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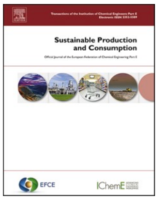

Virtual agri-food supply chains: A holistic digital twin for sustainable food ecosystem design, control and transparency

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ABSTRACT

The transition of Agri-Food Supply Chains (AFSC) toward sustainable patterns able to secure safe, quality, and affordable food whilst preserving natural and anthropogenic ecosystems is a key challenge of this century. Increasing production and distribution operations' transparency and impact visibility uncovers hidden complexities and the food ecosystem's externalities. To this attempt, this paper introduces a novel Agri-Food Supply Chain digital twin (AFSC-DT) able to virtualize the agricultural, processing, warehousing, and distribution operations holistically from-field-to-consumer and estimate economic, logistic, environmental, safety, and nutritional indicators associated with any food order, assumed as the functional unit. The AFSC-DT behaves as a control tower, providing a multi-dimensional dashboard of indicators and labels to enhance practitioners' and consumers' knowledge of FSC entities and operations. The practitioner's visibility drives top-down *operational* and *tactical* feedback controls through real-time monitoring and a-posteriori multi-dimensional performance analysis, whilst consumers, with their informed choices, perform a *strategic* bottom-up pressure on the food industry toward a sustainable redesign. A what-if simulation analysis conducted over four virtual scenarios within a regional horticultural AFSC proves how the AFSC-DT aids informed decision-making across the AFSC echelons, stimulating a virtuous cycle and favoring a progressive transition toward more sustainable patterns.

1. Introduction

Nowadays, consumers' actions impact the environment and contribute to global warming, threatening natural and anthropogenic ecosystems. Using electrical devices and transportation systems, generating waste, wearing clothes, and consuming food increases the human carbon footprint (Sala and Castellani, 2019). Consumers might reduce carbon-intensive habits but cannot abate eating food. Food production and consumption contribute up to 34 % of global greenhouse gasses (GHG) emissions, primarily for agriculture, processing, storage, and transportation (Crippa et al., 2021). Such impacts are expected to increase further with the global population's growth, and prevention or mitigation strategies must be set down urgently.

The transition of current food industries and Agri-Food Supply Chains (AFSCs) toward more sustainable patterns able to secure safe, quality, and affordable food whilst preserving natural ecosystems and ensuring profitability to growers and smallholders is a key challenge to face (Adams et al., 2021; Hoek et al., 2021). Pathways toward sustainable and carbon-neutral food industries are ambiguous and rough, disseminated of hidden externalities, conflicting interests, and organizational, operational, and technological issues. Understanding the complexity behind FSCs and increasing the visibility of agri-food companies, stakeholders, and consumers on the links that rule food ecosystems is a preliminary step to undertaking carbon neutrality (Accorsi et al., 2018). The lack of consumer awareness of the operations and impacts behind their food basket inhibits more sustainable choices (Ran et al., 2022).

To prevent chronic diseases and aid public health policies, nutritional labels (e.g., nutriscore, nutriform battery) already inform consumers of the micro- and macro-nutrients in many processed food items (Hau and Lange, 2023). However, sustainability and safety indicators that are not inherently associated with a product but depend on the supply chain (SC) networks, processes, and operations are lacking (Cao et al., 2023). Environmental indicators like the food carbon- or water-footprint, the food miles, the power consumption for processing, refrigeration, and storage, virgin materials used in packaging, the workers employed, the cultivated hectares, and the agricultural technique are examples of what is kept from consumer's visibility. The impact of a product is susceptible to the different farming and SC tasks

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Nomenclature

Logic syntax

$f.x$	x property of facility entity f
$f.x()$	x method of facility entity f
$o.x$	x property of order entity o
$o.x()$	x method of order entity o
$p.x$	x property of product entity p
$p.x()$	x method of product entity p

Parameters

$ASI(i)$	The Available Soil water Index expresses the fraction of the period of time i when the available water meets the requirements of a specific crop
$Content\%_{m,p}$	Percentage of the daily recommended dose of micronutrient m in 1 kg of product p
D_i, *mm*	Remaining soil water at the end of period i
E_a, *kJ/mol*	Activation energy of the degradation reaction of a specific food product at temperature T_0
ET, *mm/month*	Evapotranspiration is the combination of two water losses experienced by the plant: soil surface evaporation and crop transpiration
ET_a, *mm/month*	Actual Evapotranspiration: evapotranspiration measurable in a specific land portion
ET_m, *mm/month*	Maximum Evapotranspiration: evapotranspiration that occurs in optimal soil moisture conditions
$f.IB$	Inbound queue of orders in facility f
$f.OB$	Outbound queue of orders in facility f
$f.orderManagement()$	Method of facility f for orders dispatching
$f.WIP$	Queue of orders being processed in facility f
$f^p.laborThr$, *kg/hour*	Labor throughput of a processing facility
$f^p.machThr$, *kg/hour*	Machine throughput of a processing facility
$f^{pp}.H_{days}$, *day*	Duration of the harvesting period in a primary production facility
$f^{pp}.H_{dailyQty}$, *kg/day*	Maximum daily harvest performed in a primary production facility
$f^{pp}.nw$	Number of workers available in a primary production facility
$f^{pp}.thr_{day}$, *kg/day*	Harvesting daily throughput of a farm worker
In_i, *mm*	Irrigation amount in period i
ky	Empirical coefficient linking crop yield to the evapotranspiration level
m, *mg*	Micronutrient (mineral or vitamin)
$o.distributionChain$	List of facilities to be visited by order o
$o.loss\%_t$	Percentage shelf life decay of order o at time t
$o.qty$, *kg*	Order quantity
$o.shelflife_t$, *hour*	Residual shelf life of order o at time t
$o.WIPtime_f$, *hour*	Order lead time in a processing facility f
Pe_i, *mm*	Rainfall amount in period i
Q_{10}	Factor by which the degradation rate of a food product increases when subject to a temperature growth of 10 °C
R, *kJ/mol*°C*	Ideal Boltzmann gas constant
T_0, *°C*	Crop-specific temperature at which microorganism's proliferation activity is minimized without affecting the inside structure of the product
Wb_i, *mm*	Depth of water in the soil at the beginning of period i
Y_a, *kg/season*	Available crop yield given the available water
Y_m, *kg/season*	Maximum crop yield of a specific crop in specific climatic conditions

(Poore and Nemecek, 2018). The intensive agricultural systems provide high crop yields in turn of enormous energy consumption, water, pesticides, and inorganic fertilizers, which affect biodiversity and endanger the soil recovery capacity (OECD, 2020). Moreover, the growing demand for livestock products and ultra-processed food enhances intensive industrial processes, leading to higher energy, land, and water consumption (Carvalho et al., 2023; Ferronato et al., 2021). The intensification of AFSC operations to fulfill the demand for off-seasonal and exotic products increases transportation and cold chain operations (Li et al., 2022).

Overall, the modern food industry and AFSCs are net emitters of GHGs and claimed contributors to global warming, reinforcing a vicious cycle that has already reduced global agriculture productivity by 21 % since 1961 (Ortiz-Bobea et al., 2021). This evidence emphasizes the mutual influence between the sustainable development of the agri-food industry and climate change. Addressing food security, food safety, and tackling climate change are sides of the same coin. Well-informed consumers and acknowledged AFSC actors may play their part in such a challenge (Notarnicola et al., 2017). The former demands low-carbon, nourishing, quality, and safe products, and the latter supplies such products at an affordable price whilst reducing the environmental burden. Nevertheless, without AFSC operations transparency and impact visibility, there is no control, and neither bottom-up (i.e., led by consumers) nor top-down (i.e., promoted by industrials) transitions toward a more sustainable food ecosystem are viable options.

Despite attempts to inform the consumer with nutritional, safety, and environmental labels, the fragmentation of AFSCs made of uncountable stages and geographically distributed players prevents the adoption of integrated traceability architectures that aid monitoring and control of processes, operations, and performance with a multi-dimensional perspective and the required level of trust and accuracy (Hoffmann et al., 2021; Kamble et al., 2020; Verdouw et al., 2016). The lack of standards in generating, collecting, and manipulating data also discourages companies from sharing information, affects transparency, and prevents quantitative assessment of food order indicators. Whilst Internet-of-Food-Things (IoFT) architectures are still technologically and economically unfeasible on a large scale (Gallo et al., 2021; Khan et al., 2023), digital twins (DTs) might virtualize AFSC processes and operations and aid such multi-dimensional assessment.

This study aims to explore the following Research Questions (RQs):

RQ1: What are the performance areas holistically impacting the AFSC, and what metrics supporting the practitioners' and consumers' decision-making should be considered in an integrated AFSC DT?

RQ2: How can a tailored DT aid industrial decision-making throughout AFSC and enhance consumer visibility and SC transparency?

RQ3: What advantages and inferences can food industry stakeholders draw from using real or simulated impact metrics compared to mean values?

To uncover the answers to these key inquiries, this paper integrates the framework proposed by Accorsi et al. (2022) and introduces a novel AFSC digital twin (DT) able to virtualize the agricultural, processing, storage, and distribution processes and operations holistically from-field-to-retailer. A literature review on AFSC DTs outlines the most recognized performance areas supporting the estimation of the tool's KPIs on economic, logistic, environmental, safety, and nutritional metrics associated with each food order.

The AFSC-DT incorporates Geographic Information System (GIS) and routing functionalities to deal with the logistic dimension of the food ecosystem. It enables real-time control of virtualized resources, flows, and orders through a control tower. It provides labels quantifying multi-dimensional indicators on the shelf life, the carbon-, energy-, land- and water- footprint, the labor and machine time, the transportation distance, the full cost, and nutritional properties. Different KPIs dashboards guide the consumer and practitioner in the decision-making process. To the authors' knowledge, the novel contribution of this framework lies in the extensive focus on all the AFSC steps, including the agricultural, storage, and transportation tasks, the flexibility in modeling and virtualizing any SC from primary data or generated instances, and the multidimensionality of the dashboard.

The remainder of the paper is organized as follows. Section 2 classifies the digital twins applied to the agri-food industry. Section 3 illustrates the AFSC-DT design methodology, the data architecture, the models, and the user interfaces. Section 4 provides a validation testbed inspired by a regional horticultural SC and provides insights into the AFSC-DT use and integration. Section 5 discusses the results, and Section 6 concludes the paper with suggestions for future developments.

2. Literature review

The digitalization, informatization, and virtualization of AFSC processes enable decision-making at different stages and perspectives through tailored decision-support tools. In this section, a literature review outlines the state-of-art on agri-food industry digital twins (DTs). Digitalization favors computing indicators and measures of performance, estimating impacts and externalities, and assessing decisional drivers, as classified in Fig. 1.

Different surveys on AFSC performance measurement found in the literature classify indicators in performance areas. Ivo de Carvalho et al. (2022) identified eighteen topics traceable to the three main areas of environmental, social, and economic indicators. Yadav et al. (2022) found sustainability, food waste, and safety and security to be the main focuses of performance metrics. The authors also stress the key role of consumer awareness and an increasing attention to the ethics along the SC, reflecting the need to quantitatively communicate to the consumer the associated product KPIs. Desiderio et al. (2022) explored the social dimension in agri-food systems, reviewing impact assessment tools and indicators across different SC stages and stakeholders. Despite the indicators classification in macro areas simplifies the performance evaluation, the different perspectives influence each other and, for a holistic approach, all the different aspects should be considered as components of an integrated food system (Perez-Vega, 2022).

Respecting the approach found in the literature on surveys of agri-food chain performance indicators, five dimensions of indicators can be recognized in the AFSC DTs body of literature. *Operations & Agro-Industrial performance* draw the cost efficiency considering the material flow and the physical transactions among the AFSC actors. *Nutritional & Nutraceutical properties* pertain to food micro- and macro-nutrients and food engineering, including the consumer's health and disease prevention awareness. *Food Safety & Quality* focuses on spoilage and quality preservation throughout the FSC operations. *Environmental Impact & Losses* indicators include AFSC externalities, such as exploitation of natural resources, power and water consumption, GHG emissions from transportation, processing, refrigeration, and agriculture. The *Social Impact & Food Security* dimension handles social concerns associated with labor employment, growers' and workers' welfare, and consumer awareness. Both *Food Consumer* and *AFSC Practitioner* can benefit from DT applications in these fields.

Operations & Agro-Industrial performance drive food production and distribution planning and control. Advancements in agriculture involve smart farming systems aided by DT to predict crop yields, deal with uncertain climates, and address adverse events (Gallego-García et al., 2023). Virtual crop irrigation allows saving water and implementing farming practices tailored to soil composition and crop evapotranspiration (Alves et al., 2023). In processing facilities, production line scheduling can benefit from DT by guaranteeing timely supplies, increasing machine utilization, and reducing costs (Koulouris et al., 2021). Others implement time-series analysis for optimal inventory planning (Melesse et al., 2022a). Besides the use of historical data, IoT embedded in a DT architecture enables real-time monitoring of perishable goods throughout cold chain logistics, supporting anomaly detection and warnings (Wu et al., 2023). Maheshwari et al. (2023) virtualize the task planning of a food vendor with regard to suppliers and customers, identifying market opportunities. Retailer's food sales are virtualized and explored by Burgos and Ivanov (2021) to enhance resilience and tackle market disruptions.

