN(Wholesale\ Market\ Cash - Taxes - Operating\ expenses, (Cap\ Investment\ signal * Cost\ of\ capacity\ expansion + Cold\ Investment\ Signal\ * Cost\ of\ cold\ storage\ expansion * Whole\ Sale\ Market\ Stock) * Willingness\ to\ invest))$$

9. **Operating Expenses**: This flow variable denotes the monthly expenditure on holding and replenishing inventory. This includes salaries and other overhead expenses captured within the inventory holding costs. It is measured in dollars per month and calculated using the wholesale market cash, inventory holding cost, and cost of goods. The formula for this variable is:

$$Operating\ expenses = MIN(Wholesale\ Market\ Cash, Inventory\ holding\ cost + Cost\ of\ goods)$$

3.4 Developing a Stock and Flow Model

After defining the model variables and their formulations, we develop a stock and flow diagram. This builds on the existing causal loop diagram and allows the simulation of our key learnings from literature and the primary data collection. This is also where we feed the data to our model: [1] as exogenous inputs to specific variables and [2] to validate the reliability of our simulation results. This necessitates a more comprehensive understanding and formulation of the variables and their interrelationships. Stock and Flow models facilitate the representation of dynamic systems by quantifying the accumulation, inflow, and outflow of critical elements within the system.

Simulating a Stock and Flow model allowed us to observe the system's behavior over time, considering the changing relationships between variables. This deeper understanding can help inform decision-making by providing insights into the potential outcomes of different scenarios, enabling stakeholders to identify optimal strategies and interventions. We designed several scenarios to analyze our model and extract valuable insights. These scenarios allowed us to simulate various activities under diverse conditions and examine the resulting system behavior. Our analysis explored the effects of unexpected supply and demand fluctuations, differing levels of investment in infrastructure, and distinct product shelf life durations. Section 4 will further investigate these results and identify the key insights.

4 Results and Discussion

This section of our study presents an in-depth analysis of the Causal Loop Diagram (CLD), identifying key System Archetypes and developing a System Dynamics model for simulation purposes. We begin with highlighting two key system archetypes that emerge from the analysis of our CLD. We then review stock and flow diagrams capturing the system's main elements and overarching interactions. Next, we bring the data into a Stock and Flow model and provide the necessary inputs to drive the model. This allows the simulation of our quantitative analysis, leading to a deeper understanding of the system's behavior over time. We use the System Dynamics model to simulate various scenarios and explore the potential impact of different interventions and strategies on food loss and supply chain dynamics in wholesale markets.

4.1 Observed System Archetypes

This section focuses on the system archetypes that emerge from the developed CLD. For the full CLD, refer to Appendix B. System Archetypes are a set of typical dynamics that occur in various settings, consisting of different balancing and reinforcing loops combinations. These archetypes have helped us better understand the wholesale market system and behaviors and are a foundation for building more precise narratives around the wholesale market business.

We have explored two critical System Archetypes relevant to our project: "Success to the Successful" and "Drifting Goals." By delving into these archetypes, we gain deeper insights into the behaviors and interactions within the wholesale market system. This analysis will enable stakeholders to identify potential areas of intervention and inform decision-making by offering a clearer perspective on the dynamics at play.

4.1.1 Drifting Goals

In the "Drifting Goals" archetype applied to our project, we consider the interplay among variables such as yield, excess supply, market capacity, food loss, food recovery, and partnerships with food banks. When there is a gap between the objective of minimizing food loss and the reality of existing supply chain dynamics, two courses of action can be taken: corrective action or lowering the goal.

Figure 4.5

Drifting goals archetype

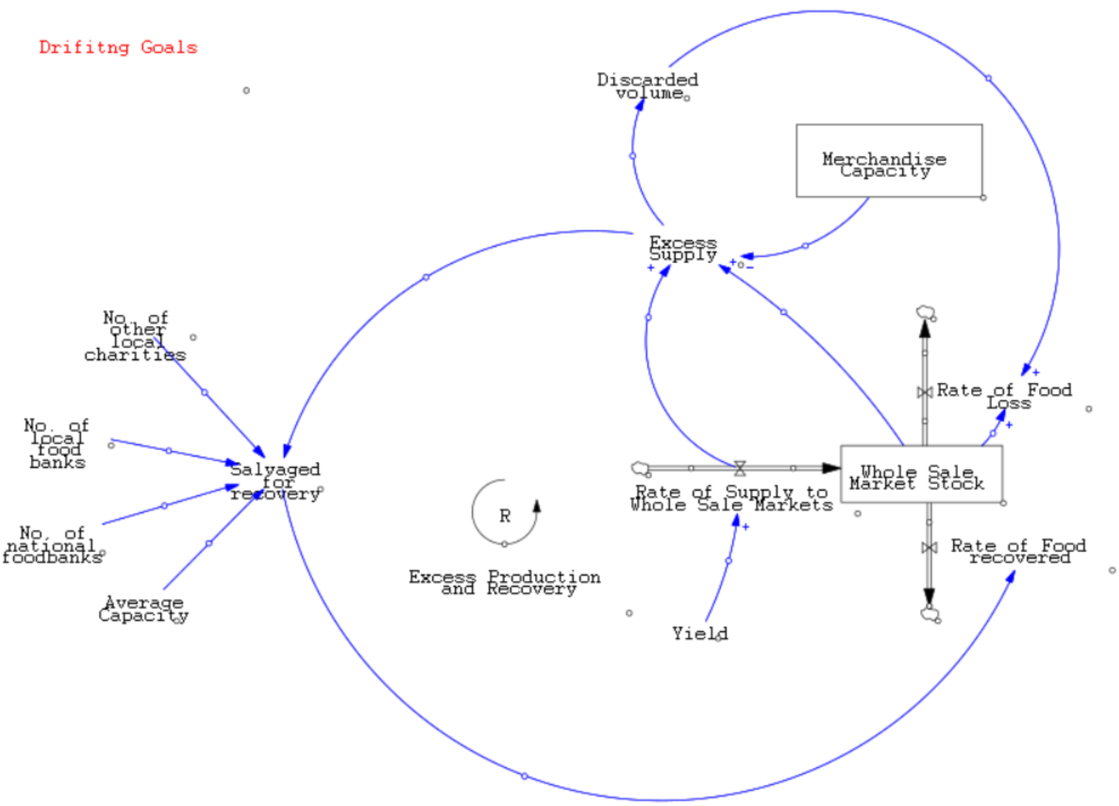


Figure 4.5 illustrates the dynamics involved here. Corrective action would require addressing the root causes of food loss by investing in infrastructure development and fostering partnerships with food banks to mitigate loss from excess. While this approach may take time and require more resources, it can lead to lasting, positive change.

On the other hand, lowering the goal means accepting a certain level of food loss as inevitable and focusing only on short-term gains, such as maximizing profit or meeting immediate demand. This approach might close the gap between the objective and reality in the short term but may limit long-term progress in reducing food waste and fostering more sustainable supply chains.

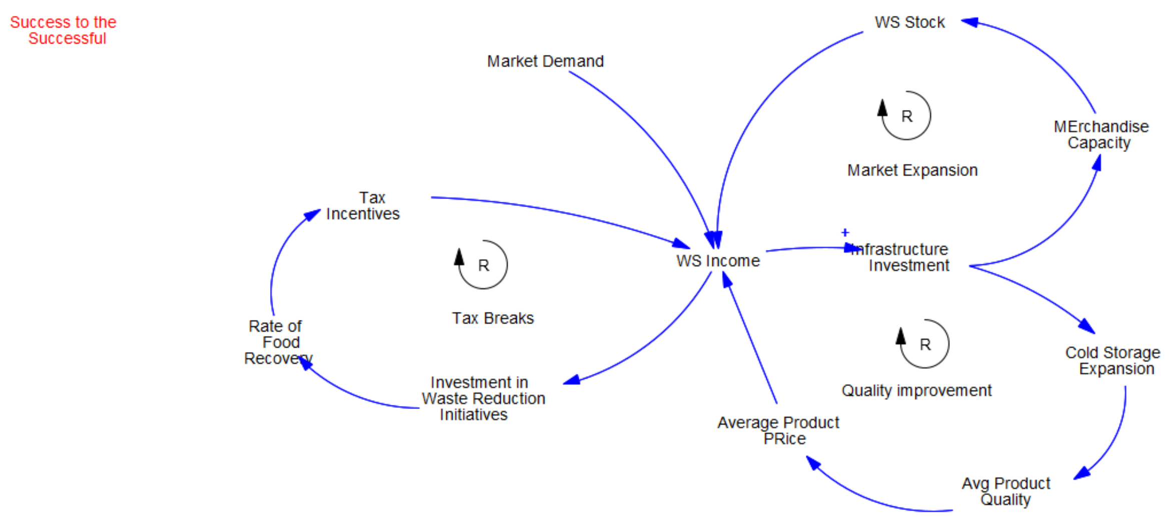
As our model presents, it is crucial to understand how poor practices and structures could have become the norm, such as discarding food instead of diverting it to food banks and discarding products due to poor quality or oversupply issues. To address these practices, we need to identify the problem behaviors at the core and develop schemes to overcome them. Often a recommended approach to managing drifting goals is introducing a sudden disruption to the system. In this case, a complete ban on discarding food, regardless of quality, could be one such intervention.

4.1.2 Success to the successful

The "Success to the Successful" archetype applied to our project explores the interaction between variables such as operational costs, investment in infrastructure, cold storage expansion, merchandise capacity expansion, and tax incentives from food loss reduction. The primary dynamics at play involve the decision-making process in wholesale markets concerning investments in infrastructure expansion projects and operational expenses.

Figure 4.6

Success to the successful archetype



Initially, expanding merchandise capacity and then simply buying more inventory may seem like the most attractive option for wholesale markets, as it enables them to sell more products and generate higher profits. As they begin to experience success, they may continue to invest more resources into further merchandise capacity expansion, reinforcing a feedback loop that amplifies their success. However, this focus on immediate gains might come at the expense of investing in other initiatives, such as cold storage expansion or waste reduction projects, leading to increased food waste even as sales grow.

On the other hand, investing in cold storage can offer long-term benefits by maintaining better produce quality and potentially commanding higher prices. The challenge for wholesale markets is to balance investments in inventory build-up and infrastructure development, such as cold storage and waste reduction initiatives.

In the "Success to the Successful" archetype, wholesale markets must navigate the resource competition between procuring more produce for immediate returns and investing in long-term infrastructure improvements. By maintaining a balanced approach, they can optimize growth potential while minimizing food waste and enhancing overall efficiency.

Recognizing the importance of balancing short-term gains with long-term sustainability is vital to mitigating the negative consequences of the "Success to the Successful" dynamic.

