BREADCRUMB

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DELIVERABLE 3.1: MODELLING FRAMEWORK

BREADCRUMB

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D3.1 - MODELLING FRAMEWORK

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LIST OF ABBREVIATIONS

ACRONYM	EXTENDED TEXT
ABM	Agent Based Model
EU	European Union
F&V	Fruit and Vegetables
FLW	Food Loss and Waste
FW	Food Waste
FL	Food Loss
FMS	Food Marketing Standard
FSC	Food Supply Chain
GHG	Greenhouse Gases
MOA	Motivation Opportunity Ability
MQS	Minimum Quality Standards
WP	Work Package
WTP	Willingness to pay

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1 EXECUTIVE SUMMARY

BREADCRUMB aims to identify the impact of Food Marketing Standards (FMS) on Food Waste (FW) generation across various food supply chains and to enhance the understanding of how FMSs influence behaviours related to FW generation. The project seeks to provide effective interventions for the prevention and reduction of Food Loss and Waste (FLW) through a comprehensive analysis and the development of a behavioural intervention model.

To achieve this, a modelling approach is adopted to better understand the underlying mechanisms through which FMSs influence FW generation and how decisions taken by actors in the supply chain impact one another. Two key models will be developed within the project: an Agent-Based Model (ABM) and an Economic Model.

The ABM will simulate interactions among heterogeneous autonomous agents representing various stakeholders, including producers, processors, retailers. ABMs are particularly suited to exploring complex adaptive systems where localized interactions can result in unpredictable, emergent phenomena. The model aims to capture the complexity of food supply chains by analyzing how FMS-driven decisions by individual actors collectively influence FW generation. On the other hand, the economic model will leverage the theory of vertically differentiated products to explore the influence of public minimum quality standards (MQS) and private marketing standards on FW. It will represent three main actors: farmers, intermediaries, and consumers. The model will specifically illustrate how FMSs shape market dynamics by differentiating products into high and low-quality categories.

Together, these models will provide a robust framework to understand and predict the effects of FMSs on FW and inform strategies to optimize food supply chains and reduce waste.

This report represents the first deliverable (D3.1) of work package 3 (WP1) and outlines the conceptual framework for the modelling approach adopted in BREADCRUMB to simulate the impact of FMSs on the generation of FW in different food supply chains. The conceptual framework developed in this report will be the theoretical backbone for the development, in Task 3.2, Task 3.3, and Task 3.4 of BREADCRUMB, of two models: an agent-based model (ABM) and a macro-economic model.

The document starts with an introduction on the overall project objectives and structure and highlights the framework we propose for understanding and exploring the impact of FMSs on the generation of FLW. In the following sections (2 to 6), complex social systems, the role of FMSs, and models' constructs are explained. The document ends with a conclusion and steps to follow to ensure timely attainment of the project's objectives.

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2 INTRODUCTION

The BREADCRUMB project aims to provide an empirical, evidence-based understanding of the purpose and nature of food marketing standards and their impact on FW generation and, based on this evidence, propose interventions that strike a balance between reducing FW and the other objectives pursued by these standards. Furthermore, the project aims at improving market access for suboptimal foods by designing tailor food businesses to select appropriate marketing channels and by fostering change in consumers' acceptance of suboptimal foods. All of this information will be structured into operational and policy guidance on how to prevent/reduce FW related to marketing standards.

Within the context of BRADCRUMB, the modelling activities conducted within WP3 are a crucial tool for enhancing the understanding of both explicit and implicit dynamics underpinning the relationship between Food Marketing Standards and the generation of Food Loss and Waste along the food supply chain.

Conceptual modelling, then, is a fundamental part of the modelling process, as a well-design conceptual model ensures that the objectives, requirements and outputs of the modelling process are understood and shared. It refers to the process of abstracting a model from a real system, simplifying and adapting it to investigate the issue of interest, with a non-software specific description of the simulation model as an output (Robinson, 2008). As presented by Robinson (2008), the actual model – meaning the model coding – is one of the four main phases of the modelling process, that also comprise conceptual modelling, experimentation and implementation. Figure 1 shows the iterative nature of this process. In this deliverable, the focus is on the conceptual modelling (signalled in orange in the figure), while the model coding, experimentation, and implementation will be addressed further on.

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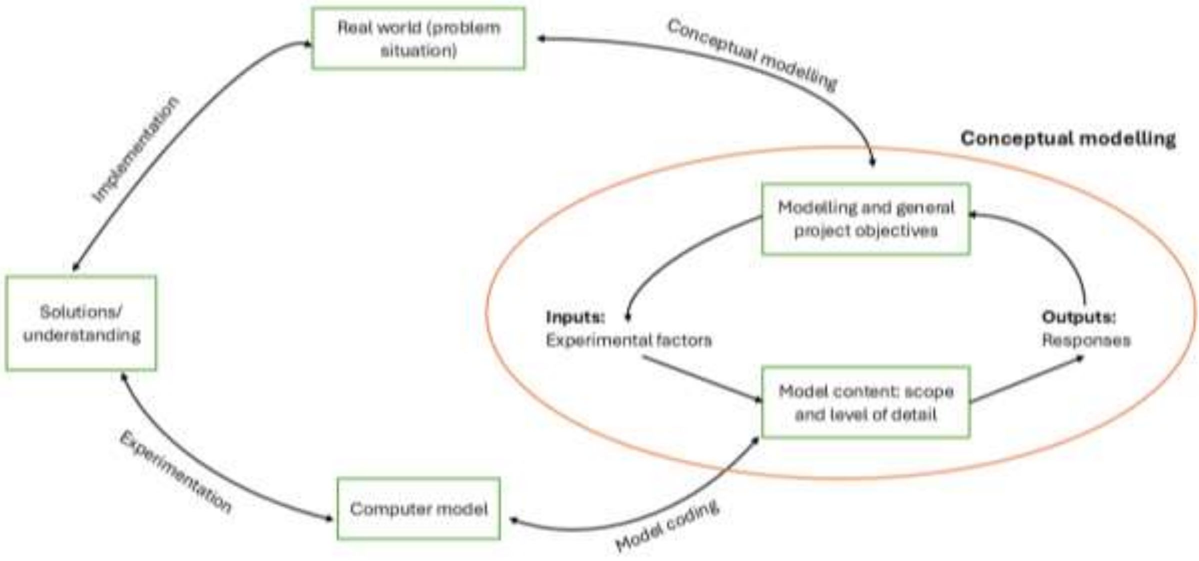

Figure 1: Modelling process (Robinson, 2008)

The main objective of the models that will be developed within the BREADCRUMB project is to study how Food Marketing Standards (FMS) influence Food Waste (FW) in diverse supply chains. As a generalization, vegetables supply chain and an animal supply chain will be modelled. The main agents will be producers, processors, and retailers. The models will not include the analysis of consumers behaviour, because processors will be used as a proxy for consumers' preferences, as will be explained in the following sections. The Motivation Opportunity and Ability (MOA) framework will be used to model agent behaviours and decision-making processes. The adaptation of MOA framework's dimensions and actors' behaviours will be further explored during the projects' activities. Through simulations, the BREADCRUMB model will provide insights into the conditions under which marketing standards influence FW generation and prevention. It will offer a valuable tool for predicting the outcomes of policy interventions aimed at valorising sub-optimal but otherwise high-quality food products while minimizing FW.