DTs are successfully applied to govern and assess *Nutritional & Nutraceutical* food properties. Genetic attributes, metabolic profiles, and gut microbiota features affect the individual's response to nutrients. Precise nutrition and functional foods aim to involve such aspects in defining a customized consumption profile. In such terms, DTs are applied to individuals to virtualize their body's response to given food nutrients. Using an individual DT, Gkouskou et al. (2020) determine

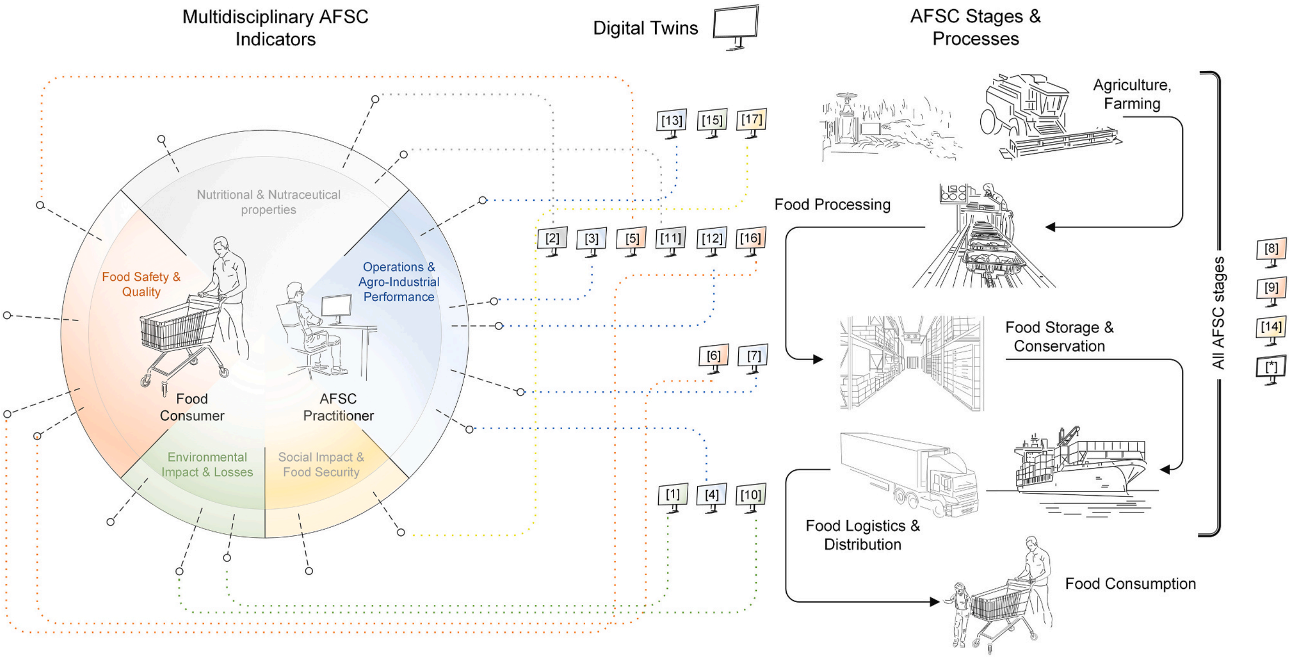


Fig. 1. Literature review framework.

Table 1

Survey of Digital Twins for the food industry. Legend: Supply stage virtualized: A-Agriculture/farming, P-Processing, S-Storage; D-Distribution, SC-Supply Chain as a whole. Industrial transfer readiness: C-Concept, P-Prototype, A-Application. Tool Flexibility: Y-Yes, N—No. Prescription/Prediction: S-Prescription, D-Prediction.

ID	Paper	Key Performance Indicators (KPIs)										
		O&AIP				EI&L				N&NP		
		SC Lead Times	SC Cost (Processing/ Logistics)	Saturation Level	Throughput	GHGs Emissions	Water Use	Energy Use	Food Waste	Macronutrients Content	Micronutrients Contents	Food Processing Level
[1]	T. Defraeye et al. (2019)								●			
[2]	Gkouskou et al. (2020)									●	●	
[3]	Koulouris et al. (2021)	●	●									
[4]	Burgos and Ivanov (2021)	●	●	●	●							
[5]	Kannapinn et al. (2022)											
[6]	Melesse et al. (2022b)											
[7]	Melesse et al. (2022a)		●	●								
[8]	Shoji et al. (2022)											
[9]	Onwude et al. (2022)											
[10]	Sengupta and Dreyer (2023)								●			
[11]	Cabeza-Gil et al. (2023)											●
[12]	Maheshwari et al. (2023)	●	●	●	●							
[13]	Gallego-García et al. (2023)	●	●		●							
[14]	Longo et al. (2023)				●							
[15]	Alves et al. (2023)		●				●					
[16]	Shrivastava et al. (2023)											
[17]	Slob et al. (2023)	●										
[*]	This paper	●	●	●	●	●	●	●	●	●	●	●

functional diets for healthy aging, disease prevention, weight loss, or mass gain. DTs find application in the setting and tuning of cooking devices to explore food's nutritional properties. For instance, Cabeza-Gil et al. (2023) trained a neural network-based DT to evaluate the dietary properties of French crêpes' preparation.

Cyber-physical twins are valid tools for investigating *Food Safety & Quality* changes during storage and distribution. A cyber-physical DT is a sensorized food reproduction collecting conservation profiles, such as hygrothermal conditions during handling and shipping. Onwude et al. (2022) designed an orange fruit twin to study how pre-harvest and post-harvest environments impact product quality. Shoji et al. (2022) monitored the cold distribution chain of several horticultural products through a cyber-physical twin to predict shelf life decay. Virtualizing the product's response to stresses aids the design of food packaging systems (Shrivastava et al., 2023; Accorsi et al., 2022). Such twins also enable simulations of processing tasks (Kannapinn et al., 2022). The advent of machine learning and efficient image processing paved the way for spoilage detection during and post-processing, as Melesse et al. (2022b) tried with banana fruit.

In the *Environmental Impact & Losses* assessment, DTs predict food losses. Defraeye et al. (2019) developed a mango fruit twin to predict maritime transportation losses. Others support retailer sales and operations planning to predict SC anomalies and reallocate food surplus for waste prevention (Sengupta and Dreyer, 2023). Still, estimating the neglected environmental burden associated with processing, storage, and transportation is an uncommon target of DTs. The assessment of carbon footprint is indeed left to other fields and methodologies like LCA.

To emphasize the *Social Impact & Food Security* aspects, DTs help evaluate alternative strategies to face food industry disruption (such as the COVID-19 outbreak) (Longo et al., 2023) or ensure demand fulfillment. DTs are also applied in workforce training at the farm (Slob et al., 2023). Table 1 outlines the main features of each DT built upon a dashboard of indicators, the AFSC focus, and the process's target, along with the proposed solution's *flexibility*, *generality*, and *applicability*.

The literature review reveals a scope limitation of the extant DTs applied to the food industry and a gap in terms of tool *flexibility*, virtualized AFSC *stages* and *performance dimensions* assessed. Within the observed DTs, one or a few performance dimensions are assessed at a time. Overall, environmental and social indicators are often neglected. Environmental impact assessment is hindered by the lack of awareness of the technologies involved in the operations, the exploitation of resources, and the emissions of pollutants. Environmental impact is usually assessed with tools like Life Cycle Assessment (LCA), commercial software built upon shared and updatable databases (Casson et al., 2023). Unfortunately, such databases are generalizable for their own nature, resulting from averages unrelated to a specific case. Better modeling and novel approaches are needed for AFSC planning and control (Sala et al., 2017). The same criticality affects evaluating social impact indicators in AFSC, which lack the required holistic perspective and a shared actors' awareness, as claimed by a recent survey (Desiderio et al., 2022). The resulting lack of visibility on the environmental and social dimensions of AFSC makes the consumer far from an active promoter of more sustainable AFSC practices.

Another limitation of the existing DTs lies in their emulated process and intended scope. A narrow scope prevents the DT's transferability and applicability to other environments (Tancredi et al., 2023). Focusing on a particular AFSC's process neglects the externalities affecting other actors or layers. The lack of holistic tools for AFSC and multi-dimensional performance assessment is indeed well-stated by the literature (Yadav et al., 2022). Understanding, formalizing, and modeling such highly complex systems is still ambitious, and a flexible and integrated DT is missing.

This paper addresses this gap by illustrating an integrated, flexible, and holistic DT for virtual AFSC. The novel contribution lies in (1) the virtualized AFSC stages from agriculture to retailers, (2) the customizable and reconfigurable networks, the multiple products handled, and (3) the ability to estimate multi-dimensional economic, environmental, nutritional, and social performance. The considered functional unit (FU) is a generic food order characterized by a product, a demand weight, a supplier, and a final customer. The DT virtualizes thousands of food orders per scenario. Each order is tracked throughout different processes and operations, and resulting KPIs are measured and estimated as long as workers, vehicles, and facilities handle the FU. Multiple decisional levers and scenarios can be virtualized and tried, including variable food demand, consumers' diet and habits, changing climate conditions affecting crop yields, enhanced or dropped processing, storage, and distribution capacities throughout the SC network. The proposed DT

Key Performance Indicators (KPIs)							AFSC focus		Tool scope		
FS&Q				SI&FS							
Shelf life	Processing Parameters	Biochemicals & Microorganisms	Cold Chain Preservation	Working Load and Workers Wellness	Traceability Label	Sustainability Label	User	Virtualized Stages	Industrial transfer readiness	Tool Flexibility	Prescription/ Prediction
							P	D	P	N	D
							C	P	C	Y	D
							P	P	P	N	D
							P	D	P	N	D
	●						P	P	C	N	D
●			●				P	S	P	Y	D
							P	S	P	N	D
●			●				P	SC	C	Y	D
●		●					P	SC	C	N	D
							P	D	C	N	S
							P	P	P	N	D
							P	P	P	N	S
							A,P	A	C	N	S
						●	P	SC	P	N	D
							A	A	P	Y	S
●		●	●				P	P	P	N	D
				●			A,P	A	P	N	D
●	●		●	●	●	●	A,P, C	SC	P	Y	D

aids decision-making by providing a holistic control tower intended for planners, practitioners, and policymakers with operational, tactical, and strategic outlooks on the food ecosystem and consumers who might be informed of the impacts beyond their food basket with a tailored multi-dimensional label.

3. Methods and materials

3.1. AFSC virtualization framework

A multi-dimensional framework inspired by the control-system theory extends Accorsi et al. (2022) and provides an overview of *boundaries* and *targets* of the proposed AFSC-DT. The *boundaries* consist of the extended geographic area where agricultural, processing, and distribution operations take place. Subject to specific climate conditions, such an area provides natural resources (e.g., irradiance, water, and soil) and experiences environmental externalities associated with food operations and consumption. Responsible for AFSC processes, *Entities* like facilities, infrastructures, and resources (i.e., humans, machines, devices, vehicles) are modeled and virtualized in the AFSC-DT. Their attributes are organized within an interdisciplinary database, feeding the AFSC-DT, enabling acquisition and manipulation through distributed sensors or other data communication gateways (e.g., RFID tags, companies' ERP systems).

Table 2
DT KPIs overview. Entity.Property (Legend: A: Agronomist, P: SC Practitioner, C: Consumer).

