A scalable digital twin for vertical farming

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Abstract

Digital twins transform agriculture with three-dimensional replicas of governable physical objects and intelligent collaboration for a sustainable bioeconomy. However, their success depends on (1) scaling up resiliency in industry-ready solutions, (2) evaluating performance in near real-time monitoring of the agri-food infrastructure, and (3) delivering design guidelines and field instantiations to inspire the practitioners. This work addresses these challenges in a two-year-long design science research, aiming to reach industrial demonstration technology readiness (TRL7) in a vertical farm structure supported by digital twin technology. Vertical farms pose new challenges for agriculture, taking advantage of three-dimensional productive spaces that change over time. Furthermore, digital twins reveal the potential to warrant more rational use of resources, food protection, prevention of disruptions, and food product traceability. For design-time scalability, this research defines the digital twin requirements for vertical farms and identifies the necessary conditions for the operational environment. For run-time scalability, the study reveals a physical and digital infrastructure that managers can use to develop their vision for vertical farming in more uncertain environments, demanding resiliency and near real-time optimization.

Keywords

Vertical farm · Resiliency · Digital twin · Scalable digitalization · Design science research

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1 Introduction

Agriculture is gradually expanding out of the fields and becoming advanced factories of indoor food production, representing a pivotal option to answer the high growth demand in the feed and food sector due to the growing human population (Kozai et al. 2019). Feeding the world also demands the creation of new forms of vertical physical structures deeply intertwined in more complex information systems that can sense the production lifecycle and act autonomously to improve productivity and sustainability (Despommier 2011). Shifting from traditional greenhouses to high-tech 3D production spaces dispersed in high buildings, cities, or plant farms raises new challenges for agriculture. For example, the need for resiliency and safety of farm structures drives the design of guidelines that create trustable commercial systems prepared for future certification and push prototypes' maturity to their limit.

Vertical farming structures need a digital counterpart. A digital twin can be defined as "an integrated multiphysics, multiscale, probabilistic simulation of complex product, which functions to mirror the life of its corresponding twin" (Glaessgen and Stargel 2012). There are many advantages to infusing physical and digital layers (Tao et al. 2019): "*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*". Digital twins include sensors, 3D visualizations of structures, and advanced data science capacity (Zheng et al. 2019). However, these solutions are only now taking the first steps in agriculture, and "*it remains to be demonstrated that the implementation of such holistic digital tools are feasible and affordable for the diverse agrofood industry*" (Verboven et al. 2020). Moreover, on many occasions, "*technologies are used rather to reduce physical workloads than to support crop or management decisions*" (Groher et al. 2020).

Our two-year-long research started when a leading research institute in biotechnology was presented with the challenges of developing an industrial version of a vertical farm for mushroom production. Several digital twin prototypes have already been published in the literature. However, their technology readiness level (TRL) (Mankins 2009) was systematically low. Many did not have a real-scale implementation, design guidelines were missing, and resilient vertical farm scalability was insufficiently addressed. Therefore, our overall research objective (RO) is *the scale-up and evaluation of a vertical farm supported by digital twin technology*. Two interrelated research objectives were formulated: (RO1) *the vertical farm should be self-supervised and self-adjusted*, and (RO2) *should have a resilient design prepared for the risks of disruptions*.

The rest of this paper is organized as follows. Next, the background section offers an overview of farming and digital twins. Subsequently, the design science research approach is explained. The following section details the technological scale-up of the vertical farm and the thorough evaluation process. Afterward, the discussion of the results puts forward a set of design guidelines for vertical farming and highlights the main implications. Finally, the paper summarizes the key outcomes, the study limitations, and the opportunities for future contributions in the research arena.

2 Background

2.1 Vertical Farming: The New Generation of Greenhouses and Bioeconomy

Vertical farms are crucial to *feeding the world in the 21st century* (Despommier 2011). They consist of vertically stacked layers used to grow crops indoors or in the external façade of skyscrapers (Despommier 2013; Benke and Tomkins 2017). The solution is appealing to reduce land use and improve production in more controlled environments (Despommier 2013). Monitoring parameters include soil humidity, temperature, water level, CO_2, solar radiation, pH, or wind speed (Stočes et al. 2016; Mahajan et al. 2021).

Traditional greenhouses are evolving to more sophisticated forms, expanding to the "vertical" space and more ingenious production (with or without soil) supported by the Internet of Things (IoT) (Ayaz et al. 2019; Chaudhary et al. 2019). The literature review presented by Al-Kodmany (2018) highlights the significant benefits of exploring vertical structures by securing the feed and food production, addressing the problem of climate change and the reduction of arable land, improving health (e.g., controlling diseases), and benefiting sustainable bioeconomy through the usage of precision processes. These authors point to its importance (for outdoor scenarios) in ecosystems and city management. More recently, autonomy, trust in food supply chains, and ubiquitous sensing have become priorities for Agriculture 4.0, requiring physical and digital capabilities (Liu et al. 2021). However, most applications of indoor vertical farms with automatic control are still experimental (Haris et al. 2019; Pisanu et al. 2020), and it has been recognized that "*the IoT architecture for smart greenhouse farming is currently in its early development stage*" (Rayhana et al. 2020).

An example of industrial-scale adoption of vertical structures in controlled environments is presented by Jiang et al. (2018). These authors proposed a lettuce's precision cultivation using a wireless network sensor and a fan-circulating system. The results suggest that "*the proposed system is able not only to assist the plant factory in establishing a more sustainable growth environment for plants, but also to improve the air circulation and provide a higher yield of the production in plant factories for farmers*" (Jiang et al. 2018). The essential contributions found in the literature can be extended with digital layers of information that mirror the physical structure and extend the interaction capabilities of the plant factory, as presented in the next section.

2.2 Digital Twin in Agriculture

Pylianidis et al. (2021) systematize six added-value characteristics of digital twins in agriculture, namely, (1) personalized curation of complex systems, (2) streamlining of operations, (3) information fusion, (4) uncertainty quantification, (5) permission level controls, and (6) human-centered intelligence. These authors highlight the capacity of adaptation to constantly changing conditions, acquiring and making sense of data, automatically controlling system actuators, and providing tailored services to humans (e.g., reports, information transparency). The recent review presented by Nasirahmadi and Hensel (2022) reveals digital twin examples in three categories: soil and irrigation (e.g., IoT-based water management), crop production (e.g., parameters identification), and post-harvest (e.g., product quality assessment). Nevertheless, "*added value of DT* [digital twin] *has not yet materialized in agricultural applications*" (Pylianidis et al. 2021), requiring an incremental approach to the sector, making scalability a critical concern. Physical structures (e.g., greenhouse, sensors, network communications) are one side of the coin in smarter agriculture. Like software hosted on clouds or in local supervision systems to capture enormous amounts of data, the digital dimension allows for visualization and data analysis aiming at automatic control (Tzounis et al. 2017). Digital twins bring together both worlds by integrating the physical product, the virtual product in 3D representations and the linkage between them (Glaessgen and Stargel 2012; Jiang et al. 2021).

The global agri-food challenge "*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*" (Hofmann 2017). Following this recommendation, some authors identified digital twins as a potential concept for farming applications (Verdouw and Kruize 2017). For example, by adopting IoT to monitor a malthouse (CO_2, temperature, humidity, and pH) and improve product characteristics (Dolci 2017). The work of Ouammi et al. (2020) broadens this perspective to a network of greenhouses that promote synergies, which is aligned with the notion of 'fleet' in digital twin developments (GE 2016).

