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Internet-of-Things paradigm in food supply chains control and management

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Abstract

Starting from the definition of the Internet-of-Things (IoT) paradigm, this paper discusses goals and strategies for the design and building of an IoT architecture aiding the planning, management and control of the Food Supply Chain (FSC) operations. A comprehensive architecture of the entities, the physical-objects, the physical and informative flows, the stages and the processes to be sensed, tracked, controlled and interconnected is given to illustrate the interdependencies between the observed supply chain and the exogenous environment.
A simulation gaming tool embedding the IoT paradigm for the FSC management is also proposed and illustrated to showcase the potential benefits and opportunities for more direct integration of the physical food ecosystems into virtual computer-aided control environment.

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Keywords: Food supply chain, Internet-of-Things, Simulation, Data architecture, Food ecosystem

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1. Introduction

The growing food demand to meet the increasing world population is forcing the conversation on reconciling the economic growth and industry production development with the environmental sustainability and safety issues [1-3]. This compels considering the extant as well as the new developing food supply chains (FSCs) over a global holistic perspective going beyond the current boundaries of the existing food ecosystems. Not only agriculture, processing, packaging, logistics and distribution operations, but also the interdependent relations among growing and consumption locations, urban and rural landscapes, carbon mitigation strategies, waste management and energy supplies [4].

To control and best manage the slight and mutual influences of such entities and processes directly related to the efficiency and the sustainability of the food supply ecosystems, new cross-disciplinary and integrated approaches are expected [5]. The design and control of integrated food supply ecosystems is challenging, while research contributions and scientific efforts are still limited and focused on design of branches of such networks.

Food supply ecosystems are constrained by a mix of interdependent issues dealing with [6]:

- the location of crops and farms;
- the climate, soil and environmental conditions;
- the access to water, energy and land resources;
- the set of harvesting areas and their allocation to processing and packaging facilities;
- the presence or set up of logistic infrastructures and distribution networks making connections to the urban areas;
- the regulatory and technological environments;
- the food distribution channels;
- the demand profiles.

In such a complex environment, decision-making has to be aided by the analysis of both the physical (e.g., raw materials, packaging, food, energy, water) and the informative flows. The former lies on the latter since the efficient control of the dynamic production-supply-consumption [6] pattern throughout the FSC stages and process requires handling a wide set of data and knowledge that are often neglected. The typical labor-intensive and human-made nature of the food sector increases the complexity of providing, gathering, storing and exploiting in-field data. Thus, the claims for developing and applying food process virtualization, food traceability and Internet-of-Things (IoT) paradigm to tackle the well-known sector's issues, that are recently characterizing the academic and industry debate [7-10], sound as at least ambitious and still tremendously challenging. Implementing the IoT paradigm in FSC means developing and extended virtualization of the items, infrastructures, resources, stages, actors and flows contributing to model the production-transformation and distribution activities. The virtualization of the FSC passes through better understanding the inside dynamics of the food supply ecosystem as a whole, the interdependencies between the flow of resources, the study of the physical and information infrastructures [11].

Starting from the definition of the IoT paradigm [12-14], the aim of this paper is to discuss goals and expected strategies for the design and building of an IoT environment aiding the planning, management and control of the FSCs operations. To this purpose, this paper aims at gradually approaching to the implementation of the IoT paradigm by proposing a simulation tool to study the extant dynamics underling the FSC as a whole. Instead of focusing on specific supply chains and processes, the proposed simulation tool generalizes the main FSC stages and processes and virtualizes the associated entities, items, resources and infrastructures. Indeed, the proposed tool can be applied to generic FSCs, which handle different products and varieties, but share the processing and logistics chain, including processing and packaging, storage, and distribution to the retailers. The illustrated tool seeks to achieve the following fourfold purposes. First, (1) modelling the connections between the aforementioned supply chain entities over a quantitative system dynamics approach. Then, it (2) explores the criticalities throughout the supply chain (e.g., bottlenecks, cold-chain breakdowns, delays, impacts on the environment and society) and accounts the associated performances. Third, the tool performs (3) feasibility studies and multi-factor analyses for the implementation of data traceability and real-time process control architecture toward the IoT regime. Lastly, the tool (4) realizes an educational game for consumers, practitioners and students to experience the impacts and inside bullwhip effects resulting by their decisions and choices at different stages.