The first section will present the problem to be addressed with the simulation models, namely the relationship between FMS and FW, also defining the model objectives. Then, the theoretical framework that will be used to inform the behavioural rules of the agents will be presented. Once the theoretical approach is introduced, the following section will move from the recognition of the problem to the definition of the model content, meaning the main components that will be modelled, focusing on agents and their attributes, their relationships and methods of interaction, and the environment in which they act.

3 THE COMPLEXITY OF FOOD SYSTEMS AND FLW

The concept of a food system includes all the practices, institutions, resources, stakeholders, and activities that collectively shape how societies organize and manage the production and consumption of food. According to the definition provided by the Food and Agriculture Organization (FAO), food systems include “the entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption, and disposal of food products that originate from agriculture, forestry, or fisheries, and parts of the broader economic, societal, and natural environments in which they are embedded” (FAO, 2018).

This definition broadens the scope beyond the narrower idea of food supply chains by integrating them into the wider economic, environmental, and social contexts in which they operate. The term “system” implies interconnectedness among various components, such as food supply chains and the drivers, dimensions, actors, and outcomes that both influence and are shaped by food production and consumption processes. Food systems operate across diverse spatial and organizational levels (Schipanski et al., 2016), and effective interventions or evaluations must consider the synergies and trade-offs that arise between actors and components of the food system.

From this perspective, food systems are viewed as complex socio-ecological systems with numerous interactions between humans and the environment. Understanding their dynamics and identifying key properties is crucial for tracking progress toward sustainability, reducing FW, and shaping policies that promote positive transformations in the actions and outcomes of these systems (Allen & Prosperi, 2016).

This complexity becomes particularly evident when addressing FW, which accounts for roughly one-third of global food production (UNEP, 2021). According to UNEP (2024) estimates, approximately 1.05 billion tonnes of food were wasted globally in 2022, representing 19% of total food production. Of this waste, around 60% occurred at the household level, 28% within food services, and 12% at the retail stage. Additionally, FAO (2023) reported that 13.2% of global food production is lost along the supply chain, from post-harvest up to but not including retail. FW is generated at various stages and is driven by different mechanisms and factors. These causes can be categorized into three groups based on their complexity and their relationship to different supply chain stages, as outlined by (HLPE, 2014):

- Micro causes: These occur within specific phases of the food supply chain and result from the actions or inactions of agents within that phase.
- Meso causes: These are structural or secondary causes that originate in one phase but lead to waste in another. They stem from interactions between agents or deficiencies in infrastructure related to food production, distribution, or sales.

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- Macro causes: These systemic issues affect the entire food system and influence both micro and meso levels. Examples include political regulations or overarching structural dynamics within the food system.

This categorization highlights that although a significant proportion of FW occurs at the consumer level, it cannot be solely attributed to consumer behaviour. Addressing FW has far-reaching implications—not only for consumers (e.g., changes in budgets, consumption habits, and health) and producers (e.g., pricing, production volumes, and logistics) but also for broader societal dynamics, as individual adjustments influence the system and lead to further adaptations of other actors.

While challenging, this complexity provides a valuable framework for analysing inefficiencies within food systems. Key to this process is understanding the individual entities within the system and how they interact. By identifying these interactions, simulation methods can reveal emergent societal patterns.

To model food system dynamics, it is essential to first define their boundaries, characteristics, and key actors. Theoretical frameworks, such as Motivation-Opportunity-Ability, provide crucial components necessary for developing simulations. Theoretical frameworks are useful also for creating agent-based models (ABMs), as they describe the key attributes needed to represent individual entities. While frameworks may differ in emphasis, a comprehensive approach must describe several critical aspects, including the drivers motivating individuals' behaviours, the internal mechanisms they use to weigh trade-offs, and how they respond to external constraints. Furthermore, a robust theory must account for how individuals are influenced by others, such as their interactions, available information, ability to influence others, and how others' opinions affect their decisions.

By integrating these components into simulations, researchers can deepen their understanding of the dynamics within food systems, explore various scenarios, test interventions, and develop strategies to address challenges and guide the system toward more sustainable outcomes.

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4 THE ROLE OF FOOD MARKETING STANDARDS IN FLW GENERATION ALONG THE FOOD SUPPLY CHAIN

The European Union defines Food Marketing Standards (FMSs) as mandatory rules or optional reserved terms aiming to address the expectations of consumers and to improve the economic conditions for production and marketing, as well as the quality of agricultural products (Regulation (EU) No 1308/2013). To achieve these objectives in terms of food security and consumers' satisfaction, FMSs establish different minimum levels of quality requirements for traded products those that are sold directly to consumers and identify agri-food products characteristics through specific terms.

FMSs can be categorized into public and private standards. Public FMSs are introduced by governmental bodies and are mandatory where applicable across the Food Supply Chains (FSC), essential for the marketing of products. In contrast, private FMS are established by individual companies or collective organizations, often taking the form of Voluntary Certification Schemes (VCS) or General Terms and Conditions. Private standards, typically more stringent than public ones, significantly influence market access for companies. These standards can lead to the production of suboptimal products, which either fetch lower prices than premium alternatives or are excluded from the market because of their inability to meet consumer expectations, generating FLW.

Despite the seemingly straightforward objectives of FMSs, their impacts on agricultural markets and on the generation of negative externalities, as the production of FW, are complex and multifaceted. This complexity, illustrated in Figure 2, arises from the diverse nature of FMSs, which vary across product sectors, regulatory levels (from EU-wide regulations to local voluntary agreements), and the positive or negative side-effects they produce.

