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Abstract

Food supply chains (FSCs) enable safe, effective, and sustainable food distribution, linking farm to table. They involve multiple sources and destinations, a broad set of actors and handling modes, variable and unpredictable environmental conditions, potentially decaying food and packaging, affecting quality and consumer satisfaction. New methodologies, approaches, and ready-to-practice solutions to improve the FSC capacity to maintain the food quality and the packaging properties at the final consumer are expected and missing. To address such aspects simultaneously, this paper proposes a novel framework, using simulation, to study food product and packaging conditions under environmental stresses throughout the FSC. The framework includes five layers of study, i.e., the *environmental* layer, the *FSC* layer, the *visibility* layer, the *simulation* layer, and the *functional* layer, linking the field, i.e. the operative physical environment, to a simulation environment, based on a fully equipped and closed-loop controlled physical twin made of a climate-controlled chamber. The cyber-physical twin description is improved by reviewing a collection of case studies we used over the years to validate the framework and explore the functionalities of the physical twin. Case studies deal with different food products and packaging alternatives, demonstrating the flexibility of the proposed framework and physical twin to support the analysis and decision-making in FSC improvement.

Keywords: Food supply chain, Simulation, Environmental stresses, Packaging, Design, Physical twin.

1 Notations

Set	Index
Configuration	c
Products	i
Samples	j
Shipping	s
Temperature	T
Time	t

Symbol	Description
$\Delta sl_{i,t}$	Percentage decrease of food quality of a generic product *i* at time *t*
ΔT	Thermal range
a	Weibull shape factor
$a(T)$	Temperature-dependent Weibull shape factor
b	Weibull scale factor
$e(t)$	Error between the current measured and setpoint value at time *t*
$Ea(i)$	Reaction activation energy of a specific product *i*
$f(t)$	Weibull probability density function
$F(t)$	Weibull distribution function
$F(t,T)$	Temperature-dependent Weibull distribution function
k	Boltzmann constant
ki	Integral constant
kp	Proportional constant
$kref$	Constant growth rate of *Pseudomonas* spp. at reference temperature
$N0$	*Pseudomonas* initial concentration
Nl	*Pseudomonas* spp limit concentration
Ns	Number of samples
$Q10$	Estimated shelf-life value (Q_{10} model)
Q_shelf	Estimated shelf-life value
R	Universal gas constant
T	Generic-sampled temperature
$T(x_{s,c,i})$	Temperature of sample *i* in package configuration *c* of shipment *s*
$T0$	Temperature for the reference shelf-life
TB_s	Thermal benchmark of shipment *s*
T_load	Conservation temperature of a generic item
$TPA_{s,c,\Delta T}$	Ability of package configuration *c* to maintain the temperature of content of package configuration in a range of $\pm\Delta T$ from the benchmark, during shipment *s*

T_ref	Reference temperature for the linear regression
$x\_c(t)$	Current measured values at time *t*
$x_{s,c,j}$	Binary variable: 1 if sample j in shipment *s* is in package configuration *c*; 0 otherwise
$x\_sp(t)$	Setpoint values at time *t*
$y(t)$	Output power modulation of the actuators

1. Introduction

Some peculiarities portray the complexity of modern FSCs. Their geographic distribution and the increasing distance food travels from farm to table affect the effective management of such operations (Julien-Javaux et al., 2019; Kim et al., 2019; Riccaboni et al., 2021). These result in time- and energy-consuming processes with quality decay risks for food and its package (Özilgen, 2017). Improvements of these processes are often unaffordable because of the high associated costs, reducing the economic margin on food (Sun and Wang, 2019). The fragmentation of supply chain parties and the uncountable food enterprises involved contribute to a scarce control of the food storage and transportation operations (Hoffmann et al., 2021; Mannheim et al., 1994), and poor visibility of the conditions products experience. Despite adopting traceability solutions (Gallo et al., 2021), supply chain actors cannot wholly avoid disruptions throughout food distribution, whereas the resulting losses and quality decay threaten consumers' trust (Kefalidou et al., 2016; Matzembacher et al., 2018). In such a scenario, climate conditions along the FSCs represent an acute stressor for food quality conservation (Butler, 2012; Zheng et al., 2020; Zimmerer et al., 2019). Critical post-harvest conditions, intensified by unpredictably severe adverse weather events, may affect the quality and shelf-life of food (Aung and Chang, 2014a, 2014b; Mercier et al., 2017), and require promptly foreseeing incidents, disruptions, and stresses that might occur. Lastly, the increasing consumers' awareness and request for quality, low-packed, and customized food (Jowitt, 1982; Meroni, 2000; Simpson et al., 2004; Vanderroost et al., 2014), compel companies to design tailored affordable product-packaging solutions and distribution strategies able to comply with regulations and standards (e.g., HACCP analyses, ISO 9001:2000), and to guarantee the proper conservation conditions (Hajnal et al., 2004, ISO standard 8402:1994) with little impact to the environment (Davies et al., 2012).

When treated together, these peculiarities of modern FSCs divergently affect decision-making on food products and packaging design (Roy et al., 2008; Cimini and Moresi, 2018). While Internet-of-things (IoT) infrastructures enhance on-field data gathering, FSC complex and broad geography limits investments in distributed traceability architectures that aid monitoring and control systems throughout the supply chain (Thakur and Donnelly, 2010; Verdouw et al., 2016; Accorsi et al., 2017a; Kamble et al., 2019). Such an environment allows few data gateways that measure and acquire the conditions food and packaging experience.

Environmental conditions and the consumers' purchasing behavior shape the FSC geography. Global warming influences climatic regions, rolls the seasonality, and disrupts the favorite conditions for traditional crops. The growers seek to rapidly adapt to the changing environment by selecting new cultivars and varieties (Ahumada et al., 2012; Flores and Villalobos, 2018; Flores et al., 2019). Consequently, the upstream of the FSCs, i.e. the food production areas, are moving, changing the structure of the supply chains and contributing to broadening the distances. On the other side, consumers' habits increasingly encompass new ingredients belonging to non-traditional and non-local diets, enhancing the need for exotic food import (Clune et al., 2017; Cho et al., 2021). Likewise to the growers, retailers impact on the end stage of FSCs frequently asking for new suppliers and opening new distribution routes. The interdependencies above break new ground in FSCs, considering food to travel throughout new, unpredictable and hazardous environmental conditions. Such challenges pertain to FSCs' environmental impact as well as food safety guarantees. Externalities relate to energy-intensive food distribution operations and cold chain preservation (Dong and Miller, 2021). Food safety is threatened by uncertainties in distribution, such as adverse weather conditions along the route, unscheduled shipping delays, and the proper level of ripeness at the harvesting for long-range deliveries.

Food packaging has a central role as an efficiency and safety enhancer, despite the claimed environmental impacts that should be addressed urgently (Pongràcz, 2020). Such issues concern the poor availability of raw materials and the pollution and energy depletion caused by production, transportation, and disposal of packaging and containers. As packaging affects product shelflife (Madhu et al., 2021) designed package can prevent food waste and associated impacts, saving up to 50% of GHG emissions (Fresán et al., 2019a). Therefore, predicting the quality of products at the consumer might drive the packaging settings, features, and performance and aid the prototyping phase. Better understanding the role of packaging in conserving food quality at the consumers enables anticipating recalls and complaints. Moreover, consumers' awareness of food packaging's footprint has recently increased (Yokokawa et al., 2021), raising the need for new, less pollutant, and dematerialized design solutions.

These issues underline the need for new product-, packaging- and route-driven monitoring, control, and design systems to provide performing, sustainable, and resilient food packaging solutions. Instead of tackling this lack using an operations management approach (Gómez-Luciano et al., 2018; Shafiee et al., 2021), we aid in designing and prototyping novel food product and packaging solutions within this paper. The several variables involved and the uncertainties in their trends justify the adoption of the IoT paradigm and technology to study the behavior of such a complex system.

We propose a novel framework, using simulation, to study food product and packaging conditions under environmental stresses throughout the supply chain. This framework (portrayed in Fig. 1), built upon previous studies and attempts, incorporates the following layers: the *environmental* layer, the *FSC* layer, the *visibility* layer, the *simulation* layer, and the *functional* layer. The *environmental* layer pertains to the exogenous stresses (e.g., hygrothermal) occurring to products and packaging throughout the supply chain and the related *FSC* layer. We gather such stresses through records acquisition in the *visibility* layer that holds data warehousing and manipulation. Within the *simulation* layer, data feeds two FSC twins: one physical and one digital. The former is a tailored climate-controlled chamber that replicates the stresses across food storage, handling, and distribution operations. The latter virtualizes food operations from the grower to the retailer into a flexible digital scenario and permits tallying economic, quality, and environmental performance and impacts. The digital twin also generates supply chain-driven profiles of stress when traceability records are missing. Here we focus on the interfaces between the twins, leaving the in-depth description of the digital platform to future outlets. Lastly, the *functional* layer lists the main functionalities of the physical twin concerning potential integrations between food- and packaging-focused disciplines.

Although the literature presents other climate-controlled systems (Tristancho et al., 2012), this framework contributes to the state-of-art with a tailor-designed and -controlled chamber to allow studying, prototyping, and selecting integrated food and packaging solutions that bear extreme and unpredictable environmental stresses. This chamber, namely the physical twin, gathers the stresses from a database fueled by stand-alone sensors, ERPs, web sources, and other generic IoT gateways. It then aids functionalities like packaging hierarchy performance assessment, Accelerated Life Test Analysis (ALTA), and experimental quality decay modeling. While Section 2 benchmarks the proposed framework with previous studies, the remainder of the paper follows the layers' architecture illustrated in Fig. 1.