Like the research stream of precision agriculture, most digital twin studies are still at the prototype stage, and the most inspiring visions are still conceptual (Alves et al. 2019; Anthony Howard et al. 2020; Smetana et al. 2021). Remarkably, a search using "digital twin" + "precision agriculture" in Google Scholar (excluding patents and citations) returns 421 hits, and near 77% of them were published in the past two years (46% in 2021). Surprisingly, when searching with the keyword combination "digital twin" + "vertical farm", only eighteen results appear in the list, half of them published in 2021.

According to Verboven et al. (2020), the "*first important step will be to integrate the essential elements of a digital twin in representative applications for demonstration* [in food process operations]" and the "*success with which the entire digital twin workflow will be implemented with respect to ease of use and reliability, will determine whether digital twins will survive for food processing operations*". The following section explains how this paper addresses the challenge.

3 Research Approach

Design science research (DSR) is a leading research approach in information systems. The primary purpose is to produce knowledge by designing and evaluating innovative artifacts (Hevner et al. 2004).

Our work follows specific guidelines for conducting and reporting DSR projects (March and Smith 1995; Gregor and Hevner 2013; vom Brocke and Maedche 2019), including frameworks available for evaluating the research outcomes (Venable et al. 2016). DSR is particularly interesting in the design of complex artifacts, usually evolving in iterations within cycles of (1) problem identification, (2) objectives definitions, (3) design and development, (4) demonstration, which may include a real instantiation of the designed artifact, (5) evaluation, and finally (6) communicating the research outcomes (Peffers et al. 2007). An artifact can be a construct, a model, a framework, or an instantiation (March and Smith 1995).

The development process resorted to adopting technological scale-up of readiness levels ranging from 1 to 7 (TRL) (Mankins 2009). Thus, multiple DSR iterations were carried out, concluding in an industrial-scale instantiation digital twin (TRL7).

Table 1 summarizes the scale-up process at design-time.

Table 1 Scaling-up a digital twin for vertical farming

TRL	Brief description of the work	Main results
1	Establish the scope of the project and perform an in-depth market survey to determine potential technologies (hardware and software) for vertical farms: (1) IoT-enabled computer systems, (2) sensors and actuators that enable real-time monitoring and control of temperature, humidity, luminosity, and CO2 concentration, and (3) Python graphical user interface (GUI) frameworks that allow easy integration with touch screens.	Input knowledge
2	Design the communication architecture between the computer system (i.e., RPi – Raspberry Pi), sensors (e.g., DHT22, TSL2591, and MG811), and actuators.	Integration mechanisms
3	Develop the initial prototypes to validate the technologies and integration potential. These were basic systems to collect and display data on the terminal or act on an SSR – solid state relay.	Model validation
4	Create the laboratory-scale prototype. Simplified monitoring is performed by a single sensor that collects data and displays it on a web page. The control system is also streamlined, consisting of changing the state of an SSR to simulate the basic operation of Heating, Ventilating, and Air Conditioning (HVAC).	Lab-scale trial prototype (first instantiation)
5	Improvement with: (1) lighting system control, (2) air-circulation system control, (3) misting system control, (4) access control system, (5) persistent storage of data collected by the system, and (6) creation of a GUI to display the collected data and update the control conditions. Placing the developed system on a small vertical farm to validate the system in a relevant environment.	Small-sized trial prototype (second instantiation)
6	Development of a larger-scale prototype containing more sensors of each type and the temperature control performed by the emission of IR signals to control the air-conditioning system. Deployment on a medium-sized vertical farm.	Medium-sized trial prototype (third instantiation)
7	Development of the industrial-scale instantiation of the cyber-physical system. Most of the requirements were aligned to the previous version by the monitoring system was scale-up to contain all sensors (i.e., 42×DHT22, 42×TSL2591, and 10×MG811). Implementation of the visualization and diagnostics capabilities of the digital twin and preparation of the forecasting one.	Industrial-scale prototype (fourth instantiation)

A Goal-oriented requirement language (GRL) was used to describe the system's main intentions, goals, and non-functional requirements (Amyot and Mussbacher 2011). A GRL diagram is composed of elements interconnected by various types of links, namely: (1) *goals* (⬭); (2) *soft-goals* (⬭), which differ from the former due to the lack of a precise classification; (3) *tasks* (⬡), which operationalize goals and soft-goals; (4) *beliefs* (⬭), which represent design rationales; and (5) *resources* (▭), which must be available for the other elements (Amyot and Mussbacher 2011). The system and its stakeholders are represented as *actors* (○). The following section details the four main DSR iterations conducted in a leading European biotechnology institute.

4 Scalable Digital Twin for Vertical Farming of Mushrooms

4.1 Design and Development

Fig. 1 represents the goal model of the digital twin and its evolution from TRL4-7.

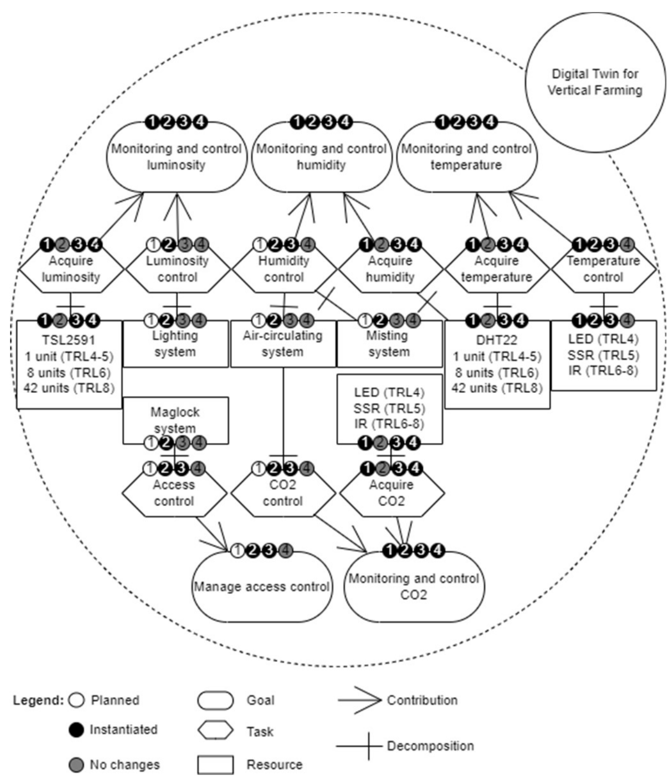


Fig. 1 Goal model of the digital twin for vertical farming

Each element in Fig. 1 includes four symbols (○), one for each DSR iteration to identify when it was (1) planned, (2) instantiated, or (3) remained unchanged. For example, the task 'Luminosity control', associated with the goal 'Monitoring and Control Luminosity', was instantiated in the second DSR iteration and improved in the two subsequent iterations (iterations 3 – medium-sized and 4 – industrial-scale). The resources (▭) include the hardware specification for each TRL stage. For example, SSR was used for temperature control while TRL was at level 5 and upgraded to IR emitters for TRL6-7. MG811 was used for CO_2 measurements during the entire project. Therefore, we present the number of MG811 during the digital twin evolution (only one at TRL4-5, but ten were required for TRL7, at the industrial-scale iteration).

The four iterations to scale-up the physical and digital twin layers are detailed in the following sub-sections.

4.1.1 Lab-scale trial prototype

The first physical instantiation of the system aimed to integrate the various sensors and actuators with RPi. Adopting low-cost elements is an obvious limitation to reliability and stability but can provide the foundations for the next steps that will gradually increase size and complexity.

