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Virtual Reality-Based Digital Twins: A Case Study on Pharmaceutical Cannabis

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Abstract: Digital Twins are digital equivalents of real-life objects. They allow producers to act immediately in case of (expected) deviations and to simulate effects of interventions based on real-life data. Digital Twin and eXtended Reality technologies (including Augmented Reality, Mixed Reality and Virtual Reality technologies), when coupled, are promising solutions to address the challenges of highly regulated crop production, namely the complexity of modern production environments for pharmaceutical cannabis, which are growing constantly as a result of legislative changes. Cannabis farms not only have to meet very high quality standards and regulatory requirements but also have to deal with high production and market uncertainties, including energy considerations. Thus, the main contributions of the research include an architecture design for eXtended-Reality-based Digital Twins for pharmaceutical cannabis production and a proof of concept, which was demonstrated at the Wageningen University Digital Twins conference. A convenience sampling method was used to recruit 30 participants who provided feedback on the application. The findings indicate that, despite 70% being unfamiliar with the concept, 80% of the participants were positive regarding the innovation and creativity.

Keywords: Digital Twin; eXtended Reality; Virtual Reality; pharmaceutical cannabis cultivation; Industry 4.0

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1. Introduction

Digital Twins [1] are digital equivalents of real life objects that mimic the states and the behaviour of their physical twins over their lifetime in a virtual environment [2,3]. Gartner documents that 75% of organizations implementing Internet of Things (IoT) technologies plan to use Digital Twins or generate innovative digital solutions regarding feature implementations [4] in the immediate future. There is a tangible increasing demand for Digital-Twin-driven technologies implemented in various industries, with the market volume previously estimated at USD 3.1 billion for 2020 and forecasted to reach USD 48.2 billion by 2026 [5]. Within agriculture, this notable increase has specifically found footing for precision farming purposes [4,6].

As part of the agricultural industry, cannabis for medical or even recreational purposes has recently been undergoing decriminalization in the USA, Canada and the EU (Malta, etc.). Subsequently, the production process has become highly regulated and controlled in equipment facilities under strict supervision and government laws [7]. As a result of the legislative changes, the complexity of modern production environments for pharmaceutical cannabis production is constantly increasing [8]. Cannabis farms are developing towards high-tech factories that are characterized by large-scale production and intensive use of technology. However, such farms not only have to meet very high quality standards and legislative requirements but also have to flexibly reassess cultivation strategies and reschedule planned activities to deal with production and market uncertainties (such as energy price fluctuations) that can have an impact on production costs.

Digital Twin solutions in combination with eXtended Reality (XR) technologies are suitably poised to address these challenges (XR includes Augmented Reality, Mixed Reality and Virtual Reality technologies). Digital Twins enable remote and automated execution, monitoring, control and coordination of operations [4]. They can play a crucial role in controlling the demand on resources while achieving high outputs of predefined regulated quality using digital information instead of direct observation and manual tasks on-site. Digital representations also provide an overview of and holistic insight regarding the systems and processes in every phase of production. In that way, the decision making is ameliorated, traceable and reproducible [4].

However, at the time of writing this article, Digital Twins as well as XR technologies for the pharmaceutical production of cannabis are still under exploration. To the best of our knowledge, this article is the first to present a Digital Twin concept coupled with XR specifically for pharmaceutical cannabis production. While there are other works covering Digital Twins [9,10] or XR [11,12] solutions, none focus on cannabis production. Therefore, the purpose of this article is to overcome this situation by analysing how XR-based Digital Twins for pharmaceutical cannabis production can be designed and implemented. The study is positioned around the following research questions: (1) How can an XR-based Digital Twin for pharmaceutical cannabis production be implemented? and (2) What are the future possibilities of the integration of XR with Digital Twin models?

The implementation is verified through developing a proof of concept of an immersive Digital Twin—a 3D virtual model. The virtual model is connected with real-world data through an application programming interface (API) integration displaying real-time IoT sensor data from a live greenhouse. The API is a software that caters to the incorporation of real-time data with the Digital Twin. The 3D environment is fully explorable, where the user takes control of an avatar character to walk around the facility and view real-time sensor readings. In addition to the domain-specific application, the scientific contribution of this proof of concept is the integration of XR technologies and Digital Twins. To the best of our knowledge, this is the first work on this specific application for pharmaceutical cannabis Digital Twins. The model was evaluated during the Wageningen University Digital Twins conference in December 2022.

The remainder of this article is as follows. Section 2 provides a background discussion regarding XR and Digital Twin technologies in agriculture and outlines the unique challenges for pharmaceutical cannabis production. Section 3 outlines the methodology and the survey process. Section 4 provides the architecture designs adopted for the implementation. The proof of concept is documented in Section 5, and a discussion of the results is presented in Section 6. Conclusions and future directions for the research are clarified in Section 7.