4.2 Model Breakdown

In this section, we delve into the different components of our wholesale market system dynamics model, examining how they interact and contribute to the overall system behavior. We begin by discussing the core structure of the model, then proceed to explore the dynamics of local market demand, infrastructure development, and market cashflows. Reviewing the different components of the model separately allows us to better comprehend the dynamics at play and understand how each subsection functions before we connect it all together.

4.2.1 Inventory and In-Out flows

Figure 4.1

Stock and Flow model for the wholesale market product flows

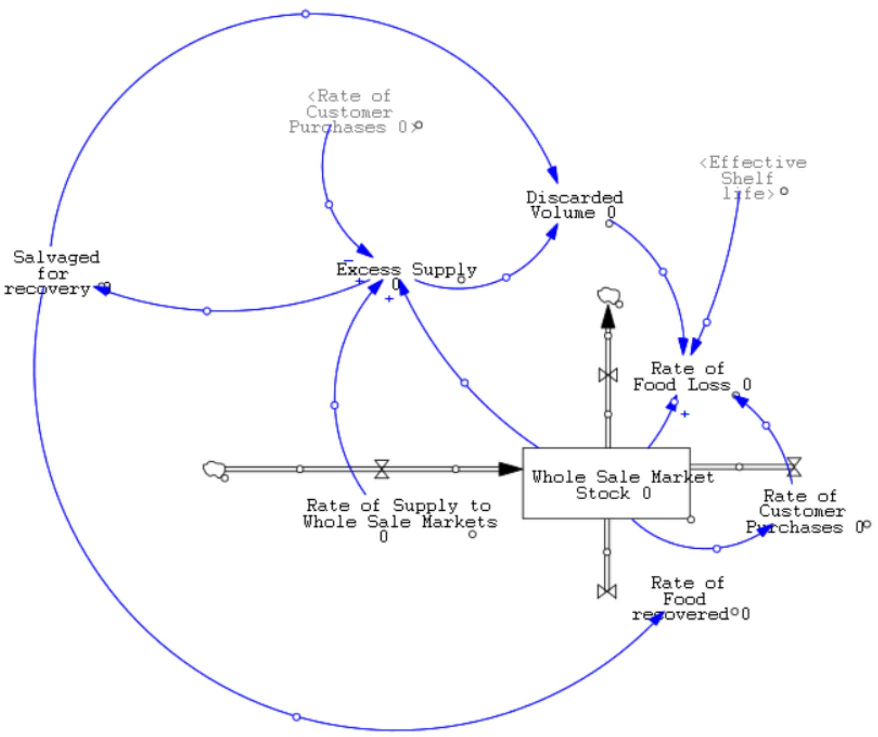


Figure 4.1 showcases the core of our wholesale market system dynamics model. Building on the formulations we developed in Section 3, we set up the wholesale market inventory as a stock and the supply as an inflow with three potential outflows depending on various conditions: [1] Customer purchases – when regular sales are made, [2] Food loss – when there is a surplus or when the product exceeds shelf life, and [3] Food recovery – food that is either processed or reallocated to a food bank or charity.

4.2.2 Local Market Demand

Figure 4.2

Stock and flow diagram for market demand

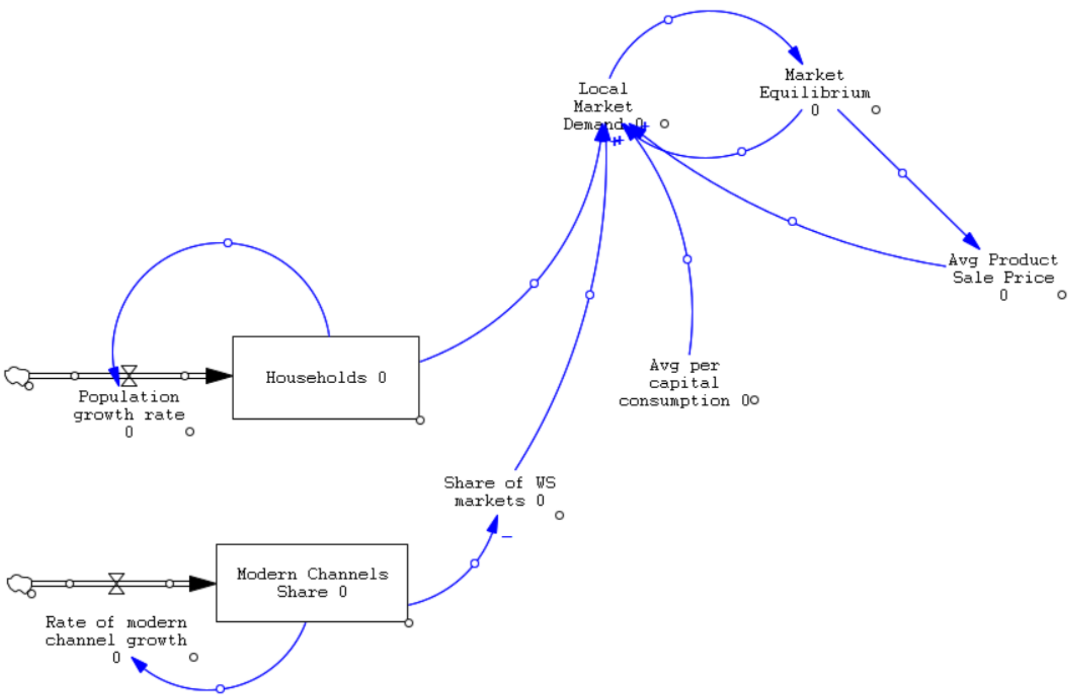


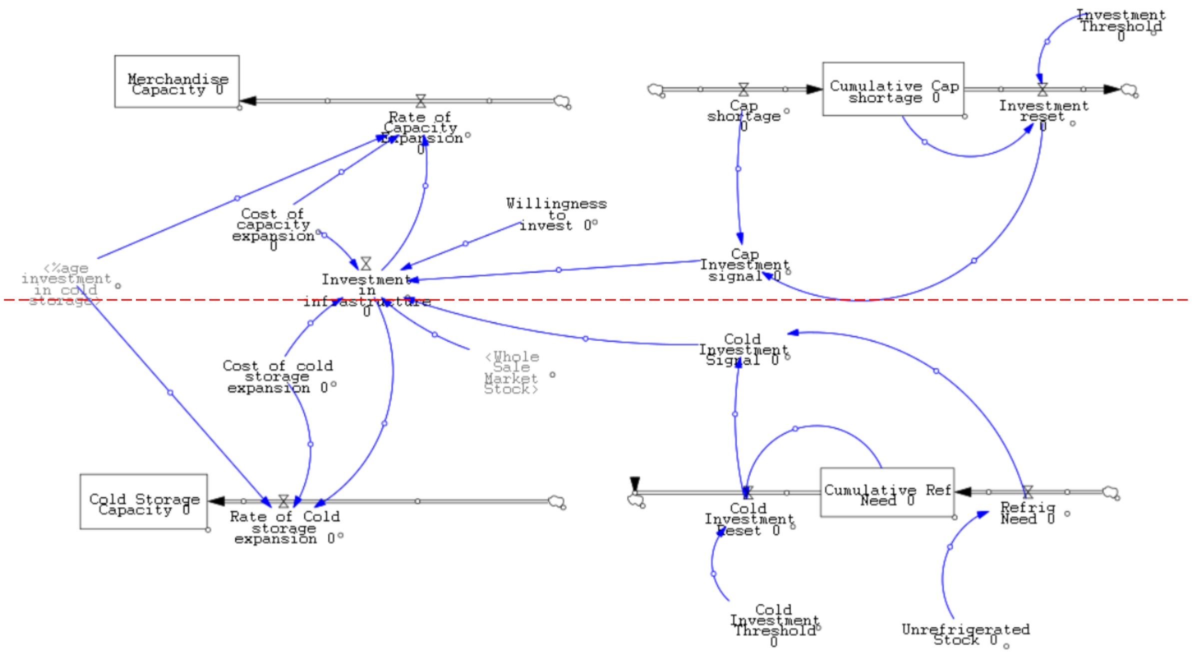
Figure 4.2 illustrates the demand creation component of our model. Demand is influenced by certain exogenous factors: average per capita consumption, the share of wholesale markets, and total households. Additionally, it depends on two endogenous factors: market equilibrium and average product sale price. This setup allows the demand to respond dynamically to changes in other model parts. For example, if the supply remains constant, an increase in demand would gradually shift the market equilibrium, raising the product sale

price. This price rise would subsequently lower the demand, thus creating a balancing loop. The local market demand signal feeds into the "rate of customer purchase" seen in Section 4.1.1.

4.2.3 Infrastructure Development

Figure 4.3

Stock and flow diagram for infrastructure development

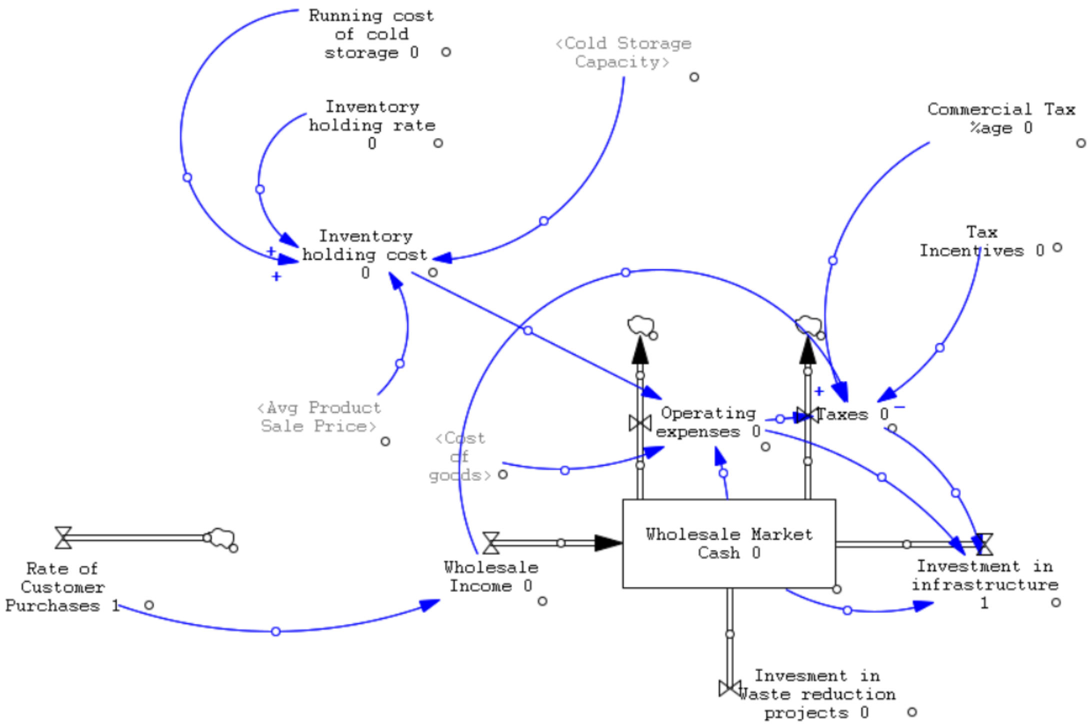


The infrastructure development component of the model can be divided into two correlated parts, as shown in Figure 4.3. The upper half represents the enhancement of merchandise capacity, while the lower half represents the expansion of cold storage. The stocks and flows on the right are designed to capture infrastructure development needs, driven by declining produce quality due to poor refrigeration or inadequate capacity to accommodate all supply. This aspect of the model enables us to represent the necessity for infrastructure development. Delays are incorporated into the model to reflect real-world scenarios more accurately. Once the infrastructure need surpasses a threshold, it feeds into the expansion section of the model, where investment drives the growth of cold storage and capacity expansions. However, this expansion is contingent upon the availability of sufficient cash for investment. We explore this further in Section 4.1.4.