This prototype version was planned to monitor temperature, relative humidity, light intensity, and relative concentration of CO_2. Moreover, temperature control is included in the requirements. However, digital interaction is not a priority at this stage. Therefore, a simple web interface was developed for parameter monitoring. The requirements were extracted from the literature about the selected type of agriculture production (Chieochan et al. 2017) and from contacts with biotechnology experts working at the institute. A single sensor monitors each parameter, and temperature control is simulated with a LED (turn on when the temperature is within the range previously set by the operator).

Three main goals are identified at the top of Fig. 1. First, luminosity and humidity are checked at specific intervals, while temperature must be within the operator's previously set range. A permissible variation interval sets this ideal range (i.e., if the operator selects the ideal temperature to 20ºC and the variation to 2ºC, thus the temperature inside the vertical farm may vary between 18ºC and 22ºC). Fig. A1 in Appendix A presents the schematic model of the physical elements integrated at this stage.

Two main classes were built for the digital layer. One class to handle system-related logic: collecting sensor monitored data, actuator control, and transmission of collected information. The other is responsible solely for user interaction, limited to a web server. A multi-thread system was adopted to increase performance. However, precautions are necessary to prevent simultaneous access to resources shared by multiple threads (e.g., variables, tables, or peripherals). To ensure that these shared resources are used consistently, they must be accessed within a critical section based on four requirements: (1) guarantee mutex – once a thread has acquired a critical section, no other attempt can continue; (2) ensure progress – critical sections cannot lead to thread interlocking; (3) avoid starvation – a thread cannot be indefinitely biased in favor of others in the critical section entry; and (4) be efficient – in the absence of continuation, the thread must be joined without relying on other conditions. The selected language (Python) has object-based solutions for handling multi-thread instantiations, thus avoiding active waiting (mutex object with an atomic-updated lock value and a list for any threads blocking it). When a thread tries to access the critical section and finds the mutex closed, the system changes the thread state to locked so that it does not compete for any computer resource until another thread opens the lock and unlocks the first thread. Temperature is the only resource shared by multiple threads in this version because it can be changed on the thread in charge of collecting DHT22 sensor data and logical testing on the liable by controlling the temperature.

More specific details are included in Appendix A: the UML sequence diagram specifying the precautions with the shared variable and callbacks triggering (Fig. A2) and the non-function and medium-fidelity GUI prototype (Fig. A3).

Having confirmed the foundational elements to produce a digital twin and fundamental integration aspects, we proceeded to the next DSR iteration.

4.1.2 Small-sized trial prototype

The second DSR iteration increased system complexity. First, using more control systems: (1) lighting, (2) air-circulation, (3) misting, and (4) access control. The three former control systems are related to productivity, while the latter was critical to ensuring authorized access to the facility and food safety compliance. Second, incorporating a new touchscreen GUI allows viewing and controlling parameters inside the vertical farm, including the system's persistent data storage. Finally, temperature control is now associated with an SSR under the HVAC system.

Two goals emerged during this iteration, namely, physical access control and CO_2 (on the bottom of Fig. 1), increasingly the tasks (⬡) and resources (▭) proportionally:

- **Monitoring and control temperature:** Connection to an SSR;
- **Monitoring and control luminosity:** This system (please see Fig. A5 for details) will operate under the vertical farm lighting system, simulating day and night conditions;
- **Monitoring and control CO_2 concentration:** The CO_2 control (Fig. A6) will be triggered whenever the CO_2 concentration collected is greater than the sum between the recommended value and the allowed

variation. In turn, this system will stop when the CO_2 ppm within the vertical farm is restored. This condition's control is carried out by the air-circulation system, shared by the relative humidity control, and only covers over-ranges breaches - biotech specialists have reported that only high CO_2 concentrations are harmful to the selected type of crop;

- **Monitoring and controlling relative humidity:** This parameter has an ideal value and an allowable range similar to the temperature. Two approaches are used to tune relative humidity. The air-circulation system will be activated if the system's relative humidity is higher than the established range. Alternatively, the misting system will be initiated. Their shutdown will occur when the collected relative humidity value falls within the range $\left[RH_{rec} - \frac{RH_{var}}{2}; RH_{rec} + \frac{RH_{var}}{2}\right]$, where RH_{rec} represents the ideal value of the relative humidity within the vertical farm and RH_{var} the allowed range (Fig. A7).
- **Manage access control:** Access control is essential for food safety and effective self-regulation mechanisms. Therefore, a touchscreen device was installed outside the structure, including an electromagnetic lock to restrict vertical farm access (Fig. A8 in Appendix A).

Fig. 2 presents a high-level diagram identifying the different devices (RPi3, LCD touchscreen, sensors, and actuators) and how they interact.

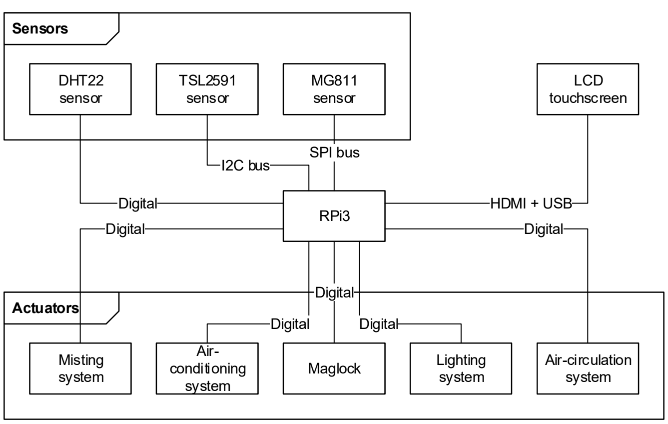
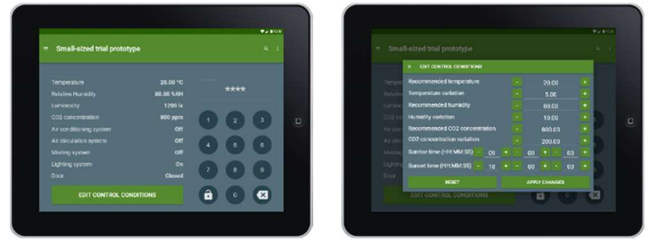


Fig. 2 Small-sized prototype high-level hardware design (systems electronic detailed in Fig. A4 of Appendix A)

The complexity of the digital twin interface increases when the focus shifts from *monitor* to *control*, namely, (1) control systems operations; (2) touchscreen GUI prototypes development; and (3) persistent storage of data handled by the system. The non-functional and high-fidelity GUI prototypes are exhibited in Fig. 3.



(a) Data presentation and access control (b) Manage control conditions

Fig. 3 Small-sized prototype high-level hardware design (systems electronic detailed in Fig. A4 of Appendix A)

The leftmost GUI prototype presents the system's last data and the virtual keypad (e.g., insert access code). This instantiation uses an SQLite database. These control conditions are updated using a form in Fig. 3b. The physical component was assembled in a rapid prototyping shield purposely designed for the RPi: provided direct access to GPIO pins, and allowed the weld's components.

The new instantiations were developed using Python and designed with touch interaction, promoting a more agile and straightforward GUI development. Testing revealed two aspects to address in the next iteration. First, preventing system operators from being locked inside the vertical farm. Second, a mechanism checks whether users who modify the system's control conditions have the necessary privileges. Nevertheless, the achieved maturity level was insufficient to ensure a reliable and precise digital twin for vertical farming. Fig. A9 in Appendix A shows the small-sized trial prototype.