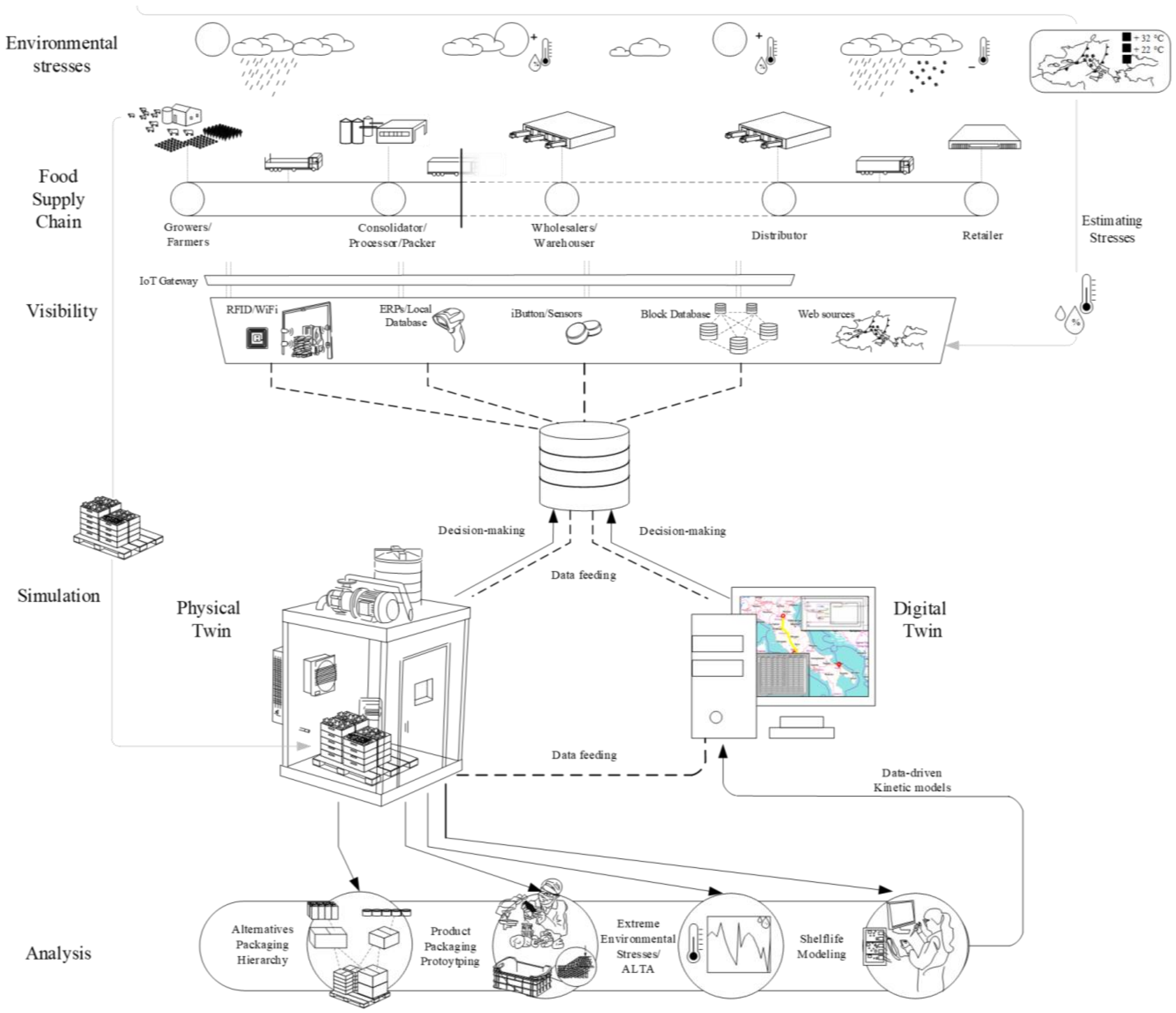

Fig. 1.The proposed framework to simulate FSC under environmental stresses.

2. Literature review

The framework illustrated in Fig**.** 1 also leads to a survey of the literature. The scope of our literature review is to study the application of monitoring and control technologies as FSC management support. To specify the conceptual boundaries, we organized research keywords into four main groups. Such keywords are linked with the *non-exclusive or* (OR) command, while the groups are linked to each other with the *logic and* (AND) command. We used the following keywords {*Food* OR *Cold Chain* OR *Perishable* OR *Vegetable* OR *Fruit*} AND {*Traceability* OR *Tracking* OR *Track* OR *Monitoring* OR *Design*} AND {*Packaging* OR *Unit Load* OR *Pallet*} AND {*Temperature* OR *Humidity* OR *Shelf-life* OR *Quality*} and searched on Scopus, ScienceDirect, Compendex EI (Engineering Village) databases.

Excluding medicine-focused papers, the conducted review revealed the control of food conservation conditions throughout the supply chain to be an interplay of several disciplines like food and packaging science (Madhusudan et al., 2018), thermal engineering (Zou et al., 2006; Rinaldi et al., 2018), and operations management (Accorsi et al., 2017a). For instance, thermal engineers are interested in minimizing energy consumption from refrigeration, cooling, or pre-processing treatments. Food and packaging engineers study the interaction between the product and the surrounding material regarding the impact of shelf-life and quality decay (Defraeye et al., 2014), while decision scientists attempt to lead disposal choices throughout the distribution operations (Ssennoga et al., 2019). Few exceptions treat these aspects simultaneously (Gwanpua et al., 2015). Undoubtedly, digitalizing FSC processes and virtualizing product features and behaviors (i.e., chemical and physical) allow, together with the diffusion of simulation models, new methods for designing and prototyping product-packaging pairs. Some virtualize the cold chain investigating the thermal response of a full pallet of packed fruit using Computational Fluid Dynamics using kinetic rate law models (Wu and Defraeye, 2018). Wu et al. (2019) build upon the same virtual cold chain to assess further the carbon footprint of alternative refrigeration processes and packaging. Conte et al. (2015) provide a dashboard of eco-indicators based on resulting food waste to predict the environmental impact of alternative packaging solutions.

Fernando et al. (2020) use simulation to evaluate the performance of two secondary packages for bananas (i.e., corrugated paperboard packaging and Reusable Plastic Containers (RPC) with vacuum tightening) under transport vibration. Göransson et al. (2018a) evaluate the difference between the label and the predicted shelf-life resulting from improper cold chain operations. They state the importance of temperature tracking systems to enable dynamic and real-time shelf-life estimation. Göransson et al. (2018b) study the thermal inertia of a full pallet of food in RPCs through a climate-controlled chamber and focus on the layout of sensors.

Virtualizing and simulating food processes along the FSC provides insights but needs data (Verdouw et al., 2016). To this purpose, scholars support data gathering through architectural frameworks, traceability systems, sensors architectures, and, recently, IoT gateways throughout the supply chain (Storoy et al., 2013). Regattieri et al. (2007) try a traceability system integrating barcodes and RFID to study the supply chain of Parmigiano Reggiano wheels and measure the storage process's performance. Abad et al. (2009) validate an RFID smart tag intended for real-time traceability of a cold food chain. This tag traces light, temperature, and humidity samples stored within a local memory. Qi et al. (2014) use a wireless sensors network (WSN) to feed a decision support system suggesting whether or not to dispose perishable food along the cold chain. Tested upon technical feasibility, WSNs need further affordability assessment, especially in distributed FSCs. Alfian et al.

(2017) also use RFID to implement an *e-pedigree* food traceability system to track products locations and environmental conditions along the chain through a WSN and predict missing data. With the development of acquisition technologies, the set of features to gather varies with the supply chain (Hardt et al., 2017) and the purpose like certification or counterfeiting detection (Sun and Wang, 2019).

Galimberti et al. (2013) use DNA barcoding to develop a traceability tool and to guarantee food safety along the chain. Shanahan et al. (2009) propose an integrated RFID-EPC traceability system with a centralized database for cattle to identify each animal from farm to slaughter. Nowadays, the increasingly common integration of the IoT paradigm allows for more capillary traceability systems. Blockchain-based databases might provide a repository to such, whereas lack of standardization in data sources represent barriers to tackle (Kim et al., 2019).

Table 1 summarizes the state of the art of traceability and virtual or physical simulation of industrial operations in the FSC. A fully integrated framework that does not focus uniquely on traceability systems and architectures or tailored simulation of impact on food products is lacking. Beyond pure acquisition and traceability technologies for FSC, this paper illustrates a cyber-physical twin that studies food products and packaging under environmental stresses. A cyber-physical system embeds computing and control functionalities into physical devices to monitor, control, and coordinate the corresponding physical activities (Shi et al., 2011). The controlled objects belong to the physical world (i.e. the FSC), while data analysis and decision-making activities fall into the cyber world. (Gunes et al., 2014). The data collection of physical objects exploits sensors to feed the cyber system's processing and analysis. Such evaluations return feedbacks to the physical objects for real-time operations regulations and post-analysis design optimization (Tao et al., 2019). In this paper, the physical twin replicates the stresses acquired throughout the supply chain to prototype safety-proof and affordable food product-packaging configurations. It enables studying the impact of extreme weather-dependent conditions on product conservation and assessing compliance with safety standards at the consumer (de Boer and Bast, 2018). It is compelling the study of new packaging solutions, such as reusable containers or dematerialized packaging, able to reduce packaging waste and environmental impacts while still guaranteeing product safety (Brennan et al., 2021; Fresán et al., 2019).