The main consequence of this complexity is the generation of mismatches between supply and demand within various FSCs. These mismatches occur across different FSC actors, who face different market demand structures

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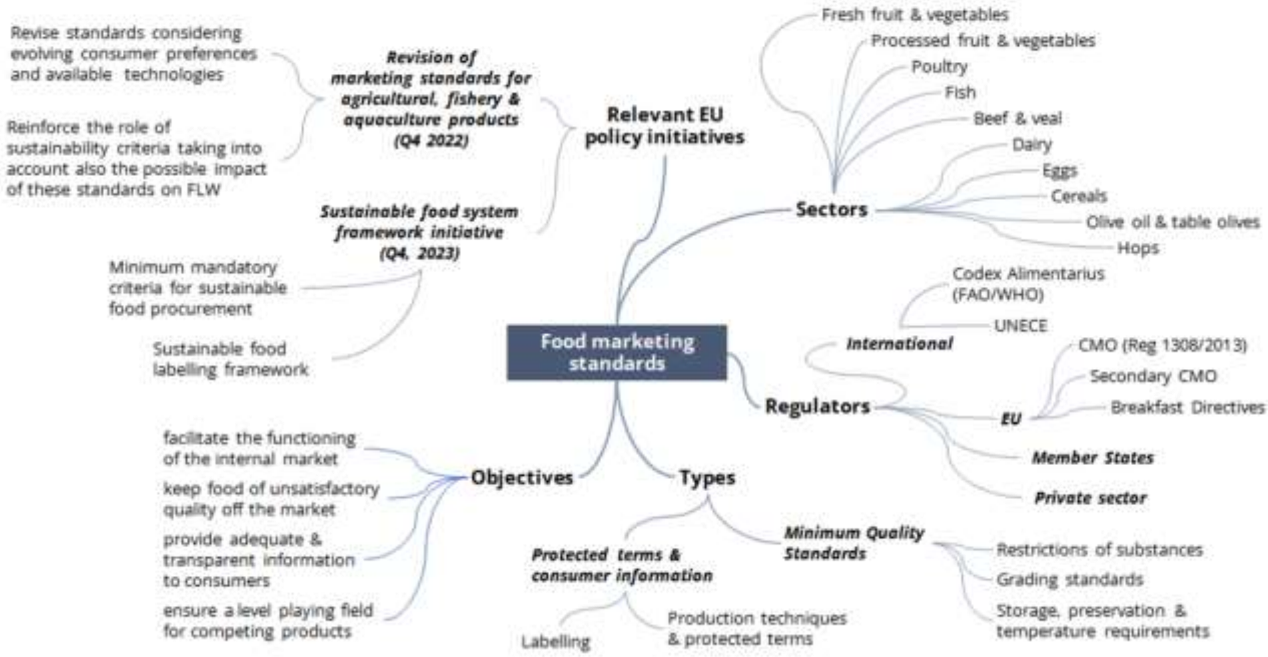
Figure 2 the BREADCRUMB approach to analysis of FMS



According to the results from research conducted by the EU (EC, 2019a, 2019b) FMS have proven to have limited, or even negative, effects on reduction of FW. The potential increase of FW due to FMS could lead to drawbacks from the environmental, social, and economic perspective. FW consistently contributes to the increase the levels of GHGs emissions and to the depletion of natural resources, limits the possibility of redistribution of surplus food to people in need and vulnerable groups, and generates consistent economic losses all along the FSC.

In this context, the relaxation of certain FMS could potentially reduce the generation of FW by increasing the availability of products on the market, even at lower prices, and by enabling the redistribution or processing of food that remains edible. However, this approach is not without drawbacks. Public FMS, in particular, are designed to ensure food safety, and relaxing these standards could introduce trade-offs between reducing FLW and increasing public health risks. Additional concerns related to the relaxation of FMS involve potential market distortions. Specifically, lowering quality requirements could increase the supply of products, driving down prices excessively, thereby reducing the income of producers and threatening the financial sustainability of different actors within the FSC.

However, the impacts of FMS on the generation of FW require further investigation, as empirical evidence remains fragmented, contradictory, and highly dependent on the specific sector or market under examination. Variations in the regulatory frameworks, product types, and market structures contribute to increase the complexity of understanding the relationship between FMS and FW generation.

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The following sections outline the process for selecting relevant FMS to be incorporated into the BREADCRUMB modelling framework considering up to three distinct supply chains. These supply chains span both plant-based and animal-based products, reflecting the diversity of the agri-food sector. The analysis aims to provide a comprehensive understanding of how different types of FMS affect FLW generation at various stages of the FSC.

4.1 Identification of relevant Food Marketing Standards

This section introduces the most relevant FMSs identified in BREADCRUMB to be considered for the modelling activities. The selection of most relevant FMS to be included in the ABM relies on the work conducted within WP1, where public and private FMSs applied in most of the EU countries have been collected and systematized to generate an inventory of FMS implemented at the EU level.

Starting from the inventory, a subset of relevant FMS categories will be selected to be potentially included in the ABM The choice of FMS was conducted on the base of the results of interviews conducted within WP1. A section of the protocol adopted for the interviews was designed in collaboration with WP3, to include questions designed to investigate the relevance of FMS on agents' activities.

Table 1 includes the typologies of FMSs to be potentially included in the ABM, the FSC in which they were identified and the actors who are affected by them.

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Table 1: Selected categories of FMSs

Food Marketing Standard category	Food Supply Chain Typology	Actors involved
Public FMSs		
Organoleptic characteristics	F&V, Animal-based	Retailers
Safety	F&V, Animal-based	Retailers, Producers
Freshness	Animal-based	Retailers
Size	F&V, Animal-based	Retailers
Colour	F&V	Retailers
Traceability	Animal-based	Retailers
Limits on residues and pesticides	F&V	Processors, distributors, retailers
Origin	F&V	Producers, Retailers
Private FMSs		
Environmental sustainability certification	F&V, Animal-based	Distributors, Producers, Retailers
Origin (local)/Traceability	F&V, Animal-based	Distributors, Retailers
Organic certification	Animal -based	Producers
Levels of chemicals lower than public FMS	F&V	Retailers, Producers
Aesthetic requirements (e.g. colour, shape)	F&V, Animal-based	Retailers, Producers
Ripeness/freshness level	F&V	Retailers, Producers
Organoleptic characteristics	F&V, Animal-based	Retailers, Producers
Size and weight	F&V, Animal-based	Retailers, Producers
Animal welfare certifications	Animal-based	Retailers
Certification of Fair treatment of producers	F&V, Animal-based	Producers

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After the identification of the most significant categories of FMSs in terms of contribution to FW generation, as carried out in WP 1, further analysis was conducted within WP 2, under Task 2.3. This task focused on refining the understanding of which specific FMSs are most closely associated with FW generation. The identification process was conducted through direct interviews with stakeholders involved in the BREADCRUMB case studies, which represent both F&V supply chains as well as animal-based FSC. These interviews provided critical insights, enabling a comprehensive assessment of practices and strategies that may lead to inefficiencies or losses along the supply chain, thereby informing targeted interventions aimed at reducing FW.

