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Towards Sustainable Digital Twins for Vertical Farming

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***Abstract*—We present a model to implement digital twins in sustainable agriculture. Our two-year research project follows the design science research paradigm, aiming at the joint creation of physical and digital layers of IoT-enabled structures for vertical farming. The proposed model deploys IoT to (1) improve productivity, (2) allow self-configuration to environmental changes, (3) promote energy saving, (4) ensure self-protection with continuous structural monitoring, and (5) reach self-optimization learning from multiple data sources. Our model shows how digital twins can contribute to the agrofood lifecycle of planning, operation, monitoring, and optimization. Moreover, it clarifies the interconnections between goals, tasks, and resources of IoT-enabled structures for sustainable agriculture, which is one of the biggest human challenges of this century.**

***Index Terms*—Digital Twins, Agriculture 4.0, Vertical Farming, Sustainability, GRL**

I. Introduction

Food production is changing and expanding at unprecedented rates. This is well justified by the high number of challenges in this bioeconomy sector [1]. Furthermore, there is a parallel need to support developing countries strongly dependent on agriculture, as well as to create production methods more efficient and sustainable and able to adapt to climatic changes. One of the promising routes to achieve these goals is paved by Internet of Things (IoT): a key technology in the ongoing fourth industrial revolution.

Nowadays, there is an imperative need for smart solutions that includes mobile phones, watches, vehicles, televisions, washing machines and fridges, even houses, industries, and entire cities. This urge for 'smart options' has also reached the agriculture sector [2]. However, current production techniques and substrates are still rudimentary considering the advances in sensors, wireless communications, and information technologies available. Although large companies already apply technologies for control and monitoring of the agrofood controlled production, there is a strong potential to explore data collected for further optimization.

Vertical farms are a recent solution that reduce land use while growing food in environments where all parameters can be controlled, suitable for indoor spaces in greenhouses or city structures [3]. IoT for vertical farms and has recently captured the attention of academia: a search in Google Scholar using the keywords "vertical farming" + IoT (2018-07-04, excluding patents and citations) returns 132 results. Interestingly, a majority (71) was published in the past two years.

Digital twins have been identified as a potential concept for application in farming [4], for example, by using IoT to monitor a malthouse (CO_2, temperature, humidity, and pH) and subsequently improve product characteristics [5]. The term digital twin "means an integrated multiphysics, multiscale, probabilistic simulation of a complex product, which functions to mirror the life of its corresponding twin" [6]. The advantages of combining the physical and the virtual information are explained by [7]: "on one hand, the physical product can be made more 'intelligent' to actively adjust its real-time behavior according to the 'recommendations' made by the virtual product. On the other hand, the virtual product can be made more 'factual' to accurately reflect the real-world state of the physical product". Nevertheless, we gathered evidence during our research that digital twins in agriculture are still in the early stages of development.

The creation of a digital twin model for vertical farming is the main objective of our research. We present the findings of the initial twenty months of a research project focused on the development of IoT-enabled structures for vertical farming. This research aims at the development of a system that, besides allowing the control, monitoring and follow-up of the vertical farming process, will help the producers optimize different parameters thus improving general productivity, sustainability, and safety. There are important studies regarding the application of IoT to agriculture that detail the hardware structure [8]. However, there is a lack of interconnected models that present the impact of each element (e.g. sensor), in the holistic system.

The remainder of this paper is organized as follows. The following Section II identifies the problem and research mo-

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tivation, stating our two main research objectives. Section III presents our design science research approach [9]. Next, we provide the background for this project addressing the topics of IoT, digital twins, and goal-oriented requirements language (GRL) – the selected modeling language for our project. Section V-A details the design of the physical and digital layers whilst Section V-B proposes our digital twin model. We conclude in Section VI, presenting the study limitations and the opportunities for future research.

