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Towards a Sustainable Digital Twin for Vertical Farming

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 the digital twins can contribute within the agrofood lifecycle of planning, operation, monitoring, and optimization. Moreover, it clarifies the interconnections between the goals, tasks, and resources of IoT-enabled structures for sustainable agriculture, which is one of the biggest human challenges in this century.

Keywords— 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 the 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 the 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, 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 the digital data collected.

Vertical farms are a recent solution that reduces land use while growing food in environments where all parameters can be controlled, suitable for indoor spaces in greenhouses or city structures [3]. IoT is essential for vertical farms and has recently captured the attention of the academia: a search in google scholar using the keyword combination “vertical farming” + IoT in Google Scholar (04/07/2018, excluding patents and citations) returns 132 results. Interestingly, the 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 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 productivity, sustainability, and safety. There are important studies of IoT in 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 next section identifies the problem and research motivation, 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 modelling language for our project. Section V.A) details the design of the physical and digital layers and in section V. B) we propose the digital twin model. The discussion of the results is included in section VI and we conclude in section VII, presenting the study limitations and the opportunities for future research.

II. PRODUCTION 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] *"~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*". The increase of data and the advances in storage capabilities and analytics raises new opportunities to create intelligent systems with the capacity of self-configuration, self-adaptation, self-protection, and self-optimization.

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

Digital twins are gaining popularity in this century and 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 agriculture contexts, meaning that there are no specific models for sustainable digital information management.

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 next 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 the 'invention' quadrant of DSR knowledge contribution framework proposed by [14].

Figure 1 presents the six phases of our DSR [15].

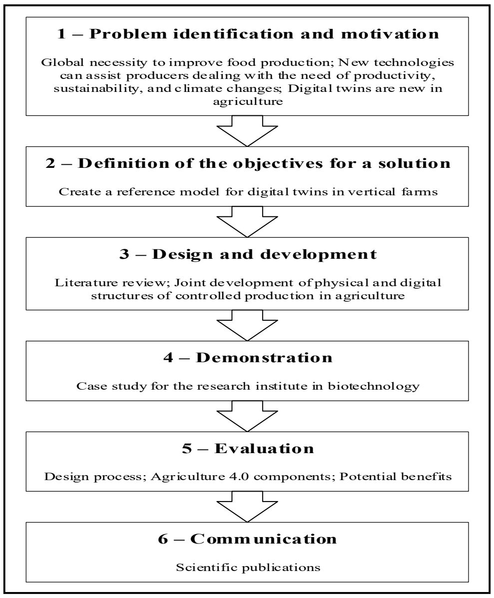

Fig. 1. Design science research approach (adapted from [15])

IV. BACKGROUND

A. 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 level, solar radiation, wind speed and soil pH, whose monitoring and analysis play a vital role in building a sustainable smart agriculture [16]. In particular, the 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 in 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 developing an IoT platform for research in agriculture, mariculture, and ecological monitoring domains is described in [18]. The objective of this work was to prototype remote control solutions in these areas. In particular, an example of application in agriculture for a smart fungicide spraying system to treat the grapevine mildew was presented. The IoT nodes used to implement and evaluate the platform were based on Arduino microcontroller and Raspberry Pi. This system was 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 penetration in agriculture of the more recent IoT technologies and their potential to modernize this area were discussed in [19]. The hardware, platforms and sensors that in this context can be used in agriculture to improve the interaction with the physical world were analyzed and compared. 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 potential agriculture applications were addressed and organized in agricultural monitoring and control, controlled environment agriculture, open-field agriculture, livestock applications and food supply chain tracking. 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 safety and security support to the IoT deployment in an agricultural environment some measures, such as authentication and data encryption, have been proposed and tested [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]. The data collected by sensors of temperature, pressure, light, humidity, and CO_2 permit that proposal to remotely take decisions regarding the control of actuators such as a fan, a curtain and a sprinkler. Another proposal involving the usage of ZigBee and the acquisition of environmental parameters to autonomously and remotely control a greenhouse is described in [22]. This proposal allows for the 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, CO2, and illuminance) were also remotely monitored and logged through ZigBee-GSM/GPRS wireless technologies. The control of the climate variables can be done either manually or automatically through a remote web server. While a fuzzy adaptive control algorithm was similarly proposed in [11] with the objective of reducing the 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, this latter proposal obtained positive results by using wireless scattered light sensors to indirectly measure the leaf area size, and consequently, to estimate plant growth.