The impact of relaxation of the selected FMSs (presented in Table 2) on the generation of FW will be simulated in the ABM. Results from ABM will be integrated in the BREADCRUMB Macroeconomic model presented in Section 6.

Table 2: Specific FMSs to be included in the Agent Based Model

Fruit and Vegetables based FSC	
Food Marketing Standard	**Public/private**
Producer	
Colour of the peel (premium level)	Public
Absence of imperfections (premium level)	Public
Calibre	Public
Brix degree/sweetness	Public
visual and organoleptic characteristics	Public
Processor	
Compliance with HACCP standard	Public
Aesthetic characteristics	Private
Retailer/Distributor	
Firmness	Private
Aesthetic standards	Private
Traceability (ISO 22005:207)	Private
Remaining shelf life	Private
Labelling	Private
Compliance to certifications (BRC, Global GAP, GRASP, SPRING, IFS, Kosher, BRCG, ZERYA)	Private
Specific supermarket requirements	Private

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Animal based FSC	
Food Marketing Standard	**Public/private**
Producer/Fisherman	
Legal specimen	Public
Size	Public
Label	Public
Regulation 543/2008	Public
Regulation 1069/2009	Public
National regulations/schemes	Public
Freshness	Private
Specimen	Private
Processor/Wholesaler	
Legal specimen	Public
Size	Public
Label	Public
Freshmen	Private
Specimen	Private
Regulation 543/2008	Public
Regulation 1069/2009	Public
National regulations/schemes	Public
Retailer	
Legal specimen	Public
Size	Public
Label	Public
Regulation 543/2008	Public
Regulation 1069/2009	Public
National regulations/schemes	Public
Freshmen	Private
Specimen	Private
Integrity	Private
Absence of preservatives	Private

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5 THE MOTIVATION-OPPORTUNITY-ABILITY THEORETICAL FRAMEWORK

Research on determinants of FW developed in the last years define it as the result of multiple and interconnected behaviours taking place at different moments and stages of the FSC (Quested et al., 2013; Setti et al., 2018; Van Geffen et al., 2016).

To understand the complexity of these behaviours leading to the generation of FW, a number of conceptual frameworks have been developed. Among others, the Motivation-Opportunities-Abilities (MOA) theoretical framework gained increasing consideration among FW researchers and scholars. The MOA framework considers FW as an unintended consequence of iterative decisions and behaviours related to food management practices, that are driven by both internal (Motivation and Abilities) and external (Opportunities) factors (Van Geffen et al., 2016).

Initially designed for marketing research (Rothschild, 1999), the MOA framework has been adapted to investigate individual behaviours in different contexts, including the analysis of FW drivers. A seminal work of adaptation of the MOA framework to the analysis of FW drivers was conducted within the European H2020 REFRESH project (van Geffen et al., 2016), a Horizon 2020 project focused on the reduction of avoidable waste and improved valorisation of food resources.

According to the MOA framework (Maclnnis et al., 1991), individual's information processing and consequential decisions are influenced by internal factors, personal motivations and abilities, and by external factors, the opportunities. While being related to the personal sphere, the context in which individuals live and operate have a strong influence on those drivers.

While the version of the MOA framework designed within REFRESH was designed to describe determinants of FW connected with consumers' behaviour, the adapted version of MOA framework applied in the BREADCRUMB approach aims to capture the determinants of FLW in the decision-making and behaviours of other key actors within the supply chain. These actors include producers, processors, distributors, and retailers. Consumers will not be considered in the BREADCRUMB model since they are not directly imposing FMS, but they have and indirect role in defining the supply structure.

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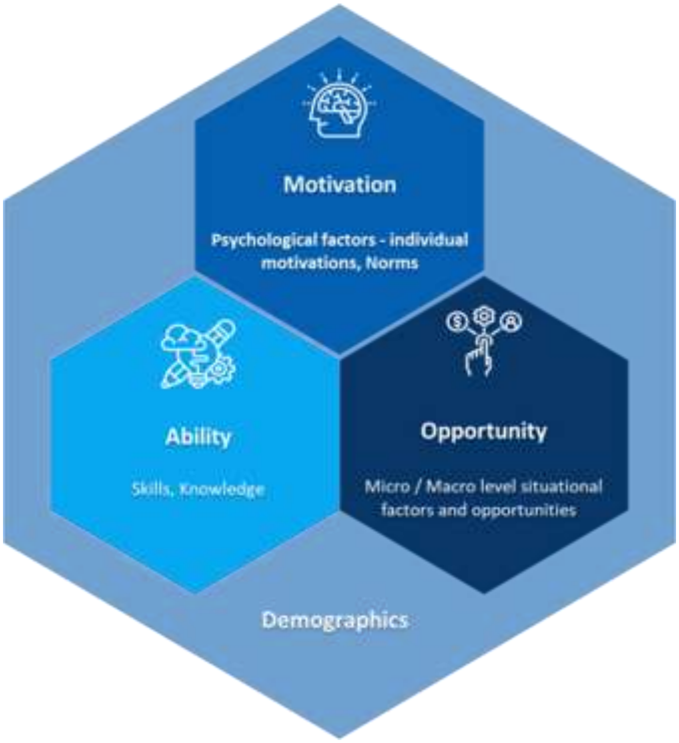
Figure 3 MOA Framework



Motivations represent the intentions of one or more individuals to carry out a set of actions. Their role in avoiding or reducing FW relies on their positive/negative effects on attitudes towards the goal. Attitudes, and consequently behaviours, towards FW are influenced by the awareness about the problem and the consciousness about global impacts related to FW (Abeliotis et al., 2014; Russell et al., 2017). Motivations are also influenced by the perceived level of control over behaviour, the ability to initiate or modify actions, and the perceived effectiveness of FMSs in influencing FL W generation. Additionally, motivation can stem from personal emotions, engagement with sustainable practices, and the influence of both social and personal norms regarding FLW.