The novel contribution of this paper lies in the creation and application of a cyber-physical twin to study the behavior of product-packaging configurations, giving visibility to product conditions during handling operations and shedding light on packaging design drivers usually neglected (Surucu-Balci and Tuna, 2021). A precious driver of the packaging design and shipping settings is the awareness of the environmental stresses affecting product quality decay. These stresses can be classified according to the FSC stage involved, e.g., the distribution phase, the handling process, or the magnitude i.e., the weather conditions experienced. The proposed framework could support practitioners in testing an existing product-packaging configuration performance on routes for new markets and commercial destinations. This architecture could also allow decision-makers to predict the quality level of the product at the consumer before future shipments. In the prototyping phase, important levers include understanding how new materials and shapes could affect the product quality, analyzing the quality trend during the shipping, and the conditions of the product at the consumer stage. Simulating transportation conditions might anticipate consumer feedback, preventing the production of inefficient packaging solutions, package and food losses, and customer’s complaints.

Author, Year	Visibility and Data Manipulation					Simulation			Analysis			
	ERP/L-DB	RFID/WiFi	OlM	BC	WS	CS	PT	DT	APH	PPP	ALTA	SM
Regattieri et al. (2007)		✓	✓			✓						✓
Shanahan et al. (2009)	✓	✓				✓						
Abad et al., (2009)		✓	✓				✓					✓
Tristancho et al. (2012)					✓		✓			✓		
Galimberti et al. (2013)			✓			✓						✓
Codron et al. (2014)			✓					✓	✓	✓		
Qi et al. (2014)		✓				✓						✓
Conte et al. (2015)	✓					✓				✓		✓
Alfian et al. (2017)		✓		✓		✓						✓
Wu & Defraeye (2018)			✓					✓			✓	✓
Göransson et al. (2018a)	✓	✓				✓						✓
Göransson et al. (2018b)	✓	✓					✓		✓			✓
Kim et al. (2019)		✓		✓	✓	✓						
Wu et al. (2019)			✓					✓	✓	✓		✓
Fernando et al. (2020)			✓				✓		✓		✓	
This paper	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 1. Systemic literature review (Legend: ERP/L-DB: *Enterprise Research Planning/Local DataBase*; RFID/WiFi: *RFID and WiFi Sensor*; OlM: *Off-line Monitoring*; BC: *Blockchain*; WS:*Web Source*; CS: *Case-Study*; PT: *Physical Twin*; DT: *Digital Twin*; APH: *Alternative Packaging Hierarchy*; PPP: *Product-Package Prototyping*; ALTA: *Accelerated Life Testing Analysis*; SM: *Shelf-Life Modeling*).

The remainder of the paper focuses on the cyber-physical twin, its hardware and control software, and the main functionalities developed, leaving the digital twin's architecture to another outlet.

3. Methods and materials

This section illustrates the hardware and software of the physical twin. We arrange the description into layers. We start from the data acquisition of stress records throughout the chain to gain visibility and store a stresses repository. Then, we use simulation to study the impact of weather-dependent stresses on alternative configurations of food products and packaging. The simulation performed by the physical twin provides the load after the stress, at the same state the consumer receives it. This load feeds analyses and tests we explore and explain in the *functional* layer.

3.1. Visibility layer

With the increasing digitalization of the supply chain operations, different data acquisition gateways are available both at the facilities and at the transportation stage. Because of the low marginality of food, distributed traceability systems are often unaffordable (Young and Hobbs, 2002; Dabbene et al., 2014; Pizzuti and Mirabelli, 2015; Pappa et al., 2018). Therefore, decision-making should rely on alternative data sources heterogeneous in accuracy and format (Bosona and Gebresenbet, 2013; Hsiao and Huang, 2016). This framework is flexible in embracing different information sources, i.e., ERPs, RFID gates, stand-alone sensors, web applications, potentially extended effortlessly.

We use Off-line Monitoring (OlM) sensors coupled with a straightforward protocol to track accurately environmental stresses like temperature and relative humidity. The protocol entails (1) locating sensors in the food packaging hierarchy at the producers' facility. The layout of sensors on the load depends on the food item, the materials used for primary and secondary packages, and the shape and configuration of the fully-loaded pallet (Göransson et al., 2018b). We can insert sensors called Hygrochron Temperature/Humidity Logger DS1923F5 iButton by Maxim that are particularly suitable for small crates and cartons. This device can record up to 2'048 temperature and relative humidity samples at a sampling rate to choose within the range of 1 second to 2 hours. Such coverage allows capturing the daily temperature variations for short and long supply chains within a distribution stage of 4-5 months. Once the shipment arrives at the destination, the importer, the last-mile distributor, or the retailer operators gather the sensors (2) and send them back to retrieve the records. Once received, the information of each sensor (e.g., temperature, humidity, and timestamp) and the origin and destination of the shipment, the companies involved, the features of the load (food and packaging), and the container hierarchy are downloaded into a database.

We use GPS (Punto1, 2021) to trace the route of the load throughout the supply chain operations. GPS coordinates have a twofold purpose. They identify the routes traveled by the product and the facilities where it pauses momentarily. When sensors fail, we use such coordinates to query weather web sources and retrieve stresses through transportation. For instance, we use web sources like WordWeatherOnline (World Weather Online, 2021) and PVGIS (PVGIS, 2021) to provide geolocalized temperatures, irradiance, and relative humidity to estimate the environmental stress. This data feeds heat transfer models aimed at assessing the conditions within the container. When either GPS fails or lacks, the digital platform retrieves the path from origin to destination through a developed GIS service built upon open-source utilities as OpenStreetMap (Open Street Map, 2021) and Itinero (Itinero, 2021). For this purpose, we always integrate data from the companies' ERPs and ITs, which provide delivery records, receiving, storage, or shipping logs, transportation flows between the facilities (Accorsi et al., 2018a). No limitation exists to acquire information from RFID gateways through a tailored interface developed in C#.NET using technology, or distributed data repositories like block databases when needed infrastructures are available.

3.1.2 Data repository

Data are stored into a tailored database already used and described in Accorsi et al. (2018). We refer to the *on-field* data level, which organizes the shipments, the supply chain facilities crossed by the products, the stresses recorded, the features of products and packaging, including the safe conservation thresholds and the package materials, and the container solutions. Table 2 reports the main tables and attributes. This database allows inferring the environmental stresses occurring at specific routes or climatic areas and assessing their impact on new configurations of food products and packaging and distribution strategies.

Table	n. of records	Main features
Node	43	Company, Role, Address, City
Product	43	Code, Category, Company, SafeTempUB, SafeTempLB
Package	16	Type, Level, Shape, Material
Shipment	38	Origin, Destination, Departure Date, Arrival Date, Product
Profiles	56’381	Shipment, Tool, Time, Measured Variable, Value
Analysis	29	Category, Description, Metric, Unit of measure

Table 2. Physical twin's data repository.

3.2. Simulation layer

The FSC physical twin consists of a climate-controlled chamber that simulates the environmental stress of distribution operations on food and packaging configurations. This chamber replicates the hygrothermal profiles, i.e. temperature and relative humidity, acquired, manipulated, and stored at the visibility layer, using a tailored hardware and software infrastructure. We incorporate sensors and actuators into a commercial 1.8 squared meter and 2.0 meter high chamber shown in Fig. 2. The cold room is equipped with two sensors of air temperature and relative humidity that trigger the actuators listed in Table 3.

Fig. 2. Physical twin: climate-controlled chamber.

Device	Description	Key technical data
1. Cooler	Compact cooling unit based on vapor compression refrigeration cycle.	Pnom = 0.9 [kW] Refrigerant: R404A Voltage: 230[V] /1~/50[Hz] Nominal Absobtion: 0.7[kW] Nominal Current: 4.2[A] Air flow: 600[m3/h]
2. Heater	n.2 power electric resistors.	Pnom: 1.0 [kW] Voltage: 230[V] /1~/50[Hz]
3. Dehumidifier	Tailored salt dehumidifier with air-flow recirculation.	Active material: calcium chloride Pnom: 2.0 [kW] Voltage: 230[V] /1~/50[Hz]
4. Humidifier	Ultrasonic humidifier with filter and water purification system.	Flow rate: 1.2l/h Pnom: 0.08 [W] Voltage: 24[V] dc
5. Fans	n.2 fans for air recirculation and air mix inside the chamber.	Pnom: 50 [W] Voltage: 230[V] /1~/50[Hz]
6. Thermocouple	Several PT100 devices to acquire temperature and humidity samples	Range T: [-20;+80] [°C] Range RH: [0;100] [RH %] Resolution: 0.05 %

Table 3. Hardware of the physical twin.

The target of the control is to minimize the difference, i.e., the error $e(t)$, between the setpoint $x_{SP}(t)$ and the current temperature and humidity values $x_C(t)$ within the chamber (see Eq. (1)). A stress profile results from a collection of records acquired at the *visibility* layer. Each sample is a setpoint to replicate in the room throughout the entire distribution process. We control the variables with a hybrid closed-loop strategy. This merges the *on-off* control strategy and a *Proportional Integral* (PI) control strategy. The former considers the actuators working into two different states, i.e., *on* and *off* states. The power modulation is not implemented, and the actuators work at their nominal power. The *on-off* strategy considers temperature and relative humidity independently and is used to control the cooler.