This way, the monitoring and control of the greenhouse 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 of IoT applications in agro industry concluded that "*most of the research still focuses on monitoring applications (62%); however there is a 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 representations but is evolving to allow interaction with the physical object, mirroring its form and behaviour. 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 important economic sectors. For example, General Electric's (GE) global research centre 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 (04/07/2018, excluding patents and citations) returns 126 results but the majority of which only point to the 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 stakeholders of a system [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 modelling the requirements of compliance to regulations.

There are several tools available to create goal models. In this research we have selected jUCMNav (for the integrated model), a graphical editor for GRL in the form of and Eclipse plug-in [27] and Microsoft Visio with the SanDriLa plugin (for the individual structure model). The elements of goal models are presented in Figure 2.

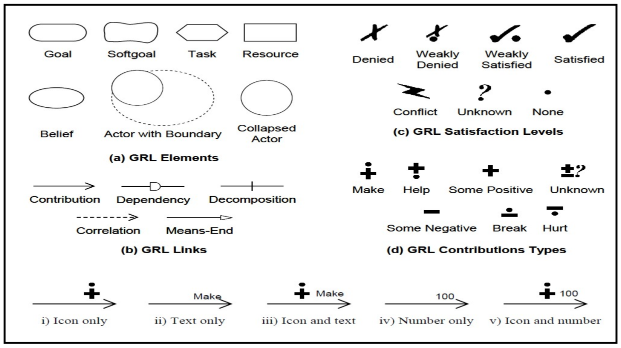

Fig. 2. Basic elements and relationships of GRL [28]

V. DEVELOPING A DIGITAL TWIN FOR VERTICAL FARMING

This section details our design science research project. Next, we present the development of the physical and digital infrastructures of the system, subsequently presenting the resulting 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 greenhouse structure (e.g. metal, glass, shelters, hardware) with a corresponding digital twin, thus being 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 greenhouse 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 greenhouse, 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.

The physical infrastructure of the system was developed in 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 inside the greenhouse. We also designed a redundant system of sensors. 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 greenhouse planning: ideal values and variation ranges of each controlled condition. The IoT architecture of the first stage of construction is presented in Figure 3.

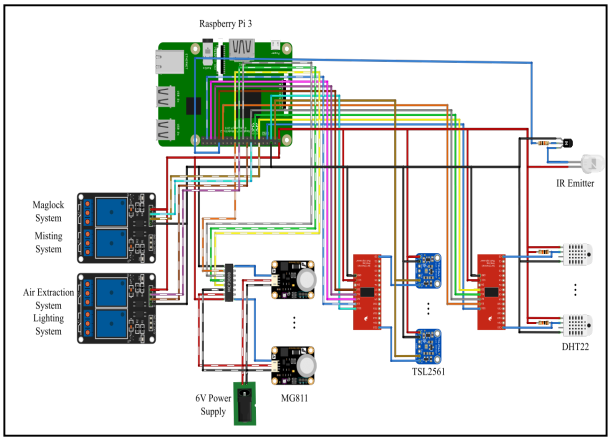

Fig. 3. IoT system architecture for the sustainable digital twin

The current system 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 on multiplexing mechanisms for the Raspberry Pi. At this stage we have already implemented the (1) physical structure of the greenhouse, (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 twin requires additional physical and digital elements to be created, namely, the cloud infrastructure, the interface, the communication protocols, and artificial intelligence algorithms. The prototype for the digital twin high level architecture and interface is presented in Figure 4, which also includes a photograph of the physical structure.