Opportunity is defined as the capacity of one or more individuals to access external resources—both material and non-material—such as time, technology, infrastructure, and information. In the context of agricultural and food production, these resources may include access to advanced technological tools and machinery that can reduce FW or improve the quality and efficiency of production processes. Also, opportunity includes the possibility to access professional training courses aimed at updating knowledge directed towards increasing production efficiency and reduce FLW.

In this context, some FMSs can be considered as opportunities for FSC actors. By complying to these standards, producers and retailers can gain access to premium markets, allowing them to sell higher-quality

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products at higher prices, increasing their income and their competitive position in the market. Premium products typically benefit from greater consumer trust and higher perceived value, which can translate into more stable demand and improved profitability for compliant businesses.

However, while FMS may offer these opportunities, they also impose challenges. Actors must invest in meeting the stricter quality, safety, and sustainability criteria established by both public and private standards. Compliance may require significant financial and human resources, including the adoption of new technologies, implementation of improved production practices, and participation in training. Hence, to be considered as an Opportunity, FMS must be considered together with the capacity of actors to meet their requirements.

Ability refers to an individual's capacity to address the creation, management, and reduction of FW, which depends on personal knowledge, skills, and experience. In the BREADCRUMB context, Ability is divided into two main components: technical skills and non-technical (immaterial) competencies. Technical skills are related to the practical expertise of actors within the FSC to comply with FMSs while effectively managing FLW. These skills may include knowledge of advanced production techniques, waste reduction methods, inventory management, and the application of technology to enhance efficiency and minimize losses. Non-technical competencies involve the understanding of regulatory frameworks, market dynamics, and industry-specific standards related to FMS. This includes awareness of compliance requirements, legal obligations, and quality control procedures that influence both production and distribution processes.

Socio-demographic characteristics are considered to have an indirect influence on Food Waste behaviours, and, differently from previous drivers, are hard to be changed or be influenced by any kind of intervention.

Table 3 summarizes the most relevant behavioural factors and FW drivers considered for the BREADCRUMB modelling approach.

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Table 3: Behavioural factors and Food Waste drivers

Behavioural factors		Examples of Food Waste drivers
Motivation	**Psychological factors/ individual motivations**	Attitude (personal attitudes towards FW and sustainability)
		Awareness/perception of consequences of FW
		Perceived control, Perceived effectiveness of FMS
		Emotions and engagement (e.g. personal engagement on promotion of sustainability)
	Norms	Social norms (injunctive norms; descriptive norms)
		Personal norms (e.g. Subjective views on FW; non-readily changeable behaviours)
Opportunity	**Micro level**	Food environment (e.g. specific standards set by retailers, consumers preferences)
	Macro level	Legal and regulatory framework (e.g. public FMSs)
Ability	**Capabilities**	Technical capability to comply with FMS
		Knowledge

6 ABM DEFINITION WITHIN BREADCRUMB PROJECT: INTEGRATING MOA FRAMEWORK INTO MODELLING ACTIVITIES

Within the BREADCRUMB project, a modelling approach will be adopted in order to understand the underlying mechanisms through which FMSs lead to FLW generation along the FSC, and how decisions taken by actors influence each other. To do so, an agent-based model (ABM) will be developed. In the previous sections, the complexity of FW and of FMSs has been mentioned. Agent-based modelling is particularly well-suited to study complex adaptive systems (Onggo & Foramitti, 2021), in which individual components interact based on their own goals and constraints, leading to emergent macro-level outcomes that are often difficult to predict. The relationship between FMSs and FW reflects this complexity, as it is influenced by the behaviours and decisions of diverse actors (producers, processors, retailers, policymakers at different levels), each adapting to the constraints imposed by FMS and their economic context.

ABMs are computational systems that simulate the action and interaction of heterogeneous autonomous agents – which can represent individuals or groups – and their interaction with the environment. This modelling

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approach allows researchers to explore the complexities of systems where individual behaviours and localized interactions lead to emergent phenomena. In the context of FSC, ABMs have demonstrated their utility across different applications, including optimizing urban farm management, assessing resilience to shocks, and understanding market dynamics. For instance, ABMs have been employed to simulate interactions among urban farms, enabling efficient management of food, energy, and water resources, reducing waste, and improving food availability (Elkamel et al., 2023; Rahman et al., 2022). Additionally, these models can help assess the trade-offs between efficiency and resilience by modelling the dynamic interactions between producers, traders, and consumers under various shocks such as climate events and market fluctuations (Van Voorn et al., 2020). ABMs have also been used to simulate supply-demand dynamics in specific markets, to predict price fluctuations and market trends based on agent interactions and environmental data (Fathallahi et al., 2020).

To the authors' knowledge, no previous studies have employed ABMs to simulate the impact of FMSs on FLW, highlighting a significant research gap and underscoring the need to establish a conceptual modelling framework that identifies the most relevant aspects to inform the model.

The initial representation of the stages of the modelled FSC is represented in Figure 4. The figure represents a generic food supply chain, as the specific steps will be refined and selected in the following activities.