4.1.3 Medium-sized trial prototype

The system scale-up in the third development cycle focused on increasing the infrastructure size. Most of the changes affect the monitoring systems, but the air-conditioning system also requires improvements. This instantiation includes eight DHT22 temperature and humidity sensors, eight TSL2591 light sensors, and four MG811 CO_2 sensors to cover the entire area of the new medium-sized vertical farm. Moreover, temperature activation is controlled via IR signals to obtain more precise actuator control. Complementary, a mechanism was designed to 'force' the opening of the access door to the vertical farm from the inside and develop a method that only enables authorized personnel to edit system configuration.

In this iteration, the main problem was the RPi's inability to read all the new sensors. Therefore, we used multiplexers, specifically the CD74HC4067 16-channel multiplexer, to solve this problem. Two multiplexers were used, one for each type of sensor, since they communicate using different protocols with the RPi (the digital DHT22 and the TSL2591 via I2C). Both multiplexers shared the connection of the I/O channel selection pins to the same digital output pin of the RPi. Thus, we reduced the number of digital pins used on the RPi and simultaneously read one sensor of each type. In addition, we stripped each of these sensors inside the production chamber and used Ethernet cables to reduce costs associated with deployment. However, special care had to be taken in connecting the sensors that communicate via the I2C protocol (TSL2891): all the SCL pins of the sensors are connected directly to the SCL pin of the RPi, and the SDA pins to each of the I/O pins of the mux and the SIG pin of the CD74HC40 to the SDA pin of the RPi. Figs. A10 - A13 in Appendix A shows the wiring diagrams.

The alternative considered most suitable to open the vertical farm from the inside is the placement of a normally closed (NC) push-button located between the SSR and the electromagnetic lock to interrupt the power supply of this component until the door has been locked through the software.

The software needed improvements to (1) use average values for actuators control, (2) join the DHT22 and TSL2591 readings in a single thread, (3) implement temperature control system optimization, and (4) create an authentication mechanism to prevent undue changes in the system's control parameters. Moreover, calculating an average value for each monitored condition is mandatory due to the increment of sensors (thread operation explained in. Fig. A14). The temperature is now controlled by the emission of IR signals simulating the remote-control operation (Fig. A15).

The user interface had minor adjustments at this stage. Load, performance, and stress tests were carried out to push it to its limit. The most relevant included the constant use of the GUI to check if blocked or slowed down the system, disconnect sensors, and continuous changes to the control conditions to verify reaction compliance in the desired time frame. Fig. 4 illustrates the infrastructure and system unlock implementation at this iteration phase.

Fig. 4 Medium-sized trial prototype facilities (details of the locking system in Fig. A16 of the Appendix A)

4.1.4 Industrial-scale prototype

The final version required a drastic increase from eighteen (i.e., 10×DHT22 + 10×TSL2591 + 2×MG811) to ninety-four sensors (i.e., 42×DHT22 + 42×TSL2591 + 10×MG811), and a consequent boost in the complexity of the physical layer. This is a typical situation that vertical farm digital twins can face at run-time phases, requiring flexibility for constant adjustments. The hardware design and analysis have followed an approach based on the RPi's GPIO multiplexing to read all sensors (six CD74HC4067 are needed to read the forty-two DHT22 and forty-two TSL2591). Likewise, two MCP3008 are needed to read the data measured by the ten MG811 (schema included in Fig. A17 of Appendix A).

All channels on the SPI bus except for CS (the device is selected through this channel) are shared. Multiplexing of DHT22 and TSL2591 is more complex due to the limited availability of RPi GPIO channels that need to be shared. The DHT22 data is digital, TSL2591 data is I2C, and two muxes can be enabled simultaneously (illustrated in Fig. A18).

Since the maximum current supplied by the RPi is 50mA, it would be necessary to verify that it is sufficient to accommodate the circuit current. The current consumed by the TSL2591 is 0.4mA; each DHT22 consumes 2.5mA: CD74HC4067 consumes 160μA when supplied at a voltage of 5V; and the MCP3008 consumes 500μA at a voltage of 6V. Moreover, these components will be powered 3.3V, requiring to calculate the current consumed by the ADC and the mux when powered at this voltage. The result is approximately 121mA, requiring an external power supply.

The modular design outlined in Fig. 5 includes three sub-systems: the central hub, the humidity, temperature and luminosity (HTL) data acquisition hub, and the CO_2 data acquisition hub.

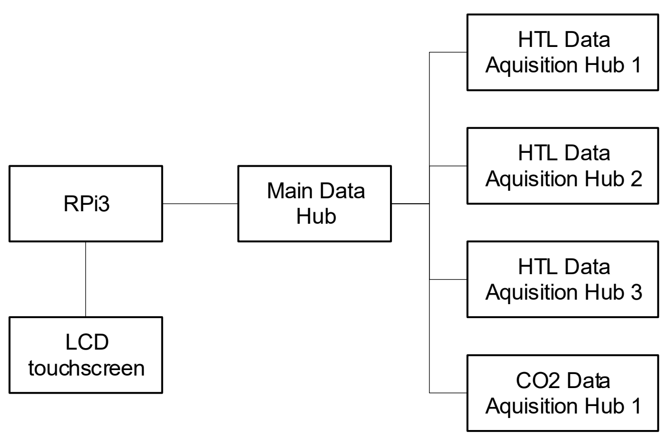


Fig. 5 Industrial-scale prototype's modular system from data acquisition and control

The central acquisition hub (in Fig. A19) interfaces the RPi and the various data acquisition hubs and actuators. The HTL data acquisition hub (see Fig. A20) and the CO_2 data acquisition hub (Fig. A21) are necessary to connect the different sensors used for the RPi (via the central hubs). While each HTL data acquisition hub allows to attach up to sixteen DHT22 and sixteen TSL2591, the CO_2 data acquisition hub can connect up to sixteen MG811. Accordingly, three HTL data acquisition hubs and one CO_2 data acquisition hub are necessary. The connection between the RPi and the central hub uses a 40-pin ribbon cable. The relationship between the various data acquisition and central hubs utilizes an Ethernet cable with RJ45 plugs.

The sensors' layout inside the vertical farm and the sensors' cable routing and connection to the data acquisition hubs are essential to optimize space and efficient communications. A high-precision technique is necessary to detect variations in the conditions measured inside the vertical farm. Therefore, a homogeneous three-dimensional mesh was created, as shown in Fig. A23.

Each sensor is connected to an RJ45 plug whose cable passes through a cable conduit and pours into a rack patch panel. An Ethernet wire connects the sensor's RJ45 jack to the data acquisition hub port. Fig. A22 in Appendix A shows a schematic of the various patches installed in the rack.

The design and analysis of the digital layer in the fourth iteration aimed to optimize the average calculation of the changing conditions inside the vertical farm, eliminate weak sensor readings, and improve the database and the GUI.

The calculation of the weighted average is based on the following procedure:

1 Calculation of the arithmetic mean ($\overline{x_0} = \frac{1}{n}\sum_{i=1}^{n} x_i$);

2 Calculation of the standard deviation ($\sigma = \sqrt{\sum_{i=1}^{n}(x_i - \mu)^2}$); and

3 Recalculation of the arithmetic value in the values that exceed the standard deviation will not be considered ($\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i, \{x_i \vee x_i \in X \wedge x_i \in [x_0 - \sigma; x_0 + \sigma]\}$).