	KPI	Formula	UoM	A	P	C	KPI	Formula	UoM	A	P	C
Operational Indicators	Agricultural water use	$\frac{f^{pp}.IrrigationWater}{f^{pp}.Harvest}$	m^3/kg	●			Queuing orders	$f.IB.count$	$Orders$		●	
								$f.WIP.TotQty$	kg		●	
		$\frac{f^{pp}.IrrigationWater}{f^{pp}.Hectares}$	m^3/he	●			Processing orders	$f.WIP.count$	$Orders$		●	
								$f.WIP.TotQty$	kg		●	
	Solar Irradiation	$\frac{f^{pp}.TotSolarRadiation}{f^{pp}.Harvest}$	kWh/kg	●			Capacity utilization	$f.Saturation$	$[0,1]$		●	
		$\frac{f^{pp}.TotSolarRadiation}{f^{pp}.Hectares}$	kWh/he	●			Cost	$f.TotCost$	€		●	
								$f.Cost(t)$	€		●	
	Rainfalls	$\frac{f^{pp}.TotPrecipitation}{f^{pp}.Harvest}$	m^3/kg	●			Power consumption	$f.TotEnergy$	kWh		●	
								$f.Energy(t)$	kWh		●	
		$\frac{f^{pp}.TotPrecipitation}{f^{pp}.Hectares}$	m^3/he	●			Water consumption	$f.TotWater$	l		●	
								$f.Water(t)$	l		●	
Tactical and Strategic Indicators	Land Use	$\frac{f^{pp}.Hectares*10000}{f^{pp}.Harvest}$	m^2/kg	●			Order cost	$o.Cost$	€		●	
	Harvest	$f^{pp}.HarvestQty$	kg	●	●		Order Resources	$o.Energy$	kWh		●	●
		$f^{pp}.HarvestDate$	$time$	●	●			$o.Water$	l		●	●
	Order status	$o.status$ (Late/Delivered/ Expired)	$label$		●		Environmental impact	$o.ShippingCO_2$	$g\ CO_2$		●	●
								$o.TotalCO_2$	$g\ CO_2$		●	●
	Transported, Stored and Processed Order	$o.TravelledKm$	km		●	●						
		$o.VisitedFacilities$	$Facility$		●	●	Labor impact	$o.HumanLabor$	$hours$		●	●
		$o.TotalSCTime$	$hours$		●	●						
		$o.ShippingTime$	$hours$		●	●	Packaging	$o.PackCost$	€		●	
		$o.StorageTime$	$hours$		●			$o.PackWater$	l		●	●
		$o.ProcessingTime$	$hours$		●			$o.PackCO_2$	$g\ CO_2$		●	●

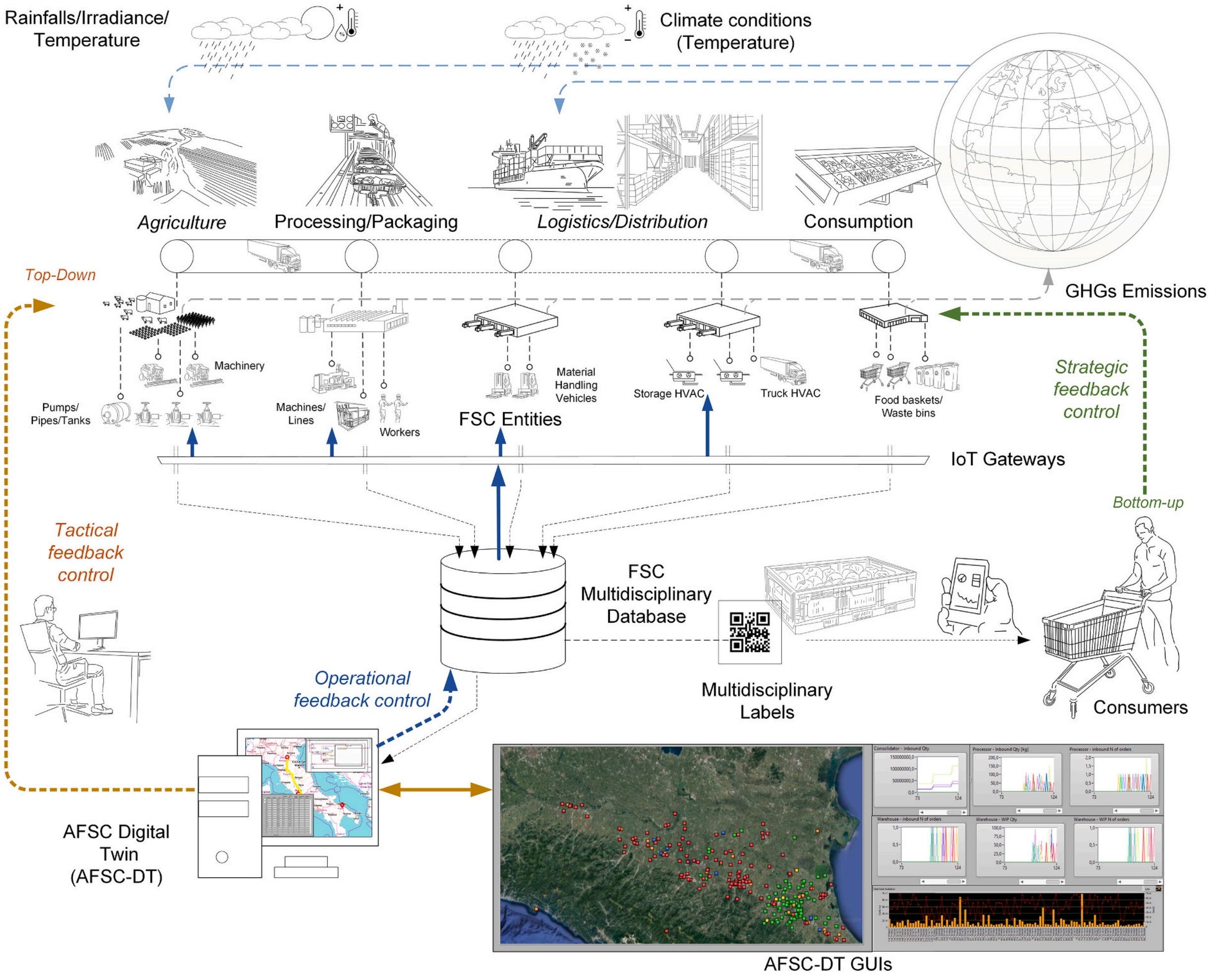


Fig. 2. FSC virtualization framework (extended from Accorsi et al., 2022).

The interdependences between the AFSC system and the environment result in a vicious impact: the increasing footprint of AFSC operations enhances global warming, exacerbating natural resource exploitation and reducing productivity in the long term (Filho et al., 2022). Three AFSC-DT *targets*, named feedback loops, contribute to tackling such a vicious cycle. A first *operational feedback loop* is triggered by sensorized resources/entities controlled in real-time by process setpoints. The setpoints depend on the state variable of the controlled device, such as the throughput of a packaging line or the target temperature of the HVAC system for a reefer chamber.

The mid-term planning of AFSC operations is achieved through the *tactical feedback loop*. Scheduling truck departures to satisfy First-Expiring-First-Out (FEFO) policy (instead of FIFO) to prevent food losses, or allocating processing capacities to fulfill incoming orders are examples of tactical levers handled by practitioners. Lastly, informed consumers may opt for more sustainable food baskets and dietary habits, sustaining environmental- and social-friendly SC operations, leading to a bottom-up transition of the agri-food industry. The latter represents a *strategic feedback control* implemented by consumers. The following methodological sections illustrate how these three *feedback* loops are implemented in the AFSC-DT.

3.2. Interdisciplinary database

The AFSC-DT data architecture is developed via a SQL relational database whose main attributes are simplified in the Entity-Relationship diagram in Fig. 3. This reflects the AFSC entities and their relationships. According to the Object-Oriented (O—O) programming paradigm, each entity is designed as a *class*. The class members (properties) are linked to the features of the associated tables (e.g., ID, facility throughput, temperature setpoint of storage chambers, truck's loading capacity).

The AFSC's entities are classified as *Facilities* and *Orders*. *Facilities* include the actors/stages of the food industry, distinguished by *type*, such as farms, consolidation facilities, processing/packaging systems, distribution centers, and Points of Demand (PoDs). Class inheritance facilitates the design of *Facility* classes: the parent class contains the common features (e.g., ID, Latitude, Longitude, Address) and methods, whilst a son class is specified for any *facility-type*. The *Primary Production Facility* is committed to the agricultural phases or livestock farming. Two modeling alternatives are implemented. In the case of climate-sensitive crops, yield, throughput, or impacts result from estimating methods encapsulated into the Facility class's members. Otherwise, like in farms or aquacultures, the facility performance is inherited from the properties retrieved from the database. Raw food is then consolidated into *consolidation-facility* (e.g., a consortium, a service temporary warehouse), which clusters producers' supplies until an order is released by the distribution channels (e.g., retailer, gross market). Food orders are handled by the *ProcessingFacility* (f^P), which is responsible for treating like washing, cutting, heating, cooking, and packing. A *StorageFacility* (f^S) receives packaged products and organizes the shipments to *Retailers*, distribution channels, or other PoDs.

The FU is a food order o supplied in response to a PoD's demand. Orders $o \in O$ are characterized by a product ID and a size (i.e., kg), a target due date/lead time, a destination f^r, and an origin as a

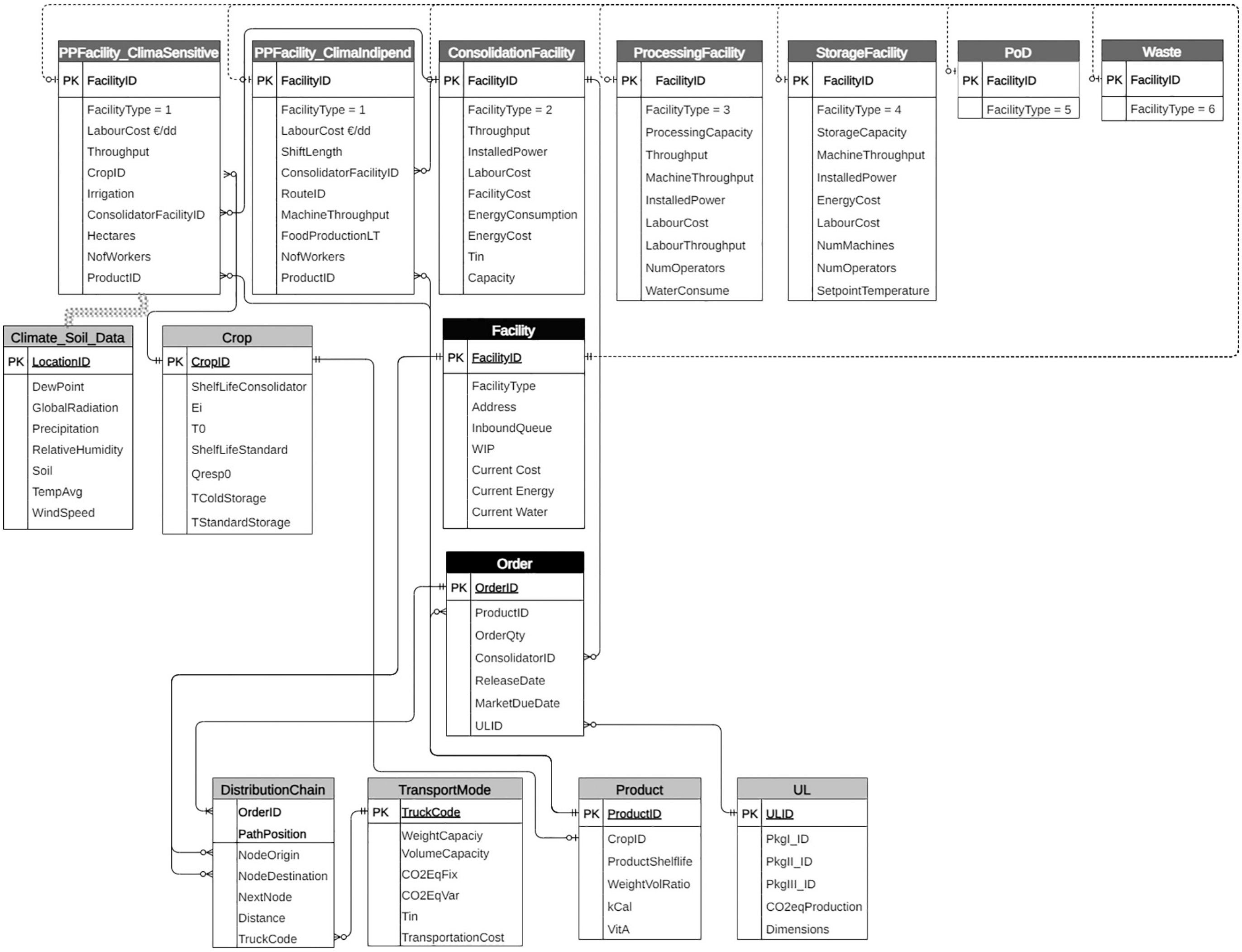


Fig. 3. A simplified view of the database *E*-R diagram.

consolidator f^c. The composition of the packaging hierarchy (i.e., boxes and tertiary package) required to estimate truckload utilization is set in the *Unit-load* table. The path followed by each *Order o* throughout the FSC is given by the *Distribution-chain* table, which defines the sequence of arcs in the route from f^c to f^r and details like the vehicle type. Lastly, food products are mapped in table *Product*, which provides parameters as shelf life and nutrients.

3.3. AFSC modeling and virtualization

The AFSC-DT simulation methodology follows the scheme in Fig. 4. Preliminarily, the decision-maker imports the data, sets the simulation calendar and clock, and the metrics update frequency. The calendar specifies the starting date, which affects all the climate-sensitive entities and processes (e.g., crop yield, primary production, temperature-driven food spoilage). The scalable clock connects the iterative loop frequency to a time horizon (e.g., an hour, one day). Objects generated by the facilities' classes, products, crops, and distribution arcs are instanced setting their attributes.