According to the outlined purposes and goals, the remainder of the paper is organized as follows: Section 2 proposes a global architecture of the entities, actors, flows, stages and processes to control and manage. Section 3 introduces the aforementioned simulation tool through some of its graphic user interfaces (GUIs) highlighting the potential benefits and opportunities resulting by highly tracked and controlled food supply ecosystems. Lastly, Section 4 concludes this paper with future research opportunities.

2. Reference framework for the IoT application within food supply ecosystems

Starting from the unbounded food ecosystem perspective discussed in [5, 15-16], the following Fig. 1 proposes a comprehensive framework for the analysis of the input and output as well as the physical and information flows throughout a food production and distribution ecosystem. The framework includes the supply chain stages, the entities, the flows and the considered food ecosystem boundaries.

While the set of the parameters undertaken at each FSC stage are not detailed in this paper (see references), the framework stresses the interdependencies between stages and processes and explores the connectivity between nodes and supply chain actors. The listed entities indicate the set of the objects that need to be virtualized for the coherent computer-aided analysis of each stage. The physical flows experienced at each stage are in accordance with the aforementioned production-supply-consumption pattern [6] by underlining whether a given entity is consumed, processed or supplied. The boundaries of the food ecosystem are further illustrated in Fig. 1. Lastly, a list of strategic and operational decisions undertaken at each supply chain stage are reported to drive the design of computer-aided decision-support tool toward the existing issues as preliminary proposed in the next Section 3.

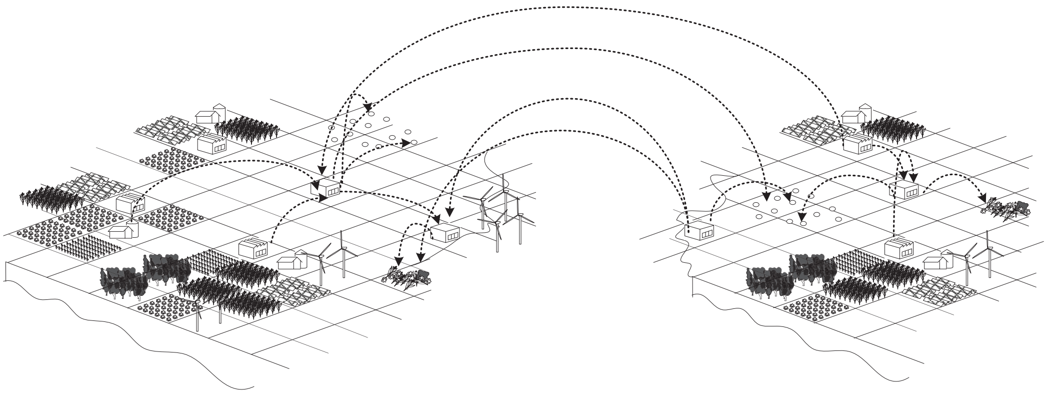


Fig. 1. Boundaries of the considered ecosystem (See Table 1 for reference)

3. IoT tool to simulate food supply ecosystems

The application of the reference schema to systematically control and manage the food supply ecosystems goes through its modelling and the development of entity-based tools reproducing the ecosystem structure and interrelations.