The PI control strategy considers the current error and the integral of previous errors. Eq. (2) expresses the mathematical formulation of PI control strategy, where $y(t)$ is the power modulation of the actuators (i.e. control signal), ki and kp are the PI constants.

$$e(t) = x\_sp(t) - x\_c(t) \quad (1)$$

$$y(t) = kp \cdot e(t) + ki \cdot \int e(t)\, dt \quad (2)$$

The right side of Eq. 2 has two addenda: the proportional component and the integral one. The proportional component allows achieving the setpoint (e.g. temperature and relative humidity) even with minor errors but lacks accuracy. The integral part considers the course of the error over time. For each control signal, each contribution is normalized linearly into the interval [0,1] and then scaled according to the power control required input (e.g. 0-10 V range in case of voltage control). PI control avoids the hysteresis of actuators and permits increasing the precision of $e(t)$ but requires accurate tuning of the proportional and integral constants ki and kp. Table 4 summarizes the values of these constants according to different control transitions.

Control Transition		**PI Control constant tuning**	
Actuator (ON)	**Actuator Switched**	***kp***	***ki***
Heater	Humidifier	0.01	0.001
Heater	Dehumidifier	0.01	0.001
Humidifier	Cooler	0.55	0.001
Humidifier	Heater	0.20	0.001
Dehumidifier	Cooler	0.05	0.001
Dehumidifier	Heater	0.10	0.001

Table 4. Tuning of proportional and integral constants.

The heater, the humidifier, and the salt dehumidifier are PI-controlled actuators. Fig. 3 draws the hybrid control strategy and shows the integration between the control blocks and the chamber. We implement the PI strategy in the first part of the block diagram, where the gap between the setpoint and measured value is evaluated. The error $e(t)$ feeds two methods (*Scale-and-Mapping*) intended for estimating the proportional and integral components, normalized and added together to generate the power modulation signal $y(t)$. This signal powers the actuators carrying out a correction, while the modulated output acquired by the sensors becomes the new input of the PI control.

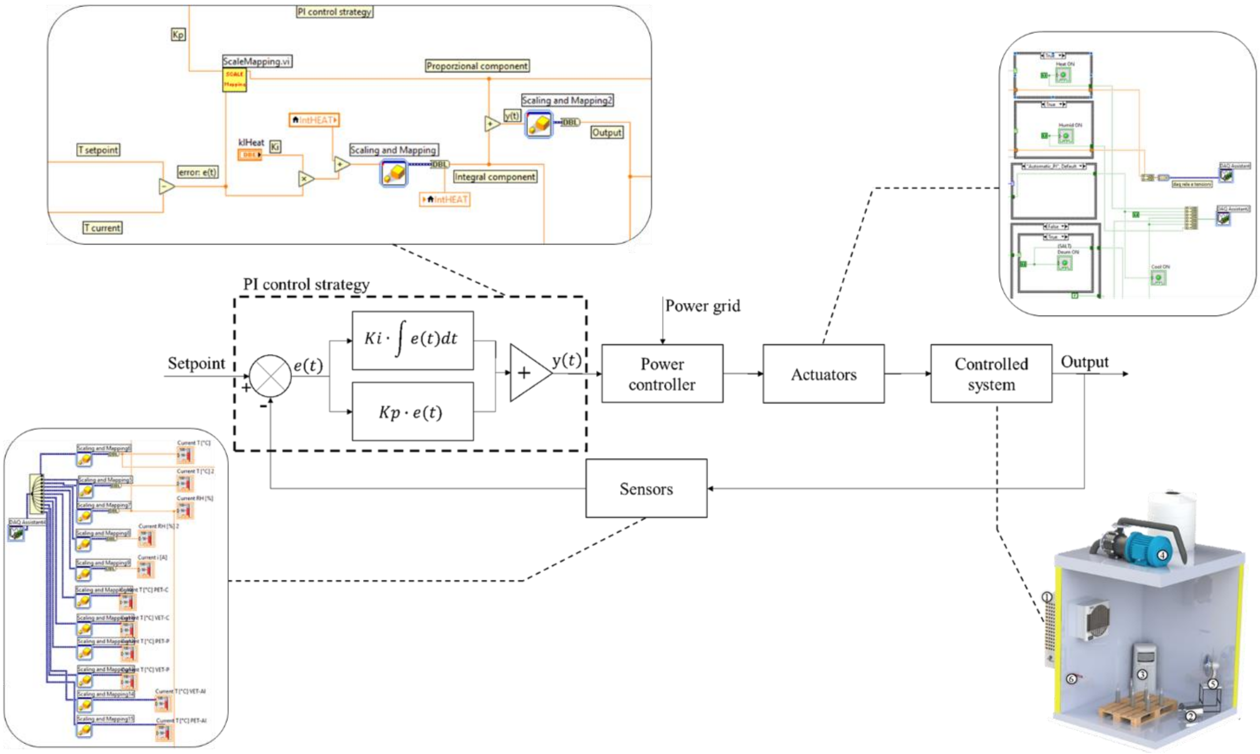

Fig. 3. Climatic chamber's PI control logic implemented in Labview NI^{TM}.

Both the control and the GUI (shown in Fig. 4) are developed in LabView^{TM}. Fig. 4 presents the interface that allows selecting the stress profile and searching through the FSC data stored in the database. Once the data source is selected, the user fills the text-combo boxes to query the database and overview the stress profiles. The interface charts the stress profile, provides details of the product and packaging, the shipment, and the crossed supply chain facilities, and lastly maps the route when GPS coordinates have been recorded.

Once the profile is selected, the panel below is intended for controlling the chamber. This interface enables setting some fundamental control parameters like the *Duty Cycle* and the *Setpoint sampling*. The *Duty Cycle* is the time between two consecutive control iterations, whilst the *Setpoint sampling* equalizes the frequency rate used during data acquisition and monitoring. The remaining panel is devoted to running the actuators manually rather than tuning the proportional and integral constants. The interface also shows the simulation's elapsed time corresponding to specific coordinates of the distribution process. Lastly, real-time convergency to the setpoint is charted with the current state of the actuators.

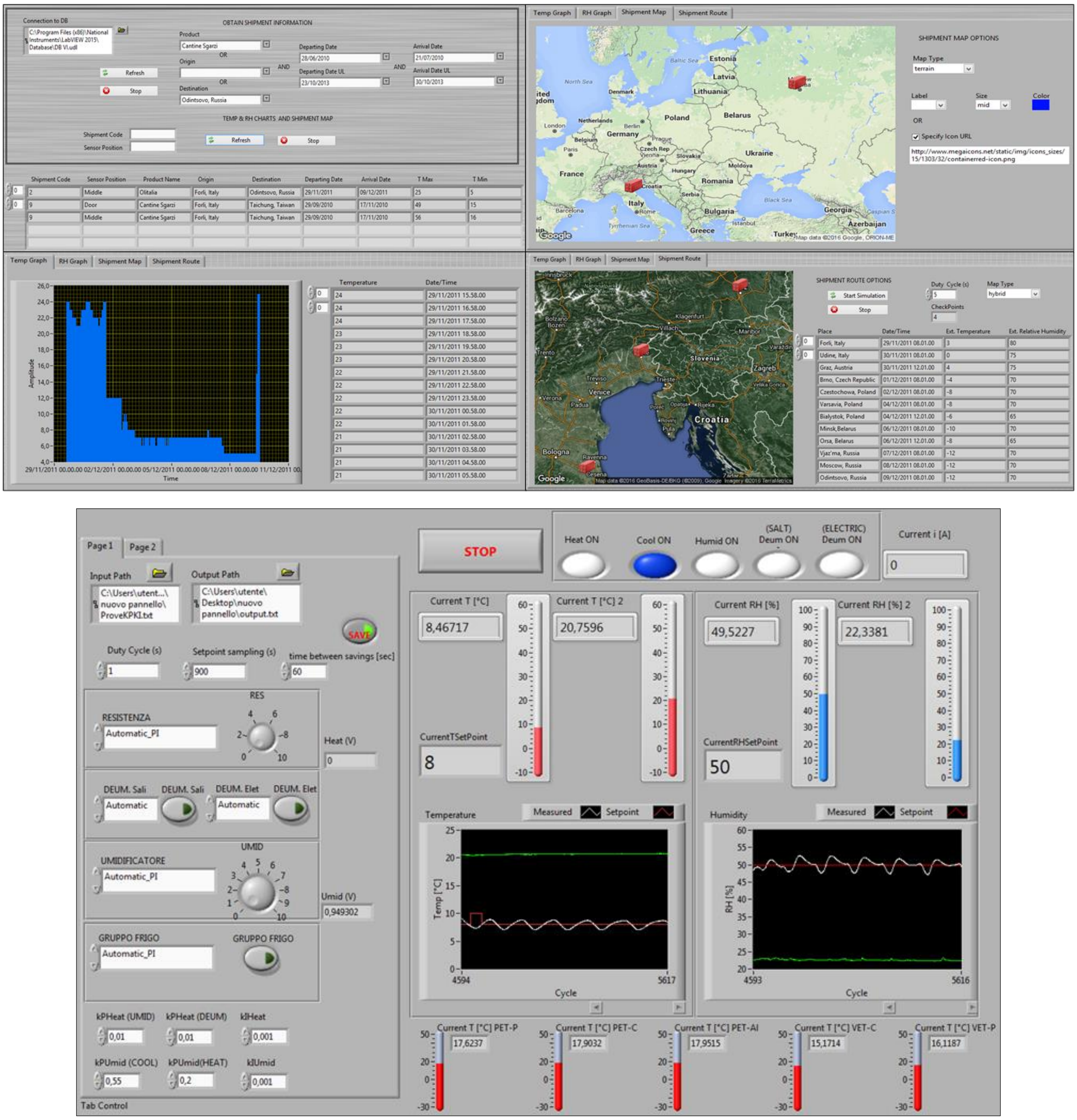

Fig. 4. The control GUI of physical twin (developed in Labview NI).