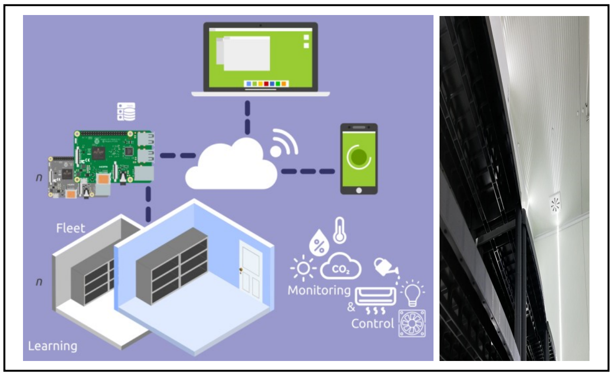

Fig. 4. Architecture for the greenhouse digital twin (on the left) and a visualization of the vertical farm (on the right)

The architecture considers multiple vertical farms (fleet) that communicate via the cloud platform (web and mobile access). It also includes the main data inputs (e.g. temperature) and outputs (e.g. luminosity). The joint design of the physical (on the right) and digital elements of the greenhouse provided the basis for our model.

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

The GRL model is depicted in Figure 5.

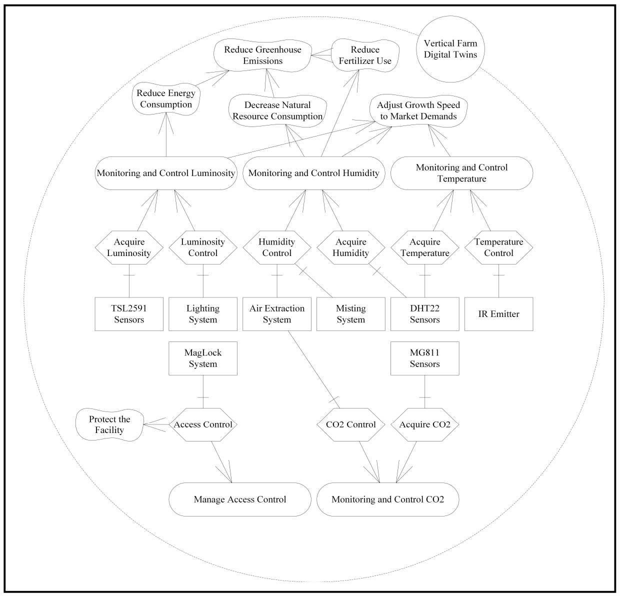

Fig. 5. GRL model for sustainable digital twin

Figure 5 represent key types of soft goals (⬭) to consider in the development of a greenhouse, 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 product 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 greenhouse structure. We have specified all the requirements for the physical elements presented on our proposed model (GRL resource ▭ in Figure 5). The IoT infrastructure was specified and implemented according to the requirements of resource optimization (resource monitoring), interaction (dashboards 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 development since no complete agrofood production cycle has been undergone, 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 greenhouse 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 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 measurement intervals during product lifecycle (e.g. dimensions, colour) and possible alerts to the manager. The greenhouse digital twin must also 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 with the aim to develop a digital twin model for IoT-enabled structures of vertical farming. Our project involved experts in agriculture, electronics, and information systems, including the physical and digital deployment. The results of our study include (1) a goal model for the digital twin, (2) definition of IoT structure, (3) specification of the operational tasks, (4) assessment of environmental conditions, and (5) identification of potential for forecasting and decision support aid.