Moreover, a fault-tolerant system was implemented to reduce potential sensor reading failures, using two variables. One that stores the last proper value read by the sensor and another that keeps a time-to-live (TTL) value. Its operation is based on the following procedure:

1 The TTL is initialized to zero, and the variable storing the data read by the sensor is initialized to a null value;

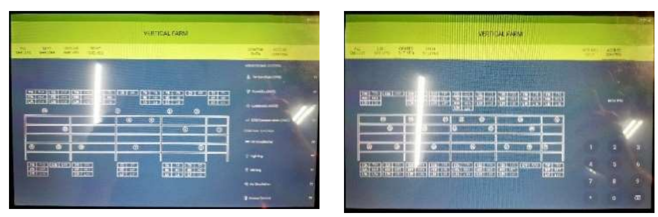
2 Whenever the sensor performs a suitable reading, the value that stores its data is updated, and the TTL is assigned its maximum value;

3 When the sensor performs an invalid reading, the variable that stores the last proper value remains unchanged, and the TTL value is decremented;

4 If the invalid reading persists and the TTL value reaches zero, then the last suitable value read null and is no longer considered for average calculation.

Figs. 6 - 8 present the final DSR iteration results, including the physical and digital elements of the digital twin. The 3D representation that characterizes digital twins (Glaessgen and Stargel 2012; Tao et al. 2019) was created at this stage to accommodate all the scalability requirements at both design-time (when the vertical farm digital twin is planned and deployed, supporting resiliency requirements) and run-time when the system needs to adapt in uncertain conditions, provide reliable data to different stakeholders, and change according to the needs of each crop.

Fig. 6 Physical structure of the vertical farm



(a) (b)

Fig. 7 Physical structure of the vertical farm

Fig. 8 Online 3D interaction with the vertical farm

The fusion of physical and digital materialities in the vertical farm is an iterative process. The model presented in Fig. 8 allows near real-time monitoring (data on the right is relative to the green element selected by the user) and interacting remotely with the structure via a web browser or smartphone. Webcams can be used in the future to monitor the human activity inside the system and provide a source for computer vision applications (e.g., predict plant growth or identify diseases).

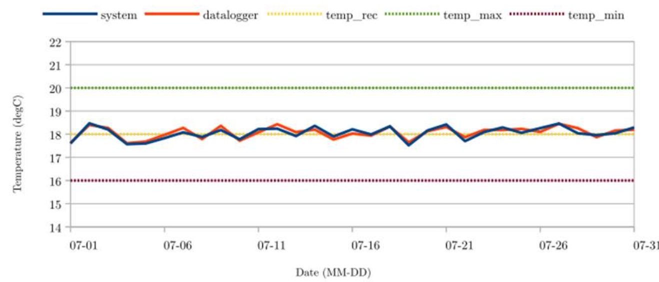
4.2 Final Evaluation of the DSR

The final DSR evaluation (Venable et al. 2016) must ensure that the highest TRL stage results are reliable and support self-regulation in changing conditions. While in previous iterations, we focused on the human risks and effectiveness (e.g., door opening). The last stage is dedicated to the system-critical parameters, such as real-time monitoring and controlling several production conditions (temperature, humidity, light, and CO_2). An external data logger was used to certify the readings made by the real-time monitoring system that the digital twin incorporates, and four quality assurance metrics were selected: the minimum percentage of requirements coverage (target 100%); the minimum percentage of requirements successful implementation (70%); the maximum number of blocking faults (3); and the maximum number of critical faults (0). Table 2 shows the control conditions selected for the evaluation episode.

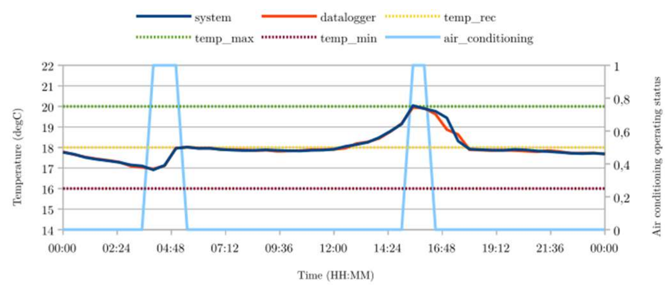
Table 2 Control conditions established for the test

Conditions	Value
Target temperature	18ºC
Temperature fluctuation	±2ºC
Target humidity	80%RH
Humidity fluctuation	±10%RH
Target CO_2	800ppm
CO_2 fluctuation	±200ppm
Sunrise time	09:00:00
Sunset time	18:00:00

Fig. 9a shows the overall temperature change. The test presented in this section was conducted in a real situation for a month, using biological material and constant human interaction (e.g., mushroom care, maintenance inspections) with the structure and the digital twin. The control system behavior is depicted in Fig. 9b.



a Monthly variation during July

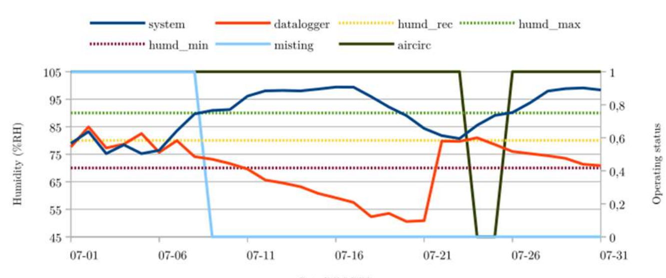


b Daily variation

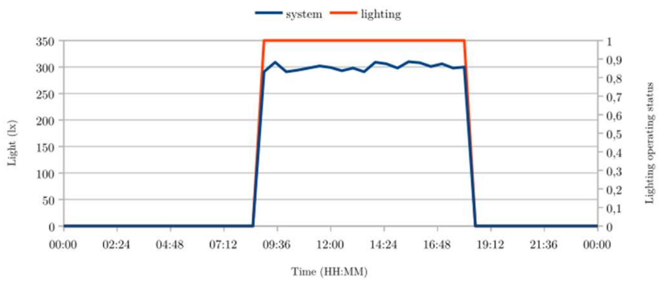
Fig. 9 Overall temperature variation

Temperature variation has remained close to its ideal value since the average of the whole test was 18.05ºC, which differs only 0.05ºC from the target value – standard deviation does not exceed 0.25ºC. Moreover, the discrepancies between the data collected by the digital twin and the data logger are negligible since the maximum difference in absolute value is 0.11ºC - the mean of the values collected by the data logger during the test period is 18.07ºC, and the standard deviation is 0.25ºC.

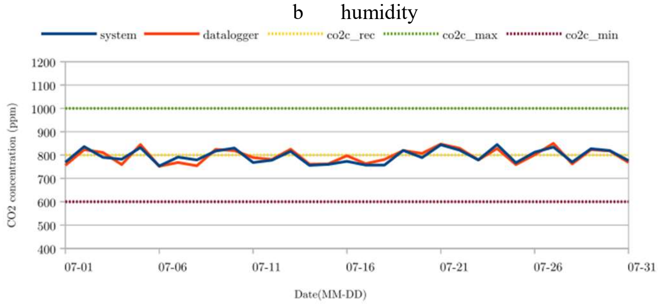
The self-supervision control system was activated twice during the 24-hour test (Fig, 9b). The real-time humidity monitoring and control system employed a similar mechanism to that adopted for temperature. Hence, the graph in Fig. 10a illustrates the overall change in humidity during the time interval in which the experiment was performed. On the right, Fig. 10b presents the variation in the measured luminosity and the state of the vertical farm interior lighting operation. Finally, Fig. 10c depicts the overall CO_2 variation.