Ad hoc electric board (see Fig. 2) complies with CE norms (EN 60204-1, EN IEC 61439-2) and allows synchronizing the control software and the hardware. The communication between the software and the hardware intended for data acquisition (input) and transmission (output) is embedded with a chassis provided by National Instrument (i.e. NI CompactDAQ). The electric panel is organized into three blocks. The upper block connects the sensors and devices for modulation and transmission of the input and output signals. The mid-block hosts the relays, the electrical transformers, and a circuit board to manage the NI CompactDAQ. The bottom block powers transmission and safety devices like fuses or motor protection switches.

3.3. Functional layer

The profiles chased in the simulation phase, using the physical twin, enable the *functional* layer of the proposed framework (Fig. 1) to bridge the simulation system to food- and packaging-focused disciplines. This layer needs and benefits from a-posteriori analyses on the products stressed through the physical twin, enabling a reliable and quantitative assessment of the efficacy and quality of a product-packaging configuration according to a panel of perspectives i.e., categories. *Physical* tests investigate how environmental conditions and FSC's operations affect the product features and the packaging, e.g. product leakage, package damage, product losses. *Chemical* analyses study the composition of the products after stress, checking the presence of toxic substances or the level of undesired chemical compounds, e.g., acidity, oxides presence, etc. Additionally, panels of experts take part to *sensorial* analyses to evaluate the products after stress, e.g. sweetness, bitterness, acidity through tasting, aroma intensity, balance through flavour, etc. *Environmental* analyses focus on the impact of a particular configuration of the package hierarchy or the distribution strategy adopted, e.g. CO_{2eq} emissions. Lastly, *economic* analyses compare cost-effective alternatives, while *statistical* analyses stress variances, fluctuations, and correlation factors. Table 5 shows a non-exhaustive list of feasible KPIs suitable for a-posteriori analyses, their acronyms (also used in the following applications in Section 4), and a brief description with units. For the sake of summary, this table includes few metrics tallied at previous studies and of significance for some food/beverage varieties like bottled wine, edible oils, cheese, fresh fruits, chocolate, wheat and bakery products exclusively.

Category	**Method**	**Acronym**	**Unit**
Chemical	Free Acidity (EVOO)	FA	g oleic / 100g^{-1}
Chemical	Peroxide Value	PV	milliequivalent O_2 kg^{-1} oil
Chemical	Free acidity Value (not EVOO)	FV	mg KOH g^{-1} oil
Chemical	Thiobarbituric acid reactant substance content	TBARs	mg malonaldehyde eq. kg^{-1} oil
Chemical	Total Phenolic content	TP	mg gallic acid equivalent/100 g
Chemical	Ortho-Diphenols	OD	mg Ortho-Diphenols / 100g
Chemical	Evaluation of the Color	CIELab	L* a* b* chromatic coordinates
Chemical	Turbidity	TD	nephelometric turbidity units
Chemical	Water Content	WC	mg/10g oil
Chemical	UV-spectrophotometric indexes	k_{232} k_{270}	Absorbance units/day
Economic	Cost US$/Shipment	$/Ship	$
Economic	Costs/Value %	Cost/Value%	%
Economic	Energy Consumption	kWh	kWh
Environmental	CO2eq	CO2eq	kg CO2eq/TEU Shipment
Physical	Leakage	L	N°
Physical	Enclosure Ejection / Cork Jump	EE	N°
Physical	Enclosure / Cap Deformation	ED	N°
Physical	Broken Glass / Bottle Break	BG	N°
Physical	Cap Break (External Layer)	CB	N°

Category	Method	Acronym	Unit
Sensorial	Sight	Sight	Homogeneity, Color, Shine
Sensorial	Touch	Touch	Fluency, Ductility
Sensorial	Hearing	Hear	Snap
Sensorial	Smell	Smell	Primary aromas, Aroma intensity, …
Sensorial	Taste	Taste	Lasting taste, Crunchiness, …
Statistical	Statistical Analysis	StatA	
Statistical	Standard Deviation	SD	
Statistical	Analysis of variance	ANOVA	

Table 5. KPIs for quality assessment at the *functional* layer.

According to the introduced categories and KPIs, *quality* assessment allows concluding about the suitability of a product-packaging configuration and FSC operations and enables studies of alternatives or improvement actions via multiple directions. We outline some of them, seconding the framework.

A first direction deals with Alternative Packaging Hierarchy (*APH*). The physical twin helps studying how different packaging solutions act against certain stress conditions. Comparisons can regard the insulation the packaging provides, e.g. containers with or without thermal coating to protect the content, or the impact of a given packaging configuration, e.g. how reefer and thermal coated containers differ in impact and quality preservation. Another application is studying how the product reacts to different packaging materials when subjected to environmental stresses.

To assess the protection ability of a specific packaging configuration, Accorsi et al. (2014) formulate a quantitative performance index based on the temperature experienced by the product, as in Eq. (3).

$$TPA_{s,c,\Delta T} = \frac{\sum_{i=1}^{Ns} |T(x_{s,c,j})| \leq (|TB_s| - \Delta T)}{Ns} \tag{3}$$

According to the Product Package Prototyping (*PPP*) direction, the focus is on the design, as new, of the proper package for each product and distribution route. In addition to the mechanical properties, packaging features should also guarantee food characteristics throughout the entire FSC and the quality and taste the consumer expects (Manzini and Accorsi, 2013). The physical twin becomes the aiding tool for prototyping resilient and durable solutions through sensorial, physical, and chemical analyses on the stressed product-packaging configurations.

Validation of shelf-life decay models (*SM*) is a, further, direction opened at the *functional* layer. The physical twin allows validating predictive models for the shelf-life decay comparing the expected status after stress and the simulation results. Different shelf-life estimation models exist in the literature. Some of them focus on predicting the level of a specific agent that irreversibly compromises the product if present over an upper limit. As an example, for fruit and vegetables, *Pseudomonas* spp. is often used as the reference indicator (Raposo, 2017). The shelf-life model is in Eq. (4).

$$Q\_shelf = \frac{\log(Nl) - \log(N0)}{kref \cdot e^{-\frac{Ea(i)}{R}\cdot\left(\frac{1}{T\_load}-\frac{1}{T\_ref}\right)}} \quad (4)$$

Another well-known general-purpose theory uses the so-called Q_{10} equation to estimate the shelf-life, given the current temperature and a reference temperature-shelf-life value, Eq. (5).

$$Q10 = e^{\frac{Ea(i)}{R}\cdot\left(\frac{10}{(T0+10)T0}\right)} \quad (5)$$

The percentage decrease of food quality follows.

$$\Delta sl_{i,T} = \frac{100}{\frac{RT0}{Q10^{[(T-T0/10]}}} \quad (6)$$

Finally, at the functional layer, a feasible last direction of study deals with ALTA, investigating the parameters of the failure distribution and the stress-life relationship of product and packaging (Dodson and Schwab, 2006). The physical twin receives the products, chooses the variable to stress, acts on product and package, and observes the effects. The stress can be cyclical, e.g. temperature fluctuation between two extremes, or fix, to represent an extreme upper condition. Typically, the failure distribution of ALTA analysis follows a Weibull function, as in Eqs. (7) and (8):

$$F(t) = 1 - e^{-\left[\left(\frac{t}{a}\right)^{b}\right]} \quad (7)$$

$$f(t) = \frac{b}{a^{b}}(t)^{b-1} \cdot e^{-\left[\left(\frac{t}{a}\right)^{b}\right]} \quad (8)$$

The Weibull probability function tailored to a fixed stress temperature *T* becomes

$$\begin{cases} a(T) = \dfrac{1}{kT^{n}} \\ F(t,T) = e^{-\left[\frac{t}{a(T)}\right]^{b}} \end{cases} \quad (9)$$

where the scale parameter is a function of the temperature.

4. Proof-of-concept and applications

We present a collection of case studies used to validate the framework and explore the functionalities of the physical twin. Table 6 and Table 7 collect these applications, highlighting the main features, issues, and targets. For each case study, Table 6 describes the *Environmental* and *FSC* layers. This table provides information on the product traced, gives the safe conservation thresholds (*Ideal Conservation Conditions*) required by the international standards or producers' specifications (*), and reports the rules to comply with along distribution (*Rule*), and the packaging hierarchy layers (*Package*) assessed. Here are also described the spatiotemporal coordinates of the distribution operations, including the traveled distance (*Travel*), date and place of origin and destination, maximum and minimum latitude, and longitude crossed by the product. Such features characterize the stress profiles in terms of weather and climate conditions crossed by the products. The last fields of the table identify the supply chain stages the product passes through and the transportation modes used. Table 7 results from the bottom layers of the framework in Fig. 1. The *visibility* layer section outlines the device for data acquisition, the number of profile's samples, and the sampling rate. It quantifies the stress intensity through the maximum, minimum, standard deviation and characterizes the overall profile in terms of TPA (TPA_0 [%]) tallied for the control variables. Within Table 7, the *simulation* layer encompasses the controlled variables and the physical twin's functionalities applied to the testbed. The columns grouped under *analysis* describe the type of analysis conducted after stress simulation, and classify the final metrics of quality, safety, and sensorial performance (*KPIs*).