2. Background

At the time of writing this article, no related peer-reviewed academic articles were available regarding the implementations of XR technologies—specifically VR—combined with Digital Twins for the domain of pharmaceutical cannabis production. However, a recent review by Ariesen-Verschuur, et al. shows that Digital Twins are under research and development from many stakeholders in the greenhouse horticulture domain [13]. The study identifies only one paper in the cannabis domain published by Wang et al. [14]. The authors of this paper propose a Digital Twin system accompanied by a blockchain system for the overall management, supply chain traceability and compliance of hemp. However, this supply chain Digital Twin is not used for production management, and, moreover, it does not include VR. To the best of our knowledge, such a Digital Twin does not yet exist, thus indicating that the digitalization of pharmaceutical cannabis production by means of Digital Twins and VR is in its infancy.

However, pharmaceutical production can readily be shifted into new concepts [10] in which virtual enterprises can remotely control the production of crops under regulated remote environments with the use of Digital Twins, artificial intelligence and XR technologies in order to transform the future autonomous intelligent production. Evidence of this will be provided in this section by discussion of pharmaceutical cannabis production and related works on Digital Twins for agriculture.

2.1. Pharmaceutical Cannabis Production

Companies within the pharmaceutical cannabis production domain must adhere to specific processes and activities to obtain a high-quality final product [15,16]. The production processes usually start with the general strategic planning of activities according with the production needs of every company. Next, the pre-selected seeds with the pre-defined specifications and genetics are germinated and tracked throughout the production. Regarding the actual cultivation process, each company starts with female mother plants in separate growing compartments, from which track and traced cuttings are later taken to restock the growing rooms or the same compartment with the best selected genetics.

The cuttings are later placed into rooting plugs and then the rooting process starts in order to be moved next to a different growing compartment in pots for the vegetative period. In every compartment, the microclimate conditions for sustainable cultivation are controlled and monitored accordingly from the system [17]. The flower formation and maturation are the next stages in the production phase. The harvest involves drying and the separation of cannabis flowers and leaves from the stem. The corresponding machinery involves the subsequent activities of the production. The dry products can later be stored in lot baches or commercial packs that are tracked and traced. The products are controlled and quality-tested throughout the production cycle.

Subsequently, the products are dried and stored in batches, and they can later be transferred to the extraction facility of the company itself or a different extraction facility according to the corresponding laws for extraction of cannabis by products in every country. The techniques employed for extraction include using supercritical CO_2, ethanol or hydrocarbon in order to isolate specific desirable cannabinoid compounds [18–20].

Based on the complexity of the business process of pharmaceutical cannabis cultivation, any future research is conducted and recommendations are provided for the purpose of augmenting all stages of production. For example, controllable sustainable cultivation strategies could be promising as it pertains to tracking the digital pharmaceutical production of cannabis, remote monitoring of the different production stages and optimisation of service production. Thus, to achieve this, the augmentation of production tunned with an autonomous digital twinning coupled with VR is considered a recommendation for future exploration. For example, the user in a future smart digital concept may have the ability to guide (within various facilities from a remote location), obtain data and access various functionalities (yield prediction, robotic harvest, robotic repair, etc.) provided from the smart system. As evidence, the following section draws on related examples of XR and digital twinning technologies within the wider agriculture domain.

2.2. Virtual, Augmented and Mixed Reality (XR) in Agriculture

XR technologies integrate the physical world with the digital. These technologies include augmented reality (AR), mixed reality (MR) and Virtual Reality (VR) technologies, as well as various levels of sensory immersion interacting with both the virtual and physical world [21]. AR embeds digital content into the real environment with the use of various smart gadgets (smartphones, tablets, glasses). In MR, a headset recognizes the physical environment and provides a multifunctional interaction between the digital content and physical environment in multiple dimensions. VR technologies involve visually immersing the users in digital worlds using head-mounted smart glasses [22]. XR technologies can be implemented in various domains of human activity, including education, agriculture, training, therapeutic treatments [23,24], data management oriented processes, etc.

XR technologies belong to a niche market. For example, AR within the domain of agriculture has achieved several technological achievements in the last decade [25,26]. However, there remains a need for research and development of new technologies that will combine all the available resources and data into the new era of smart farming and digitalization [27,28]. To offer an example, via immersive models, existing research demonstrates that assistance can be provided throughout the whole farming process such that farmers can ensure higher yields while utilizing fewer assets [11,12]. AR in agriculture is considered to be a revolutionary technology that may support the technological digital transition of current agribusinesses [26].

Precision farming combined with AR is considered to be a crucial concept for crop management utilization by achieving higher yields using fewer resources [29,30]. For instance, future concepts of smart farming may include robotic systems that can support various tasks within the product life cycle of agricultural products and sophisticated precision farming models (yield prediction, irrigation management, etc.) [26]. AR has the potential to combine each precision farming feature in parallel with Industry 4.0 applications of virtualising physical objects while integrating these technologies into prototype farming solutions [11].

Virtual technologies are contributing to the new era of smart data manipulation and digitalization of different environment processes. New virtual technologies and applications combined with AI and sensor technology are being discovered and implemented in various domains, such as agriculture, animal breeding, etc. [31]. Over the last 5 years, more research has emerged by various institutions and companies regarding the virtualization of agricultural crops, animals, agricultural tasks, soil absorption, emissions, migration process, data derived from smart IoT sensors, etc., as outlined in [32]. This technological evolution, combined with the need for virtualisation of various agricultural aspects for sustainable agricultural production, has led to the creation of a new domain of virtual agriculture. The implementation of agriculture based on VR-driven technologies can provide useful information for educational and non-educational purposes [33]. Additionally, it can create possibilities for smart agriculture, create new export routes and generate venture capital [34,35].