a Humidity



b humidity



c luminosity

Fig. 10 Overall variation of the vertical farm's conditions

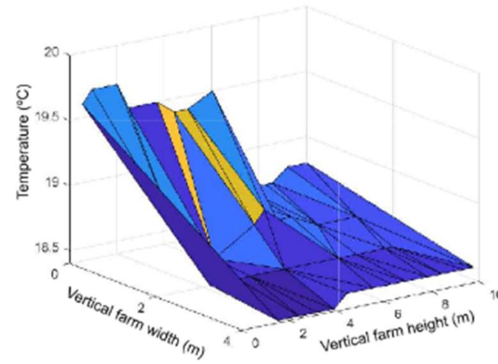
The control system responded as expected, but data measurement problems emerged in this evaluation episode due to the discrepancy between the values collected by the digital twin and those measured by the external data logger. The humidity monitoring anomalies appeared on the ninth day, converged from the twenty-third to the twenty-fifth day, and continued with new deviations. The misting system caused the humidity monitoring system's poor operation. It caused the humidity sensor to saturate during extended periods in a highly humid environment and sometimes with water condensation. Therefore, the sensor was replaced by waterproof sensors (e.g., the SHT-10), and a mechanism that forces the misting system to turn on if it does not work during a pre-established period defined by the vertical farm administrator was implemented.

A lux meter was used in this test at about 40cm from one of the LED strips measuring 313lx. Therefore, the lighting control behaves as expected, starting and ending its operation at predetermined times (Fig. 10b).

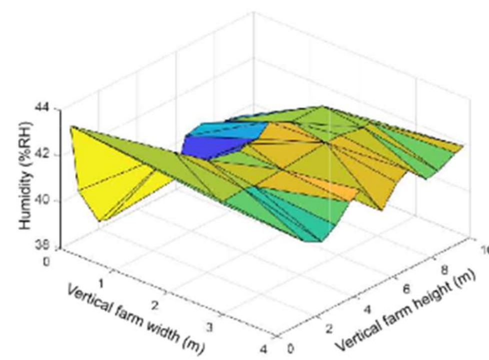
The CO_2 values collected by the digital twin (mean value 795ppm and standard deviation 30ppm), and those measured by the data logger (mean value 795ppm, and standard deviation 31ppm), are close to the recommended value.

The integration test results suggested increasing the waiting time between sensor reading cycles because a slight delay was detected when the user interacted with the LCD touchscreen. This delay was motivated by the scarcity of computational resources (processing time) to deal with the inputs made to the LCD touchscreen and the updates to the database. The change had no impact on the system capacity (the time necessary to read all sensors increased from twenty seconds to thirty seconds), allowing 120 complete and validated readings per hour, significantly impacting the overall system performance.

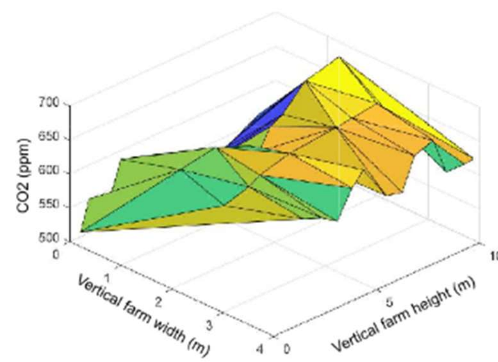
Fig. 11 illustrates the differences inside the structure.



a Temperature



b Humidity



c CO_2

Fig. 11 Distribution of temperature, humidity, and CO_2

The topmost image in Fig. 11 shows the temperature distribution in the three-dimensional space. The most relevant difference is found near the air-conditioning system (1ºC compared to the minimum value but not reaching the threshold). Like temperature measurements, humidity values (ranging between 38% and 44%) and CO_2 were taken while the system was adjusting to the desired state. Again, the three variables behaved within the desired interval: 2º; ±10%RH – the average 41% humidity would require an interval between 36.9 and 45.1; and ±200ppm CO_2 corresponding to the interval 400-800.

The system consumed 262kW during the month-long test: 229kW by the lighting and air conditioning systems (i.e., the reduction was due to the more efficient actuation of the air conditioning system); 12kW by the misting system (i.e., 102kW less compared to the previous system, which operated intermittently for 5 minutes every 30 minutes); and 21kW by the IoT infrastructure. The misting system consumed 50L of water (i.e., 425L reduction). Thus, representing a monthly cost below 40 euros (nearly half the cost compared to the traditional system). Nevertheless, resource consumption can be optimized by adding a solar panel and a rainwater harvesting system, including a water purification system to prevent crop contamination.

5 Discussion

This DSR step results from a joint reflection by researchers and practitioners involved in the project.

5.1 Organizational Advances

Vertical farming has relevant differences compared to traditional farms and greenhouses, requiring specific precision agriculture techniques - namely, the necessity to address a three-dimensional space context that varies over time. Furthermore, the same variable (e.g., temperature) differs in each part of the structure (e.g., lower vs. higher racks and near the door or the ventilation system), requiring support to run time scalability of multiple cultures in each layer. Three-dimensional digital replicas of physical objects are particularly suited to address this challenge.

The chamber's ventilation patterns, lighting, and parameter control can produce different "micro-conditions" inside the vertical farm (Tsitsimpelis et al. 2016; Eaves and Eaves 2018), allowing to distribute crops according to the most productive environmental needs (e.g., the low temperature near the HVAC, as shown in Fig. 11, which enables a shift from 2D to 3D). Adopting multi-crop strategies would require a significant overhead in crop treatment and monitoring using traditional vertical farm structures.

Bellettini et al. (2019) systematize the extrinsic factors affecting the production of *Pleurotus* spp mushrooms, which served as foundations for choosing the optimal operating conditions (temperature, humidity, luminosity, and air composition). Other studies like Llarena-Hernández et al. (2014) present the optimal production conditions for *Agaricus subrusfescens* that the vertical farm can also replicate. Let us consider a multi-crop production of *P. ostreatus* and *P. eyngii*, where the optimal fruiting temperatures range between 20 and 25°C and at the harvest stage are 15-22°C for *P. eyngii* and 5-25°C for *P. ostreatus* (Bellettini et al. 2019). The 3D environmental control of the vertical farm provided by the digital twin (Fig. 11a) enables real-time (1) HVAC adjustments to the crop combination and location and (2) reposition suggestions to each production bag. For example, place *P. eyngii* bags, which have more specific production conditions, on the upper shelves of the vertical farm, and place in the remaining ones the *P. ostreatus*, which are comparatively more resistant, using more natural ventilation to reduce HVAC consumption.

The human-machine interaction supported by the digital twin is fourfold: (1) local console, (2) web dashboard, (3) mobile device, and (4) messaging system. The local console (Fig. 3) provides real-time status and local configuration management. The web dashboard displays the state at a given timestamp via a three-dimensional representation of the vertical farm (both in real-time and for analytic purposes. The web platform is fully responsive and suitable for mobile devices. Nevertheless, the social aspects of vertical farming are understudied. For example, hydroponic and aeroponic indoor production systems (Despommier 2013) are increasingly supported by technology, requiring changes in the university agricultural curriculum and opening new market possibilities for decentralized production systems. Vertical farms can be adapted to reduced land contexts in future research.

5.2 Technology Infrastructure

The data acquisition modules include standard communication protocols (e.g., Digital, PWM, I2C, SPI, or Serial), supporting integration with various commercial sensors. Therefore, the digital twin infrastructure can be modified to collect data on soil properties, plant image, or environmental conditions depending on the crop.