4.2.4 Market Cashflows

Figure 4.4

Stock and flow model of market cashflows



In this section, we model the income and expenditures of the wholesale market, enabling us to simulate the investments a market can make in infrastructure development and waste management project development. Market income is driven purely by the rate of sales. This income is then allocated to various areas: [1] operational expenses, which include inventory holding and overhead costs, the cost of purchasing goods, and transportation; [2] taxes paid on profit; [3] investment in infrastructure when a need has been identified, and cash is available; [4] and investment in waste reduction. For our simulation, waste reduction investments will not be endogenized for scope.

This approach allows us to understand better the financial aspects of wholesale market operations and how available funds can be allocated to support infrastructure development and waste management projects. By simulating these aspects, we can identify optimal resource allocation strategies and prioritize investments contributing to improved efficiency and reduced waste.

4.3 Simulation Modeling

We can simulate the wholesale market supply chain dynamics by establishing our stock and flow model. The model consists of two types of variables: endogenous and exogenous. Endogenous variables are those formulated based on other variables in the model and are calculated as the simulation runs. We defined equations for these variables, as discussed in Section 3.2. On the other hand, exogenous variables are treated as input values for the model.

For our purposes, we divide exogenous variables into two categories, represented by the green boxes in Figure 4.7. Gathered data is fed into the model as "fixed values" (Refer to table 4.1) while other exogenous variables are used to drive the system. These driving variables enable us to model various scenarios and investigate how the system might behave under different circumstances. Section 4.4 will explore the scenarios we simulated and the variables utilized in each case. Please refer to Appendix A for a comprehensive list of variables and their formulations.

Figure 4.7

Concept diagram for simulation process flow

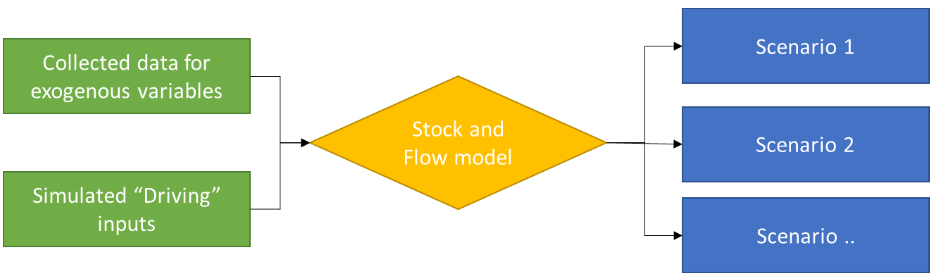


Table 4.1

List of Values for "non-driving" Exogenous Variables

Variables	Values
Average per capita consumption	4.8 kg/month
Baseline Price	3.4 $/kg
Commercial Tax Percentage	0.1
Cost of capacity expansion	0.5$/kg
Cost of cold storage expansion	1.25$/kg
Electricity Availability Factor	1
Farm gate price	1.7$/kg
Households	5.5mn (opening)
Import price factor	1.5
Inventory holding rate	0.1
Investment Threshold	1mn $
Population growth rate	0.51% per anum
Rate of modern channel growth	0.05
Running cost of cold storage	0.006$/kg

4.4 System Dynamics Modelling – Simulating Scenarios

In this section, we utilize the System Dynamics model to simulate various scenarios, exploring the potential impact of different interventions and strategies on food loss and supply chain dynamics in wholesale markets. Our primary research through interviews brought to light potential challenges. The scenarios we have developed here aim to explore these challenges better:

- Role of proactive infrastructure investment in reducing food waste
- Impact of demand spikes from panic buying
- Potential role of alliances and partnerships with foodbanks in waste mitigation
- Navigating periods of exceptionally high harvest

The following are the seven scenarios we simulated with the control variables. In most cases, we use the supply to drive the model.

1. Baseline – This scenario serves as a reference point, testing the functioning of our model under essential circumstances and representing the current state of the food loss and supply chain dynamics in wholesale markets without any interventions.
2. Growing yield without infrastructure investment – This scenario will illustrate how the model behaves when there is a steady increase in supply, simulating the effects of agricultural advancements or favorable weather conditions on food loss and supply chain dynamics.
3. Growing yield with infrastructure investment- This scenario illustrates the same factors as above – except it introduces a high willingness to invest in infrastructure development.
4. Loss mitigation by establishing alliances with food banks and charities – This scenario explores the impact of forming partnerships with local food banks and charities to redistribute unsold food, thus reducing food waste and improving food security in the community. In this case, we keep the budget for such alliances are unconstrained – any excess food gets donated.
5. Panic Buying– This scenario explores the supply chain's reaction to a sudden surge in demand and how it affects food loss and the overall efficiency of the supply chain. Here we simulate the impact of a sudden doubling (2X) in demand
6. Perishability impact on waste and infrastructure investment – Models the different approaches wholesale markets could take for low-shelf products like tomatoes vs. long-shelf products like potatoes. Tomatoes are modeled with a shelf life of 2 days (cold storage) or 10 days (room temperature). Potatoes are modeled with a shelf life of 60 days.

7. Sudden supply shock – models the impact of potentially exceptional harvest or high import order. This will allow us to investigate whether it will produce a slow response in infrastructure investment.

Values for each scenario are captured in Table 4.2.

Table 4.2

Control variable specifications for simulated scenarios

Sr. no	Scenario	Control Variables and values					
		Yield	**Local Demand**	**Willingness to invest**	**Product Shelf life**	**Cold Product Shelflife**	**Active Partnerships**
1	Baseline	Flat 0.8mn kg/day	Endogenous	0	2	10	0
2	Growing yield without infrastructure investment	Seasonal and Growing (0.8 to 1.8mn)	Endogenous	0	2	10	0
3	Growing yield with infrastructure investment	Seasonal and Growing (0.8 to 1.8mn)	Endogenous	1	2	10	0
4	Loss mitigation by establishing alliances with food banks and charities	Seasonal and Growing (0.8 to 1.8mn)	Endogenous	1	2	10	1
5	Panic Buying	Flat 0.8mn kg/day	Flat with a single spike, then dip +-1mn	1	2	10	1
6	Perishability changes infrastructure investment priorities	Seasonal and Growing (0.8 to 1.8mn)	Endogenous	1	60	60	1
7	Sudden Supply shock	Flat (0.8mn) with 3 (2.2mn) sudden spikes	Endogenous	1	2	10	1

4.4.1 Baseline

In this scenario, we establish a baseline by simulating the current state of food loss and supply chain dynamics in wholesale markets without any interventions. This provides a solid foundation to build upon and analyze the effects of different interventions in subsequent scenarios.

As shown in table 4.2 characteristics of the Baseline scenario are:

- Yield is set to constant, representing a stable supply without significant fluctuations.
- Willingness to invest is set to 0, indicating no additional investment in supply chain infrastructure.
- Demand growth is negligible, maintaining consistent demand for the products.
- No partnerships are established with local food banks or charities for redistributing unsold food.

Figure 4.8

Baseline Simulation Output

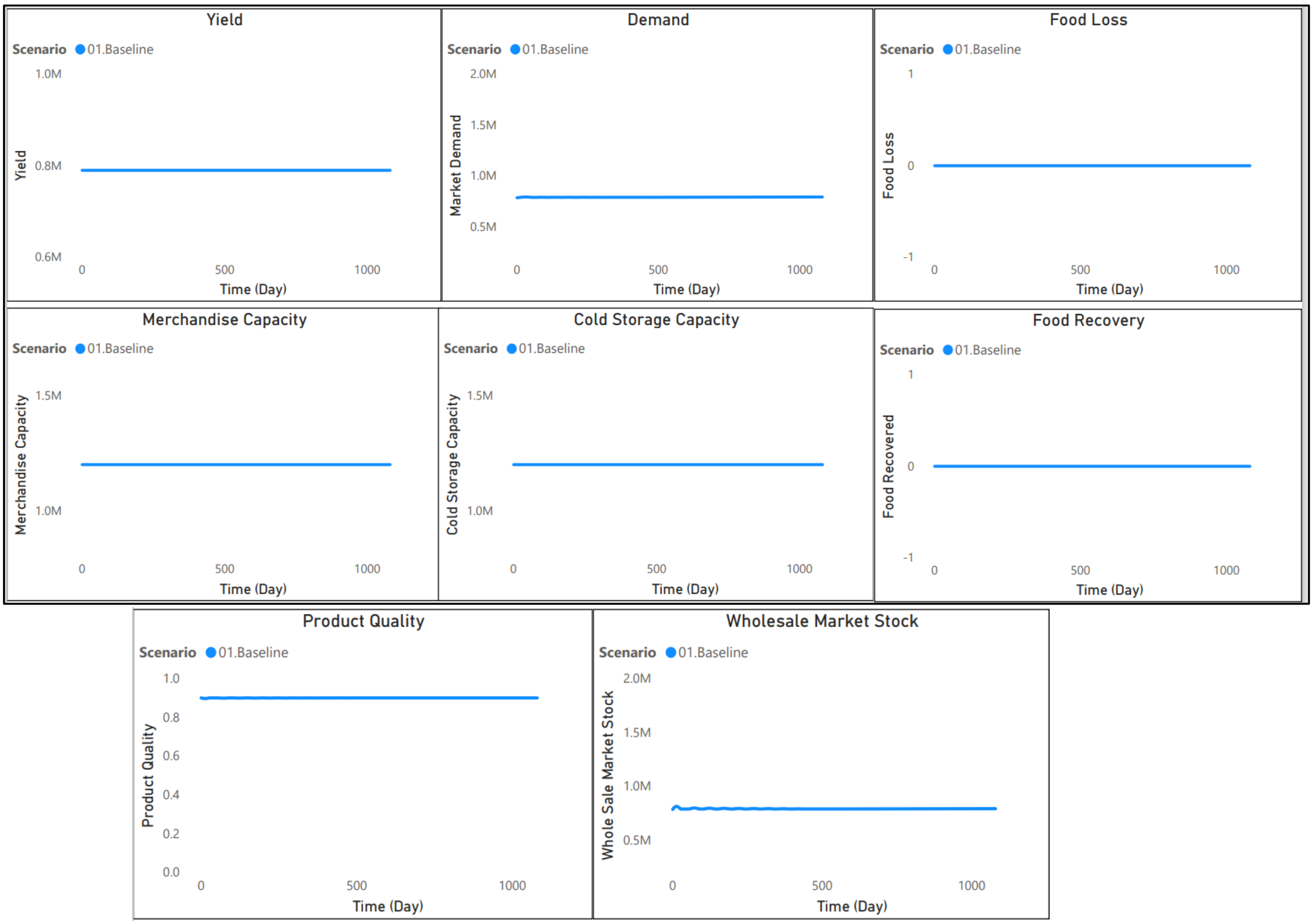


Figure 4.8 displays the simulation outcomes of the Baseline scenario, which is designed to demonstrate the steady-state functioning of the model. We introduce a stable yield in this scenario, as seen in the top-left graph. As expected, there are no changes in demand, capacity,

quality, or stock levels. Also, no loss or recovery measures are required, as the supply matches the demand perfectly.