2.3. Digital Twins in Agriculture

The virtualisation process enables farmers to observe and manage operations from remote locations based on visual systems. As discussed, Digital Twins are considered to be digital equivalents of real-life objects; thus, they have the potential to mimic variations in their physical counterparts by combining advanced data analytics, such as predictive models, artificial intelligence and machine learning. As Ariesen-Verschuur et al. discuss, focusing on greenhouse horticulture in particular, the virtualised objects may vary between individual plant-level genetics to a sophisticated cultivation facility or the full value chain (depending on the usage) [13]. The technology can support growers (and other stakeholders) in the administrative and managerial process while empowering them with tools to remotely control operations. Additionally, integrating AI-driven intelligence enables qualified horticultural experts in Digital Twins to learn constantly from retrieved data. This has the potential to decrease the growing labour force demand while enhancing production performances with the predefined quality that is required at the ideal time [13].

Concerning the user interface and generating human-level interaction with a Digital Twin, processes may vary from advanced 3D interfaces (e.g., VR, AR or MR, which is the focus of this article) to 2D graphical user interfaces (computers, smartphones, tablets, etc.). Virtualising plants into 3D representations of their physical twins is a newly introduced area of research used in agronomy, forestry, ecology, etc. [36]; it is used in real-time simulation of the growth process in order to derive conclusions regarding synergies between changes in the environment and the plants themselves.

Such technologies can be used to simulate the real-time growing process of different agricultural crops by incorporating the long-lasting process of the plant life cycle utilizing the resources used for the production (inputs, time, labour, capital, etc.). The farmer, in that way, can learn about and be trained regarding crop properties while appropriately adjusting the factors responsible for high sustainable quality yields with precise predictions [33].

XR-based Digital Twins do not only virtualize the plant aspects but pave the way for development of new revolutionary agricultural machinery and devices used throughout the complete product life cycle (cultivation, irrigation, harvesting, etc.), contributing towards the transition to smarter agriculture. Based on the above discussion, there are noticeable advantages for the use of XR technologies and Digital Twins within an agricultural setting. However, there are no existing architectures specifically for the integration of Digital Twin solutions with XR within the pharmaceutical cannabis domain.

3. Methodology

The research reported within this article is based on a design-oriented methodology, which is widely applied in information technology research [37,38]. The approach is typically involved with "how" questions, i.e., how should we design a model or system that solves a certain problem?

3.1. Schematic Design Approach

Design-oriented research focuses on building purposeful artefacts that address heretofore unsolved problems and are evaluated with respect to the utility provided in solving those problems [39]. We applied a design-testing approach, which is comparable with theory testing methods in traditional empirical science [40,41]. In such an approach, generic design knowledge is developed based on deductive reasoning, and, after that, the design is tested by applying it to a specific domain. In our study, the generic part of the design includes the viewpoints that are adopted from existing architectural frameworks. We applied these viewpoints to the domain of pharmaceutical cannabis production, which resulted in the domain-specific architecture.

This design process followed an agile approach in which the research analyst modelled the views and iteratively refined them based on the input of the involved software company experts and scientific staff. The modelling tool *Draw.io* was selected because it supported all required views and is freely available.

Third and finally, a proof of concept has been implemented in the open-source software Unity (https://unity.com/ (accessed on 27 February 2023)) game engine, which is widely used for 3D Augmented Reality/Mixed Reality construction. Main criteria for selecting this platform were its openness, independency of specific operating systems and the integration with low-cost glasses, as well as pragmatic reasons, especially the accessibility of support for the researchers.

The research was carried out in close collaboration with Aryzon, a Netherlands-based XR company. Concerning the integration with the real greenhouse, we have chosen to integrate the Digital Twin with an experimental greenhouse of 30 MHz, a vendor of a greenhouse data platform and sensors. The main reason was that, for the purposes of this explorative research, we wanted to use open state of the art digital technology. Moreover, it was not feasible to integrate with a real operational cannabis greenhouse because the contacted growers were reluctant to cooperate due to sensitivity of this domain. In the 30 MHz experimental greenhouse, a broad range of sensors are implemented that are widely used in modern greenhouse horticulture, many of which are also found in a pharmaceutical cannabis greenhouse. This includes sensors for temperature, humidity, light, air quality and nutrient availability. Specific requirement sets include regulation of temperature to 18–26 degrees Celsius, humidity of 40–60%, 18 h of light and high-quality nutrient and air circulation. With the presence of sensors available to record these readings, the 30 MHz experimental greenhouse provided an ideal reference base for the proof of concept development. Based on the designed architecture, we selected the sensors that are expected to be most relevant for the cannabis domain.