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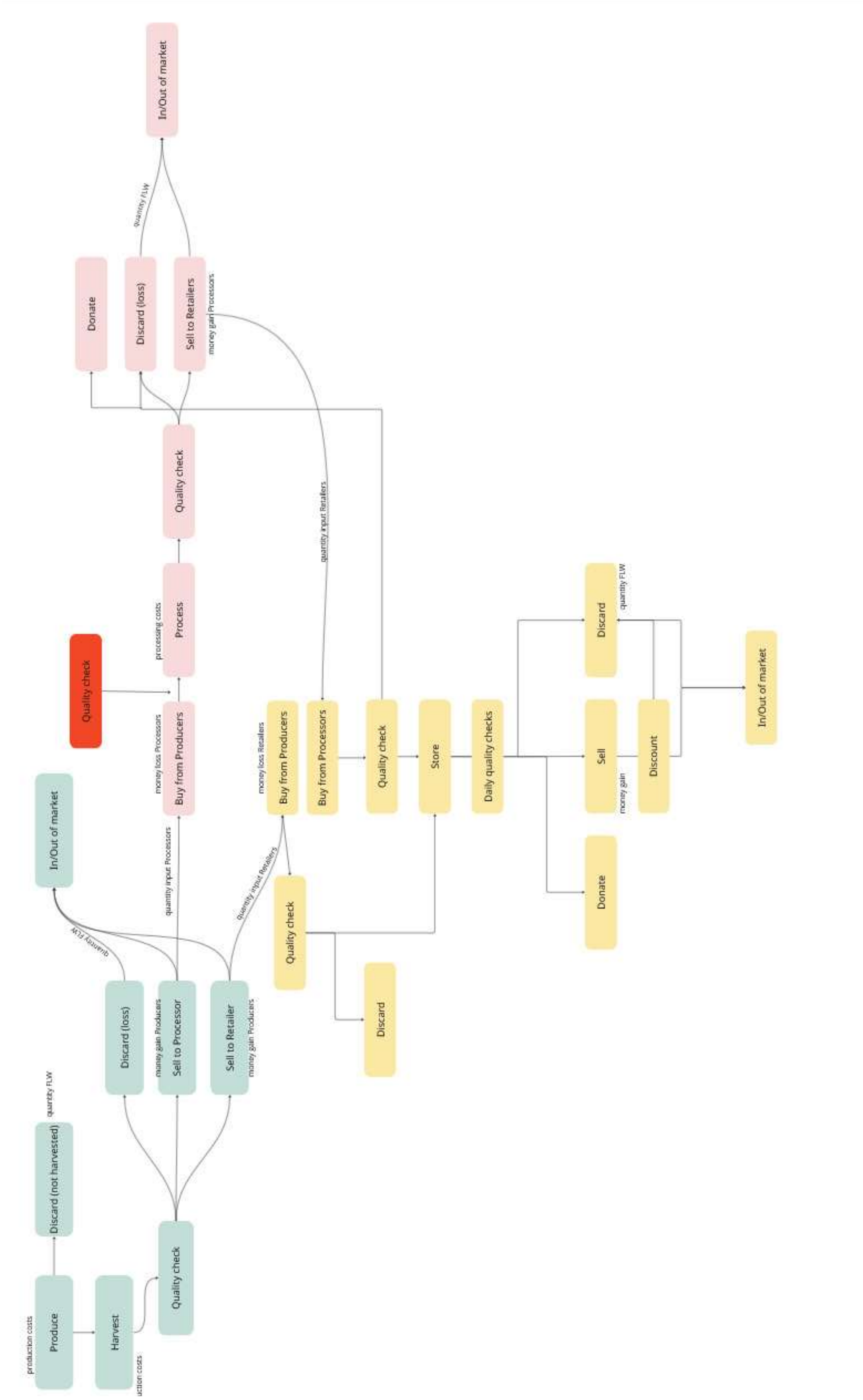

Figure 4: Initial representation of a general food supply chain to be modelled

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6.1 Relevant food supply chains and involved actors

The BREADCRUMB project addresses five food commodities, engaging 16 different case studies to ensure the integration of informed perspective by relevant stakeholders. The five food commodities included in the project are: fruits & vegetables, cereals, meat (poultry,bovine, and pork), eggs, fish. Each of them is characterized by specific production and market dynamics that govern the supply chain, and a vast heterogeneity is present also within the same food commodity category, depending on the products. The modelling activity must necessarily take into consideration this heterogeneity, seeking to simplify it by isolating the most important factors to be simulated to address the problem of interest. At the same time, it must reconcile with the fact that building a model is a highly time-consuming process. Therefore, it was decided to model two food commodity categories, one related to plant value chains and one related to an animal value chain. The choice to model two food supply chain was guided by three main criteria:

- Relevance: Research conducted in the earlier phases of the project highlighted that FMSs have a particularly significant impact in the fruit & vegetables sector, justifying the decision to model this supply chain to better understand its dynamics in relation to the phenomenon of interest;
- Variability: The decision to model one plant-based supply chain and one animal-based supply chain ensures variability and a broader perspective.

6.1.1 Agent types: actors considered in the ABM

In the context of ABMs, agents are defined as individual entities that can make independent decisions in order to reach their goals (Onggo & Foramitti, 2021).The developed models will include three typologies of agents, to represent the main actors of interest in the two supply chains selected. Considering the objective and scope of BREADCRUMB project, the models will focus on three main actors – or agent types – chosen as an abstracted and simplified representation of FSCs. The following agent types are intended to be an initial indication of the ones that will be developed, which will be adjusted and better specified according to the modelled supply chains.

- Producers: They are the initial actors responsible for creating and supplying raw or primary products within the simulated market network. They manage their finances, ensure product quality, and interact with processors and retailers to sell their goods. Their decisions are influenced by both public and private marketing standards;
- Processors/Intermediaries: Agents that take products from producers, process them, and then pass them on to retailers. They serve as intermediaries in the supply chain, adding value to the raw products received from producers. They manage their finances, ensure product quality, and interact with retailers to sell their goods. Their decisions are influenced by both public and private marketing standards:

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- Retailers: Agents that receive products from producers and processors and sell them to the end consumers. They are the final link in the supply chain, handling the distribution of products to the market. They manage their finances, ensure product quality and are strongly influenced by consumers' preferences. The models will simulate imperfect competition market; thus, the retailers will be represented by few large-quantity buyers that purchase products from a high number of suppliers, represented by both producers and processors.

The decision not to simulate consumers as agents stems from the primary goal of the model, which is to investigate how FMSs influence the generation of FW. Consumers are not direct actors in the supply chain who impose FMS; instead, their preferences and behaviours indirectly shape the dynamics of the supply chain. While consumer preferences have been integrated into the behaviour of retailers, who act as "proxies" for consumers' demands. Retailers translate consumers' preferences into specific requirements for upstream actors in the supply chain (i.e. producers and processors). By incorporating consumer-driven preferences into retailers' behaviour, the model accounts for their influence in FMSs and FW without explicitly including consumers as an agent type. This approach allows the model to focus on the direct interactions and decision-making processes within the supply chain.

The models will represent heterogeneous agents, characterized by complex behaviours. In fact, these three agent types will be represented as internally diverse, meaning that different producers, processors, and retailers will be characterized by varied values to describe their market power, preferences, attitudes towards sub-optimal foods, relationships with other actors along the supply chain. For example, the internal diversity may include differences in company size, pricing strategies, or approaches to sustainability. Additionally, the models will include details on how imperfect competition market dynamics will be simulated, such as considering barriers to entry or disparities in bargaining power between actors.

In order to simulate market dynamics, agents will interact with each other, first of all to sell and purchase food products. Another crucial factor that will drive agents' interaction will be represented by private FMSs determined by one agent and that will determine changes in the decisions and behaviours of other agents. Related to this, agents will adapt their behaviour to the environment and the model's dynamics.