The DT virtualizes food production and distribution, addressing peculiarities characterized by products and shelf life, the sequence of visited facilities (and their capacities), the processing/packaging cycles, technology, and throughputs, and the type of transportation vehicles. The FSC network's geography is a pivotal dimension as it influences the order indicators in terms of traveled distance, SC lead time (SC LT), shelf life decay, and the harvested yield influenced by environmental temperatures. Food is classified into two main families (i.e., crops vs. livestock-based and industrial products), distinguished by the sensitivity of the primary production in f^{pp} to climate conditions. To rule yields and harvest time, an agronomic forecasting method (f^{pp}*.cropYield)* based upon site-driven climate and soil parameters is implemented. This method follows the FAO Crop Yield Response to Water paper (Steduto et al., 2012) that considers irrigation and rainfall to balance plant *evapotranspiration* given soil and climate characteristics. Evapotranspiration (*ET*) is the combination of two water losses experienced by the plant: soil surface evaporation and crop transpiration. The available crop yield (Y_a) differs from the maximum crop yield (Y_m) according to the following empirical relationship between crop yield and available water:

$$\left(1-\frac{Y_a}{Y_m}\right)=ky\left(1-\frac{ET_a}{ET_m}\right) \tag{1}$$

where ET_m is the maximum evapotranspiration that occurs in optimal soil moisture conditions, and ET_a is the actual evapotranspiration. *ky* is an empirical factor specific to each crop. According to (1), in ideal hydration conditions $Y_a = Y_m$, notwithstanding that Y_m depends on soil composition and solar radiation. ET_a is estimated through the Available Soil water Index (*ASI*), which expresses the fraction of time (i.e., month *i*) when the available water meets the requirements considering the

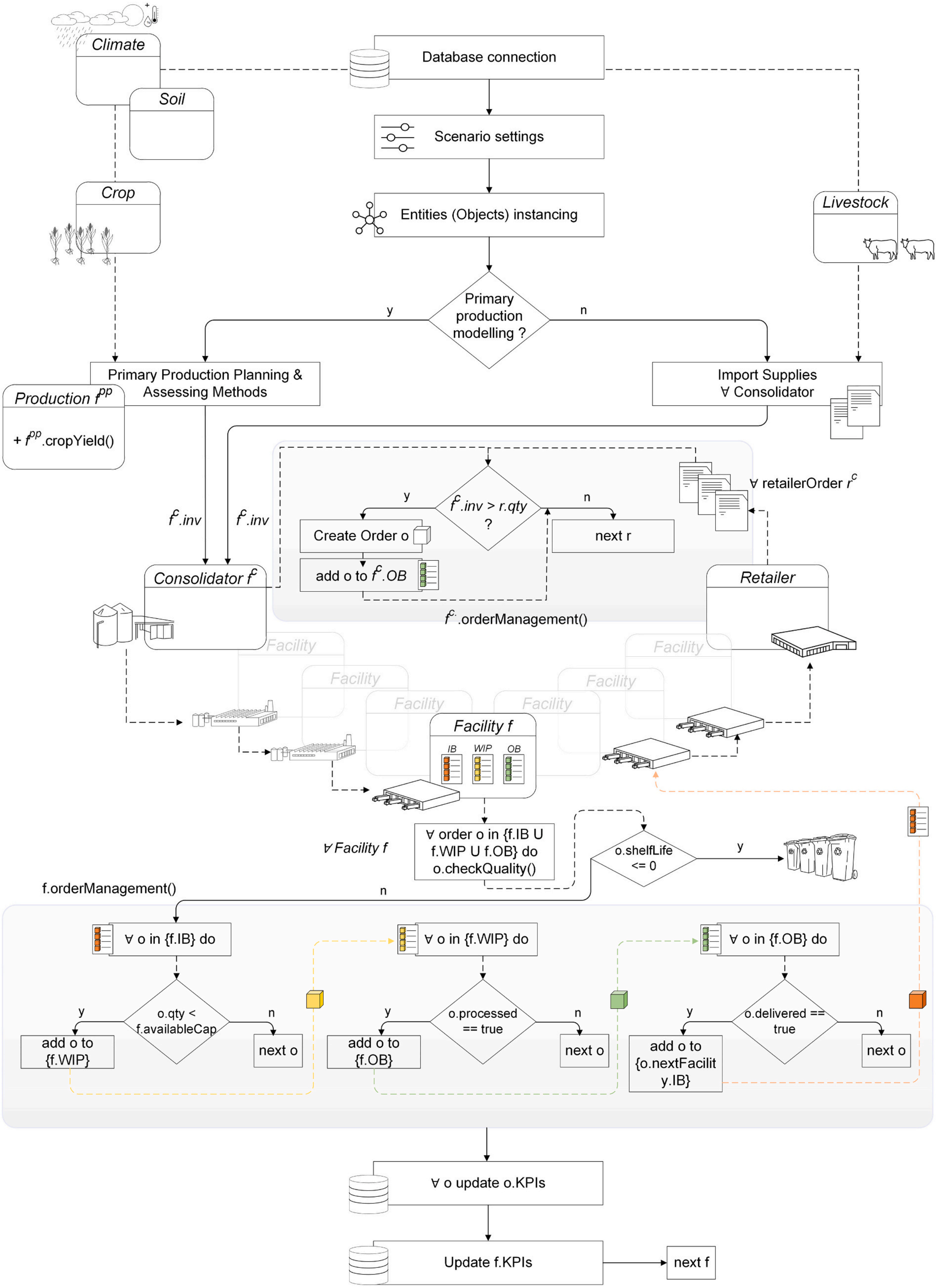


Fig. 4. DT architecture and layers integration.

monthly irrigation In_i [mm] and the rainfall Pe_i [mm]:

$$ASI(i) = \frac{In_i + Pe_i + Wb_i - D_i}{ET_m(i)} \in [0, 1] \tag{2}$$

Wb_i is the depth of water at the beginning of the month, whilst D_i is the remaining water that depends on the root depth.

$f^{pp}.cropYield$ evaluates Y_a for every planting month (1 to 12), identifying the peak. Found the month, the harvesting day is coherent with the irradiance, rainfall and irrigation from sprout to maturation stage. The harvesting activities are subjected to labor constraints, i.e., the available workers $f^{pp}.nw$ and the daily labor throughput $f^{pp}.thr_{day}$. The maximum daily harvest $f^{pp}.dailyQty$ in kg/day results from the following:

$$f^{pp}.H_{dailyQty} = f^{pp}.nw \cdot f^{pp}.thr_{day} \tag{3}$$

In order to avoid field ripening, a harvest calendar is generated per each f^{pp}. The shortest harvesting period (days) is:

$$f^{pp}.H_{days} = \frac{f\ pp.Y_a}{f^{pp}.H_{dailyQty}} \tag{4}$$

For any other livestock or processed food, the supplies from f^{pp} to a consolidator f^{c} are not sensitive to the climate conditions and are set from the database over the time horizon.

An iterative loop implements the simulation, virtualizing the continuous time in scalable units. At each iteration, class methods evaluate and update the properties of *Orders* $o \in O$ and *Facilities* $f \in F$ resulting from virtualized harvesting, processing, packaging, handling, warehousing, and transportation.

The interaction between *demand* and *supplies* is a pivotal pattern in any SC simulation (Tordecilla et al., 2021). In the proposed AFCS-DT, demand is released at each period from each PoD f^{r} to a specific consolidator f^{c}. Each consolidator f^{c} behaves as a buffer until an o is received. The consolidators f^{c} couple the supplies, pushed by the agricultural phase sensitive to seasonality and climate, with the demand, pulled by the market, performing several operations and services like cold (i.e., fresh food) or bulk storage (i.e., food commodities). A new Order o is instanced whether the origin consolidator inventory $f^{c}.inv$ is greater than the request $o.qty$. The Order's attributes also include the multi-dimensional indicators summarized in Section 3.4.

Orders o are handled throughout the virtual SC by the *f.orderManagement()* method. As facilities provide different services, a peculiar definition of such a method is implemented per each facility type. Overall, *f.orderManagement()* manages $o \in O$ using three queues per each facility *f*. An inbound queue, *f.IB*, contains orders waiting at the inbound. Order *o* belongs to *f.IB* until enough capacity (i.e., processing, handling, warehousing) is available for service. The *f*.WIP queue contains Orders-in-Progress during a certain task (e.g., processing, storage). The lead time of *o* in *f*.WIP is a function of *o.qty* and the facility throughput. For example, in processing *Facilities* the throughput depends on the processing line and labor time. The order lead time in a f^{p} facility is quantified as follows:

$$o.WIPtime_f = max\left(\frac{o.qty}{f^{p}.machThr}; \frac{o.qty}{f^{p}.laborThr}\right) \tag{5}$$

At Facility f^{p}, labor, energy, water, and machines are employed to transform *o* into a finished batch to deliver. Warehouses f^{w} are visited for consolidation and buffering. An outbound queue *f.OB* contains the orders departed from *f* but not yet at the destination, i.e., the queue $f^{next}.IB$ of the next facility f^{next}. The sequence of facilities to visit is set as order property o.*distributionChain*. Dynamic dispatching and methods' delegates enable the DT to invoke a method from a parent class according to the calling method (belonging to the child class). Therefore, f^{next} does not necessarily coincide always with the same facility but is arbitrarily set and tailored to each order's path. This guarantees flexibility in the sequence of visited facilities per each *o*.

Throughout the FSC's operations, orders bear environmental conditions that accelerate shelf life decay. Each *Product p* is characterized by a nominal shelf life *p.shelflife₀* at the ideal temperature $p.T_0$. At T_0 the microorganism's proliferation activity is minimized without affecting the inside structure of the product. The sensitivity of food quality to temperature is expressed by the Q_{10} coefficient, which represents the factor by which the degradation rate increases with a temperature growth of 10 °C:

$$o.Q_{10} = e^{\frac{p.E_a}{R}\left(\frac{10}{(p.T_0+10)p.T_0}\right)} \tag{6}$$

$p.E_a$ is the activation energy (kJ/mol) of *Product p* degradation reaction, and *R* is the ideal Boltzmann gas constant. At each iteration (i.e., after each period *t*), the status of the order's remaining shelf life (*o.shelflife*) is estimated as a result of the experienced thermal stresses (i.e., temperature $o.T_t$). Given $o.Q_{10}$, the percentage shelf life decay of *Order o* of *Product p* in a period *t* is:

$$o.loss\%_t = 100 \Bigg/ \frac{R \cdot p.T_0}{o.Q_{10}^{\frac{o.T_t - p.T_0}{10}}} \tag{7}$$

where the remaining shelf life is evaluated as follows:

$$o.shelflife_t = o.shelflife_{t-1} - o.loss\%_t \cdot p.shelflife_0 \tag{8}$$

Each order is sent to disposal and labeled as spoiled if *o.shelflife* is under a certain threshold (i.e., zero by default). After each iteration, the status of Orders and Facilities is updated, and associated indicators are quantified and stored in the database for manipulation.

Besides food quality indexes, products' nutrients can be assessed through a tailored vitamin and mineral index (*VitMineral Index*). Such index accounts for the main vitamins (i.e., VitA, VitB1, VitB2, VitB3, VitB6, VitB9, VitB12, VitC, VitE, and VitK) and minerals (i.e., Potassium, Phosphorus, Calcium, Magnesium, Manganese, Iron, and Zinc) required in a balanced diet (WHO and FAO, 2001). Each micronutrient *m* content is evaluated for 1 kg of product *p* as follows:

$$Content\%_{m,p} = \frac{m\ in\ 1\ kg\ of\ p}{m\ daily\ reccomended\ dose} \tag{9}$$

The *VitMineral Index* of a product *p* is defined as the average of all the micronutrients' $Content\%_{m,p}$ for such product.

3.4. Multidisciplinary indicators

The AFSC performance indicators (KPIs) pertain to several disciplines and dimensions, as outlined in Fig. 1. Decision-making requires tailored data visualization and control tower interfaces (see Fig. 5). KPIs' cross-cutting nature entails different decision-making stages and actors. The consumer is informed by *Nutritional & Nutraceutical properties*, *Food Quality* metrics, and *Environmental Impact* that might drive purchasing habits and conscious choices, reinforcing a bottom-up transition toward more sustainable targets, i.e., *strategic feedback* Control. Estimating Food Safety, Food Security, and SC indicators enhances practitioners' visibility upon cost and inefficiency, leading to a *tactical feedback* control of production and logistic operations. The *tactical feedback* is handled by managers and practitioners who focus on operational and organizational issues resulting from tactical considerations on bottlenecks and industrial inefficiencies. Mid-term decisions regarding the future distribution path of the orders, the capacity of processing and warehousing facilities, or the location where to consolidate crops are examples of tactical feedback to prevent food losses and increase food security. Lastly, whether properly transmitted via PLC or physical actuators, Operations & Agro-Industrial performance indicators aid real-time control of the entities toward variables' setpoints, i.e., *operational feedback*.