Although the data presented shows innovative advances on the use of digital twins in agriculture, our research still presents limitations. First of all, digital twin is a recent concept in high-tech industries and only now is finding its opportunity in agriculture. The knowledge on digital twins is expected to evolve in the next years with practical implementations and improvements in its technological enablers, namely, mixed reality, human-computer interaction, smart sensors, cloud, big data, and artificial intelligence. Second, although we support our findings in a real implementation, this is the primary proposal of our GRL model. Therefore, our field work focused in the IoT infrastructure development (Figure 3), and the interface for the digital twin of a single greenhouse structure (Figure 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 greenhouse producers, although other components could also be tested. Fourth, since we focused this stage of our research in the physical and digital greenhouse development, we could not evaluate the effect of the 'fleet' [6] with multiple farms. Finally, we selected GRL to create our models because the language was already familiar to two of the researchers, but other modelling languages could be used. These limitations are also starting points for our future research work.

Our findings provide a base for the development of agriculture 4.0 and smart IoT-enabled structures of vertical farming by introducing digital twins to improve the problematic situation of food supply. Moreover, digital twins can contribute to 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 architectures for greenhouse (e.g. [8]) by introducing a comprehensive goal model that interrelates 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 representations 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.

REFERENCES

[1] T. Hofmann, "Integrating Nature, People, and Technology to Tackle the Global Agri-Food Challenge," *J. Agric. Food Chem.*, vol. 65, no. 20, pp. 4007–4008, 2017.

[2] M. Azaza, C. Tanougast, E. Fabrizio, and A. Mami, "Smart greenhouse fuzzy logic based control system enhanced with wireless data monitoring," *ISA Trans.*, vol. 61, no. 2016, pp. 297–307, 2016.

[3] D. Despommier, "Farming up the city: The rise of urban vertical farms," *Trends Biotechnol.*, vol. 31, no. 7, pp. 388–389, 2013.

[4] C. N. Verdouw and J. W. Kruize, "Digital twins in farm management: illustrations from the FIWARE accelerators SmartAgriFood and Fractals," in *7th Asian-Australasian Conference on Precision Agriculture Digital*, 2017, pp. 1–5.

[5] R. Dolci, "IoT Solutions for Precision Farming and Food Manufacturing: Artificial Intelligence Applications in Digital Food," *Proc. - Int. Comput. Softw. Appl. Conf.*, vol. 2, pp. 384–385, 2017.

[6] E. Glaessgen and D. Stargel, "The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles," in *53rd Structures, Structural Dynamics, and Materials Conference: Special Session on the Digital Twin*, 2012, pp. 1–14.

[7] F. Tao, F. Sui, A. Liu, Q. Qi, M. Zhang, B. Song, Z. Guo, S. C. Y. Lu, and A. Y. C. Nee, "Digital twin-driven product design framework," *Int. J. Prod. Res.*, vol. 7543, pp. 1–19, 2018.

[8] G. Burchi, S. Chessa, F. Gambineri, A. Kocian, D. Massa, P. Milazzo, L. Rimediotti, and A. Ruggeri, "Information technology controlled greenhouse : A system architecture," *IEEE IoT Vert. Top. Summit Agric.*, 2018.

[9] A. R. Hevner, S. T. March, and J. Park, "Design Science in Information Systems Research," *MIS Q.*, vol. 28, no. 1, pp. 75–105, 2004.

[10] B. Lipinski, C. Hanson, J. Lomax, L. Kitinoja, R. Waite, and T. Searchinger, "Reducing Food Loss and Waste - World Resources Institute Working Paper," 2013.

[11] Y. Su, L. Xu, and E. D. Goodman, "Greenhouse climate fuzzy adaptive control considering energy saving," *Int. J. Control. Autom. Syst.*, vol. 15, no. 4, pp. 1936–1948, 2017.

[12] R. K. Kodali, V. Jain, and S. Karagwal, "IoT based smart greenhouse," in *2016 IEEE Region 10 Humanitarian Technology Conference (R10-HTC)*, 2016, pp. 1–6.

[13] H. Simon, *The sciences of the artificial, (third edition)*. MIT Press, 1996.