Author, year	Food Supply Chain																	
	Product	Package	Ideal Conservation Conditions		Travel	Origin	Destination	Departure Day	Arrival Day	Latitude Min	Latitude Max	Longitude Min	Longitude Max	Stages			Transportation Mode	
			T [°C]	RH [%]										Ship.	Stor.	Hand.	Road	Vessel
Valli et al. 2013	Oil	I	15-25		Long	Forlì	Taiwan	Sept 29	Nov 17	0.4460	44.0300	9.8972	120.6757	✓		✓		✓
Accorsi et al. 2014	Wine	IV - SC IV - TLC IV - RC	23-25*		Long	Verona	Detroit	July 28	Sept 02	35.9898	43.5395	-82.9701	10.2552	✓			✓	✓
		IV - SC IV - TLC IV - RC	23-25*		Long	Verona	Tokyo	July 25	Sept 12	0.4460	44.1038	9.8171	139.7565	✓			✓	✓
		IV - SC IV - TLC IV - RC	8-10*		Long	Verona	Quebec	Gen 30	Feb 29	35.9524	49.4542	-71.1605	10.2552	✓			✓	✓
Accorsi et al. 2016	Cheese	I	4-8		Medium	Modena	Bari	May 18	May 22	41.0159	44.6502	10.9217	17.0212	✓				
					Medium	Modena	Frosinone	May 18	May 19	41.7443	44.6502	10.9217	13.1378					
					Medium	Modena	Teramo	May 22	May 24	42.657	44.6502	10.9217	13.9352					
Ayyad et al. 2017	Oil	IV - TLC IV - SC	15-25		Long	Verona	Los Angeles	June 26	Aug 03	7.2016	45.4362	-118.2345	10.9898	✓	✓	✓	✓	✓
		IV - TLC IV - SC			Long	Verona	Quebec	Gen 30	Feb 29	35.9524	49.4542	-71.1605	11.0092	✓	✓	✓	✓	✓
Manzini et al. 2017	Oil	I	15-25		Long	Forlì	Iran	Sept 9	Sept 11	11.7138	44.2175	10.3026	61.2023	✓			✓	✓
Manzini et al. 2019	Chocolate	I	13-18		Medium	Bologna	Messina	Oct 14	Oct 28	38.1783	44.4905	11.3396	15.5646	✓			✓	
Gallo et al. 2021	Cherry	IV	0-10	90-95	Short	Melzo (MI)	Orzinuovi (BS)	Feb 5	Feb 5	45.4044	45.4944	9.4157	9.9348	✓			✓	
	Peach	IV	0-4	90-95														
	Grape	IV	0-15	60-90														
	Wine	IV-SC,TLC	8-18		Long	Verona	Australia	Aug 25	Oct 26	-20.3067	45.4375	10.2985	118.6038	✓			✓	✓
	Cous-Cous	I II III	10-20	<75	Medium	Ferrara	Heřmanův Městec	Dec 20	Dec 23	44.5958	49.9518	11.8495	15.6733	✓			✓	
	Pasta	II	1-20		Long	Napoli	New York	Dec 01	Gen 5	35.9524	40.6932	-84.193	14.2623	✓	✓	✓	✓	✓
	Strawberry	I - RPET I-WoodPulp I-Cardboard	5-12	90-95	Medium	Caserta	Forlì	May 10	May 11	41.0754	44.2424	12.0217	14.3247	✓	✓	✓	✓	
	Wine	II III	8-18	60-90	Long	Verona	Thailand	March 12	Apr 29	7.9105	45.4184	11.2576	100.5155	✓		✓	✓	✓

IV

Table 6. Case study, FSC features (Legend: SC: *Stadard Container*; TLC: *Thermal Liner Cover container*; RC: *Referee Container*; T: *Temperature* [°C]; RH%: *Relative Humidity* [%]).

Author, year	Visibility layer														Simulation layer		Analyses	
	Product	Tool		Profile											Physical Twin Analysis	Controlled variables	Ex-Post Analysis	KPIs
		Sensors	N.	Sampling Rate [Min]	Duration [days]	N of Sample	Tmin [°C]	Tmax [°C]	SD T	TPA_0% T	RH min [%]	RH max [%]	SD RH%	TPA_0% RH%				
Valli et al. 2013	Oil	OlM	2	120	52	1184	15	56	5.0190	46%					APH	T	C	FA, FV, PV, k_{232}, k_{270}, OD
Accorsi et al. 2014	Wine	OlM	1	120	36	435	16.5	53.5	4.4255	31%					APH, PPP	T	Stat, Env, Eco	TPA (1,2,3,4°C), CO_2eq, CB, $/Ship, Cost/Value%
			1	120		435	20	32.5	1.4771	62%								
			1	120		435	23	27	0.6815	84%								
		OlM	1	120	49	591	21.5	46	2.3739	8%					APH, PPP	T	Stat, Env, Eco	TPA (1,2,3,4°C), CO_2eq, CB, $/Ship, Cost/Value%
			1	120		591	23	31	1.8118	15%								
			1	120		591	23.5	31.5	1.6907	24%								
		OlM	1	120	34	366	-11.5	19	6.5052	20%					APH, PPP	T	Stat, Env, Eco	TPA (1,2,3,4°C), CO_2eq, CB, $/Ship, Cost/Value%
			1	120		366	-0.5	22.5	4.6303	23%								
			1	120		366	6.5	11	1.5518	42%								
Accorsi et al. 2016	Cheese	OlM	1	5	4	1151	-2	16.5	2.0878	19%					SM	T	Stat	StatA
			1	5	1	3380	2.5	17	2.901	47%								
			1	5	2	575	7	14	2.1205	14%								
Ayyad et al. 2017	Oil	OlM	7	60	37	6426	23	29	1.1175	28%					APH	T	C, Sens, Stat	FA, VP, FV, TBARs, TP, CIELab, TD, WC, Smell, Taste, SD, ANOVA
				60	37	1836	11.5	58	4.2645	23%						T		
		OlM	1	120	30	366	6.5	11	1.5078	0%					APH	T		
			1	120	30	366	-11.5	19	6.5823	17%						T		
Manzini et al. 2017	Oil	OlM	3	60	3	5745	13	61	5.6994	30%					ALT, PPP	T	P	OL,EE,ED,BG
Manzini et al. 2019	Chocolate	OlM	1	10	14	2042	12	28.5	4.6268	25%					EES	T	S	Sight, Touch, Hear, Smell, Taste
Gallo et al. 2021	Cherry	WS, ERP/L-DB		1	1	556	2.4	11.5	1.1532	99%					SM	T	Env, Eco	CO_2eq, kWh
	Peach			1		556	2.4	11.5	1.1532	5%					SM	T		
	Grape			1		556	2.4	11.5	1.1532	100%					SM	T		
	Wine	OlM	2	60	62	2960	6.6	44.9	7.6506	29%					ALT, PPP	T	P, Stat	EE, ED, BG, CB
	Cous-Cous	OlM	4	15	3	1100	3.3	6.1	0.8704	0%	56%	66%	3.0284	100%	SM	T, RH%	Stat	StatA
			4	15		1100	3.5	5.9	0.7374	0%	56.20%	64.60%	2.2186	100%	SM	T, RH%	Stat	StatA
			4	15		1100	0	10	1.9754	0%	75.40%	90.60%	2.4173	0%	SM	T, RH%	Stat	StatA
	Pasta	OlM	1	60	36	843	-6.5	23.5	5.8877	93%					SM	T, RH%	Stat	StatA
	Strawberry	OlM	4	2	1	3000	7	26	5.6404	74%	37.40%	62.70%	6.3917	0%	APH	T, RH%	Stat	StatA
			4	2	1	3000	6.6	25.6	4.4675	80%	42.40%	59.90%	4.4675	0%		T, RH%	Stat	StatA
			4	2	1	3000	7.1	27.6	5.3978	73%	42.60%	62.00%	4.8499	0%		T, RH%	Stat	StatA
	Wine	OlM	3	20	48	3525	8.1	39.6	7.628	45%	35.70%	61.90%	7.0843	3%	SM	T, RH%	Stat	StatA
			6	20		3525	6.1	38.6	7.9565	44%	46.80%	69.60%	5.6845	48%		T, RH%	Stat	StatA

1	20	3525	4.1	36.1	8.1219	42%	39.30%	72.50%	8.1055	56%	T, RH%	Stat	StatA

Table 7. Case study, visibility, simulation and analyses.

The physical twin replicates the stress profiles, thereby supporting several analyses, as outlined by the *functional* layer of the framework. About post-simulation for SM, we explore it in Gallo et al. (2021) where a WS and a ERP/L-DB estimates temperatures inside a container along transportation without GPS or sensors. Fig. 5 shows a thermal map along the route and how this framework uses it. This profile, in turn, feeds shelf-life prediction models, e.g. Eqs. (4) and (5), applied to fresh fruits: cherries, peaches, and grapes. The same profile fuels the chamber loaded with a sample of each product packed within PET trays and a plastic crate as for the real distribution process. Post-simulation, shelf-life analyses are carried out on the stressed products to validate prediction models, tune the empirical parameters, or formulate new bespoke models. In a scenario with new products or routes never experienced before, the application of general rules and best-practices would not be as accurate as the results delivered by our framework. It provides indeed quality assessment of the specific product-package solutions under environmental stresses measured or estimated for the specific route. The SM functionality of the cyber-physical twin underlines the FSC's peculiarities relevance on shelf-life prediction models' accuracy, allowing better SC operations control and a finer stress-dependent quality prediction.