3.2. Survey Process

To test the efficacy of the application, we adopted a convenience sampling survey methodology. The intention was to demonstrate the POC at the Wageningen University

Digital Twin conference that took place in December 2022. This was due to several reasons: (1) the attendees would likely be either enthusiasts or experts in the Digital Twin domain; (2) the governing panel in attendance are domain experts and (3) the event provided access to over 150 individuals, which meant that a random sampling methodology was possible.

A survey comprised of 11 questions was constructed using Google forms, and answers were recorded by use of an Android tablet for portability. The survey included a combination of qualitative and quantitative questions. Open-ended questions (qualitative) were integrated due to their potential to provide in-depth and new understandings [42] (such as positive and negative feedback), with the Likert-based questions (quantitative) catering to the identification of trends in the responses. Table 1 details the list of questions used for the survey process that were developed to represent the study objectives and align with the research questions presented in Section 1, which is an approach used in other XR-related works, such as that by Joshi et al. [43]. Further, each response logged a time stamp, and the surveys were completed fully anonymously. The intention was to, firstly, receive feedback on the POC and secondly to gain expert opinions on the future potential of coupling XR and Digital Twin technologies for pharmaceutical cannabis production. It should be noted that pre-tests were not conducted to validate the expertise level. However, a question related to profession was included to provide insight into the participants' areas of knowledge, which can be used to substantiate the findings provided.

Table 1. Survey Questions.

Number	Question	Type
1	Age	Check box
2	Gender	Check box
3	Profession	Open Response
4	How familiar are you regarding DT-driven concepts applied in the greenhouse horticulture industry?	Likert
5	How familiar are you regarding DT-driven concepts applied in pharmaceutical cannabis production specifically?	Likert
6	How familiar are you regarding DT-driven concepts that combine XR (e.g., AR/VR) services in pharmaceutical cannabis production?	Likert
7	Grade in terms of innovativeness and creativity the created VR based Dt driven technology applied in the pharmaceutical cannabis production	Likert
8	Grade in terms of future applicability the presented proof of concept	Likert
9	In your opinion, can the presented DT driven concept, if further modified, be used for monitoring pharmaceutical cannabis production by augmenting all the cultivation information?	Open Response
10	How much would you grade the future market value of such a proof of concept?	Likert
11	If possible, could you provide some brief thoughts about the future of VR-based DTs	Open Response

4. Architecture Design

This section presents an architecture design for the implementation of the pharmaceutical cannabis-based VR Digital Twin. The guideline for the application of the architecture was adopted from previous work by one of the co-authors (Verdouw et al.) involving schematic presentation of the development steps [39,44]. In this instance, we select three components and outline the design requirements, viewpoint definition and the information model. These three are selected in order to outline the necessary requirements, to describe the architecture and organisation of the developed Digital Twin and to define the data entities and their relations and attributes regarding VR-based cannabis crops.

4.1. Design Requirements

The research started with identifying the requirements for designing Digital-Twin-based systems for pharmaceutical cannabis cultivation. Thus, the following basic design requirements are defined:

- R1: The architecture must present the interaction between the elements of the physical and the corresponding Digital Twin in the virtual environment.

- R2: The architecture must support the processes and activities regarding the implementation of DT/XR smart IoT remote monitoring management systems applied in modern or future pharmaceutical cannabis production.
- R3: The architecture must provide concise information and representation of activities, processes and features enabled by the organisation's designed system.
- R4: The architecture must provide precise information regarding data acquisition, management integration and augmentation processes of the physical twin in real time.
- R5: The architecture should provide concise information about systems and functionalities provided regarding the overall control physical twin's future or current state and behaviour.
- R6: The architecture should provide information about the integration of Digital Twins with the ERPs of pharmaceutical cannabis production farms.

4.2. Viewpoint Definition

The next step was to define the viewpoints needed to address the design requirements. These viewpoints are derived from views of existing frameworks, as presented in Table 2.

Table 2. Selected Viewpoints.

View	Definition	Viewpoint	Reference Architecture
Context Diagram	Depicts the interconnected entities' relations and interactions within the boundaries of the systems.	IDEF0	TOGAF
Domain Model	Generic view of essential functionality aspects of the system in scope, including relationships and interactions between system objects and with the outside world.	UML	IoT-A
Information Model	Depicts the data entities and their relations, including the usage of data for virtual entities in a conceptualized manner.	UML	IoT-A
Functional Decomposition Model	Decomposes the complexity of a DT-based system into a layered form with numerous technical layers, ranging from security layer to device layer.	OSI	IoT-A
Business Process Model	Provides an overview of all business processes and activities of the product life cycle, ranging from managerial to operational control.	BPMN 2.0	ISA-95

The remainder of this section introduces the application of these viewpoints to a Digital-Twin-based system for the cultivation of pharmaceutical cannabis. VR technologies can be used for the remote control and precise augmentation of pharmaceutical industrial production. The hardware parts of the model are depicted with dark green colour, deferring each time in accordance with the object that is virtualised. Many aspects of the plant can be monitored and visualised in a more effective manner with XR technologies if tunned with the Digital Twin of a conventional facility.