While the agent types of producers, processors, and retailers represent food supply chain actors, the model will also include another category of agent types, aimed at representing the individual food products. The decision to include individual food products as agents was made to enable the simulation of how specific food items produced by an actor might or might not meet FMSs. By treating each food product as a separate agent, we can account for product-level variation in quality, waste, and handling, independent of the producer, processor, or retailer from whom they originated. This level of granularity allows the model to reflect more accurately the fact that not all items from the same batch will necessarily meet marketing standards, leading to potential waste or product rejection, even when they come from the same actor.

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Table 4 4provides an initial list of agents' attributes. As shown, attributes can be static – meaning that they do not vary during the simulation – or dynamic – thus subjected to variations during the simulation according to precise coded rules that will update their values. The list will be integrated during the iterative process of model development, following stakeholders' suggestions to be collected during the following project's activities.

Table 4 4: Attributes of the Agents

Agent type	Attribute	Description	Static/Dynamic
Producers Processors Retailers	ID	Unique identifier assigned to each agent	Static
	Type of production/processing/distribution	e.g., fish, fruit, vegetables, etc.	Static
	Production/Processing/Storage capacity	Maximum quantity of food they can produce, process, or store (e.g., kg/week)	Static
	Average quality	Average quality of their products	Dynamic
	Average cost	Average cost per unit of product	Dynamic
	Average selling price	Average price per unit of product	Dynamic
	Bank balance	Current financial resources available to the agent. Proxy of firm size.	Dynamic
	Current production	Quantity currently being produced	Dynamic
	Adoption of sustainable practices	Level of importance attributed to sustainability	Dynamic
	Food Waste	Amount of product that is discarded (also due to FMSs)	Dynamic
	Current contracts	Who they are collaborating with (producers, processors, retailers)	Dynamic

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Produced products **Processed products** **Distributed products**	ID	A unique identifier assigned to each food product	Static
	Product type	The category or type of food product (e.g., apple, pear, anchovy, etc.)	Static
	Production date	The date when the food product was initially produced or harvested	Static
	Safety	Product's compliance with food safety standards and regulations	Static
	Quality	How well the product adheres to the required marketing standards (e.g., size, appearance, freshness). This attribute will be defined in a more precise way once selected the FMSs to be modelled.	Static
	Unit cost	Cost of production for each product	Static
	Unit selling price	The price assigned to the product, which may change based on quality, condition, and market demand	Dynamic

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6.1.2 Description of supply chain stages of interest for the models

The ABM will simulate the behaviour of value chain actors operating in different steps —primary production, processing, and retail—each incorporating a quality control mechanism. At the primary production stage, raw food products/animals are cultivated/raised/captured and undergo an initial quality check to verify compliance with FMS. These standards vary depending on whether the product is consumed as such or intended for processing. Products that do not meet the required characteristics are typically downgraded (e.g., sold at a lower price) or redirected to alternative value chains, such as bio-energy production or animal feed.

Products that pass quality control move forward in the value chain. For products intended for direct consumption, intermediaries oversee their distribution to retail points. Conversely, products destined for processing are sent to processing companies, where they undergo a secondary quality check to ensure they meet the necessary characteristics for transformation.

Once both fresh and processed products reach the retail stage, they undergo a final quality inspection to verify compliance with FMS, which, at this point, are primarily set by retailers (private FMS). This check also includes an analysis of the remaining shelf life, to ensure that products can be displayed for long enough to allow consumers to purchase them before they expire.

Products that do not meet FMS requirements at the retail stage are rejected. Fresh products are rarely returned to producers or intermediaries because of their short shelf life, which causes them to expire during or shortly after transport, thus making it very difficult to valorise them for human consumption. As a result, these products are typically discarded, contributing to FW. On the other hand, processed products are often returned to processors, who may adopt various waste reduction strategies. These include repackaging and resending products to retailers (if the remaining shelf life complies with private FMS requirements), selling at a discount, or donating to charitable organizations.

It is essential to highlight that this description represents a generalized food value chain and does not apply to a specific product. Depending on the type of product—such as fruits and vegetables, meat, or fish—the supply chain may include additional or fewer steps, quality checks or actors. Management strategies for discarded items also vary, with different strategies for reuse, donation, redistribution or disposal depending on the characteristics of the product and its perishability.

6.1.3 Potential fitting between MOA dimensions and ABM

As mentioned in Section 5, the MOA framework offers a structured theoretical perspective for studying the generation of FW. To be effectively applied in an ABM simulating how FMSs influence FW, the framework — primarily used to explore FW drivers at the consumer level — needs to be adapted to the decision-making dynamics of FSC actors such as primary producers, processors, and retailers. The key difference between consumers and FSC actors is that the latter can be viewed as economic agents whose primary goal is to

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remain competitive in the market. For this reason, a particular relevance will be given to this goal in the model. Motivations will capture the economic and operational goals of actors seeking to meet market requirements and remain competitive, including attitudes toward compliance with marketing standards, waste minimization efforts and, if emerging as relevant from case studies' data, the attitude towards sustainability. Opportunities represent external conditions such as access to technologies, infrastructure, market demand, and regulatory frameworks that affect decision-making about food management. In this context, FMSs can be considered as an Opportunity, meaning a constraint that influences the decisions and behaviours of FSC actors. Abilities encompass knowledge and skills related to the operational actions, for example the ability to grade product, assess the quality, and efficient food handling processes.

Additionally, it is important to note that the ABM is probabilistic in nature, meaning that the behaviours of agents are not fixed but are based on probabilities influenced by their attributes and rules of behaviour. The dimensions of the MOA framework will influence these probabilities, determining the likelihood of specific actions being taken by agents in response to different situations. For example, an agent's motivation to minimize FW might increase the probability of that agent taking actions to optimize production, reduce waste, or adopt more sustainable practices. Similarly, opportunities such as access to technology, infrastructure, or market demand might alter the likelihood of an agent adopting certain behaviours, such as meeting FMS requirements or making strategic production decisions. Knowledge and skills will influence the probability of an agent successfully carrying out its operational tasks. By incorporating these probabilistic elements, the ABM can simulate more realistic and dynamic interactions among actors in the FSC, accounting for the complexity and variability of their decision-making processes.