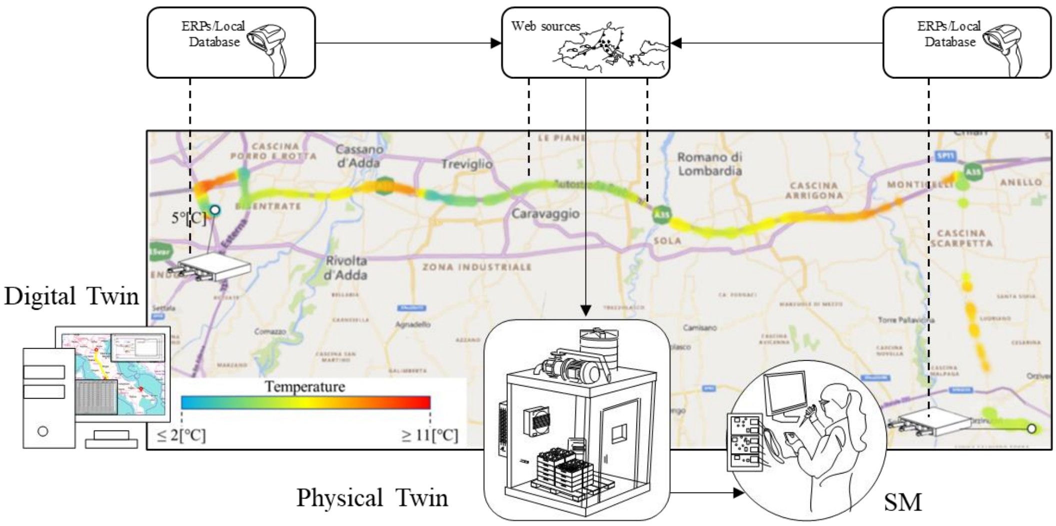

Fig. 5. Modeling and predicting shelf-life decay (SM) through the framework.

When assessing the role of packaging in food conservation along the supply chain, the physical twin allows a comparative analysis through the APH functionality. It studies different packaging layers. At the first layer, we evaluate the products wrapped into the primary package. We assess cartons and crates of different materials and shapes at the second layer, while the pallet arrangement is considered at the third layer. An application of such functionality is illustrated in Ayyad et al. (2017), where different shipping containers of three edible oils' typologies (i.e., extra virgin olive oil, grade seed oil, and rice oil) throughout simulated maritime shippings are assessed via chemical analysis. A monitored temperature profile of 35-day and 30-day shipments from Italy to Los Angeles and from Italy to Quebec fuels the cyber-physical twin. Post-simulation chemical analyses are carried out on samples, i.e. acid content, oxidation level, UV-spectrophotometric index, to determine the favorite packaging configuration in preserving the original product's characteristics.

A major result derived from these analysis regards the oils' oxidation. Thiobarbituric acid react substance content (TBAR) and peroxide (PV) values are measured before and after the shipping. PV is a product of the primary oxidation of the oil, while TBAR derives from PV and represents a second oxidation product, indicating a higher level of deterioration (Frankel, 1991). Fig. 6 shows the values measured in a no-insulated container (dot line) and insulated container (continuous line) before and after the shipping simulation. Both the PV and the TBAR values are higher in the standard container. This analysis indicates that greater degradative reactions occurred in the standard container and quantifies to what extent the oil quality benefits from insulated containers. The accuracy of chemical analysis in defining product quality and the cyber-physical twin system to reproduce the exact conditions experienced by the products allows setting a reliable protocol to evaluate packaging hierarchies' performance in specific circumstances.

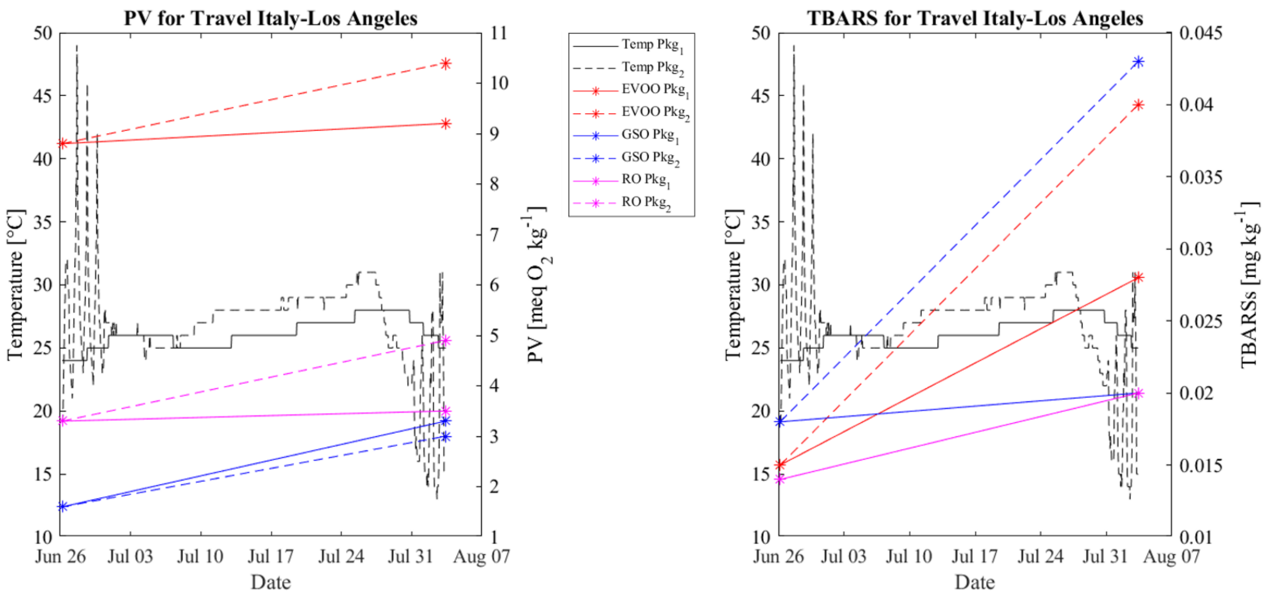

Fig. 6. Comparison of different packaging solutions (*Legend*: *EVOO*: Extra Vergin Olive Oil; *GSO*: Grape Seed Oil; *RO*: Rice Oil).

In long FSCs, the packaging characteristics become more critical since they have to protect the product quality and maintain its organoleptic properties for weeks. In such contexts, the APH functionality can be applied to reproduce the stresses of a route, monitor the quality KPIs trends during the shipping, and understand how different configurations react to the stresses over time. In these terms, APH allows observing the consequences of a product-packaging configuration in terms of its heat transfer properties, humidity absorption properties, and product quality decay, without the need for an actual formulation of such properties.

For instance, a product that frequently undergoes long shipping is the kiwi fruit, produced mainly in northern Italy and New Zealand and exported worldwide[1,2]. Two different primary packaging for kiwi fruit have been tracked during a 44-day shipping from Italy to New York. The temperature outside the packaging was

[1] https://www.worldstopexports.com/kiwifruit-exports-by-country/
[2] Central Intelligence Agency, The World Factbook *Field Listing: Exports – Commodities*. Accessed on July 25, 2021

recorded, and the same conditions reproduced in the chamber for the two alternative packaging solutions. Punctual measurement of the Brix degree during the simulation is used as an indicator for fruit ripening. Fig. 7 shows in black the temperature trend recorded over time, while in red and blue is shown the evolution of the Brix degree for the two alternatives under the environmental stresses. The observation of the monitored indicators allows correlating the packaging configuration performance with the environmental stresses without analytically modeling the physical, chemical, and microbial processes occurring inside the fruit.