4.3. Information Model

The information model, as depicted in Figure 1, defines the data entities and their relations and attributes based on the IoT-A information model [45,46]. Each named attribute has a type and one to many values. The type refers to the type of an attribute. Regarding the example presented in Figure 1, it is the value of relative humidity (RH). Every ValueContainer categorizes one value and zero to many metadata information units that belong to the given value. The timestamp of the value and other quality-related parameters (e.g., accuracy or the unit of measurement) are saved by means of metadata. In Figure 1, the VRCC is connected to the ServiceDescription. This is achieved via the ServiceDescription Digital Twin association process. In this instance, the ServiceDescription is employed to describe relevant aspects regarding a service, for example, the interface. Additionally, contained within the ServiceDescription, one (or more) ResourceDescription(s) may be present describing a resource. If this is the case, the resource functionality is provided by the service.

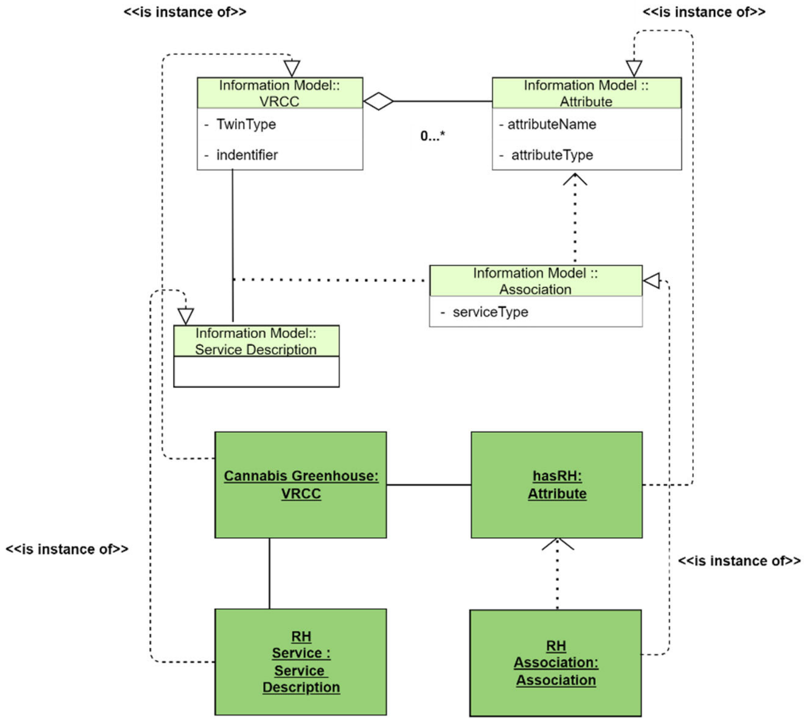


Figure 1. Information Model (based on IoT-A, Bauer et al., 2013 [45]).

5. Results

Following the documentation of the architecture, the next stages involved testing the model by means of construction of a Digital Twin in VR using the template outlined in Section 4. In this section, a concept case study is presented for which the developed application was exported as an Android Application Package (.APK) loaded to the Quest2 VR glasses (https://store.facebook.com/nl/quest/products/quest-2/ (accessed on 27 February 2023)). After uploading, a user has the ability to enter the facility via means of real presence transfer into the virtual mode. An avatar was also created by means of the Aryzon World (https://www.aryzon.world/ (accessed on 27 February 2023)) platform (Figure 2).

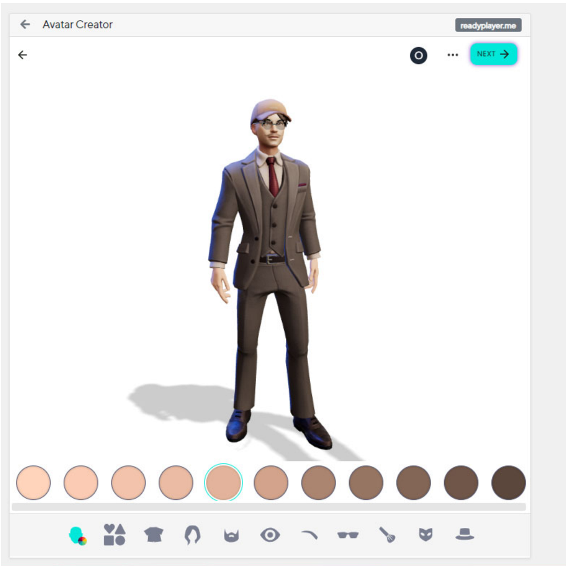
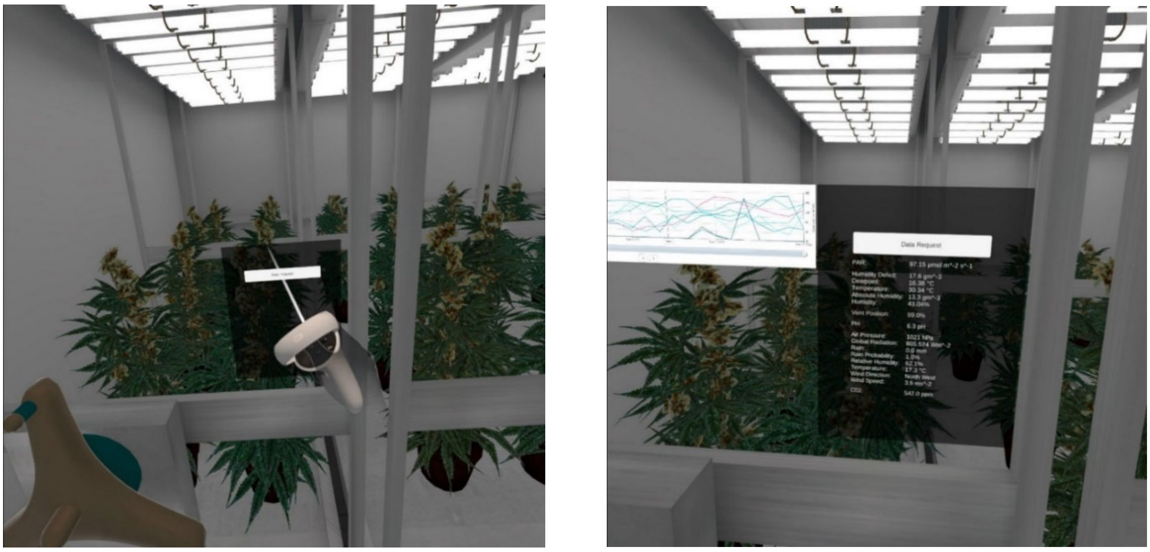