4.4.2 *Growing yield without infrastructure investment*

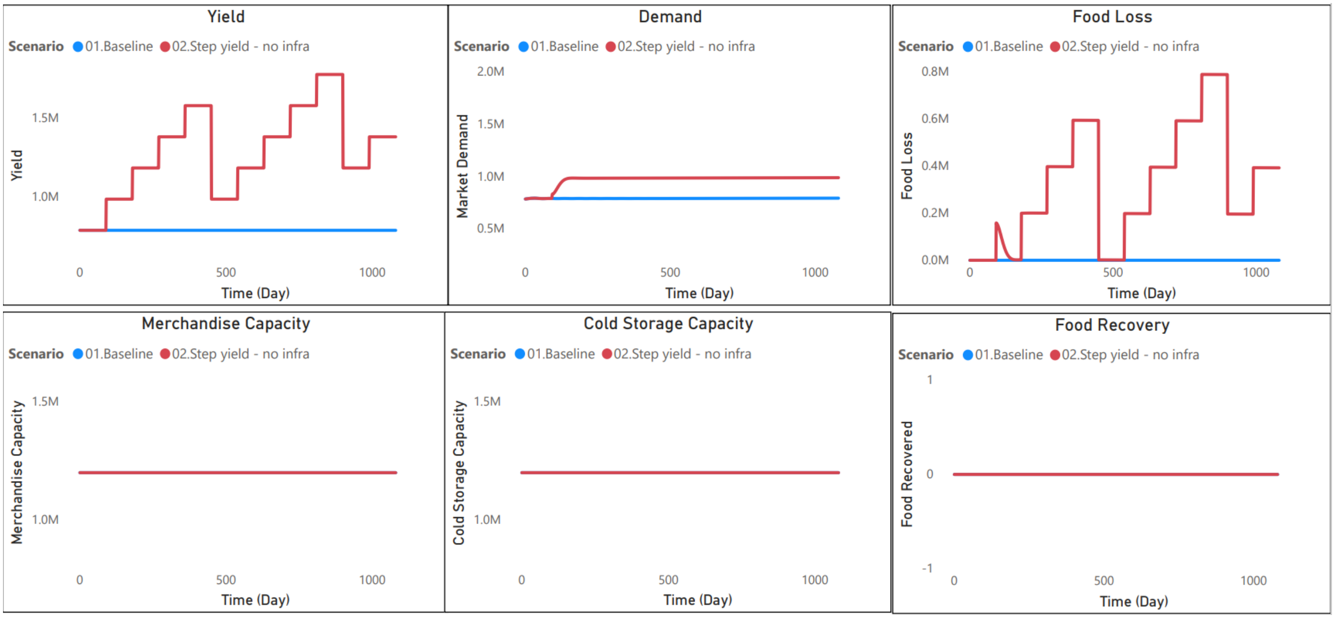
In this scenario, we explore the effects of a growing supply with no infrastructure development on wholesale markets' food loss and supply chain dynamics. We aim to understand how losses develop in the system as it cannot adapt.

Characteristics of this scenario:

- No technology development is used initially, and there is minimal capacity in the wholesale markets = 0.8 mn
- A seasonal supply is observed, rising from 0.8mn to 1.8 mn, then down again
- Capacity and cold storage are not developed since willingness to invest is set to 0
- No partnerships are established with local food banks or charities for redistributing unsold food in this scenario. We will look at this inverse approach in section 4.4.4

Figure 4.9

Growing Yield without Infrastructure VS Baseline Simulation



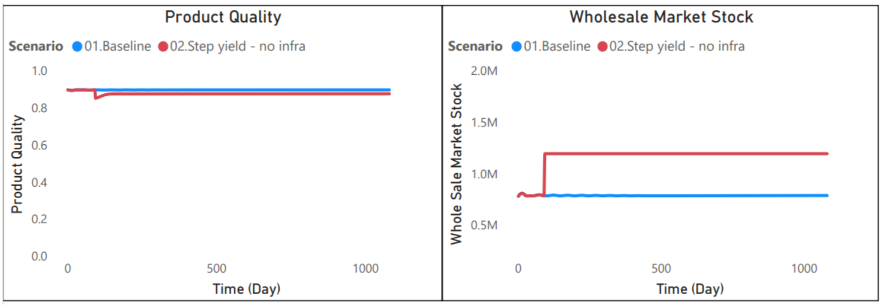


Figure 4.9 depicts the effects of an increasing supply without infrastructure development in wholesale markets, contrasting it with the initial baseline scenario to highlight the differences. The yield now follows a rising seasonal pattern, which also mildly elevates demand due to a market equilibrium shift toward a higher supply end, subsequently reducing prices. However, with a fixed willingness to invest at 0, no merchandise or cold storage capacity growth is observed. The system's failure to adapt results in declining average product quality, stemming from the absence of cold storage development, static stock levels as capacity cannot expand, and significant food waste (evident in the 'Food Loss' chart), as all surplus supply is discarded. This scenario underscores the importance of infrastructure development in wholesale markets for effective supply management, product quality maintenance, and minimization of food waste.

Key insight: A reluctance to invest timely in infrastructure can lead to stagnation of market operations and increase losses

4.4.3 Growing yield with infrastructure investment

In this scenario, we explore the effects of a growing supply and gradual infrastructure development on wholesale markets' food loss and supply chain dynamics. The infrastructure development is endogenized and dependent on capacity shortages or increases in unrefrigerated stock. We aim to understand how the system adapts to increasing supply and improves capacity and cold storage over time.

Characteristics of the 'Growing Yield with high willingness to invest' scenario:

- No technology development is used initially, and there is minimal capacity in the wholesale markets = 0.8mn
- A seasonal supply is observed, rising from 0.8mn to 1.8 mn, then down again
- Capacity and cold storage are developed based on internal signals
- No partnerships are established with local food banks or charities for redistributing unsold food. This we explore in Section 4.4.4

Figure 4.10

Growing Yield without Infrastructure development VS High Infrastructure development

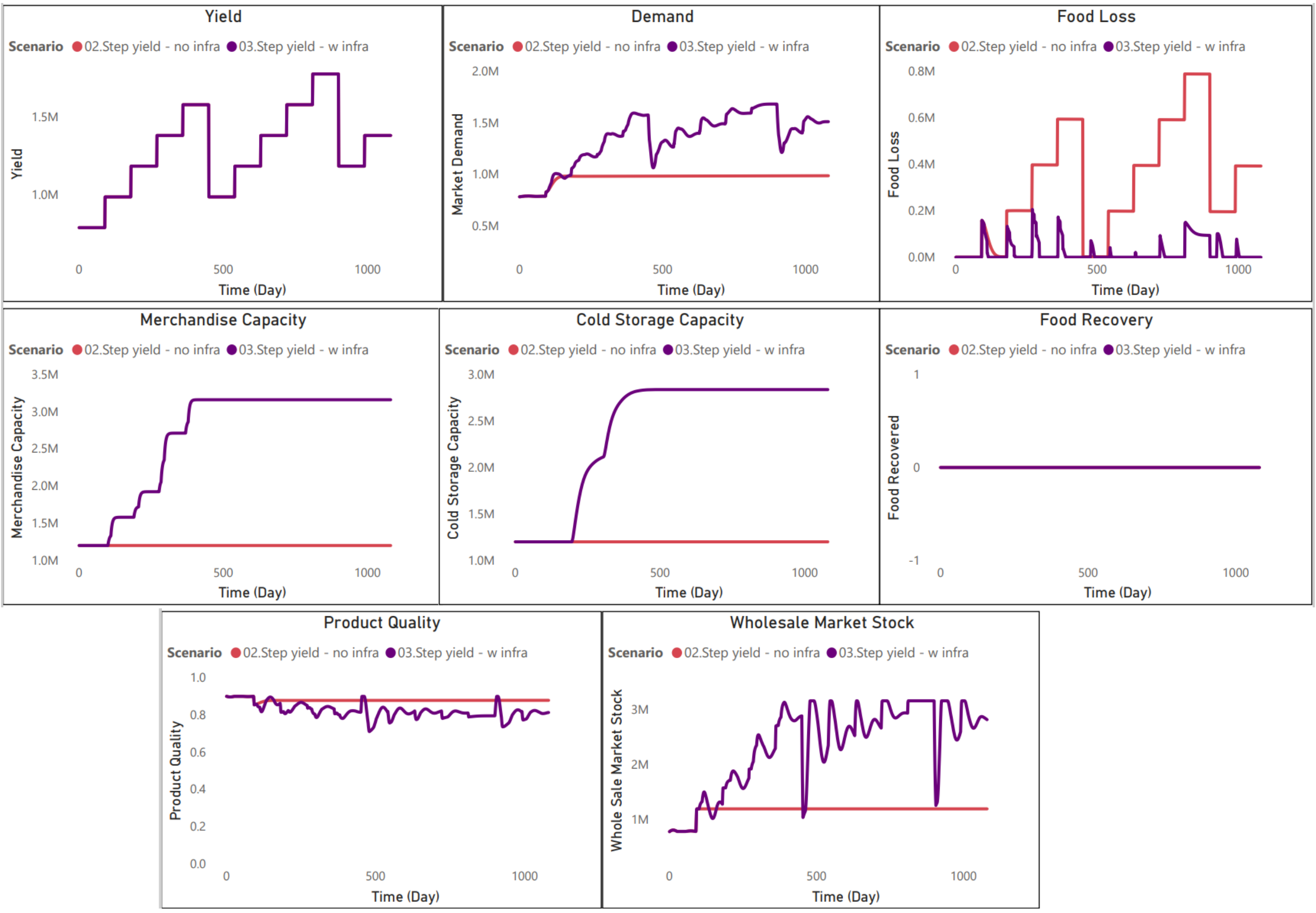


Figure 4.10 depicts the effects of an increasing supply with a high willingness for infrastructure development in wholesale markets, contrasting it with the no infrastructure development scenario to highlight the differences. This scenario underscores the complexities

of adapting to increasing supply and infrastructure improvements in wholesale markets. In Fig 4.10, we can observe how ‘Merchandise Capacity’ and ‘Cold Storage Capacity’ are rapidly built in the initial phase, responding to the expanding market and growing yield. Once sufficient capacity is built up, changes in yield no longer create a response in market growth. We also observe fluctuations in ‘Wholesale Market Stock’ in response to the changing yield, which follows a similar pattern but offers some stabilizing effect. Product quality oscillates due to the interaction between enhanced cold storage and wholesale market stock; variations in stock levels affect the time spent in inventory, which in turn alters the quality. This fluctuation is evident in the 'Product Quality' chart, where we also observe brief improvements in quality during periods of low stock (which means high turnover). The ‘Food Loss’ chart shows that a much smaller quantity is lost as the market can use much more of the available supply.