II. Problem Identification, Motivation, and Research Objectives

There are two global challenges that researchers must address in agriculture research. First, the increase in worldwide population requires the design and application of new information systems for food production [1]. It is crucial to increase productivity, taking advantage of modern technologies for remote monitoring and control (e.g. sensors, wireless communication, cloud platforms), assisting the producers in their daily operations. The continuous population growth and changes in dietary practices requires a drastic increase in food production (around 60 %) to feed the estimated over nine billion people in 2050 [10]. As noted by [1] "$\sim$50 % of the world's vegetated land is already used for food production, and 33 % of soils are degraded by erosion. The agri-food sector accounts for 25 % of global CO_2 emissions and consumes 70 % of global freshwater extractions, but 32 % of all food produced is wasted. Without change, we will not be able to feed the world with enough quality food in the future". Data increase and the advances in storage capabilities and analytics raise new opportunities to create intelligent systems with the capacity for self-configuration, self-adaptation, self-protection, and self-optimization.

The second global challenge is the climate changes [11] with implications in resource utilization (e.g. water), energy consumption in vertical farm facilities, and the creation of artificial conditions for different food products during the year. Vertical farms and the advances in technology, for example, IoT [12], are solutions that require additional research and have profound organizational implications, for example, in the work processes and information transparency in supply chains.

Digital twins can be defined as digital mirrors of physical objects [6]. Based on emerging technologies and enablers of the fourth industrial revolution such as IoT, augmented reality, artificial intelligence, and simulation, these mirrors consist of three parts: the physical product, the virtual product, and the linkage between them [6]. When using a digital twin, the users of a specific object (e.g. a machine, a factory) can monitor its operation and optimize the system performance through advanced data analytics. The potential of digital twins for agriculture has recently been suggested by some authors, that state that some challenges of agriculture "will not be possible without a number of technological breakthroughs, not least of which is the realization of a 'digital twin' and the threads that connect it to the physical world" [1]. However, there is a clear lack of research on their design in the agriculture context, meaning that there is no specific digital information management.

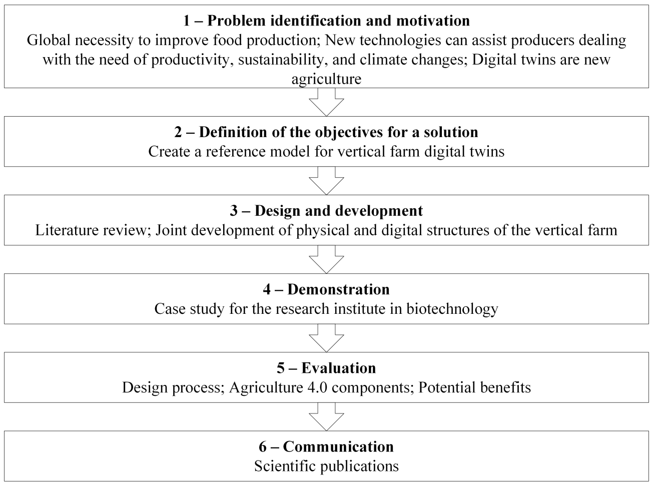

Fig. 1. Design science research approach (adapted from [15])

A leading research institute in biotechnology was presented with this particular problem, when wanting to develop a new system for vertical farming. The present work was designed in order to comply with their needs, and consequently, the following research objectives were formulated:

- *RO1: Joint development of the physical and digital structure for vertical farming*;
- *RO2: Creation of a reference model for sustainable digital twins in vertical farming*.

The following Section introduces the approach used to address the two interrelated research objectives.

III. Method

Our paper follows a design-science research (DSR) approach [9], having its foundations in the work of [13]. The outcome of our project is presented as a model for digital twins, representing the technologies, processes, and services provided. Considering that the concept of digital twins is new to the agriculture sector and that it is a new concept associated with the fourth industrial revolution, our problem is positioned in 'invention' quadrant of DSR knowledge contribution framework proposed by [14].

Fig. 1 present the six phases of our DSR [15].

IV. Background

A. Controlled Vertical Farming and IoT

In recent years, the cornerstones for a smart, efficient and sustainable agrofood production have been created with the emergence of the IoT paradigm. Through this remote sensoring technology several critical aspects in food production can now be more proficiently monitored, analyzed and used to control and improve the traditional agriculture. The monitored parameters include variables such as temperature, soil humidity, water level, CO_2, luminosity or soil pH, whose monitoring and analysis are vital for a sustainable smart agriculture [16]. In particular, data acquired by sensors will permit to automate the action of actuator devices used to manage among others the irrigation, fertilizers, pesticides, illumination, and access control. Moreover, not only the collected data obtained by the deployment of IoT will permit the automation of the production, but also the usage of artificial intelligence algorithms will create new opportunities for achieving predictions, self-learning and support for control and planning [17].