Figure 2. Avatar Creation.

5.1. Development and Sensor Output Display

Different stages of the product life cycle of pharmaceutical cannabis production (outlined in Section 2.1) are depicted in VR. The goal is to showcase the potentialities of applying modern VR remote monitoring of an actual smart cultivation facility by augmenting various stages of production.

The user (after entering the virtual environment (https://www.turbosquid.com/3d-models/cannabis-production-facility-3d-1366533 (accessed on 27 February 2023))) has the ability to visualize real-time sensor readings with a single press of the data request button using an interface attached to each individual cultivation rack (displayed in Figure 3A). Real-time rigid sensor readings are obtained from the sensors connected to a physical greenhouse. Table 3 displays a list of the sensor data collated. The projection of graphical data is also showcased in Figure 3B.



(**A**) (**B**)

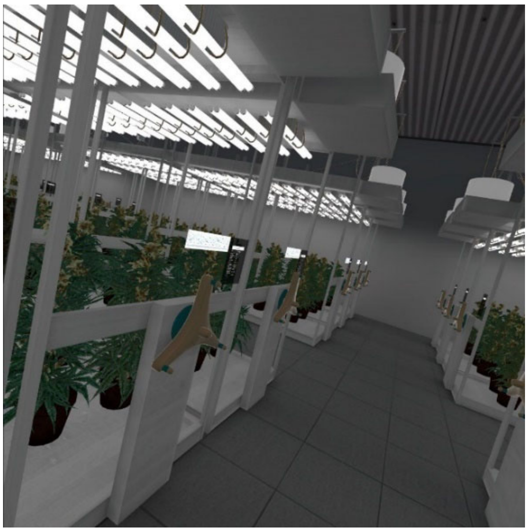
Figure 3. (**A**) VR Experience Data Request Button. (**B**) VR Experience Data Response.

Table 3. Sensor List.

Sensor Type	Description
PAR	Photosynthetic active radiation
CO_2	Carbon dioxide
Temp.	Temperature and Humidity Dewpoint
Ph	Potential of hydrogen
Weather Data	Live data from weather station
Vent Position	Position of greenhouse vent according with sensors readings

Figure 4A displays the possibility to include sensor readings at a granular level, for example, by row or individual plant.

Here, the physical plant data can be visualised in real time, enabling responsive actions to be taken (such as control of actuators to change the environmental parameters) for the cultivation strategy. In Figure 4B, the virtual cuttings room of the facility is depicted in which the plants are in medium growth with the rooting system and medium growth canopy under development. This is the stage before the plants (https://store.speedtree.com/store/speedweed-unity/ (accessed on: 27 February 2023)) are transferred to the next room and growing pots where the proper conditions will be adjusted for the vegetative period until the flower formation stage, at which point they will be transferred to the corresponding growing compartment.



(A)

(B)

Figure 4. (**A**) Multiple Data Visualisation. (**B**) Cuttings Room.

The drying area is displayed in Figure 5, where optimal conditions (temperature, humidity, etc.) of the environment should be maintained under regulated control for the plants to dry. The correct humidity ratio must be maintained before beginning the separation of the individual parts (stem, flowers, leaves, etc.).