Key insight: Strategically developing infrastructure and capacity in response to market growth and potentially beforehand can result in improved sales and reduced losses

4.4.4 Establishments of partnerships with food banks

In this scenario, we aim to understand the changes in the system dynamics when we introduce an arbitrarily large number of partnerships. This helps highlight how recovery modes can take over from potential loss.

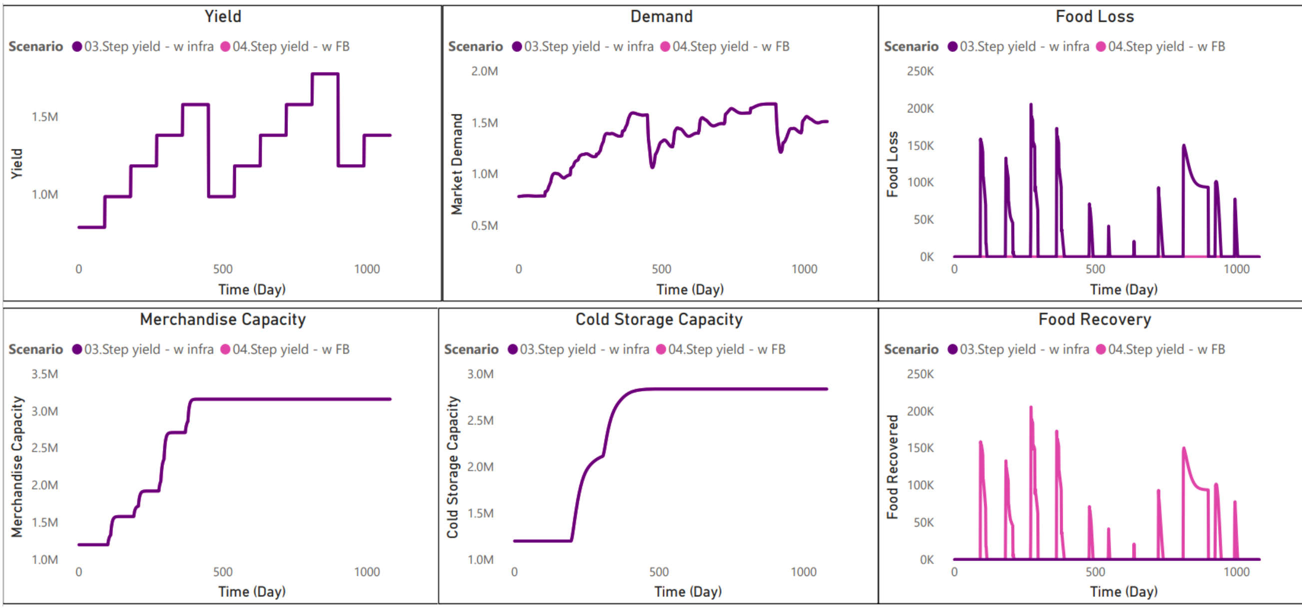
Characteristics of the Partnerships with Foodbanks scenario:

- No technology development is used initially, and there is minimal capacity in the wholesale markets = 0.8mn
- A seasonal supply is observed, rising from 0.8mn to 1.8 mn, then down again
- Capacity and cold storage are developed based on internal signals

- Partnerships are established with local food banks or charities for redistributing unsold food. We set an extreme number (100) for this scenario that allows for the recovery of all excess food – to contrast with prior scenarios

Figure 4.11

Establishments of Partners VS Growing Yield with Infrastructure Development (No Partners)



This scenario, for the most part, does not significantly differ from the previous one. Figure 4.11 highlight the key difference between the 'Food Loss' and 'Food Recovery' charts. Since we use many partnerships for the scenario, we see all food is recovered. Real-life cases may fall somewhere between the two extremes.

Key insight: Alliances with foodbanks and charities can easily convert potentially lost food to recovered food, especially during periods of erratic supply

4.4.5 Panic Buying

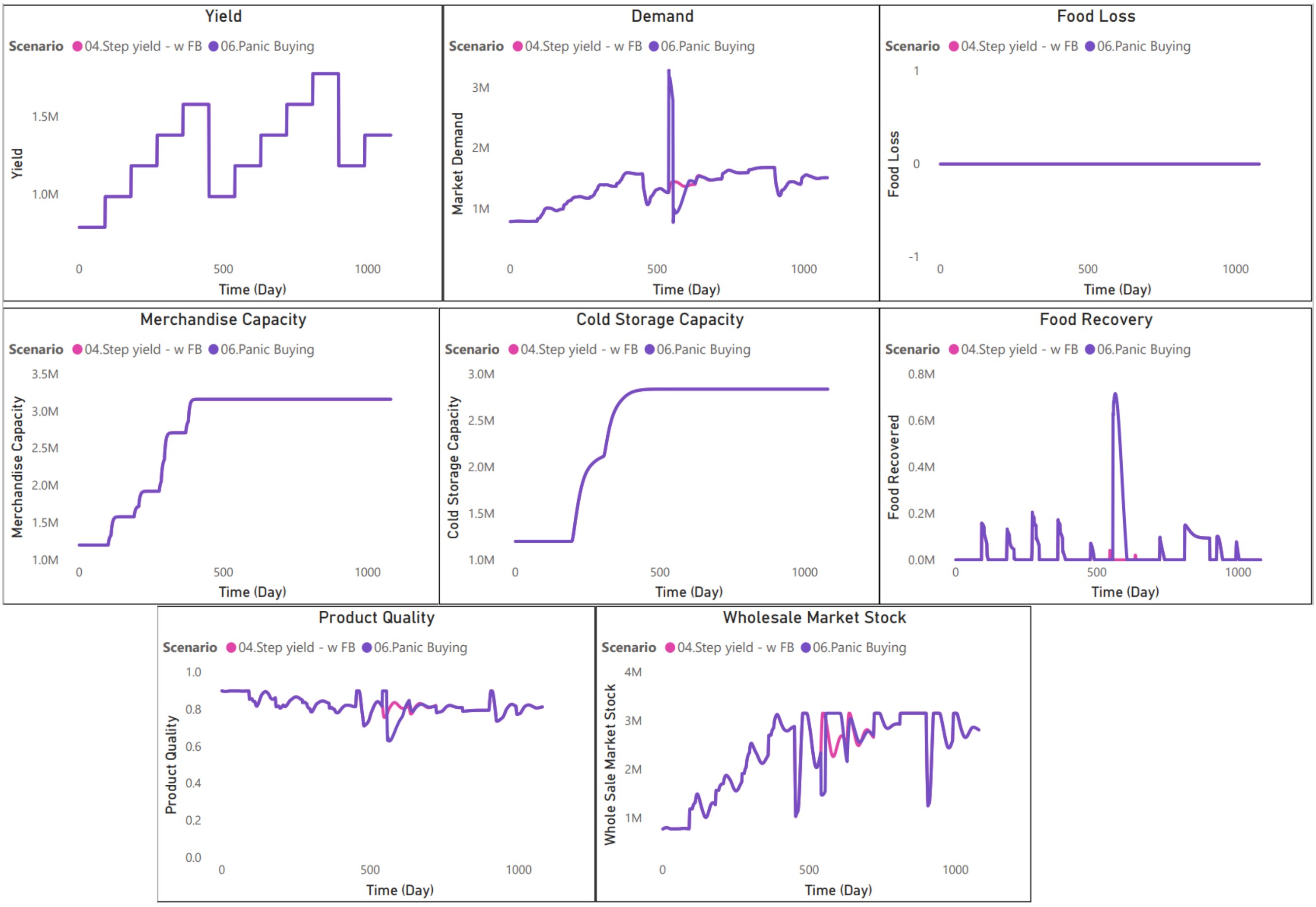
In this scenario, we aim to understand the dynamics of the system in response to a sudden increase in sales followed by a dip. This would help highlight how the market potentially behaves in response to sudden changes in demand

Characteristics of the Panic Buying Scenario:

- No technology development at the start and minimal capacity in the wholesale markets = 0.8mn
- A seasonal supply is observed, rising from 0.8mn to 1.8 mn, then down again
- Capacity and cold storage are developed based on internal signals.
- Demand is a function of product quality, price, and the wholesale market's share of the overall market, but an artificial peak is introduced at t=500 days. This is after the capacity has stabilized, and we can better observe the specific impact of the demand spike.
- Partnerships are well established with food banks (same as section 4.4.4).

Figure 4.12

Panic Buying VS Growing Yield with Infrastructure



This scenario emphasizes the role of demand in shaping wholesale market dynamics. Demand is influenced by factors such as product quality, price, and the wholesale market's share of the overall market. When a sudden peak is introduced at t=500 days to simulate panic buying, we see a ripple effect in stock levels and a subsequent dip, which may result in potential losses. This scenario underlines the importance of understanding and managing demand fluctuations to minimize negative impacts on the wholesale market supply chain.

Key insight: Sudden changes in demand can largely be absorbed if sufficient infrastructure supports it. Short-term fluctuations would be observed however

4.4.6 Perishability

In this scenario, we change our simulated product from ‘tomato’ to ‘potato’ to understand the impact of varying shelf lives on the system's dynamics. It should help highlight how different storage modes are prioritized and how food loss changes.