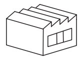
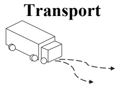
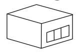
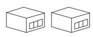
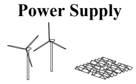
To this purpose, the Authors are working on an ICT platform progressively integrating the introduced entities active on common food supply ecosystems and reproducing the value flows that, from the market demand, move back to the transformation and agricultural phases. Developed within Labview^{TM} Integrated Development Environment, this tool aims at experiencing the users/planners the effect of a decision on a given link of the network to the whole system. This way of working is called *'gaming'* because of the users/planners play on the leverages of the network to directly experience the effect of the propagation of their choice on the final food demand supply.

At its current stage of development, the food supply ecosystem is highly simplified including the following key network stages:

- Agricultural/production stage: this node represents the complex of entities making available the finished products to the market, feeding the forthcoming supply chain including those tasks related to the control and certification of the product quality and safety.
- Distribution/transport stage: at the current stage of development, the tool includes two stages of distribution. The former moves products from the producers to the warehousing system, the latter moves products until the final consumers, i.e. the retailers;
- Storage stage: it represents the intermediate storage node for the temporary storage, sorting and repacking of products before the final delivery to the retailers/consumers;
- Consumption stage: it is the final node collecting the orders delivered on time to the final consumers;
- Waste/disposal stage: it is the final node collecting the orders not delivered on time and consequently wasted because of the product shelf life is exceeded.

The modular structure of the whole tool architecture allows expanding the boundaries of the system to include other entities and interrelations among the existing and the future nodes. Finally, it is expected to add to this tool a parallel working mode, called *'planning'*, that allows comparisons against the existing control and management rules and best strategies, i.e. optima, to be identified and calculated by using a set of best modelling and optimisation techniques.

Table 1. Reference framework for the system dynamics analysis of food supply ecosystems.

Stages	**Crop**	**Processing**	**Transport**	**Storage**	**Market**	**Waste Processing**	**Power Supply**
							
Entity	Soil Seeds Food variety Fertilizer Water Energy Growers Harvest equipment	Package Product Pkg. lines Working station Worker Facility	Vehicle Unit load Driver Route Transport modality	Unit load Racks Handling equip. Worker Warehouse area Order Facility	Shelf Store Order Consumer	Waste Facility Worker Recycling lines	Power Energy Plant Demand Distribution Grid
Transform				Delivered food	Delivered food	Waste	Energy
Resource	Water Energy Fertilizer, Seeds Soil Labor	Water Energy Labor Time	Energy Fuel Labor Time Shelf Life	Energy Labor Time Shelf Life	Energy Labor Shelf Life	Energy Labor	Energy
Supply	Unpacked food Waste	Packed/processe d food Waste	Delivered Food	Repacked food Waste	Consumable food Waste	Energy Fertilizer	Energy
Parameter	Soil moisture Soil texture Soil sodium-carbonate content Rainfall Temperature Wind speed	Throughput Labor cost Energy cost Processing Capacity Working shifts Layout Prod. Technologies	Transport mode Shipping capacity Distribution speed Transport costs Transport GHGs Loading capacity	Storage mode Storage capacity Handling throughput Handling equip. Labor costs DC network	Demand volume Order frequency Expected Service level Retailer network	Collection capacity Recycling capacity Reverse network Recyclable, reusable, recoverable fractions	Solar irradiance Temperature Sundays Sun-hours Wind speed Geothermal sources Hydropower sources
				See [5, 15] for a full and comprehensive list of parameters			
Decision	Crop allocation Crop turn over Harvest scheduling Irrigation planning	Batch scheduling Pkg. Design Processing station design Layout Planning Facility location	Vehicle routing Vehicle loading problems Shelf life protection	Inventory Mng. Storage Allocation & Assignment Loss prevention Facility Design Network Design Picking Opt.	Shelves planography Grocery network design	Processing station design Layout Planning Facility location	Grid management Infrastructure design Grid design Power assignment
Boundary				See Fig. 1			