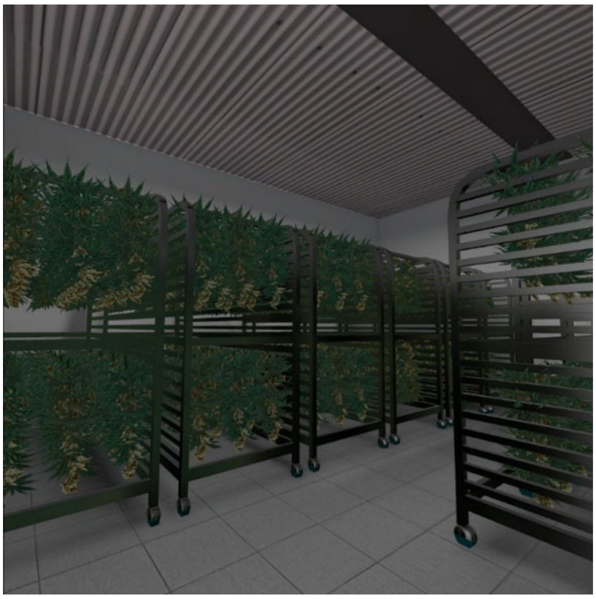


Figure 5. Drying Room with Drying Racks.

5.2. Survey Outcomes

During the Wageningen University Digital Twins conference, thirty participants (twenty-four males, five females, one preferred not to say) took part in the survey. The date and time were also recorded; thus, we can state that the answers were provided between 13 December 2022 11:56 and 14 December 2022 15:40. Table 4 displays the profession of the participants (three did not provide a response).

Table 4. Survey Participants' Professions.

Profession	Count
Msc Student	1
PhD student	2
Assistant prof	2
Public relations	1
Researcher	6
Engineer	2
Climate control greenhouses	1
Intern	1
Lecturer	1
Author	1
Professor	1
Statistician/Modeler	1
Indoor farming specialist	1
Data Scientist	1
3D Content Creator or XR developer	2
Bioinformatics	1
Sr advisor Corporate strategy and accounts	1

The first section of the survey was designed to ascertain the participants' familiarity with Digital Twins as a concept, Digital Twins with XR and Digital twins specifically for pharmaceutical cannabis (Figure 6). As expected, given the nature of the conference, 77% of the participants were predominantly familiar with Digital Twins as a concept. Further, 10% were either neutral or unfamiliar. However, regarding the integration of XR with Digital Twins, 70% were unfamiliar, with 7% neutral. Again, this trend is also evident as it pertains to the notion of Digital Twins for pharmaceutical cannabis, where 70% were unfamiliar with the concept and 20% neutral, with very few (10%) familiar.

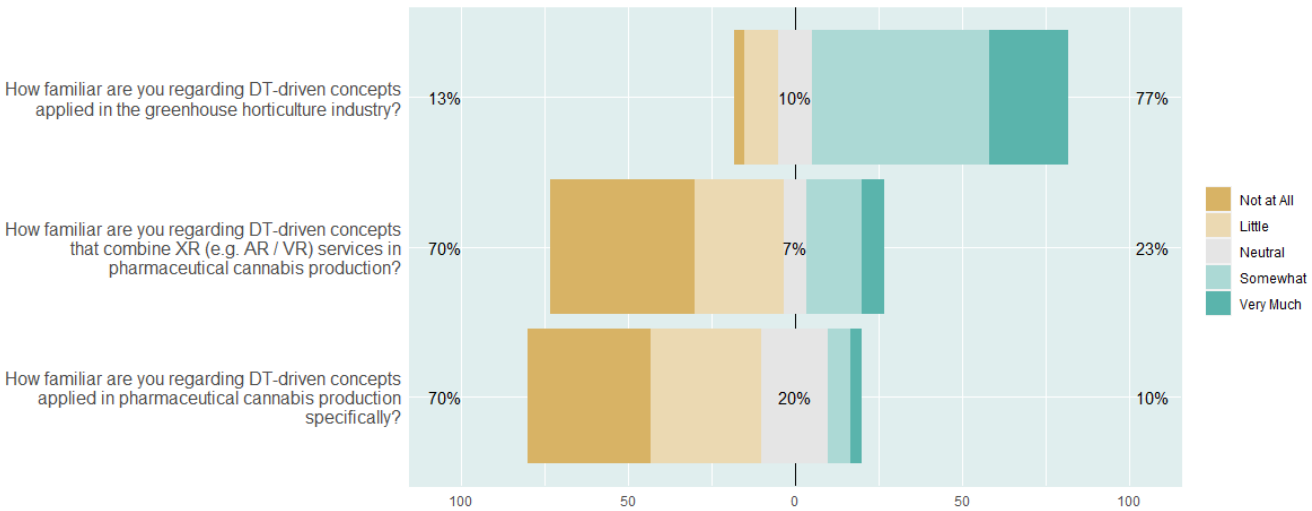


Figure 6. DT User Survey—DT Familiarity.

In the second part of the survey, the participants were asked to provide Likert-based grading on a scale of 1 to 5 for the innovation, creativity, future market value and applicability (Figure 7). Prior to completing the grading, the participants were allowed to view a video demonstration of the proof of concept projected on a large screen, in which a user navigated around the environment and demonstrated the features, interaction and sensor data integration (to avoid queuing, it was decided that a VR headset would not be ideal for demonstration purposes). The participants were also allowed to ask for clarification on anything they viewed, or rewatch sequences.