The control tower in Fig. 5 offers real-time visibility of the entities

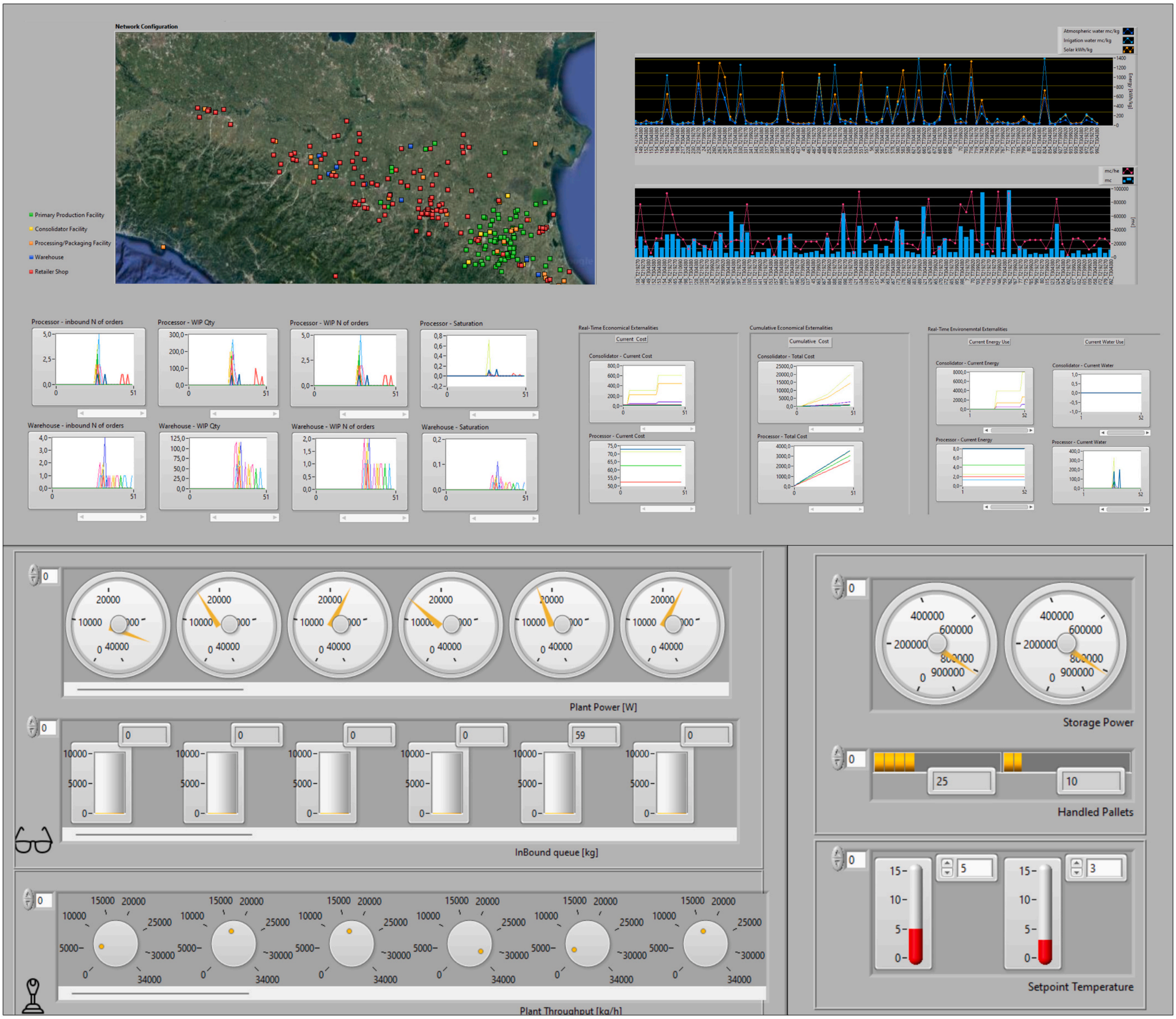
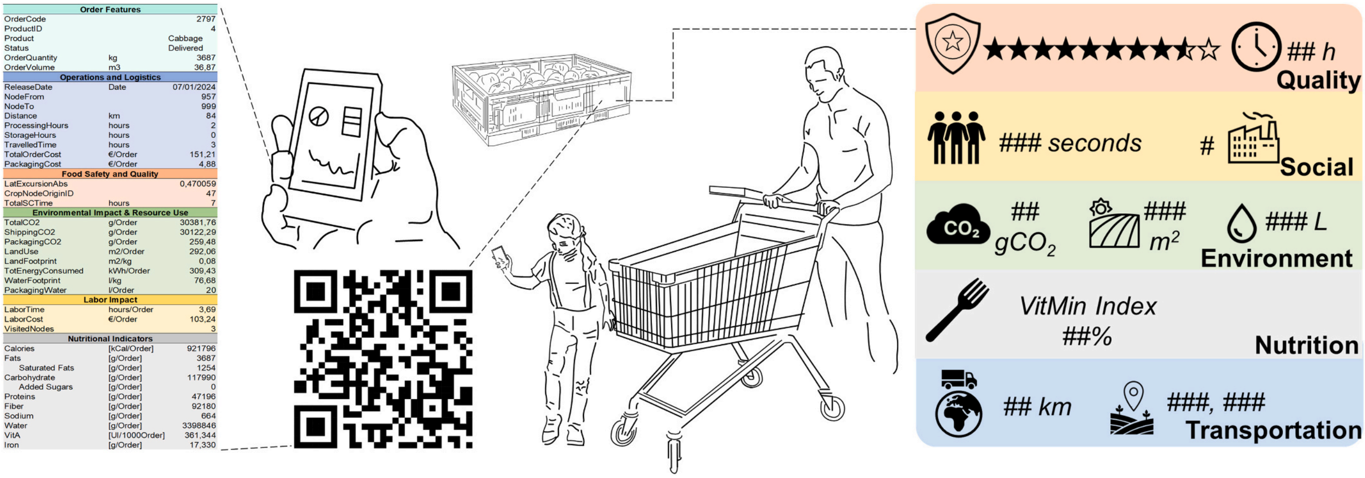


Fig. 5. AFSC-DT control tower and Graphic User Interfaces (GUIs).



Order Features		
OrderCode		2797
ProductID		4
Product		Cabbage
Status		Delivered
OrderQuantity	kg	3687
OrderVolume	m3	36,87
Operations and Logistics		
ReleaseDate	Date	07/01/2024
NodeFrom		957
NodeTo		999
Distance	km	84
ProcessingHours	hours	2
StorageHours	hours	0
TravelledTime	hours	3
TotalOrderCost	€/Order	151,21
PackagingCost	€/Order	4,88
Food Safety and Quality		
LatExcursionAbs		0,470059
CropNodeOriginID		47
TotalSCTime	hours	7
Environmental Impact & Resource Use		
TotalCO2	g/Order	30381,76
ShippingCO2	g/Order	30122,29
PackagingCO2	g/Order	259,48
LandUse	m2/Order	292,06
LandFootprint	m2/kg	0,08
TotEnergyConsumed	kWh/Order	309,43
WaterFootprint	l/kg	76,68
PackagingWater	l/Order	20
Labor Impact		
LaborTime	hours/Order	3,69
LaborCost	€/Order	103,24
VisitedNodes		3
Nutritional Indicators		
Calories	[kCal/Order]	921796
Fats	[g/Order]	3687
Saturated Fats	[g/Order]	1254
Carbohydrate	[g/Order]	117990
Added Sugars	[g/Order]	0
Proteins	[g/Order]	47196
Fiber	[g/Order]	92180
Sodium	[g/Order]	664
Water	[g/Order]	3398846
VitA	[UI/1000Order]	361,344
Iron	[g/Order]	17,330

Fig. 6. Multi-dimensional QRCode and informing label.

Table 3
What-if multi-scenario analysis: examples of drivers and features.

Drivers	Feature Value	SC stages
SC length	Direct	1 stage: f^c - f^r
	Short	2 stages: f^c - f^p - f^r
	Medium	3 stages: f^c - f^p - f^s - f^r
	Long	4 stages: f^c - f^p - f^s - f^s - f^r
	Distributed	5 stages: f^c - f^p - f^s - f^s - f^s - f^r
Level of Centralization	Low	10 available f^s
	High	1 available f^s
Lead Time	1-to-1	order release - order delivery ≤24 h
	1-to-2	order release - order delivery ≤48 h
	1-to-3	order release - order delivery ≤72 h
	1-to-4	order release - order delivery ≤96 h

and processes virtualized by the AFSC-DT and quantifies the metrics summarized in Table 2. It provides the grower/farmer with climate data, like daily rainfalls and solar irradiance, and soil features required to predict crop yields, preserve water, and predict the harvesting period. The production and logistics managers benefit from the utilization (i.e., %) of processing and storage capacity or the bottlenecks (i.e., queues state), aiding workflow balancing throughout the SC network. Costs and shelf life are estimated for each o in agreement with the temperature experienced throughout the operations.

On the consumer's side, carbon and water footprints are quantified per each o, as nutrient content traveling distance, energy consumption, and labor time. Such information is encoded within a QR code and a multi-dimensional label, printed over the primary packaging, as exemplified in Fig. 6. The visualization of the externalities behind each food basket's product drives the consumer toward more sustainable consumption choices (Majer et al., 2022).

3.5. *Developing languages and software*

The proposed DT is developed using the OO paradigm in G language for LabVIEW NI, a licensed graphical programming environment used to develop automated acquisition and device control systems. LabVIEW enables easily automating sensors, instruments, and devices regardless of vendor or connection and provides embedded libraries for controlling and communicating with common industrial equipment and third-party hardware and protocols (TCP/IP, Ethernet, USB, Serial, VISA, etc.) as for the FSC entities of Fig. 2. It also favors the connectivity to enterprise data management solutions supporting industrial IoT. Developers can add algorithms, data analytics routines, and connections to other scripts written, for example, in Python, C, and .NET languages. Whereas real-time acquisition from on-field connected sensors and instruments is not possible, data are gathered from a MS SQL server database accessible via ODBC proxy. The relational database is developed according to the *E*-R diagram of Fig. 3. GUIs are also developed in LabVIEW, whilst QR label generated from the simulation is readable by a generic optic reader installed in the consumer's cell phone as an Android OS app.

4. Validation and application

The tool validation aims to showcase the performance implications across various logistic network configurations. Authentic data pertaining to orders, products, and network geography features are sourced from multiple food industry players. On the other hand, the delivery features of each order are defined according to the chosen setting of the key logistic levers to stress and analyze. The different distribution choices and constraints produce four different scenarios. The following paragraphs will present the real-world network features and the different characteristics of the four scenarios.

The selected case study is inspired by a regional retailer AFSC. The emulated SC network is spread over Emilia-Romagna, a fertile region with plenty of medium and small growers in the North of Italy. The demand is gathered and collected from the retailer ERP per each PoD. In the proposed proof-of-concept, nine different horticultural products are virtually distributed to consumers to fulfill an orders profile. Orders $o \in O$ are generated via the Monte Carlo method based on the Probability Density Functions of the product's demand per shop. The network consists of farms, facilities, and PODs; their harvesting, processing, storage, and handling capacities are fixed and defined according to the real-world configuration.

According to the flexible design approach, the decision-maker can arbitrarily assign crops to a farm location. In the designed case study, crops are assigned to growers until a target (or expected) seasonal demand is met according to predicted yields. Annual planting and harvesting times are suggested for each f^{pp} to maximize the yields, as in Vanuytrecht et al. (2014). Crop yield is estimated by the DT via an agro-climate forecasting method based on rainfalls, solar irradiance, temperature, and a series of plant and soil parameters, as illustrated in Section 3.

In relation to the configurated scenarios, Table 3 outlines the key logistic levers in the design of AFSCs (Surucu-Balci and Tuna, 2021; Yadav et al., 2022). These drivers pertain to the geographical (i.e., supply chain length) and temporal (i.e., imposed delivery lead time) extensions of the SC, and the centralization level of the network. The real-world demand profile is a combination of these three features. In order to study the implications that such logistic drivers have on the orders performance, the selected scenarios are defined according to distribution solutions at the extremes of the driver domain. Table 4 states the four scenario features, showcasing the level (%) of each selected value per each feature.

In the first scenario (*Overstressed*), orders travel through long distribution chains but with a short window of time available to reach the PoD. The *Centralized* scenario has only one distribution center, with short SCs and tight time windows. The Long and Short scenarios have

Table 4
Resulting scenarios characteristics.