Nonetheless, the design and implementation of IoT systems can be challenging. A case study of IoT development for agriculture, mariculture, and ecological monitoring domains is described in [18]. The objective of this work was to prototype remote control solutions and a present and an example of smart fungicide spraying system to treat the grapevine mildew. The IoT nodes used to implement and evaluate the platform were based on Arduino microcontroller and Raspberry Pi. This system was also supported by a cloud-based file management. It is important to notice that, despite the great importance and future of cloud storage in the operation of IoT systems, this technology has not been widely adopted (7.32 %), with most of the studies proposing private storage solutions in detriment of this resource [17].

The authors in [19] analyzed and compared hardware, platforms and sensors that can be used in agriculture to improve the interaction with the physical world. In particular, wireless technologies such as 6LowPAN, ZigBee, Bluetooth, LoRa were evaluated regarding their range of operation and data rate. The Low-Power WAN (LPWAN) technologies have become popular within the IoT paradigm due to its low cost, low energy consumption, and large area of coverage. Moreover, the hardware used in these systems such as Raspberry Pi and Arduino was also presented and evaluated. The pertinence of security in IoT, namely the physical security of the sensors, was also described. This security aspect is particularly important in agriculture since the devices could be deployed in open unattended fields. In order to provide the necessary security support for the IoT deployment in an agricultural environment some measures have been proposed and tested, such as authentication and communication encryption [20].

The potential usage of IoT in controlled environment agriculture has been addressed in some works [20]. A greenhouse monitor system based in the utilization of ZigBee to control its climate is described in [21]. Data collected by temperature, pressure, light, humidity, and CO_2 sensors permit the system to remotely take decisions regarding the control of actuators such as a fan, a curtain and a sprinkler. Another proposal involving ZigBee to autonomously and remotely control a greenhouse is described in [22], allowing remote control through a web application or a mobile application.

Several artificial intelligence strategies can be added to obtain a smart automation system. For example, a fuzzy logic control technique was used in [2] to create a stable climate for plants and simultaneously save energy and water. The climate parameters managed by the fuzzy logic controller (i.e. temperature, humidity, CO_2, and illuminance) were also remotely monitored and logged through ZigBee-GSM/GPRS wireless technologies. While a fuzzy adaptive control algorithm was similarly proposed in [11] with the objective of reducing energy consumption, a different approach using a machine learning algorithm (SW-SVR) was described in [23] to deploy a smart greenhouse environmental control system. Interestingly, the latter obtained positive results by using wireless scattered light sensors to indirectly measure leafs size, and consequently, to estimate plant growth.

In conclusion, monitoring and control of the vertical farm environment through IoT will make it possible to efficiently and sustainably produce different types of crops. This has particular importance in vertical farming. In this context, a prototype for a smart agrofood controlled production was presented in [24]. However, this proposal only considered the monitoring of humidity to control the automatic switching of the water sprinkler and fog.

A recent review on IoT applications in agro-industry concluded that “most of the research still focuses on monitoring applications (62 %); however, there is growing interest in closing the loop by doing control (25 %), and there are some preliminary solutions in logistics and prediction (13 %) for agro-industrial and environmental applications using IoT” [17]. These authors concluded that cloud platforms have not yet been extensively adapted to this subject and “that future solutions will need to fully embrace Cloud services and new ways of connectivity in order to get the benefits of a truly connected and smart IoT ecosystem”. In agreement with the referred review [17], the following Section presents a promising solution to this claim.