RPi allows for easy integration with most sensors and actuators currently used and has good processing capacities. However, this computational system also has its limitations revealed when a single RPi monitor multiple sensors, controls several actuators, and still serves the GUI. Multiple RPis based on a hierarchical structure can mitigate this problem and improve run-time scalability: a master device coordinates the system operation, and multiple slave devices are in charge of repetitive tasks, such as reading the sensors, controlling the actuators, and serving the GUI. The choice of sensors for reading luminosity and CO_2 worked correctly. However, it was also concluded that a smaller number could be used, which would increase the system's efficiency and reduce its production cost. Likewise, the obtained results attest to the correct operation of the chosen actuators.There are also significant opportunities to adapt the innovative proposals emerging in other industry sectors. For example, the digital twin-driven architecture proposed by Leng et al. (2019) for smart workshops.

5.3 Contextual Factors

A new agriculture infrastructure development and maintenance industry are necessary for vertical farms. Essential studies in commercial instantiations start to appear (Anthony Howard et al. 2020), and our work contributes to a longitudinal study of technological scale-up to reach that target at both the design stage (useful for engineering purposes) and run-time (useful for business operation support). However, the run-time phase of vertical farming requires additional research. For example, it will be interesting to evaluate the different business models of vertical farm suppliers (e.g., renting, pay-per-use) and the structure maintenance model (e.g., corrective maintenance contract or maintenance outsourcing). The digital twin's artificial intelligence layer is another promising research avenue to aggregate data from a fleet of vertical farms. Adopting outdoor vertical farms is particularly challenging and an opportunity for new services in the construction sector (e.g., facilities management services that include green façades implementation and management).

Certification of vertical farms is also attractive to (1) improve the customer perception of the quality and reliability of vertical farms and (2) pressure suppliers to implement adequate testing and monitoring techniques that comply with regulations and the needs of advanced farming infrastructures.

5.4 Resilience and Intelligence

The TRL 7 version uses a wired network to improve reliability and performance. Moreover, data exchange cables are adopted to power the sensors (similar to PoE). Contrasting to the traditional agri-food control system, redundant and scalable digital twin infrastructure provides accurate decision support and includes fault-tolerant mechanisms.

Several security mechanisms guaranteed the reliability and fidelity of the data and sensors. First, using sensor calibration and TTL mechanisms. Second, we created a daemon that periodically creates a backup to a network attached storage (NAS). Third, we avoid unauthorized access to the system and data by only enabling SSH (secure shell) and configurable CRUD (create, read, update and delete) authorizations level. Fourth, restricting authorized (and traceable) personnel access to (1) the physical vertical farm chamber and (2) the system rack.

The mesh of sensors spread across the vertical farm enables near-real-time (every 42 seconds) assessment of the vertical farm, helping biotech experts in the operation and product traceability logs. Forecasting capabilities are still limited due to the amount of data collected in TRL 7, but other capabilities (visualization and diagnostics) are validated for commercial use. In addition, the self-diagnostics capability checks if the various sensors/actuators are operating correctly: (1) comparing the current value with the last valid reading obtained, and (2) comparing the value obtained with other sensors nearby. The system can discard faulty readings, replacing them with the last valid read. When the TTL value reaches zero, the data from this sensor is no longer considered, and a warning is generated. Digital twins enable fault-tolerant vertical farms via (1) self-correction and (2) warning escalation (e.g., if the vertical farm operator does not report corrective actions on time, the digital twin administrator is alerted). The actuators' warning is triggered when the sensors do not detect a change in the actuator controls after a predefined operation time. For example, when the average humidity collected by the system is below $RH_{rec} – RH_{var}$ over ten readings (~7 minutes).

The operating principles of the on-line parallel controlling part comprise *"a set of linked operation evaluation metrics of suitable dimensionality for their intended manufacturing management purpose, and it not only serves monitoring purposes but is also applicable for making predictions about the expected system behavior for manufacturing optimization and improvement*" (Leng et al. 2019). Our project includes the ongoing development of a data lake to support simulation models. The vertical farm digital twin supported on simulation models will provide "*diagnosis and prediction of failures/faults in the operation of physical equipment*" (Leng et al. 2020), enabling predictive maintenance.

A robotic shelve was not used in our fieldwork. However, it can be an interesting investment in exploring digital twin synergies: self-adjustment to extrinsic conditions, multi-crop optimization in different product lifecycle stages, and intelligent multi-crop location. Product price prediction techniques to guide the best multi-crop selection and adjust the desired growth rate of each crop is another exciting future research avenue.

5.5 Design Knowledge for Scalability

The dimension of the term "scalable" used in this project is twofold. On the one hand, our work evaluates the design scalability from the early prototype stages to a TRL 7 infrastructure, which is particularly relevant to designers and engineering activities. The evolution of system complexity is proportional to the increase of sensors used, design of the digital model, control of the various parameters, data storage, diagnostics, visualization, and user interaction capabilities with the digital twin. On the other hand, the lessons learned contribute to the run-time scalability of farming. First, providing guidelines on how to upgrade the system in case of the dimensional increase of the structure (size of the vertical farm or multi-vertical farms). Second, creating horizontal and vertical scalability capabilities is crucial to Agri-food 4.0.

Horizontal scalability refers to the data value increase in different segments of the agri-food supply chain (e.g., distributors, end-users). For example, traceability data for certification purposes or information for retailers and end-users to support sustainable choices. Vertical scalability is improved with the possibility of integrating different crops, each one with its specific needs, into the vertical farm.

It is suggested that digital twin researchers state the proposed solutions' technology readiness levels and identify how scaling-up can occur in future research opportunities. Digital twins can be adopted in more simple objects (e.g., refrigerators) and complex structures like vertical farms, cities, or entire regions. Therefore, explaining how horizontal and vertical scalability may occur can enrich the contributions in this field.

The scalability process follows the six key characteristics of digital twins in agriculture (Pylianidis et al. 2021). First, a 3D IoT infrastructure accurately replicates the physical twin in different operating conditions, thus offering a personalized curation of the complex system. Second, an automated operation pipeline is supported (e.g., data collection, actuators control, data fusion, visualization, storage, and reporting), assisting the producers. Third, (internal) data collected from the physical twin is correlated with external information extracted from sensors (e.g., external temperature) and manual inputs (e.g., substrate composition, optimal production conditions, crop location inside the vertical farm) to support decision making. Fourth, uncertainty management is inherent to the vertical farm (environmental conditions, sensor failure warnings, fault-tolerant architecture) or the market needs. For example, the digital mirroring capabilities allow to accelerate or delay crop growth via parameter manipulation. This feature can be interesting to optimize transport to distributors of the selected products on the required date. Fifth, embedded permission level controls exist on two levels: (1) restricted physical access to authorized personnel and the interface filters and restrictions. Finally, the "*DT may demonstrate human-centered intelligence to control mechanisms for aspects that were neglected in the past, like human-machine interaction for safer working environments*" (Pylianidis et al. 2021).

Design science research is a promising research approach to develop ambient intelligence in vertical farms. First, to guide the development of theory engrained artifacts that may be replicated in different contexts. Second, to adopt rigorous and relevant research approaches, improving the quality of publications. Finally, it increases the focus on artifact evaluation and improves its quality.