Scenario	SC drivers			Facilities Type					Orders n.
	SC length	Level of Centralization	LT	f^{pp}	f^c	f^p	f^s	f^r	
Scen01 – *Overstressed*	Short 15 % Medium 35 % Long 50 %	Low	1-to-1 55 % 1-to-2 45 %	60	9	22	10	138	4157
Scen02 – *Centralized*	Direct 35 % Short 45 % Medium 20 %	High	1-to-1 55 % 1-to-2 45 %	73	9	22	1	138	4152
Scen03 – *Long*	Short 15 % Medium 35 % Long 50 %	Low	1-to-3 45 % 1-to-4 55 %	66	9	22	10	138	4155
Scen04 – *Short*	Direct 35 % Short 45 % Medium 20 %	Low	1-to-3 45 % 1-to-4 55 %	69	9	22	10	138	4159

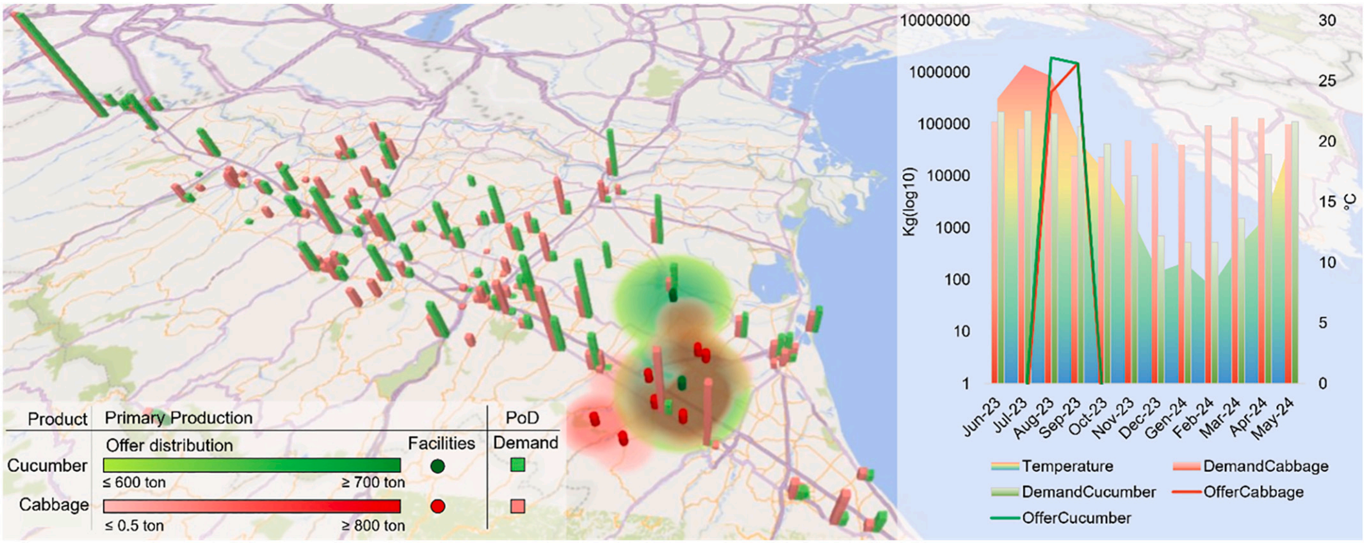


Fig. 7. Typical horticultural offer and demand spatial and temporal unbalance.

more relaxed time constraints, with long and short SCs, respectively.

Fig. 7 exemplifies the spatial configuration of the horticultural offer and demand (i.e., in Scen04) for two horticultural products. The map draws the geographic location of PODs f^r and growers f^{pp} underlining the growers' density, their small and medium size, and the imbalance across the region with respect to the demand. Such imbalance is not only spatial but temporal as the harvest is concentrated within the favorable season (e.g., summer for cucumber and autumn for cabbage at these latitudes), whilst demand mildly covers the year. Cold SC systems, enabled by refrigerated consolidation facilities f^c, fulfill off-season demand, extending shelf life and coupling offer and demand. Such aspects are all modeled in the proposed DT.

4.1. Results

Results from the simulation concern different outlooks aiding *operational*, *tactical*, and *strategic* feedback. As shown in Fig. 5, indicators for facilities, lines, and resources like capacity utilization, costs, power, and water consumption, and GHG emissions are plotted in real-time in the DT control tower. Orders' indicators are tracked and stored in the database for a-posteriori analysis by the practitioner (i.e. *Tactical feedback*). In the testbed, GHG emissions account only for FSC operations (i.e., processing, refrigerated storage, and transportation) even though the AFSC-DT can easily quantify agricultural pollution by considering specific process attributes.

Cross-analysis among multi-dimensional indicators is possible. Fig. 8 investigates how different distribution scenarios affect the SC's capability to fulfill the demand and address food security. Per each scenario and product, the percentage of orders delivered, late, or spoiled is plotted. The chart also reports the ratio of a product's shelf life over an annual period, as a measure of the product's lifespan under refrigeration in the consolidator f^c at a nominal temperature. The unmet demand is sensitive to the product and the distribution scenario, pointing to possible causes of food insecurity. For example, the % of fulfilled orders grows with the cold storage's lifespan. This confirms that increasing the refrigerated storage capacities at the early SC stage allows balancing temporal offer-demand mismatch, particularly for durable products (e.g., *Maize*, *Onion*, and *Potato*). Beyond the chart, the DT even quantifies the refrigerated storage need for each product and consolidation facility f^c assessing how their location, power, and size influence logistic costs and environmental externalities. Considering the kCal not supplied to consumers (in orange in Fig. 8), the comparison between products highlights opportunities for reconfiguring the logistic network with the attempt to facilitate the provision of calorie-dense o and reduce food insecurity. The overstressed *Scenario 1*, characterized by short TLT and longer distribution paths, experiences late deliveries despite the broad availability of distribution centers.

Fig. 9 compares the product-related indicators across the four scenarios. The order size varies in agreement with the product's demand and year-round availability. The distribution costs in *Scen01* and *Scen03*, characterized by multiple SC stages, are triple than the others' despite longer traveling occurring in *Scen02*. Indeed, the centralization of warehousing prevents shorter transportation routes, demonstrating how the strategic configuration of the logistic network affects costs and externalities sensibly. Considering the provision of nutrients, all nine horticultural products present high fibers-, vitaminic-, iron- and protein-contents, and the four scenarios fulfill the demand properly, with the exceptions of *eggplant* and *radish*, characterized by short shelf life.

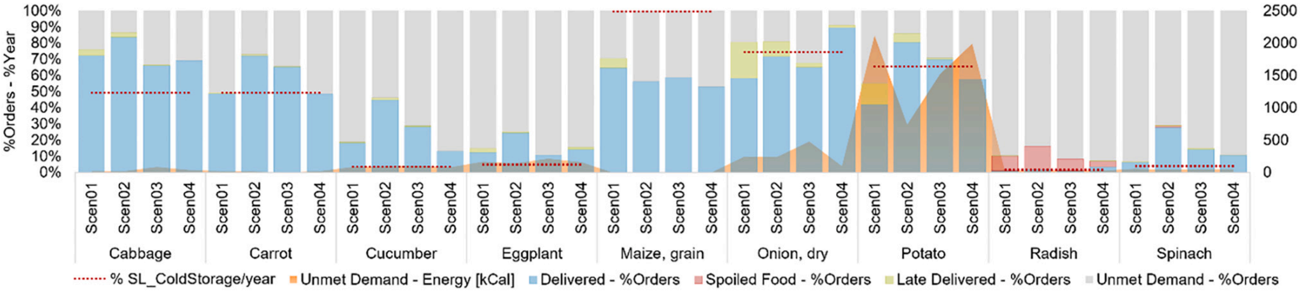


Fig. 8. Demand fulfillment and food security performance: Scenarios indicators.

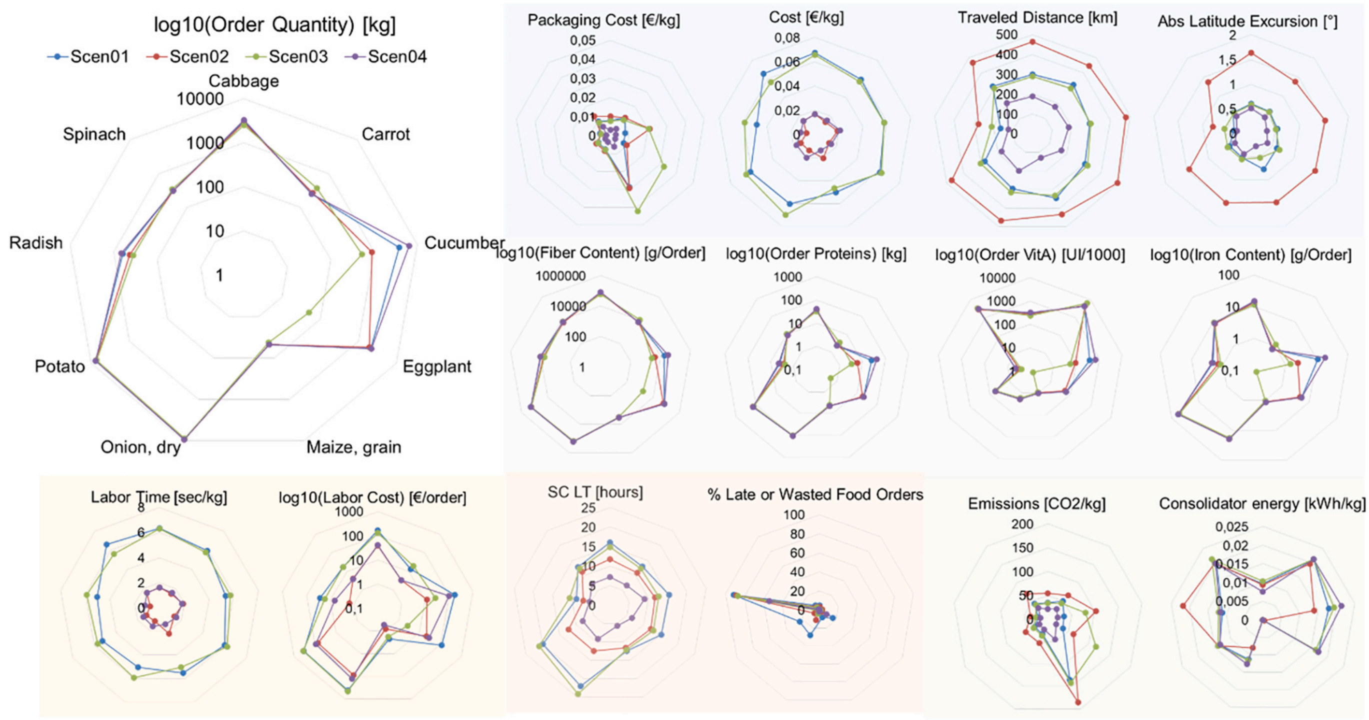


Fig. 9. What-if multi-scenario analysis: Products indicators.

Social impact indicators are quantified in terms of labor time and cost. The number of SC stages combined with the product's average harvest rate increase labor involvement, quantifying employment opportunities in the food industry and enabling a comparison among different agricultural and logistics techniques and equipment. Lastly, upon environmental sustainability, the SC LT measures the average time spent by products throughout the distribution operations, highlighting unexpected and resource-consuming bottlenecks. Losses, GHG emissions, and power consumption for processing, refrigeration, and transportation pertain to environmental externalities and are sensitive again to the product, but mostly, to the SC configuration scenario.