3.1 Entity flows

Fig. 2 presents the GUI of the introduced tool modelling the food supply ecosystem. According to the *'gaming'* working mode, a set of controls allows the players to set up the supply chain ecosystem features. By adopting the so-called pull paradigm, the flow starts from a specific food need (in net kg). Associated to such a quantity, the food shelf life is set (in days). The bars and the knob on the left side of the panel allow entering such data. Multiple clicks on the left side bar allow generating a series of orders to supply. For each of them the correspondent shelf life is associated. These orders enter the processing order FIFO list and they are processed according to the plant productivity (in kg/day). After this level of the food chain, products are delivered to an intermediate warehouse for the temporary storage before the second stage shipment to the final consumption site, e.g. grocery, market, etc. The distribution stages allow setting the commercial speed of the vehicle fleet (in km/h), the global fleet and the vehicle capacities (in kg), the vehicle fuel consumption (km/l of fuel) and the average travel distance to connect the two food network levels (in km). Setting such a distance to zero means cutting off a stage of the food chain. Furthermore, the intermediate warehouse has its own capacity (in kg), its handling throughput (in kg/day), its cost and energy need. Finally, the destination of the food is twofold. In case the supply system allows processing and shipping food, i.e. from the entry order to the final shipment, within the food shelf life, the delivery is finalised and the customer is supplied. On the contrary, the order is lost and the food is wasted. In addition, the food is wasted and exits the chain at the intermediate storage node if it entries, i.e. arrives, or exits, i.e. delivered, such node after its shelf life time. Food delivery and food waste are the consequences of the right and wrong control and management of the supply chain network. Finally, a set of efficiency, economic and environmental parameters allow quantifying the overall performances of the network, benchmarking the player ability to manage the system.

Fig. 2. User view of the Gaming-Simulation tool for IoT testing in FSC

3.2 Ecosystem performances driving the feedback actions

A dedicate section of the working tool collects data and systematically shows the effect of the decisions taken to manage the food supply ecosystem. At first, the two tables on the right side of the panel report the lists of the delivered and wasted orders. In this way, the player can conclude about the final effect of all its choices, e.g. the systematic waste of food, the network is pulled correctly, idle time exists (see Fig. 3).

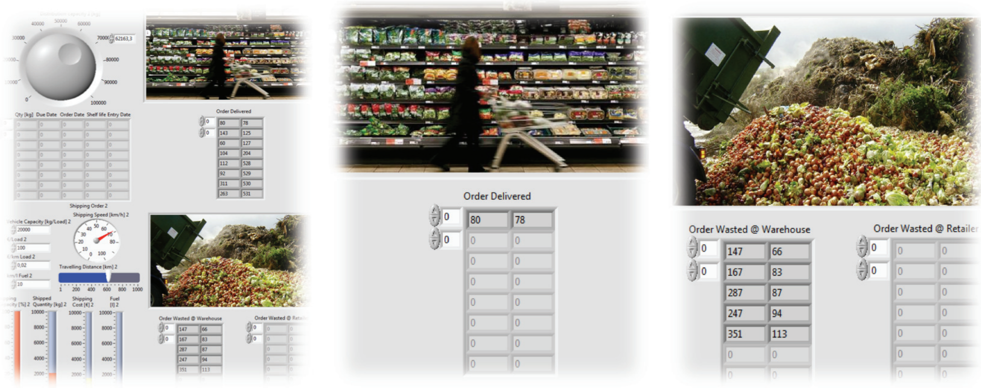


Fig.3. Order delivered and food losses assessment

Furthermore, the real-time dynamics and trend of the ecosystem is provided by a set of bars showing the current residual storage and shipping capacities of the production, distribution and storage nodes. Close to them, some aggregate statistics about the rising costs and impacts, i.e. energy and/or water needs, per node level complete the set of information the player has to know to study possible improving feedback actions. Within the next Fig. 4, the red bars are about the node efficiency, the yellow bars show the cumulate rising cost of each node, the dark green, blue and black bars indicate the energy, water and fuel consumption of the node, i.e. the network level or stage they refer.