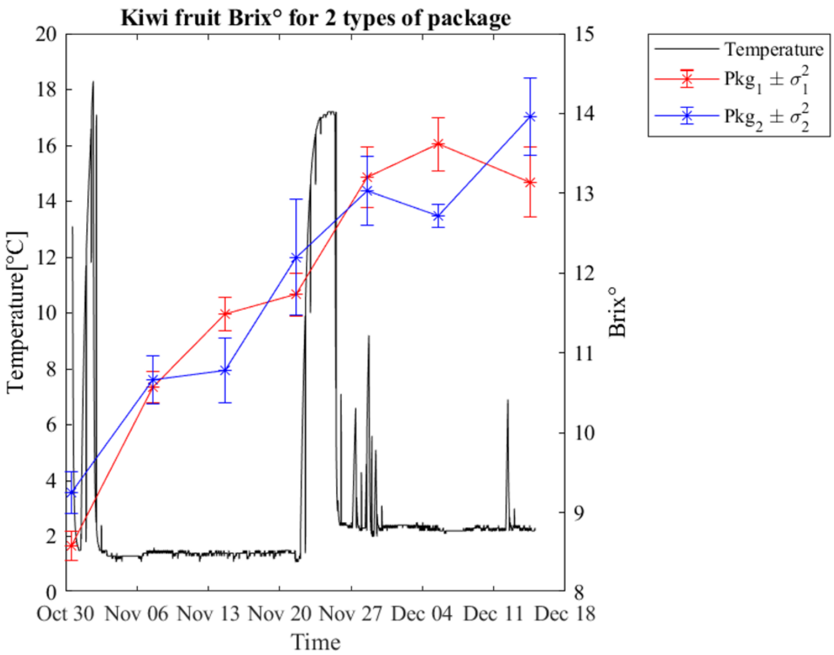

Fig. 7. Brix degree in different packaging solutions

Finally, applications of ALTA via the physical twin are in Manzini et al. (2017). Different packaging and stress functions are studied for edible oil bottles, focusing on the physical KPI category in Table 5. The first and second case studies analyze how constant stresses, coupled with an aluminum or plastic cap, affect glass bottles. The last case study observes the consequences of cyclical stress profiles on bottles with different aluminum caps. The temperature profile for all three cases starts from a one-month shipment from Italy to Iran, with temperatures recorded in two standard containers. During this month, the temperature reached peaks of 61°C that are, further, overstressed during ALTA. Fig. 8 exemplifies how this framework can perform both AHP and ALTA studies and feedback re-design suggestions or hints on the different layers of packaging. The use of the cyber-physical twin allows including logistics' issues in the packaging design drivers beyond the marketing, costs, and technical feasibility ones. Performing stress analysis highlights issues concerning product quality decay and packaging failures. Such tests are carried out before the product commercialization when there is no way to determine how the product-packaging matching would bear distribution stresses. Using the proposed cyber-physical system paves the way for studying the effects of logistics on product conservation, preventing consumers and distributors' complaints, and lastly, food losses. Here, an Italian export company was receiving claims from the customers. The foreign oil importer received several containers with damaged goods, resulting from oil leakage through the enclosure. The tracked shipping temperature is used via our climate-controlled chamber in the ALTA to compare alternative enclosures under stress conditions and design the ideal enclosure structure and packaging hierarchy.

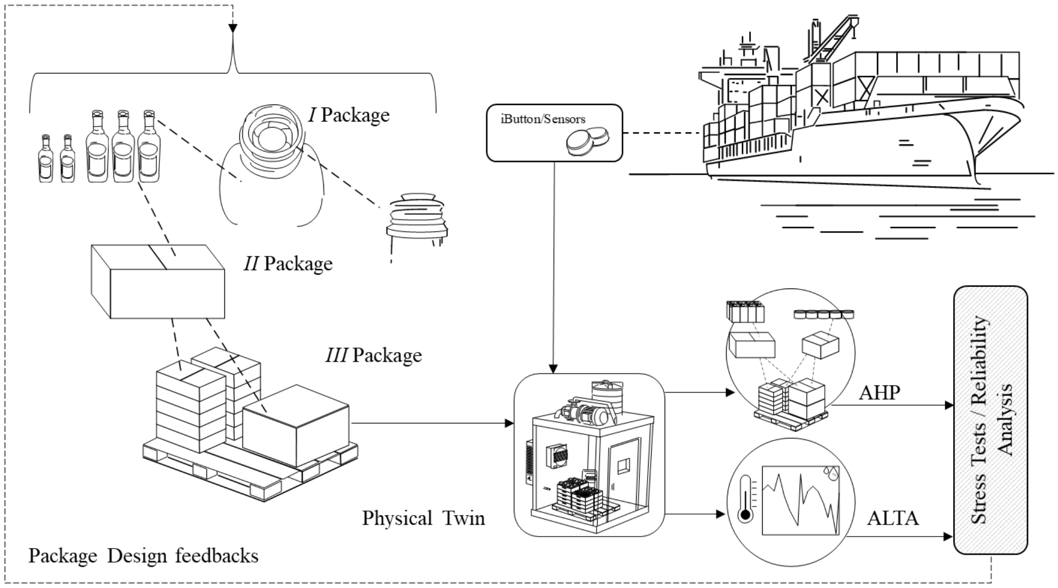

Fig. 8. Performing AHP and ALTA through the framework.

5. Discussion

The proposed framework improves FSCs starting from the field, i.e. the *environmental* and *FSC* layers, and, using simulation, drives prototyping, re-design and actions on food products and packaging, i.e. the *functional* layer. This framework benefits and is strengthened by the spread of cost-effective traceability systems in FSCs (Tsang et al., 2019) to gather information and data to fuel simulations and what-if analyses. From a win-win perspective, the capillary diffusion of the IoT paradigm and technologies throughout the FSC enables the framework to provide key input and reference field data. Industry 4.0 technologies need reference methodologies and guidelines for their application, tailored to specific contexts (Kayikci et al., 2020; Bortolini et al., 2018). This framework aids the decision-making of product-package design and distribution strategies, taking into account consumers' expectations in terms of quality, safety standards, new or tentative supply chain routes and itineraries, involving IoT and traceability systems as enabling technologies and methods (Camaréna, 2020; Lezoche et al., 2020; Nasurudeen Ahamed and Karthikeyan, 2020).

In detail, this physical twin serves as an aiding tool to simulate 'off-line' the conditions experienced by the food product and package under specific stresses and to compare alternative design configurations, matching with the specific environmental conditions of each supply chain itinerary or distribution process (Aramyan et al., 2006). Following our framework, we tested and stressed several product-package combinations to predict their behavior, inform the practitioners and the supply chain's actors, and feed redesign actions suitable for the following shipments. The framework hence operated *a-posteriori*. Nevertheless, embedding the cyber-physical twin with real-time sensors of quality and freshness (e.g., biosensor, optical sensors and RGB camera, gas sensors) and coupling simulation to 'on-line' monitoring along the FSC would make real-time control of food distribution operations feasible. The availability of real-time data on products and packaging conditions would enable correlation analyses to predict the expected food quality, acting on the logistic operations and choices simultaneously. Applications are the identification and disposal of corrupted batches, real-time vehicles routing, inventory and stock conditions' detection and improvement. This approach matches with new food products when decision-makers design the FSC strategies and operations from green field together with the monitoring system (Nychas et al., 2016), and it can be tailored to existing FSCs to make changes acting on their critical stages. The climate-controlled chamber might also operate, both 'off-line' and 'on-line', with artificial food and package prototypes embedding sensors to track a specific configuration's thermal and vibrational history, enabling the precise simulation of product conditions. An example of such artificial sensored-products, i.e. physical twin, is developed for apples by (Defraeye et al., 2017). They conclude by highlighting the potential of their technology at an industrial scale to study supply chain conditions and leave additional room for the joint development of our frameworks.

We build upon the Virtual Cold Chain (VCC) modeling developed by (Wu et al., 2018) through the proposed cyber-physical twin. They indeed explore the optimal cooling and refrigeration strategies during transportation and storage using CFD to predict the quality decay of products at the retailer. The same authors (Wu et al., 2019) explore how different package designs respond to cooling and refrigeration air-flow directions and how they perform in energy consumption and environmental impacts. They use the temperature set-point as a statement. Conversely, the novel aspect handled in our framework lies in the unpredictable thermal and hygrometrical stresses occurring during the logistics and supply chain operations that affect the conservation of the product far from its nominal set points.

Globally, from a holistic perspective, the framework contributes to the triple bottom line concept (Bortolini et al., 2019; Shou et al., 2019; Khan et al., 2021; Pedroso et al., 2021). The consumer-driven (i.e. social), economic, and environmental aspects of FSCs are explored and included within the framework boundaries as the applications presented in Section 4 showcase when targeting the consumers' awareness preserving products' quality and safety (Matzembacher et al., 2018). In conclusion, as a supporting tool in the product-packaging design and FSC enhancement, this framework can be integrated to other decision supporting tools focusing on operations and FSC design and management (Accorsi et al., 2017b; Bortolini et al., 2016).

6. Conclusions and next steps

FSCs are crucial for the safe distribution of food from the farm to the table. Multiple perspectives make modern FSCs complex systems, e.g. their wide geographical extension, the presence of several players with different viewpoints and interests, etc. Furthermore, strong dependence of quality and safety of food is from uncontrolled variables, function of the environmental conditions experienced by food and food package along the supply chain. The current literature outlined these challenging perspectives of FSCs and still seeks methods and holistic tools to support decisions and new product-, packaging- and route-driven monitoring, control, and design systems to provide performing, sustainable, and resilient food and food packaging solutions.

In this paper, we propose five layers of analysis within a framework able to empower FSCs. We develop and adopt a cyber-physical twin to study and assess food behavior, existing and new packaging solutions under their conditions during handling and transportation operations. The framework includes *environmental* and *FSC* layers to represent the system to investigate, while the *visibility* and *simulation* layers allow the creation of the cyber-physical twin of the FSC to study. The twin is based on a climate-controlled chamber enabling tests along multiple directions, i.e. the *functional* layer dimensions, to keep high standards in quality and safety of food match technical, economic, and environmental targets. At this stage, the proposed framework is limited to the chemical, economic, environmental, physical, and sensorial categories as the quality assessment KPIs. Extensions of the framework to other relevant tests, e.g. microbiological, aesthetic, etc., are possible.

Furthermore, the in-depth analysis of the digital twin and artificial food devices is a next step at the current stage and improvements of the chamber features (e.g. a shaker platform to test vibrational stresses) to make the simulation even closer to reality. Notwithstanding the examples of applying this framework to company-driven case studies, we believe significant advances are needed to promote it at an industrial scale in the visibility layer. Integrating new ICT systems should enhance further supply chain data monitoring and acquisition both off-line, through RFID or wireless sensors, or online, via smart tags and block chain infrastructure. Lastly, an extension of the simulation boundaries including multiple FSC stages and conditions is a, further, next step we leave to forthcoming studies.

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