Characteristics of the Perishability Scenario:

- No technology development is used initially, and there is minimal capacity in the wholesale markets =0.8mn
- A seasonal supply is observed.
- Capacity and cold storage are developed based on internal signals.
- Partnerships are well established with food banks (same as section 4.4.4).
- Shelf life is modified to 60 days for both cold and standard storage (Refer to table 4.2)

Figure 4.13

Perishability VS Growing Yield with Infrastructure

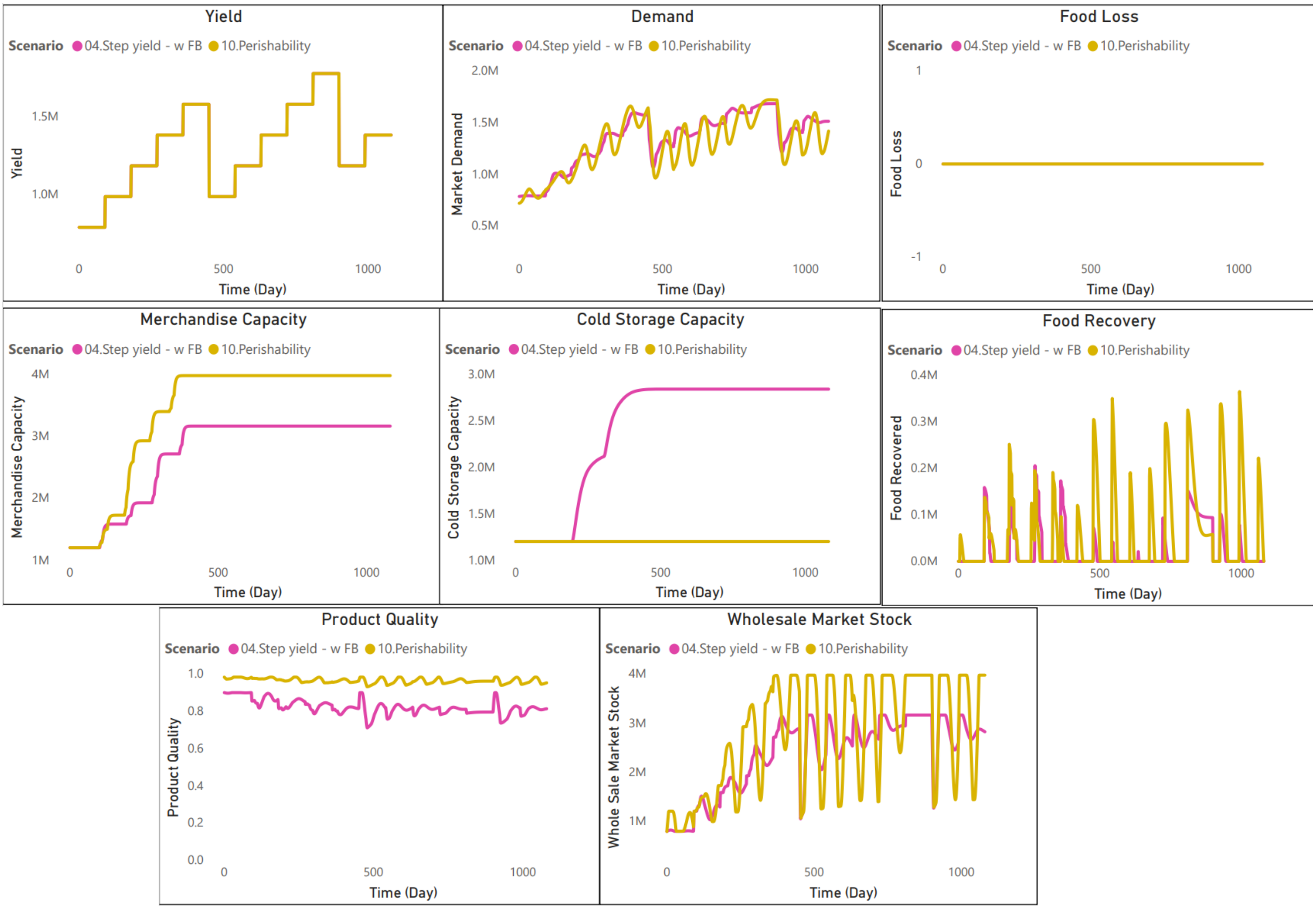


Figure 4.13 illustrates the effect of increased shelf life on market dynamics. One notable change is the investment shift from 'Cold Storage Capacity' to 'Merchandise Capacity,' as cold storage becomes less necessary. This expands the merchandise capacity, allowing for a larger stock to be held, as seen in the 'Wholesale Market Stock' chart. As anticipated, product quality is higher than that of more perishable items.

4.4.7 Supply shock

In this scenario, we replace our seasonal yield with a generally flat yield, the same as the baseline (0.8mn) but introduce two peaks, one upwards and one downwards. This will help illustrate the system's behavior in response to sudden changes in yield vs. gradual changes.

Characteristics of the Partnerships with Foodbanks scenario:

- No technology development is used initially, and there is minimal capacity in the wholesale markets = 0.8mn
- The supply profile is flat at 0.8mn except for two rapid increase and decline instances.
- Capacity and cold storage are developed based on internal signals.
- Partnerships are well established with food banks (same as section 4.4.4).

Figure 4.14

Supply Shocks VS Growing Yield with Infrastructure

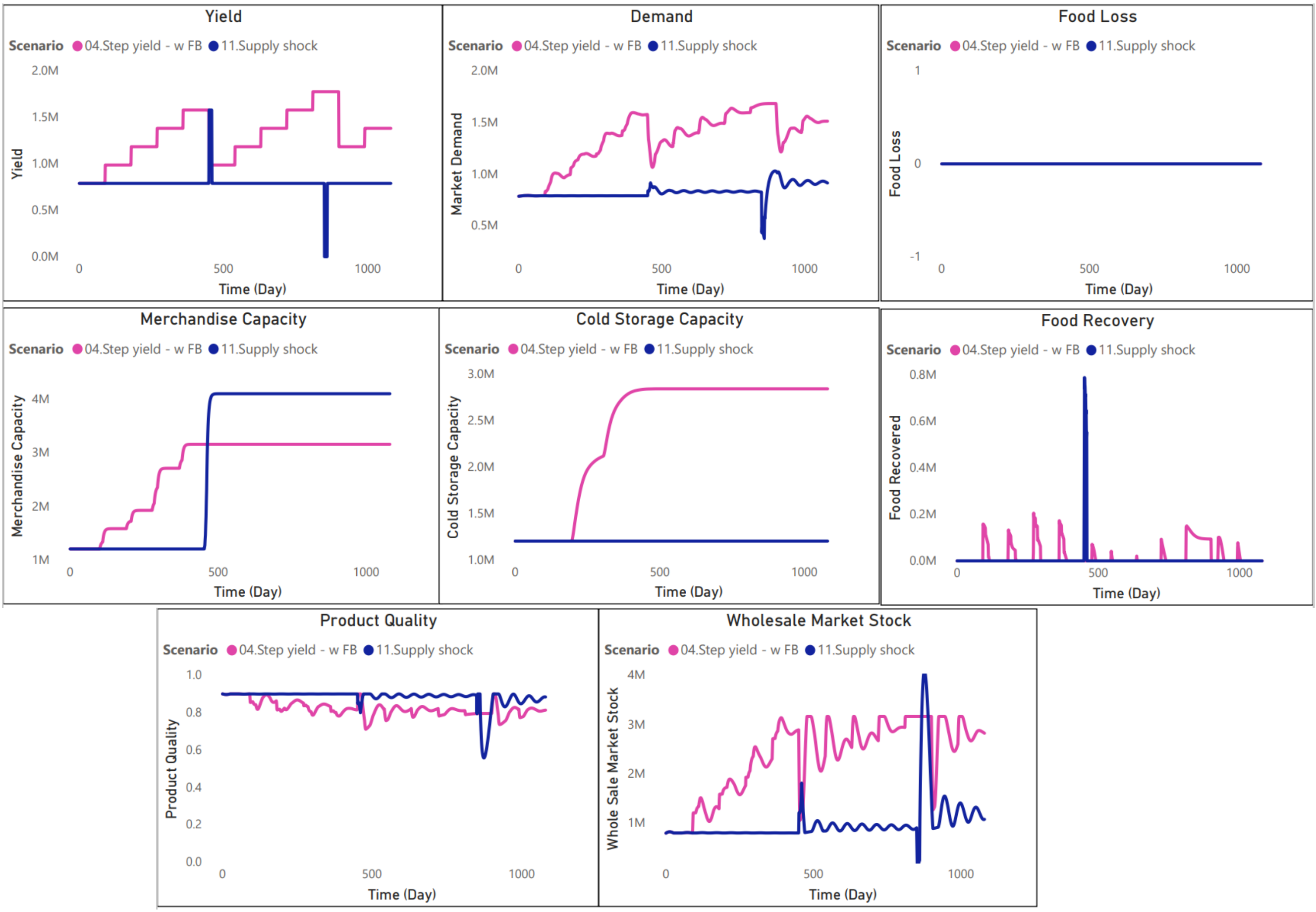


Figure 4.14 shows a comparison between standard seasonal demand vs. sudden supply shocks. The sudden supply bursts create a disproportionate increase in ‘Merchandise Capacity’ investment even though the average supply may be significantly lower. Naturally, since the market is not prepared for the sudden uplift in supply, we see a peak in ‘Food Recovery.’ We also notice that demand lags behind supply due to the market equilibrium, which causes prices

to fluctuate based on supply and demand levels. This results in a substantial increase in stock when demand declines after supply has returned to normal levels. In such cases, markets may attempt to forecast and plan for these disruptive supply events to mitigate their impact.

Key insight: Markets can overreact to sudden shocks. Strategic investments and developments can potentially offer greater stability

4.5 Recommendations

Table 4.3 summarizes the crucial insights derived from analyzing each scenario presented in Section 4.4. Based on these findings, we formulate specific recommendations for wholesale markets to adopt to mitigate the losses observed in each scenario.

In addition to the insights and recommendations gained from the analysis of our scenarios, we observed some additional problematic behaviors highlighted by the emergent system archetypes, 'drifting goals' and 'success to the successful.' These patterns reveal how a declining emphasis on waste can lead to increasing losses and competition for cash between buying more stock to sell and investing in cold storage infrastructure, ultimately focusing on short-term gains while neglecting long-term strategy.

Table 4.3

Summary of Insights and Recommendations

Scenarios	Dimensions Explored					Key Insights and Recommendations
	Strategy	Operations	Infrastructure	Partnerships	Macro-trends	
Baseline						
Growing yield without infrastructure investment		x				A lack of investment in infrastructure would cause the market to stagnate both in terms of revenue growth and loss prevention
Growing yield with infrastructure investment	x	x	x			Prioritize proactive infrastructure investment to improve storage capacity and cold chain development, ensuring the supply chain's adaptability to increasing yields and maintaining product quality.
Partnerships and Alliances				x		Develop strategic alliances and partnerships with food banks, charities, and other key stakeholders to redistribute unsold food, reduce waste, and improve food security in the community.
Panic Buying		x	x		x	Implement contingency plans to manage sudden demand spikes (e.g., panic buying) and minimize the negative impacts on food loss and supply chain efficiency.
Perishability		x				Monitor and address perishability and its impact on waste and infrastructure investment by adopting tailored approaches for products with different shelf lives. For low-shelf products, consider approaches to extending shelf life through processing, like making soups or pulp.
Sudden Supply shock		x	x			Give strategic thought to investments both in procurement and infrastructure. A highly reactive approach can unnecessarily destabilize the system.