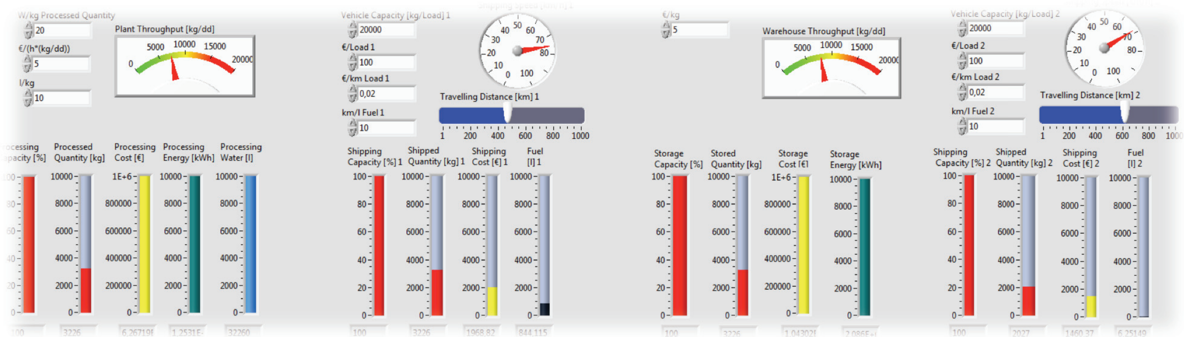


Fig. 4. FSC Performances Indicators: Dynamic bar charts.

Globally, the performances allow identifying the ecosystem bottlenecks linking them to global inefficiencies and waste of food. The player is expected to detect the poor links of the value chain, act to strength them reaching a global optimum with no waste of food. The next steps, upgrading the tool, have to improve the performance panel including a benchmark to best management achievable results, so that the player has the possibility to know how far his/her way of working is from top results, i.e. full implementation of the aforementioned *'planning'* working mode.

4. Conclusions and future research opportunities

The application of the Internet-of-Things (IoT) paradigm to the analysis and best planning of Food Supply Chains (FSCs) is a systematic approach to tackle such a challenging issue leading to a potential dramatic reduction of inefficiencies, costs, emissions and social impacts. Nevertheless, research efforts in such a direction are still limited and often refer to specific cases or they consider few links of the FSC.

This paper aims at contributing to setting up a general method to build an architecture of entities, physical-objects and flows to design and best manage the interdependencies between the observed supply chain and the exogenous environment in terms of inputs and mutual impacts. Starting from the analysis of the key features and peculiarities of the food supply ecosystem, from the field crop to the auxiliary energy requirements, a reference framework of the parameters, decisions and boundaries is done and, then, virtualized into a working tool. This enables to lead companies to better understand their processes and the interdependencies with other actors, to simulate their supply chain operations, to identify bottle necks or quantify the benefits from adopting some monitoring, traceability and real-time control technologies. The tool allows indeed experiencing the effects of a decision on a FSC link onto the whole system.

Furthermore, the tool, actually at an early-stage of development, allows gaming and gamification of FSC operations into a user-friendly environment. It is conceived to work in *gaming* and *planning* working modes so that its target is for both learning and planning. A preliminary panel of performances allows the real-time analysis of the FSC possibility not to waste food and to ship it according to its shelf life saving money and not highly polluting the environment.

Upgrades are in the direction of fully including the *'planning'* mode and extending the toll boundaries in accordance with the proposed reference scheme for the FSC dynamic analysis. The final goal to reach, at the end of the research stream, is the development of a methodology, an integrated simulation and optimization platform to support food industry, distributors and planner in the study, design and management of effective FSCs. The further extension of this research will state on its application to significant real-world environments to fully validate and demonstrate its advantages and to support practitioners' decisions and educational purposes.

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