7 THE BREADCRUMB ECONOMIC MODEL

The key assumptions and mathematical framework of the BREADCRUMB economic model have been developed. The BREADCRUMB modelling framework relates the effect of FMSs on FW to the theory of grading, minimum quality standards, and private marketing standards in the literature. The model represents three main actors in the FSC: farmers, intermediaries, and consumers. It is based on the theory of vertically differentiated products, meaning that a product exists in two distinct quality levels. The lower-quality version meets the baseline public minimum quality standards (MQS), which all producers must adhere to, while the higher-quality version exceeds this minimum threshold due to additional requirements imposed by marketing standards. Following numerous studies on the literature, the model assumes a competitive farm sector, wherein only two types of products are produced in terms of quality. First, farmers choose the quality of the product they want to produce, and then, they choose quantities. The marketing sector is also assumed to be competitive where farmgate prices result from the balance between the upstream farmers' supply and the downstream retailers' demand. In the marketing sector, we consider two (groups of) retailers, each handling one of the two products, and competing against the other. Competition between the two retailers takes place in two stages. In the first stage, they set their respective quality by purchasing the low- or high-quality product

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from farmers and maintaining or improving that quality level. In the second stage, they compete in prices given the qualities already chosen. These retailers perform all the relevant marketing functions between the farm level and the consumer level. They buy products from farmers, move them through a distribution chain, and sell them to consumers. As farmers can produce one or both products, retailers may buy the product of their interest from any one farmer. We assume a constant unit handling cost incurred by each retailer for each product type handled, because of the need to maintain or improve different quality levels.

At the consumer level, demand for differentiated products arises from heterogeneous preferences, which we formally structure using the Mussa & Rosen (1978) framework. This well-established framework represents consumers as a continuum distributed according to a taste parameter (willingness to pay, WTP) for quality, allowing us to derive demand functions and examine equilibrium market outcomes systematically. The model is specifically designed to analyse how variations in the stringency of FMS affect the equilibrium values of key economic variables, including FW, prices, quantities, and profits. By explicitly modelling these mechanisms, the framework provides a theoretical basis for understanding how regulatory policies and market-driven quality differentiation interact to shape the efficiency of the FSC. In the framework of our model, FW is a consequence of whether the market is covered in equilibrium. A covered market means that each consumer buys one of the two products (low or high quality). This occurs when prices are set such that even consumers with the lowest taste parameter (WTP) buy at least the low-quality product. An uncovered market means that some consumers do not purchase any product. This happens when the low-WTP consumers (who would have bought the low-quality product) find it too expensive to purchase the low-quality product due to the introduction of FMS. This shift from a covered market to an uncovered market leads to FW. That is, when demand shrinks, but supply has already been produced, the unsold portion may go to waste. If low-quality products become unmarketable because of the new FMS-induced pricing, they may be discarded. As it stands, our model predicts the preliminary analytical expressions of these effects. Currently, we are refining the model in response to several insightful comments from reviewers.

8 POTENTIAL INTERACTION BETWEEN ABM AND THE MACROECONOMIC MODEL IN BREADCRUMB

The integration between the ABM and the Economic Model in the BREADCRUMB project is critical for gaining a comprehensive understanding of the impact of FMS on FW in FSC.

While the Economic Model provides a strong theoretical framework by focusing on mathematical relationships between key variables such as marketing, FW, prices, quantities, and profits, it is expected that some numerical simulations will be more informative. These simulations will be supported by the ABM, which will offer insights into the underlying mechanisms that lead to FW along the supply chain.

The Economic Model primarily uses analytical expressions to explore how variations in the stringency of FMS affect equilibrium values of the variables mentioned. However, some complex phenomena related to the

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behaviours of the actors in the FSC are challenging to represent solely with mathematical equations. To address this, the ABM will be employed to provide simulated data for parameters that are difficult to quantify in a theoretical model. For example, the ABM will offer insights into demand fluctuations, the decision-making processes of agents (such as producers, intermediaries, and retailers), and the way these decisions influence FW generation in the system.

The role of the ABM is crucial in guiding the Economic Model by uncovering the dynamic and complex interactions that lead to FW. The ABM can simulate the behaviour of individual agents, considering the heterogeneity and complexity of their decisions. These simulations help to refine the Economic Model's predictions, providing a more accurate representation of the supply chain dynamics that contribute to FW.

The integration of both models will allow for a better understanding of the market behaviours and decision-making processes that influence FW generation. It will enable the identification of the most relevant factors in FSC dynamics, ensuring that the resulting policies and strategies are well-informed and effective in reducing FW.

9 CONCLUSIONS AND NEXT STEPS

Given the methods and theoretical frameworks selected to understand the complex interrelation between Food Marketing Standards and Food Waste, the next phase of the activities will focus on the development of the models. The first key step will involve the selection of the vegetable and animal supply chains that will be modelled. Once these FSC are identified, the main steps of the supply chain and the operational activities of the involved actors will be integrated into the model flow. This will be accompanied by the inclusion of the most relevant FMSs that regulate operations at various stages. In this process, the collaboration and knowledge of the case study partners will be essential to establish the baseline model, ensuring that real-world conditions are accurately represented.

Regarding the validation and calibration of the models, data collected from the case studies will serve as the primary source of information. In instances where data from the case studies is unavailable or insufficient, previous literature and secondary data sources will be consulted to fill in the gaps. This approach ensures that the models are grounded in reliable, empirical evidence.

For the validation of the ABM, a Role-Playing Game (RPG) will be employed. RPGs are a well-established tool for identifying stakeholders' decision-making rules and for qualitatively validating ABMs. By involving stakeholders directly in the simulation process, RPGs allow the model to more accurately reflect real-world behaviours and trade-offs. The validation process will involve comparing the outcomes of the RPG to those of the ABM.

The RPG will be designed to mirror the tasks of the key stakeholders represented in the ABM, ensuring that the simulated environment reflects the routine operations of the real actors. Experiments will then be conducted as part of the validation process, during which the players (representing the agents in the ABM) will engage in the simulated activities. Data will be collected from these experiments through observation, post-game

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interviews, and debriefing sessions. Consistency between the RPG data and ABM results will be assessed to quantitatively validate the decision rules and hypotheses embedded in the ABM.

By combining qualitative and quantitative validation techniques, the integration of RPG and experiments will ensure that both models are robust and reliable, ultimately leading to a better understanding of the mechanisms that drive FW in supply chains and the role of FMSs in this process.

An important next step will be the creation and empirical assessment of different scenarios to explore potential solutions for reducing FW, while maintaining a balance with other objectives. Starting from the baseline models, scenarios will be co-designed and co-created in collaboration with case-study partners. These scenarios will aim to identify which modifications or relaxations in FMS could lead to a reduction in FW and what potential side-effects may arise from such changes. The results of this analysis will provide valuable insights into which marketing solutions can help minimize FW while balancing other supply chain goals.

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