Based on this analysis, we recommend the following:

1. Ensure consistent tracking of waste. Even simple measures like weighing waste before discarding it can significantly improve the long run.
2. Strategically invest in long-term growth, as it can reduce waste and generate increasing profits over time.

5 Conclusion

This project has explored the dynamics of food supply chains in wholesale markets and their role in food waste and food insecurity. By partnering with the World Union of Wholesale Markets (WUWM) and focusing on the case of Mercabarna and the Barcelona region, we have employed system dynamics (SD) models to provide valuable insights into the factors affecting food waste and possible intervention strategies. We solved the research questions: *1) What significant supply chain factors may help address overarching challenges like food waste in wholesale markets and their food ecosystems? And 2) What intervention schemes should enhance affordability and access to nutritious goods through wholesale markets?*

We identified the most prominent supply chain factors influencing food loss through a comprehensive literature review and semi-structured interviews with key stakeholders across wholesale markets. These factors were classified under five overarching dimensions: Strategy, Operations, Infrastructure, Partnerships, and Macro-trends. Using a system dynamics approach, this classification enabled us to develop a causal loop diagram illustrating the interactions between various factors. Two system archetypes emerged from this analysis, underscoring the importance of monitoring and prioritizing waste management and proactively and strategically investing in infrastructure rather than solely focusing on short-term gains.

By incorporating data from external sources and the Mercabarna market, we built a stock and flow model to simulate various scenarios, illustrating the dynamics and identifying potential intervention schemes. The critical insights included: [1] proactive infrastructure investment to ensure adequate capacity and cold storage capability, [2] strategic alliances and partnerships with food banks and charities to repurpose potentially wasted food, [3] and [4] introducing processing capabilities to extend food shelf life through transformation into pulp or soups.

In conclusion, our findings and recommendations offer valuable guidance for stakeholders to implement effective strategies and interventions to reduce food waste and enhance operational efficiency in wholesale markets.

Given our approach to creating a generic model for the wholesale markets and the case study in one European, there are opportunities to apply the model in other regions, validate, and extend the conclusions. However, including more diverse areas of the analysis could broaden the generalizability of our findings and aid in developing universally applicable strategies.

While our research emphasized identifying high-level, overarching challenges, a more in-depth analysis of individual markets could be conducted in future work. This approach would translate strategies and interventions from simulation to real-world implementation. If available, constructing more comprehensive models using finer-grained data could yield even more robust findings and help inform better decision-making processes.

Another opportunity is to dive deep into analyzing food waste categories and understand how sorting, cooking, and other alternative ways to prevent food waste may help wholesale markets to divert flows into different industries and create circular supply chains. Finally, the behavioral component behind decision-making processes must be broken down into logistics activities, such as ordering, storing, selling, and replenishing. We identified that a significant source of variability is how sellers individually change their logistics activities and how this impacts their individual performance and wholesale market targets.

References

About. (n.d.). WUWM. Retrieved October 14, 2022, from https://wuwm.org/about/

Allen, S., & de Brauw, A. (2018). Nutrition sensitive value chains: Theory, progress, and open questions. Global Food Security, 16, 22–28. https://doi.org/10.1016/j.gfs.2017.07.002

Background paper on the economics of food loss and waste. (n.d.). 83.

Bechoff, A., Shee, A., Mvumi, B. M., Ngwenyama, P., Debelo, H., Ferruzzi, M. G., Nyanga, L. K., Mayanja, S., & Tomlins, K. I. (2022). Estimation of postharvest nutritional losses along food value chains: A case study of three key food security commodities in sub-Saharan Africa. Food Security, 14(3), 571–590. https://doi.org/10.1007/s12571-021-01238-9

Bilska, B., Wrzosek, M., Kołożyn-Krajewska, D., & Krajewski, K. (2015). Food Losses and Food Waste in the Context of Sustainable Development of the Food Sector. *Chinese Business Review*, *14*. https://doi.org/10.17265/1537-1506/2015.09.005

Canali, M., Amani, P., Aramyan, L., Gheoldus, M., Moates, G., Östergren, K., Silvennoinen, K., Waldron, K., & Vittuari, M. (2017). Food Waste Drivers in Europe, from Identification to Possible Interventions. Sustainability, 9(1), Article 1. https://doi.org/10.3390/su9010037

Chauhan, C., Dhir, A., Akram, M. U., & Salo, J. (2021). Food loss and waste in food supply chains. A systematic literature review and framework development approach. Journal of Cleaner Production, 295. https://doi.org/10.1016/j.jclepro.2021.126438

Craig, P., Dieppe, P., Macintyre, S., Michie, S., Nazareth, I., & Petticrew, M. (2013). Developing and evaluating complex interventions: The new Medical Research Council guidance. International Journal of Nursing Studies, 50(5), 587–592. https://doi.org/10.1016/j.ijnurstu.2012.09.010

Delgado, L., Schuster, M., & Torero, M. (2021). Quantity and quality food losses across the value Chain: A Comparative analysis. Food Policy, 98. https://doi.org/10.1016/j.foodpol.2020.101958

Densley, B., & Sánchez-Monjo, E. (1999). Wholesale market management: A manual. Food and Agriculture Organization of the United Nations.

Diaz-Ruiz, R., Costa-Font, M., López-i-Gelats, F., & Gil, J. M. (2018). A Sum of Incidentals or a Structural Problem? The True Nature of Food Waste in the Metropolitan Region of Barcelona. Sustainability, 10(10), Article 10. https://doi.org/10.3390/su10103730

Fact sheets—Malnutrition. (n.d.). Retrieved October 14, 2022, from https://www.who.int/news-room/fact-sheets/detail/malnutrition

GFN. (2021, September 27). How food banks mitigate effects of climate change. The Global FoodBanking Network. https://www.foodb anking.org/innovate-to-alleviate-reducing-food-loss-and-waste/

Gudbrandsdottir, I. Y., Olafsdottir, G., Oddsson, G. V., Stefansson, H., & Bogason, S. G. (2021). Operationalization of Interorganizational Fairness in Food Systems: From a Social Construct to Quantitative Indicators. Agriculture, 11(1), Article 1. https://doi.org/10.3390/agriculture11010036

Kaipia, R., Dukovska-Popovska, I., & Loikkanen, L. (2013). Creating sustainable fresh food supply chains through waste reduction. International Journal of Physical Distribution & Logistics Management, 43(3), 262–276. https://doi.org/10.1108/IJPDLM-11-2011-0200

Kc, K. B., Haque, I., Legwegoh, A. F., & Fraser, E. D. G. (2016). Strategies to Reduce Food Loss in the Global South. Sustainability, 8(7), Article 7. https://doi.org/10.3390/su8070595

Lai, M., Rangan, A., & Grech, A. (2022). Enablers and barriers of harnessing food waste to address food insecurity: A scoping review. Nutrition Reviews, 80(8), 1836–1855. https://doi.org/10.1093/nutrit/nuac012

Lima, D. M., Marsola, K. B., de Oliveira, A. L. R., & Belik, W. (2022). Strategies for reducing the waste of fruit and vegetable supply chains: The search for sustainable wholesale systems. Horticultura Brasileira, 40(3), 334–341. https://doi.org/10.1590/s0102-0536-20220313

Lum, J. (2021, April 21). Food waste along the supply chain—What we can do. Circular Cities Asia. https://www.circularcities.asia/post/food-waste-along-the-supply-chain-what-we-can-do

Muflikh, Y. N., Smith, C., & Aziz, A. A. (2021). A systematic review of the contribution of system dynamics to value chain analysis in agricultural development. Agricultural Systems, 189, 103044. https://doi.org/10.1016/j.agsy.2020.103044

Muriana, C. (2010). Experimental analysis of shelf life-based inventory management policies for RFID-enabled supply chains.

Muriana, C. (2016). An EOQ model for perishable products with fixed shelf life under stochastic demand conditions. European Journal of Operational Research, 255(2), 388–396. https://doi.org/10.1016/j.ejor.2016.04.036

Muriana, C. (2017). A focus on the state of the art of food waste/losses issue and suggestions for future researches. Waste Management, 68, 557–570. https://doi.org/10.1016/j.wasman.2017.06.047

Ocicka, B., & Razniewska, M. (2018). Food Waste Reduction as a Challenge in Supply Chains Management. Logforum, 14(4), 549–561. https://doi.org/10.17270/J.LOG.2018.303

Ortiz-Gonzalo, D., Ørtenblad, S. B., Larsen, M. N., Suebpongsang, P., & Bruun, T. B. (2021). Food loss and waste and the modernization of vegetable value chains in Thailand. Resources, Conservation, and Recycling, 174. https://doi.org/10.1016/j.resconrec.2021.105714

Parry, A., James, K., & LeRoux, S. (2015). Strategies to achieve economic and environmental gains by reducing food waste. WRAP, London, UK.

Priefer, C., Jörissen, J., & Bräutigam, K.-R. (2016). Food waste prevention in Europe – A cause-driven approach to identify the most relevant leverage points for action. Resources, Conservation and Recycling, 109, 155–165. https://doi.org/10.1016/j.resconrec.2016.03.004

Queenan, K., Cuevas, S., Mabhaudhi, T., Chimonyo, M., Shankar, B., Slotow, R., & Häsler, B. (2022). A food systems approach and qualitative system dynamics model to reveal policy issues within the commercial broiler chicken system in South Africa. PLOS ONE, 17(6), e0270756. https://doi.org/10.1371/journal.pone.0270756

Rieder, E., Larson, L. R., 't Sas-Rolfes, M., & Kopainsky, B. (2021). Using Participatory System Dynamics Modeling to Address Complex Conservation Problems: Tiger Farming as a Case Study. Frontiers in Conservation Science, 2. https://www.frontiersin.org/articles/10.3389/fcosc.2021.696615

Rolker, H., Eisler, M., Cardenas, L., Deeney, M., & Takahashi, T. (2022). Food waste interventions in low-and-middle-income countries: A systematic literature review. Resources Conservation and Recycling, 186, 106534. https://doi.org/10.1016/j.resconrec.2022.106534

What we do. (n.d.). The Global FoodBanking Network. Retrieved October 14, 2022, from https://www.foodbanking.org/what-we-do/

Yilmaz, S., & Yilmaz, I. (2008). Evaluation of the wholesale market system for fresh fruits and vegetables in Turkey: A case study from Antalya Metropolitan Municipality. New Zealand Journal of Crop and Horticultural Science, 36(2), 85–95. https://doi.org/10.1080/01140670809510224

Zhang, R. J., Lee, B., & Chang, H.-H. (2019). What Is Missing in Food Loss and Waste Analyses? A Close Look at Fruit and Vegetable Wholesale Markets. Sustainability, 11(24), 7146. https://doi.org/10.3390/su11247146

ReFED Releases New Food Waste Estimates and Calls for Increased Action by Food System. (n.d.). Retrieved May 9, 2023, from https://refed.org/articles/refed-releases-new-food-waste-estimates-and-calls-for-increased-action-by-food-system/

Zhong, T., Si, Z., Crush, J., Scott, S., & Huang, X. (2019). Achieving urban food security through a hybrid public-private food provisioning system: The case of Nanjing, China. *Food Security*, *11*(5), 1071–1086. https://doi.org/10.1007/s12571-019-00961-8

Subramanian, K., Bavinck, M., Scholtens, J., Hapke, H. M., & Jyotishi, A. (2022). How Seafood Wholesale Markets Matter for Urban Food Security: Evidence from Chennai, India. *European Journal of Development Research*, 1–23. https://doi.org/10.1057/s41287-022-00519-z

De Santis, A., Giovannelli, T., Lucidi, S., Messedaglia, M., & Roma, M. (2023). A simulation-based optimization approach for the calibration of a discrete event simulation model of an emergency department. *Annals of Operations Research*, *320*(2), 727–756. https://doi.org/10.1007/s10479-021-04382-9

Meadows, D. H. (2008). *Thinking in Systems: A Primer*. Chelsea Green Publishing.