Whilst the product indicators analysis results from averages, further insights come from comparing the indicators tracked per each order *o* from-field-to-consumer. *Delivered*, *late*, or *spoiled* orders are like "*bullets" shot/*generated by the emulated AFSC. Such bullets are plotted in Fig. 10 (i.e., *overstressed* scenario) and in Appendix A (i.e., other scenarios). Observing the DT outputs as the bullets' trajectories and multidimensional order coordinates enables exploring the food ecosystem dynamics. It allows discovering the variability behind products and SC processes and reveals hidden behaviors, trends in impacts and externalities, general rules, or improvement levers toward sustainability. The five-dimensional charts in Fig. 10 and Appendix A plot each delivered,

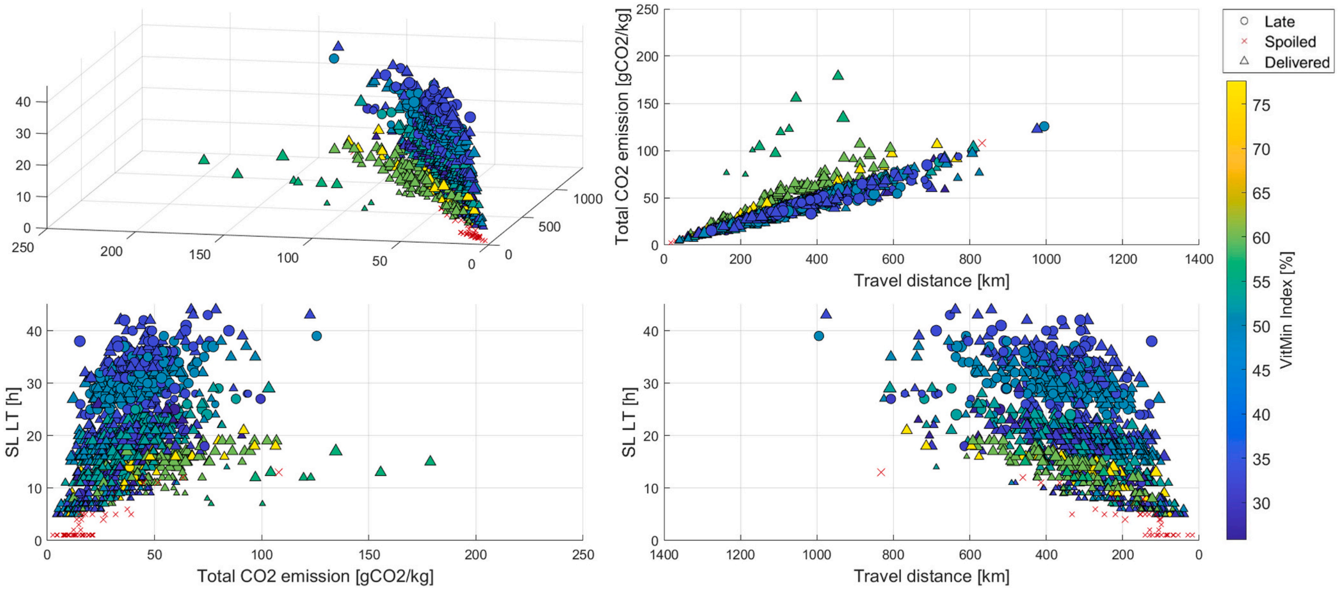


Fig. 10. Orders indicators variability: *Overstressed* scenario.

late, or spoiled o total emissions, traveling distance, SC LT, VitMineral index, and size. Although the results are not generalizable because of their sensitivity to the instance and the emulated distribution scenarios, the following evidence is worth noting:

- In the *overstressed* scenario, characterized by short TLT and long SC, spoiled orders depend on product perishability rather than the SC configuration. Conversely, in the *centralized* scenario, spoilage is sensitive to traveling because a unique warehouse constrains the distribution routes, affecting the shelf life.
- The o labor time increases with the SC LT and the number of SC stages, but not necessarily with transportation. Therefore, it is possible to broaden employment opportunities without enhancing food miles.
- The GHG emissions are also not influenced by the labor time accounted for an order o.
- Carbon footprint is extremely sensitive to transportation. Therefore, changing and improving the logistic network configuration throughout the AFSC is pivotal in reducing the environmental burden.
- In the *overstressed* scenario, highly vitaminic products emit more GHG than expected, mainly due to refrigerated storage and transportation, suggesting prioritizing some horticultural products and their distribution to address food security.
- SC LT and traveling distance (i.e., food miles) are linearly independent and must be both considered in environmental impact mitigation strategies.
- In the *centralized* scenario, size and related processing time lengthen the delivery time.
- *Short* SC minimizes late orders and makes logistic network configuration almost negligible.
- *Overstressed* and *centralized* scenarios present temporal and spatial constraints that affect the orders' behavior beyond product and size. On the contrary, *short* and *long* scenarios draw clearer trends, enabling more accurate operations management and impact prediction.

Overall, analyzing and comparing orders metrics reveals that, behind the general trend and behavior associated with a scenario, SC, logistic, labor, and environmental impacts are extremely sensitive to distribution operations, and using average indicators neglects externalities, drawbacks, and levers of improvement.

5. Discussion

The DT output provides several outlooks of the agri-food ecosystem dynamics and behavior. The practitioners' and consumers' visibility of the operations' efficiency, impacts, and externalities is enhanced from multiple perspectives. The gained awareness drives the *operational*, *tactical*, and *strategic* feedback loops. Fig. 11 draws process-, product-, and order-indicators associated with four delivered orders of the same horticultural product (i.e., cabbage) to the same PoD picked from the four distribution scenarios. Per each o, the simulation infers the hourly conservation temperatures experienced throughout processing, storage, and transportation, assessing the corresponding shelf life decay. Whether available over time, such measurement triggers automatic or manual real-time *operational feedback* control like warnings, refrigerated chambers' temperature adjustments, or workflow rebalancing to prioritize certain distribution operations. Furthermore, the orders' residual shelf life can aid sustainable distribution and marketing policies, such as smart pricing and warehousing strategies (La Scalia et al., 2019).

The performance indicators' dashboard displayed in the QR Code allows the practitioner to *tactical feedback* control of the food operations. Considering all the orders' profiles (as in Fig. 10), a manager overviews the costs, inefficiencies and impacts, finding general rules, bottlenecks, and improvement levers. Decisions like resetting some orders' distribution paths, shortening transportation routes by opting for more convenient warehouses, and reallocating demand to alternative consolidation facilities f^c pertain *tactical feedback* control taken by FSC managers. Furthermore, alternative order dispatching policies (e.g., *First-Expiring-First-Out*) can be tried to evaluate costs and impacts of increasing the provision of a specific horticultural product and nutrients. Analyzing how the orders' coordinates (i.e., indicators values) span the n-dimensional *performance space* would lead to order classification/clustering and tailored distribution strategies. Lastly, optimization techniques may come in handy with cost and externality minimization.

Such levers might be changed using the DT's GUI and tried a priori via simulation in what-if analyses. Future scenarios ruled by, for example, a food demand spike within a geographic area, the prioritization of nutrients from livestock, legumes, dairy, fish, fruits, vegetables, or alternative proteins in the consumers' diet, or by climate change effects like drought, temperature growth, and soil degradation can be virtualized, measured, and assessed to identify sustainable transition pathways and strategic configurations of AFSC ecosystems.

Consumers, informed by the multi-dimensional label, are encouraged to compare products not only on prices but also considering their nutritional contents, the efficiency and quality of logistic operations, and the resulting social and environmental externalities. Increased and shared visibility and awareness of consumers of food ecosystem behavior paves the way for sustainable policymaking strategies or tailored marketing policies to favor healthier and more sustainable choices, enabling *strategic feedback* toward the food industry transition.

Table 5 summarizes the key practical and theoretical implications resulting from the proposed AFSC DT, aligning them with the RQs outlined in the introduction section. In the top part of Table 5 implications for the various stakeholders are provided to answer the related RQ of the second column. The citations in the first column support these implications by linking them to the current state of the art. In the lower section, Table 5 draws practical implications tailored for each stakeholder, whilst theoretical ones are proposed in the context of the RQs.

Whilst the presented AFSC DT provides valuable insights into sustainable AFSC design and control, some limitations need consideration. From an application perspective, data acquisition poses a challenge in recreating the SC. Without a traceability system, the accuracy of metrics remains uncertain, leading to potential discrepancies in estimations compared to actual values. Moreover, to accurately assess saturation levels, throughput times, and identify bottlenecks, a complete dataset covering the entire supply chain is essential. Excluding some product categories from the simulated environment could lead to an underestimation of the real stress levels of the SC. Shifting to methodological limitations, set-up times, maintenance times, breakdowns, and emergencies are not yet taken into consideration in the tool, which allows only for deterministic considerations. Lastly, the order is assumed to be an indivisible and independent agent, preventing the evaluation of the benefit that products consolidation could convey in logistic operations.

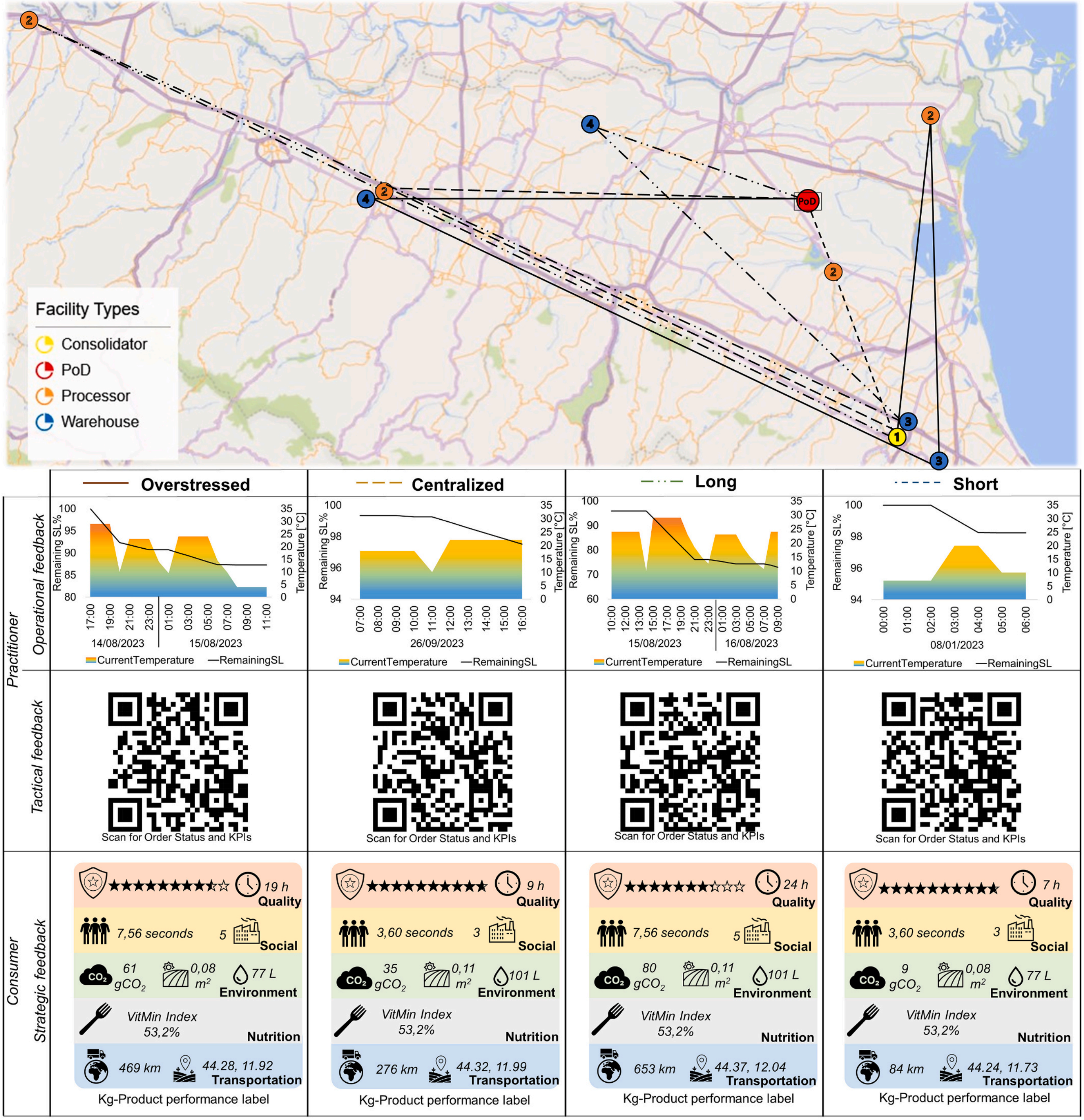


Fig. 11. Output visualization and indicators to aid *operational*, *tactical*, and *strategic* feedback.

Table 5
Stakeholders, practical, and theoretical implications of the presented DT connected to the RQs and literature gaps identified.