B. *Digital Twins*

The development of digital twins started as basic CAD – Computer Aided Design representation but it is evolving to allow interaction with the physical object, mirroring its form and behavior. The work presented by NASA and the U.S. Air Force is one of the most cited papers on the topic [6]. It explains the importance of digital twins to improve safety and reliability of flying objects. According to the authors, the digital twin can assist in the simulation of complex systems and in real-time monitoring and management of its operation. It represents a combination of digital representations of the real object, using sensor data and all available historical data of the fleet to ‘forecast the health’ of the vehicle and predict response to specific events [6].

The digital twin technology has already captured the attention of other economic sectors. For example, General Electric’s (GE) global research center presented a digital twin application for their fleet of steam turbines, using mixed reality to interact with the digital object, artificial intelligence to evaluate data operation of the multiple steam turbines and sensors, and the possibility to interfere in the objects’ operation [25]. However, the application of digital twins in agriculture is still in its early stages of development. In fact, a search with the keywords “digital twin” AND (agriculture OR agrifood OR agrofood) in Google Scholar (2018-07-04, excluding patents and citations) returns 126 results but the majority of which only point to the

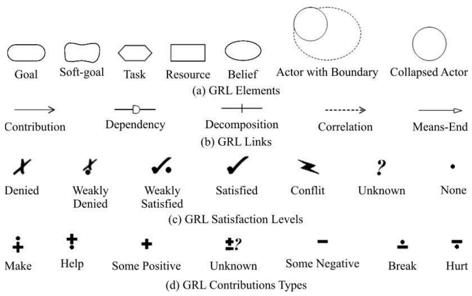

Fig. 2. Basic elements and relationships of GRL [27]

relevance of digital twins in agriculture, lacking case studies and models for the development process.

C. Goal Modeling with GRL

GRL can be used to describe intentions, goals and non-functional requirements of different system stakeholders [26]. A GRL goal graph includes elements interconnected by various kinds of links (e.g. contribution, correlation, dependency). GRL elements can be in the form of *goals* ( ), *soft-goals* (; which differ from the former due to the lack of a clear quantification), *tasks* (; to operationalize goals and soft-goals), *beliefs* (; that represent design rationales), and *resources* (; that must be available to the other elements) [26]. In GRL, systems and their stakeholders are represented as *actors* ( ), with a potential interest for modeling the requirements of compliance to regulations.

There are several tools available to create goals models. For example jUCMNav, a graphical editor for GRL in the form of an Eclipse plug-in, and Microsoft Visio with SanDriLa that we used in this research. The elements of goals models are presented in Fig. 2.

V. Developing a Digital Twin for Vertical Farming

This Section details our design research project. Next, we present the development of the physical and digital infrastructures of the system, subsequently presenting the resulting reference model for the digital twin.

A. Design and Development

The solution conceived and implemented in the past eighteen months imbricates the physical elements of the vertical farm structure (e.g. metal, glass, shelters, hardware) with a corresponding digital twin, thus compared to the sensory and nervous system of a human being. A mesh composed by dozens of sensors enables the system to 'feel' the conditions of the vertical farm operation, allowing the monitorization of temperature, humidity, luminosity and relative CO_2 concentration (first stage of implementation). The existence of a sensor mesh is imperative in order to accurately measure the conditions experienced at any given point in the vertical farm, which can be obtained by weighting the data collected by the sensors closest to the target point. It is possible to establish an ideal value for each measured condition, as well as a range of variation. If the variation range is infringed, then the actuators will start operating until the ideal conditions are restored. In this way, it is possible to establish a correspondence between the actuators (namely, air conditioning, air extraction, lighting, and misting system) and the sensor layer of the digital twin.

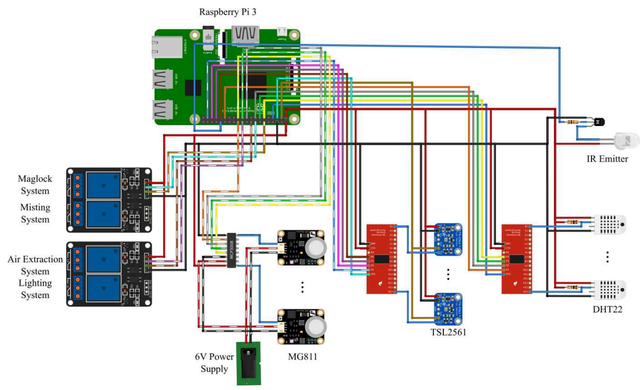

Fig. 3. IoT architecture for the sustainable digital twin

The physical infrastructure of the vertical farm was developed during the first year, optimizing the space and mitigating potential risks to the species produced, for example, the door of the production chamber only opens after the antechamber door is closed, to minimize contaminations and create an environmental barrier. Redundancy is useful to identify potential malfunctioning of a physical (e.g. damaged sensor) or a digital (e.g. wrong data) element, and to obtain more precise measurements comparing data from multiple sources.