Kim, D. H. (1994). *Systems archetypes*. Pegasus Communications.

Appendix A – Table of Variables and Formulations

Sr. no.	Variable	Type	Model Section	Description	Units	Formula
1	Wholesale Market Stock	Stock	Core	The total volume of available produce items	kg	Initial value + Rate of Supply - Rate of Food Recovered - Rate of Food Loss - Rate of Customer Purchases
2	Rate of Customer Purchases	Flow	Core	The volume of products bought by customers per month	kg/month	Local Market Demand
3	Rate of Food Loss	Flow	Core	The volume of produce lost per month	kg/month	Rate of spoilage in transit + Rate of spoilage in storage + discarded volume
4	Rate of Food Recovered	Flow	Core	The volume of produce moved to some recovery mode per month	kg/month	Salvaged for recovery + Investment in Waste reduction projects*Waste reduction factor
5	Rate of Supply to WS Market	Flow	Core	The volume of products supplied to the market per month	kg/month	Yield + Import volume
6	Population Growth Rate	Flow	Demand	Population growth rate	People/month	Fixed Exogenous value
7	Households	Stock	Demand	Total households served by the market	People	Initial value + Growth Rate
8	Avg per capita consumption (tomato/potato)	Aux	Demand	Quantity of produce consumed per household	kg/people-month	Fixed Exogenous value
9	Share of WS Markets	Aux	Demand	The proportion of the local population served by the wholesale market	dmnl (%)	1 - share modern channels
10	Share of modern channels	Stock	Demand	The proportion of the local population served by the modern channels. Modern channels refer to big box retailers like Walmart, Target, Carrefour, etc.	dmnl (%)	Initial value + growth of modern channels
11	Growth Rate of modern channels	Flow	Demand	Annual growth rate of modern channels	dmnl (%)	Fixed Exogenous value
12	Local Market Demand	Aux	Demand	Total local market demand for the product that is served by the wholesale market	kg/month	Households * Avg per capita consumption * share of WS market * (Baseline Price/Avg Product Sale Price)
13	Avg Product Sale Price	Aux	Demand	Average price of the produce at a wholesale market level.	$/kg	MIN(Max Price, Baseline Price * Avg Product Quality * (1+Import Volume/Yield) * Rate of Customer Purchases/Rate of Supply to WS Market)

14	Baseline Price	Aux	Demand	Reference price at which product demand can be indexed at 1. and increase in price would create a drop in demand and vice versa.	$/kg	Fixed Exogenous value
15	Max Price	Aux	Demand	Maximum price of products as set by the government or other bodies. It may or may not be active. It would be controlled with the Price control switch	$	Fixed Exogenous value
16	WS Price Control Switch	Aux	Demand	Binary value. It determines whether or not a max sales price cap is applied.	dmnl	Binary fixed exogenous value
17	Market Equilibrium	Aux	Demand	It gives the balance of demand and supply. A higher value denotes demand higher than supply and vice versa	dmnl	Local Market Demand/Wholesale Stock
18	Avg Product Quality	Aux	Cold storage	It determines the %age of product that is of acceptable quality for sales	kg/kg	Time held in stock *(Ripening rate - Rate of ripening reduction) / Whole Sale Stock
19	Average time held in Stock	Aux	Cold storage	It represents the average time produce is contained in stock	months	Whole Sale Stock / Rate of Customer Purchases
20	Ripening Rate	Aux	Cold storage	Rate at which produce ripens and therefore degrades in quality. Here it is assumed that at the start of the product's life in the WS market, it is at the optimal ripening stage - with time, the quality degrades.	kg/month	1/Effective shelf life
21	Effective Shelf life	Aux	Cold storage	It is the average shelf life of the product based on the volume stored in cold and warm storage and the respective shelf life of each	month	Unrefrigerated Stock*"Warm shelf-life"+(1-Unrefrigerated Stock)*"Cold shelf-life"
22	Warm shelf life	Aux	Cold storage	It refers to the shelf life of a product in the absence of refrigeration	month	Fixed Exogenous value
23	Cold shelf life	Aux	Cold storage	It stands for the shelf life of a product in refrigeration	month	Fixed Exogenous value
24	Unrefrigerated Stock	Aux	Cold storage	It is a proportion of the stock kept in warm storage as a proportion of the total stock of the product	dmnl	MAX(0,(Whole Sale Market Stock-Effective Cold Storage Capacity)/Whole Sale Market Stock)

25	Effective cold storage capacity	Aux	Cold storage	Effective cold storage capacity represents the available storage capacity given electricity availability	kg	Cold storage capacity * Electricity Availability Factor
26	Electricity Availablity Factor	Aux	Cold storage	Mainly applicable to developing markets and areas without a fully reliable electricity supply. It captures the proportion of time when the regular electricity supply is off	hours	Fixed Exogenous value
27	Cold Storage Capacity	Stock	Cold storage	Total built capacity of cold storage at the WS market	kg	Initial value + rate of cold storage expansion
28	Rate of cold storage expansion	Flow	Cold storage	It accounts for the rate at which new cold storage facilities may be developed, given the availability of appropriate funding and need	kg/month	Investment in infrastructure * %spend on cold storage/cost of cold storage
29	Cost of cold storage per meter cube	Aux	Cold storage	It represents the cost of building additional cold storage capacity	$ / kg	Fixed Exogenous value
30	Inventory holding cost	Aux	Inventory	Average holding cost of inventory	$ / month	WS market stock *inventory holding factor
31	Inventory holding rate	Aux	Inventory	It gives a proportion of goods cost contributing to inventory holding cost	dmnl	Fixed Exogenous value
32	Running cost of cold storage	Aux	Cold storage	Average running cost of holding inventory in cold storage	$ / month	Fixed Exogenous value
33	Willingness to invest	Aux	Infrastructure investment	It is a proportional constant from 0 -1 defined to control the strategic decisions in the market	dmnl	Years of Experience/10
34	Inflation	Aux	Macroeconomic	The average increase in produce prices over time	% dmnl	Fixed Exogenous value
35	Years of experience	Aux	Macroeconomic	Years of experience running the WS market	Years	Fixed Exogenous value
36	Investment in infrastructure	Flow	Financial	Amount of cash invested into infrastructure. A subset of total revenue	$ / month	Willingness to invest
37	Time for construction	Aux	Inventory	Time delay in carrying out infrastructure development projects	months	Fixed Exogenous value
38	Commercial tax %age	Aux	Financial	It represents the tax percentage on profit		Fixed Exogenous value

39	Taxes	Flow	Macroeconomic	Amount of cash expended in taxes. A subset of total revenue	$ / month	WS income*Commercial tax %age
40	Tax incentives/breaks	Aux	Macroeconomic	Tax reduction policies provided by the government	dmnl(%)	Rate of Food Recovered / Rate of S
41	cubic meters of merchandise capacity	Stock	Inventory	Total built capacity of dry storage of the WS market	kg	Initial value + rate of capacity expansion
42	Rate of capacity expansion	Flow	Inventory	It defines the rate of increase in merchandise capacity	kg/month	Investment in Infrastructure *(1-%spend on cold storage) / Cost of cap expansion
43	wholesale income	Flow	Financial	The total revenue earned by the WS market	$	Rate of Customer Purchases * Avg Product Sale Price
44	Average Lead Time	Aux	Transportation	Average lead times from farms or other sources to the WS market	month	Fixed Exogenous value
45	Loss per day	Aux	Transportation	The expected loss of food for each day of travel	kg/month	Fixed Exogenous value
46	Rate of spoilage in transit	Aux	Transportation	Defines the increased rate of waste during transit	kg/month	Fixed Exogenous value
47	Rate of spoilage in storage and transit	Aux	Transportation	The rate at which produce spoils during transportation	kg/month	Fixed Exogenous value
48	Farm Gate Price	Aux	Farm	The price at which produce is bought from the farmer	$/kg	Fixed Exogenous value
49	Farm Price controls switch	Aux	Farm	Binary variable. Controls whether a minimum price point for farmer gate price is active	$/kg	Fixed Exogenous value
50	Yield	Aux	Farm	Produce harvested per period	kg/month	Baseline yield * %age days favorable weather
51	Import Volume	Aux	Farm	Amount of volume imported	kg/month	Yield - Local Market Demand
52	%age days of favorable weather	Aux	Farm	It gives the proportion of days that the weather was favorable for crop growth	dmnl(%)	Fixed Exogenous value
53	Excess Supply	Aux	Transportation	Represents the mismatch between supply and demand where supply is greater than demand	kg/month	WS Stock + Rate of Supply - Rate of Customer Purchase - Merchandise Capacity
54	Export volume	Aux	Demand	Amount of food supply dedicated to exports	kg/month	Fixed Exogenous value
55	Discarded volume	Aux	Transportation	Amount of excess food supply that is wasted	kg/month	Excess Supply - Salvaged for recovery

56	No. of national foodbanks	Aux	Recovery	No. of national foodbanks	dmnl	Fixed Exogenous value
57	No. of local food banks	Aux	Recovery	No. of local food banks	dmnl	Fixed Exogenous value
58	No. of local charities	Aux	Recovery	No. of local charities	dmnl	Fixed Exogenous value
59	Average FB capacity	Aux	Recovery	Average capacity of	kg	Fixed Exogenous value
60	Salvaged for recovery	Aux	Recovery	The total quantity of food that is moved to recovery modes like foodbanks	kg/month	(No. of national local FB + local charities + national FBs) * Average FB capacity
61	Wholesale Market Cash	Stock	Financial	Represents total cash on hand at any time available for investment	$	initial value + wholesale income

Appendix B – Full Causal Loop Diagram