Literature gap	Connected RQ	Impacted stakeholder		
		Producers and Farmers	SC operators	Consumers
Ivo de Carvalho et al. (2022); Moreno-Camacho et al. (2019)	RQ1	• Agricultural operations timing (sowing, harvesting); • Crop yield estimation; • Working tasks and time; • Visibility on energy and water use; • Visibility on environmental impact;	• Plant and resource utilization; • Labor time and cost; • Operational capacity use (processing, storage, and distribution); • Visibility on energy use;	• Punctual environmental and social footprint per food item; • Normalized and comparable measures; • Comprehensive and holistic label; • Visibility on FSC stages and operations;
Thijs Defraeye et al. (2021)	RQ2	• Strategic planning of agricultural operations (crop selection, sowing, and harvesting timing); • Irrigation needs; • Punctual assessment of agricultural system's footprint and cost under different farm configurations; • Comparison of alternative production systems;	• Supply and delivery dispatching; • Visibility of other SC actors' capacities and performance; • Prediction on shelf life decay during distribution; • Evaluation of costs, environmental burden, labor needs, and energy use;	• Aligned and normalized comparison among products; • Comprehensive and synthetic multidisciplinary label; • Visibility over SC processes and operations impact; • Informed purchasing based on nutritional, environmental, and social characteristics;
EC-JRC (2010)	RQ3	• Tailored performance assessment on agricultural assets, resources, and processes; • Crop yield estimation upon site-driven conditions (precipitations, climate, soil features);	• Study of future demand trends and performance prediction; • Decision-making aid by primary or case-oriented data (based on facilities' network, orders profile, and resource availability) instead of empirical metrics and thumb's rule;	• Brand environmental benchmarking; • Understanding of seasonality and logistics' impact on product performances and social and environmental externalities;
Practical implications		• Long-term planning of agricultural operations (crop selection, sowing, and harvesting timing); • Workers management; • Resource use efficiency; • Enhanced transparency of agricultural impact on consumers;	• Improved operations control (scheduling, resource allocation, distribution planning); • Shelf life decay control in logistic operations; • Food loss prevention; • Synergies and reliable communication among SC actors; • SC transparency toward consumers;	• Fair comparison between alternative food products; • Improved visibility on environmental and social externalities; • Enhanced purchasing experience; • Multi-dimensional understanding of food products properties and impacts (economical, nutritional, environmental, social, quality);
Theoretical implications	RQ1	• Classification of KPIs dimensions in AFSC for DT design; • Identification of a multi-dimensional dashboard for sustainable FSC management;		
	RQ2	• Integration of different disciplines and perspectives to holistically study and evaluate AFSC ecosystems; • Design and development of a digital twin overcoming the state of the art in AFSC control and impact assessment; • Novel contributions of the DT are the adaptability (flexibility in SC stages and products), the holistic perspective (from farm to shelf), and the multi-dimensional view;		
	RQ3	• The variability observed in the quantified indicators reveals the limitations and unreliability inherent in assessments relying on average secondary data methodologies;		

6. Conclusion and future developments

The current agri-food system underlies humans' subsistence and development but represents a crucial externalities' source threatening both natural ecosystems and human health. With global food production contributing to 34 % of GHG emissions and resource exploitation (Feng et al., 2023), under broadly unsolved food security, food safety, and public health issues (i.e., chronicle disease, obesity, undernourishment), a rapid transition toward more sustainable AFSC systems is compelling. A main obstacle to tackle is the lack of transparency and shared visibility in AFSC operations and processes, leading to blind and opportunistic decision-making from AFSC practitioners. On the other hand, consumers, who can nudge a bottom-up FSC transformation, are often unaware of the complexities and externalities associated with food production and distribution.

This paper addresses this gap by illustrating a novel AFSC-DT able to virtualize agri-food systems and processes and assess their multi-dimensional impacts and externalities. This DT goes beyond the traditional understanding achieved via heterogeneous traceability architectures by modeling and virtualizing the whole AFSC from the agricultural phase to consumers. It enables mapping entities, resources, and material flow at each stage, providing a comprehensive outlook on economic, logistic, environmental, safety, and nutritional indicators associated with any food order. The novel contributions lay in the *flexibility* (i.e., the number and type of facilities and stages encountered by an order), the *applicability* to different food categories and geographic boundaries, and the *generality* of the multi-dimensional indicators' dashboard able to drive decision-making from different AFSC stakeholders (i.e., growers, SC practitioners, and managers, consumers).

The enhanced practitioner and consumer's awareness of operations' efficiency, impacts, and externalities, enabled by the proposed AFSC-DT lead to three pivotal control feedbacks. Operationally, real-time control of processes' state variables (e.g., refrigerated chamber temperature) can trigger adjustments or warnings. A-posteriori analysis of orders profile performance may convey tactical planning of the AFSC operations (as exemplified in Fig. 10). Strategic feedback is incentivized by informed consumers whilst opting for more sustainable food baskets from multiple perspectives.

The AFSC-DT validation is conducted within the context of a regional horticultural SC. A what-if analysis conducted over four virtual scenarios proves how the AFSC-DT aids informed decision-making across the AFSC echelons, stimulating a virtuous cycle and favoring a progressive transition toward more sustainable patterns.

The DT's functionalities are not limited to those illustrated in this paper and would deserve an in-depth focus in future research. The DT's functionalities shall be expanded to model the stochastic behavior of orders and plants, allowing more realistic and reliable observations. The Monte Carlo method enables a *What-If* analysis of the AFSC performance sensitivity to the uncertainty in agricultural production and food demand. Future scenarios ruled by decreasing production exacerbated by climate change and need spikes can be easily tried using this DT, driving preventing policymaking and infrastructural strategies. The environmental burden of each product's agricultural stage can be further quantitatively assessed considering, as farm ($f.^{pp}$) attributes in the database, peculiar air, soil, and water polluting agents associated with pesticide and fertilizer, soil degradation, and water eutrophication. Furthermore, quality-decay methods could be refined to capture the logistic operations' impact on micro and macro nutrients' alteration in delivered food. Lastly, the benefit of prescriptive approaches such as optimization and machine learning techniques incorporated within the AFSC-DT (Tancredi et al., 2022) for operational and tactical feedback has yet to be explored. Such features would facilitate autonomous FSC's entities, processes, and systems adaptation and improvement in response to micro and macro disruptions like adverse weather events, market perturbations, consumers' diets, or geopolitical issues and climate change.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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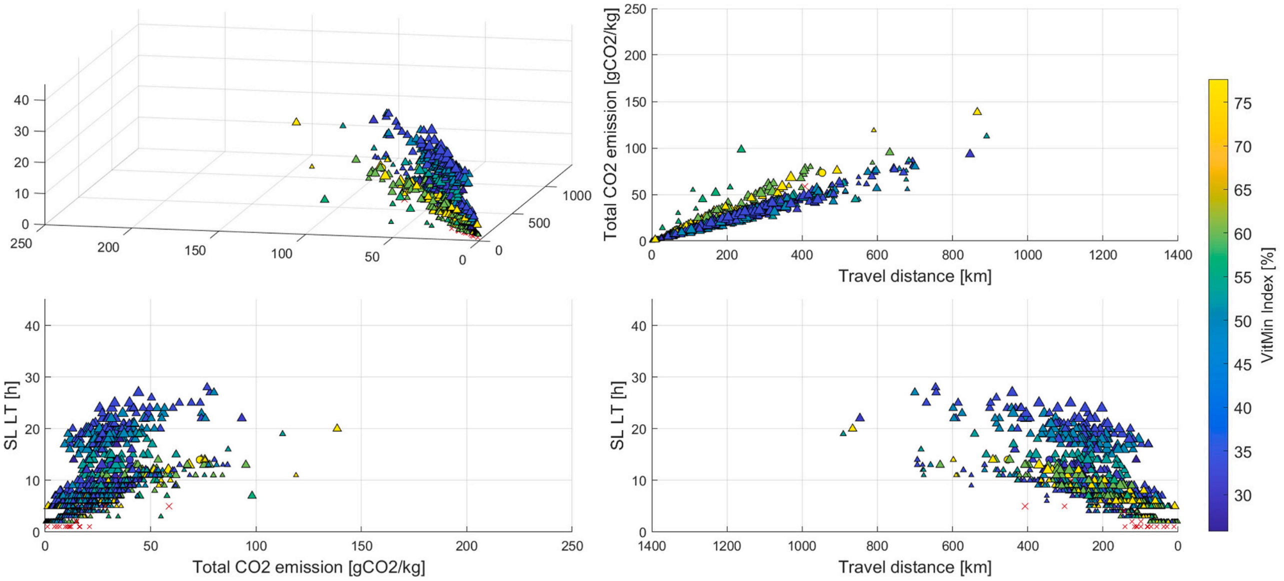
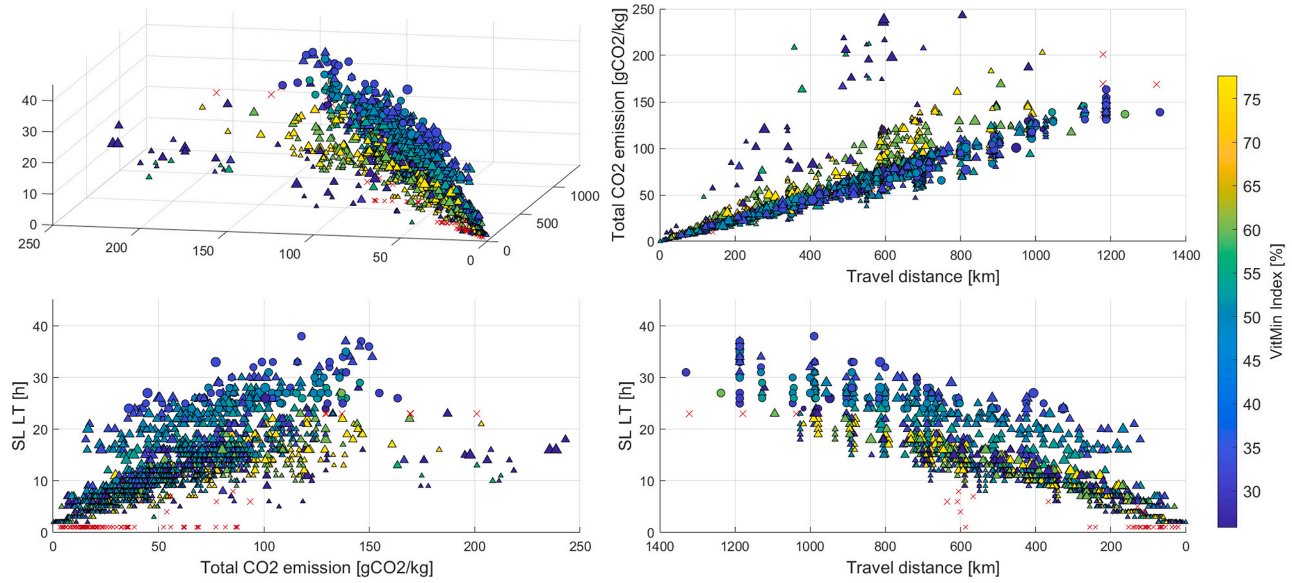
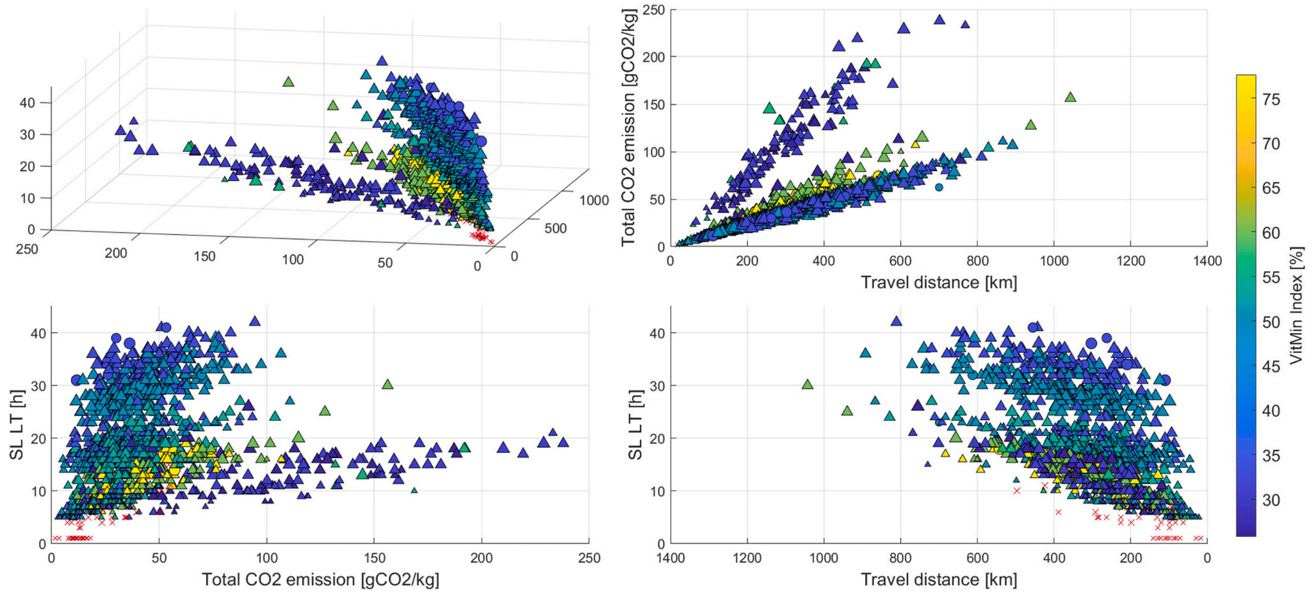
Appendix A



Orders indicators variability: *Short* scenario (×: spoiled; ▲: late; ●: delivered).



Orders indicators variability: *Centralized* scenario (×: spoiled; ▲: late; ●: delivered).



Orders indicators variability: *Long* scenario (×: spoiled; ▲: late; ●: delivered).

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