The data collected over time is stored in a cloud infrastructure for intelligent data analysis – the system will be able to provide recommendations to producers in order to improve their production process. The producer can access the system either locally or remotely via the digital twin interface. The system also provides mechanisms for vertical farm planning: ideal values and variation ranges for each controlled condition. The IoT architecture of the first stage of construction and the layers of the vertical farm are presented in Fig. 3.

The current system version uses the following sensors: DHT22 (temperature and humidity), TSL2561 (luminosity), and MG811 (CO_2 concentration). The main reason that led to the choice of these sensors was their low cost when compared to their read accuracy. As the system consists of several sensors of each type it is necessary to resort to multiplexing mechanisms for the Raspberry Pi. At this stage we have already implemented the (1) physical structure of the vertical farm, (2) IoT architecture, (3) cloud platform and communication mechanisms, and (4) developed the GRL reference model. In the following six months we will include additional sensors for safety (e.g. camera and movement sensors) and resource monitoring (e.g. water flow sensor), and develop the algorithms for self-optimization and forecasting of the plant.

The digital twins requires additional physical and digital elements to be created, namely the cloud infrastructure, the interface, the communication protocols, and artificial intelli-

Fig. 4. Architecture for the sustainable digital twin (on the left) and a visualization of the vertical farm (on the right)

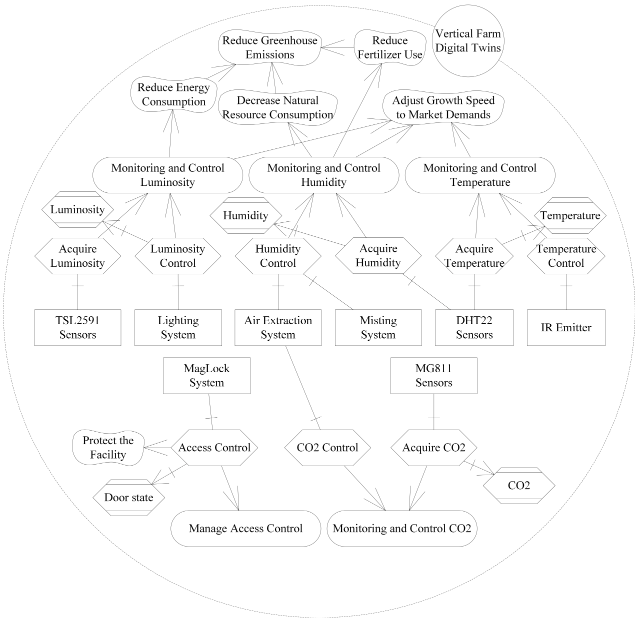

Fig. 5. GRL model for sustainable digital twin – vertical farm

gence algorithms. The prototype for the digital twin high level architecture and interface is presenting in Fig. 4, which also includes a photograph of the physical structure.

B. A GRL Model for Sustainable Digital Twins in Vertical Farming

The GRL model is depicted in Fig. 5 where key types of soft-goals ( ) to consider in the development of a vertical farm, namely (1) productivity, (2) sustainability, and (3) safety. It includes the reduction of resource consumption (e.g. water, energy, fertilizer), the implementation of communications and hardware required for the digital twin, the awareness of market situations and its implications on planning and distribution of the obtained products, and the necessary tools for the product lifecycle management, covering the complete cycle from the raw materials to the logistics of production distribution. The goals ( ) describe what needs to be monitored or controlled by the IoT infrastructure, each one supported by specific tasks ( ). Then, each task requires a set of IoT resources ( ).