5.6 Scalable Digital Twin for Vertical Farming: A Reference Model

Fig. 12 presents a reference model for scalable digital twins applied to vertical farming. This new physical model has two main goals: first, to mitigate the problems related to the shortcoming of computational resources, and second, to provide the system with additional processing power to implement the future digital twin capabilities (e.g., forecasting). Considering a "divide-to-rule" strategy, we took the modular system presented in Fig. 5 and upgraded it by adding a processing unit to each data acquisition module and creating new control modules, including dedicated computing systems. Thus, the central processing module will be relieved of ancillary and repetitive tasks (e.g., data reading, performing auxiliary calculations) and thus be available to compute the digital twin function (visualization, diagnostics, and forecasting).

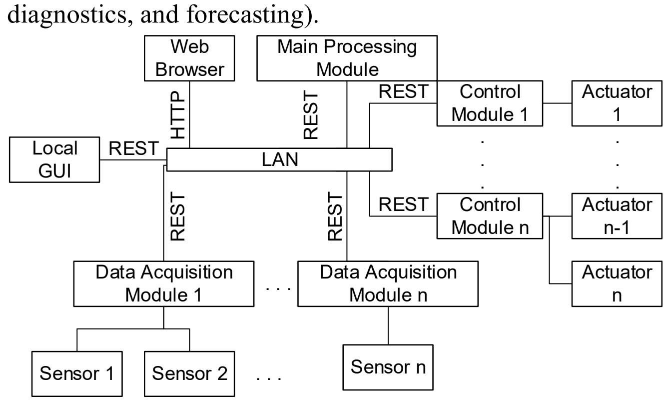


Fig. 12 Scalable digital twin infrastructure

Four main sub-systems are suggested: (1) main processing module; (2) data acquisition modules; (3) control modules; and (4) GUI module. Data collection is ensured by the data acquisition modules, which receive the data from the connected sensors. The data acquisition module (the slave device) transmits this data to the main module (i.e., the master device). Then, the control modules will operate the control of the actuators based on the commands issued by the master device. The central processing module, or master device, can be considered the system's brain since it contains the logic inherent in the farming process and is based on the user's data (entered through the local GUI) and the data obtained by the data acquisition modules.

The proposed model is aimed at continuous and sustainable indoor agriculture. Therefore, different crops are suggestible under the proposed model, particularly food crops (e.g., leafy greens and herbs, tomatoes, strawberries, or mushrooms) and pharmaceutical crops (e.g., alfalfa for human growth hormone, tomatoes for resins, duckweed for biofuels, or medical cannabis). An advantage of the proposed scalable digital twin for vertical farming is its flexibility in adjusting to the (1) type, (2) number, and (3) orchestration of the sensor layer adapting quickly to the selected crop. Reduced consumption of resources (electricity and water) is another advantage, but more longitudinal studies are necessary to evaluate the impact in more detail.

The access control implemented by the system avoids potential contaminations. Combined with maintaining ideal production conditions leads to an increase in the performance of the vertical farm compared to the traditional structures.

6 Conclusion

The future of bioeconomy, mainly the feed and food sectors, requires resilient, safe, and compliant structures that deliver effective self-monitored production mechanisms. Our research presented the technological scale-up of an industrial-scale digital twin for vertical farming. Moreover, our design science research contributes to indoor agriculture advances, detailing the design, development, and testing of the vertical farm's physical and digital layers.

The design-time scale-up raises new challenges for agriculture researchers that are not evident in small-scale prototypes. Access control, cross-check of measurements, and three-axis structure management are crucial. Our study reveals the deeper integration between physical and digital layers of agriculture structures that adapt to (1) the environment and (2) the farmer's needs.

This project also provides guidelines for run-time scalability. Future agricultural production facilities will need more demanding requirements to deal with unexpected events (e.g., system failures, attacks, and risks for product quality) and operate under the most profitable conditions possible. The proposed vertical farms are three-dimensional, requiring a reliable and redundant sensor/actuator mesh. Moreover, the agriculture sector should be prepared for more demanding certification procedures. It is plausible to expect that an increase in vertical farming requires evidence to the society of (1) rational use of resources (e.g., water and energy), (2) protection of feed and food, (3) prevention of disruptions, and (4) product traceability. More specific data collected in different vertical farm zones can be used to tune operation conditions and increase productivity.

6.1 Study Limitations

This research has limitations that must be stated. First, our work focused on indoor environments, and technical architecture was designed for a specific product. For example, outdoor vertical farms becoming popular in modern skyscrapers present different characteristics (e.g., rain and direct luminosity). Moreover, other cultures may require different self-monitoring (e.g., different variables to measure) and self-management (e.g., different optimum operating conditions). Nevertheless, the design guidelines and the technical layer can be applied to different data sources and cultures.

The second weakness that can be pointed out is that the digital twin concept is still recent in high-tech industries and has only now gained an opportunity in the agricultural sector (Verboven et al. 2020). Our digital twin focused on the production stage. However, it is also possible to build other twins for energy equipment or food logistics: an inspiring vision for cooperative digital twin fleets, sharing data but focusing on different aspects of the same physical environment.

Third, despite the instantiation of both the physical and the digital components, the digital twin designed for vertical farming does not yet incorporate predictive or machine learning capabilities. Moreover, the physical layer can be extended to include other functionalities such as intelligent and sustainable ventilation and cooling measures (Kurtzman 2010; Pakari and Ghani 2019).

Finally, we did not evaluate our vertical farm from the assessors' perspective (e.g., product certification) and financial outcomes.

6.2 Agenda for Future Research

Digital twins are a vibrant area of research. One of the most promising related concepts is the 'fleet' (Glaessgen and Stargel 2012), representing a group of similar digital twins capable of sharing information and learning much faster. The inspiring example implemented by GE in turbines (GE 2016) can be extended to vertical farms. Future decentralized structures, adjusted to different products, need to share data and use advanced algorithms to improve digital twin efficacy. The reliability of data, the resilience of structures, and the capacity to explore the entire space of the vertical farm will be crucial to achieving better results. The fleet of digital twins may refer to replicas of the same physical object sharing data or multiple digital twins focusing on specific layers of the reality (e.g., crop digital twin, vertical farm digital twin, supply chain digital twin).

Another possible topic is the integration of agriculture supply chain digitalization and product digital twin. An example is presented by Defraeye et al. (2019), creating product digital twins that extend the production space to food logistics. Moreover, consumers can use augmented reality or virtual reality to obtain detailed information about their products. For example, endogenous products and specific brands (e.g., GEOfood label for UNESCO) can use scalable digital twins to support local farmers with data analytics and certification processes.

Blockchain is another emerging technology that will play a leading role in digital twins. On the one hand, the "incorporation of blockchain into a digital twin for individualized manufacturing on a decentralized network" (Leng et al 2020) will contribute to vertical scalability. On the other hand, blockchain enables transparency, traceability, and security of products and data to be ensured along the supply chain and can thus contribute to horizontal scalability.

The impact of the vertical digital twin on production efficiency is a promising research stream, namely, conducting longitudinal studies. The insights collected in longitudinal studies will be essential to farmers' adherence to digital twin-enabled vertical farms.

The integration of data external to the future digital twin is an improvement. For example, including recent models that balance external conditions of the facility, incorporating data related to product price (which can be used to adjust the product portfolio, speeding up some cultures and slowing down others, which are less relevant to the market needs), and exploring the opportunities for the data market. The increasing amount of data generated in the production process will be relevant to companies (e.g., fertilizer development) or even governments pressured to anticipate their food production capacity in case of disruptions in increasingly adverse climate conditions.

Declarations

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Conflicts of interest/Competing interests: The authors declare no conflict of interest.

Availability of data and material: Detailed hardware diagrams, structural elements, and circuits are available as supplementary material – on-line appendix.

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