[14] S. Gregor and A. R. Hevner, "Positioning and presenting design science research for maximum impact," *MIS Q.*, vol. 37, no. 2, pp. 337–355, 2013.

[15] K. Peffers, T. Tuunanen, M. A. Rothenberger, and S. Chatterjee, "A Design Science Research Methodology for Information Systems Research," *J. Manag. Inf. Syst.*, vol. 24, no. 3, pp. 45–78, 2007.

[16] M. Stočes, J. Vaněk, J. Masner, and J. Pavlík, "Internet of Things (IoT) in Agriculture - Selected Aspects," *Agris on-line Pap. Econ. Informatics*, vol. VIII, no. 1, pp. 83–88, Mar. 2016.

[17] J. M. Talavera, L. E. Tobón, J. A. Gómez, M. A. Culman, J. M. Aranda, D. T. Parra, L. A. Quiroz, A. Hoyos, and L. E. Garreta, "Review of IoT applications in agro-industrial and environmental fields," *Comput. Electron. Agric.*, vol. 142, pp. 283–297, 2017.

[18] T. Popović, N. Latinović, A. Pešić, Ž. Zečević, B. Krstajić, and S. Djukanović, "Architecting an IoT-enabled platform for precision agriculture and ecological monitoring: A case study," *Comput. Electron. Agric.*, vol. 140, pp. 255–265, Aug. 2017.

[19] A. Tzounis, N. Katsoulas, T. Bartzanas, and C. Kittas, "Internet of Things in agriculture, recent advances and future challenges," *Biosyst. Eng.*, vol. 164, no. 4, pp. 31–48, Dec. 2017.

[20] S. Sivamani, J. Choi, K. Bae, H. Ko, and Y. Cho, "A smart service model in greenhouse environment using event-based security based on wireless sensor network," *Concurr. Comput. Pract. Exp.*, vol. 30, no. 2, p. e4240, 2018.

[21] D. Liu, X. Cao, C. Huang, and L. Ji, "Intelligent agriculture greenhouse environment monitoring system based on IOT technology," in *International Conference on Intelligent Transportation, Big Data and Smart City (ICITBS)*, 2016, pp. 487–490.

[22] R. A. Li, X. Sha, and K. Lin, "Smart greenhouse: A real-time mobile intelligent monitoring system based on WSN," in *10th International Wireless Communications and Mobile Computing Conference (IWCMC)*, 2014, pp. 1152–1156.

[23] Y. Kaneda, H. Ibayashi, N. Oishi, and H. Mineno, "Greenhouse environmental control system based on SW-SVR," in *Procedia Computer Science*, 2015, vol. 60, no. 1, pp. 860–869.

[24] O. Chieochan, A. Saokaew, and E. Boonchieng, "IoT for smart farm: A case study of the Lingzhi mushroom farm at Maejo University," in *2017 14th International Joint Conference on Computer Science and Software Engineering (JCSSE)*, 2017, pp. 1–6.

[25] GE, "Minds + Machines: Meet A Digital Twin," 2016. [Online]. Available: https://www.youtube.com/watch?v=2dCz3oL2rTw. [Accessed: 21-Apr-2018].

[26] D. Amyot and G. Mussbacher, "User requirements notation: The first ten years, the next ten years," *J. Softw.*, vol. 6, no. 5, pp. 747–768, 2011.

[27] D. Amyot, R. Rashidi-Tabrizi, and G. Mussbacher, "Improved GRL Modeling and Analysis with jUCMNav 5," in *Proceedings of the 6th International i* Workshop (iStar 2013), CEUR Vol-978*, 2013, pp. 137–139.

[28] D. Amyot, S. Ghanavati, J. Horkoff, G. Mussbacher, L. Peyton, and E. Yu, "Evaluating goal models within the goal-oriented requirement language," *Int. J. Intell. Syst.*, vol. 25, no. 8, pp. 841–877, 2010.