At the current stage of our research, the model has already been partially demonstrated and evaluated during the creation of the vertical farm structure. We have specified all the requirements for the elements presented on our proposed model (GRL resource – – in Fig. 5). The IoT infrastructure was specified and implemented according to the requirements of resource optimization (resource monitoring), interaction (dashboard data), time-to-market (adjust the production parameters), and product lifecycle information (e.g. number of days of each production and the corresponding environmental parameters). Although we already included data analytics in our model, this element is still under test since no complete production cycle has been performed, and consequently, the optimization algorithms will require more data to be produced and tested in practice. We found the model simple enough to facilitate the communication between vertical farm owner and producers, considering the main digital twin technologies and the specificities of Agriculture 4.0.

The food product is the focal point of the digital twin. Therefore, it is necessary to define relevant product characteristics and its interrelations with other goals of the system. For example, product size may be dependent on temperature conditions, being necessary to define measurements intervals during product lifecycle (dimensions, color) and possible alerts to the manager. The vertical farm digital twin must consider other sources of information, for example, weather report and market analysis (e.g. product price to decide the best moment to sell). Both, the physical (e.g. electronics) and the digital (e.g. software) infrastructures need periodic evaluation, including its functioning conditions, and it is crucial to take advantage of artificial intelligence algorithms tailored for each type of product (e.g. mushroom, strawberry, ...).

VI. Conclusions

We present a design science research project with the aim of developing a digital twin reference model for IoT-enabled structures of vertical farming. Our project involved experts in agriculture, electronics, and information system, including the physical and digital development. The results of our study include (1) a reference model for the digital twin, (2) definition of IoT structure, (3) specification of the tasks, (4) assessment of environmental conditions, and (5) identification of potential for forecasting and decision support aid.

Specific applications of digital twins in the agrofood lifecycle include the integration of production monitoring and control, product quality improvement, and intelligent adjustment of environmental conditions to foster sustainability and self-protection of the structures. Perhaps the most promising advantages are (1) the decision support, and (2) the proximity that it allows between the (increasingly decentralized and complex) agriculture process and it multiple stakeholders. For example, digital twins can be used to promote sustainable smart cities, supporting inhabitants to create vertical farms in their homes. Moreover, digital twins can support food auditors in the assessment of the production conditions and product characteristics. Nevertheless, the scalability of our digital twin model to other domains (e.g. smart cities), requires additional research.

Our research has limitations that are important to point out. First of all, digital twin is a recent concept in high-tech industries and only now is finding its opportunity in agriculture. Second, although we support our findings in a real implementation, this is the primary proposal of our GRL model. The scope of our model is restricted to the design and development in Section V-A. Therefore, our work focused in the IoT infrastructure development (Fig. 3), and the interface for the digital twin of a single vertical farm structure (Fig. 4), not yet including the forecasting and decision support layers, which are expected to be concluded during the next semester of our research project. Future developments will include the creation of algorithms for production optimization. Third, our research used technology that is widely available in the market (e.g. Raspberry Pi) and low cost sensors, in order to make the results accessible to the majority of producers, although other components could also be tested. Finally, we have selected GRL to create our models because the language was already familiar to two of the researchers, but other modeling languages could also be used. These limitations are also starting points for our future research work.

Our findings provide a solid base for the development of Agriculture 4.0 and smart IoT-enabled structures for vertical farming by introducing digital twins to improve the problematic situation of food supply. Moreover, digital twins can contribute to important energy savings and sustainable practices (e.g. adjusting cycles of production to the expected shortage of water due to climate changes). Our proposal extends previous research that propose physical systems architecture for vertical farming (e.g. [8]) by introducing comprehensive goal models that interrelate the goals, tasks, and resources of the proposed system. Additionally, our model can be used to identify the goals of multiple stakeholders of IoT-enabled structures. The benefits of GRL models include the identification of "why" the elements of the system are used, complementing representation of "what" or "how" they are implemented. We found benefits in using goal models in the initial phases of the digital twin development, fostering communication between experts with different backgrounds. We hope that our work can inspire other researchers to develop digital twins to different areas of agriculture and to other traditional sectors of the economy.

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