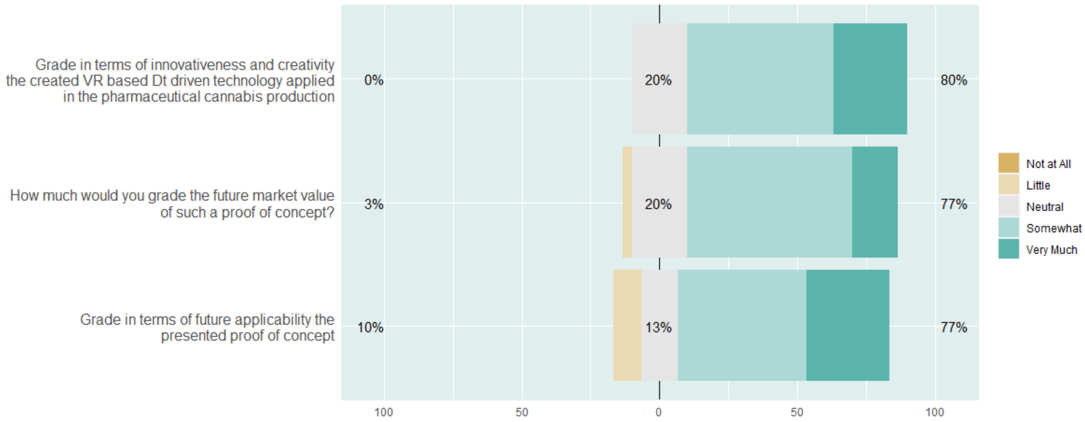


Figure 7. DT User Survey—Innovation Focus.

In terms of the innovation and creativity, none of the participants provided a negative response. Further, 80% of the participants were positive, with 20% neutral towards the application. In providing a grade, 3% of the participants provided a negative score, with 77% providing positive feedback. The final grade concerning the future applicability also received a 77% positive feedback score, with 13% neutral and 10% negative.

Regarding question 9, which was an open question, we identified that the participants provided seven categories of answers, as displayed in Table 5. Thirteen participants replied directly with 'Yes' to the question, with four answering 'Don't Know'. Further, seven provided no answer and skipped the question, with three others providing a response regarding blockchain, accuracy and the future potential. Table 6 provides an overview of the participants' opinions provided in question 11 that related to the future potential of VR with DTs. In this instance, qualitative responses are grouped into four categories: positive, negative, interaction and future direction (participants' typing errors were corrected in the tables presented).

Table 5. Survey Participants' Response Categories.

Question	Response	Count
In your opinion, can the presented DT driven concept, if further modified, be used for monitoring pharmaceutical cannabis production by augmenting all the cultivation information?	"Yes"	13
	"Don't know"	4
	"Blockchain for tracking tracing"	1
	No answer	7
	"I think so"	3
	"It depends how accurate it is."	1
	"I think this app has a lot of potential . . . after explanation it seems really interesting"	1

Table 6. Survey Participants' Brief Thoughts About the Future of VR-based DTs.

Theme	Quote
Positive	"As VR is very immersive, you see and remember the data much better. Therefore I see a lot of potential"
	"This is the future" × 2
	"It could be applied in a wide variety of field"
Negative	"I see them as potentially useful in a number of application settings, but not all."
	"Why VR instead of real-time video that can be steered in a similar way (e.g., webcam on robot)"
Interaction	"Useful for training people, production efficiency gain TBC"
Future Directions	"Only with the ability to simulate different emergency scenarios for training, VR based dt might provide big value to production."
	"I think that the more detailed and advanced the visualisation, the more accurate information on flowers might be extrapolated from VR visualisation and simulation"

6. Discussion

In this sub-section, the research questions outlined in Section 1 are addressed and the relevance as well as limitations of the research are discussed.

6.1. Reflection on Research Questions

The research questions outlined in Section 1 are addressed as follows:

A. RQ1 *How can an XR-based Digital Twin for pharmaceutical cannabis production be implemented*?

In Section 4, an architecture design is presented. This is a unique combination of existing viewpoints that appear to be appropriate for modelling the architecture of Digital Twin/VR-based systems for pharmaceutical cannabis. Included as well is existing reference architecture, such as IoT-A, which entails valuable inputs that enable designing an architecture for implementing Digital Twin/VR in the domain of pharmaceutical cannabis. The present paper added domain-specific architectural knowledge that is relevant to pharmaceutical cannabis production. In terms of the theoretical contribution, it is clear that the use of XR in this setting can revolutionise the way designers/operators simulate and operate complex systems. By using XR with Digital Twins in this setting, cannabis growers can develop highly realistic interactive representations that can enhance both the holistic understanding of the system and support making informed decisions about production.

B. RQ2 *What are the future possibilities of the integration of XR with Digital Twin models*?

The designed architecture is used as a basis to develop a proof of concept outlined in Section 5. The application proved to be a valuable initial template and guideline for developing a consistent and well-structured system in a relatively short period. In addition, it was also very helpful in discussing and deciding on the scope of the prototype to be developed and to identify opportunities for future improvements, as demonstrated during the conducted survey process. The study indicated that there was a lack of familiarity both regarding the use of XR with Digital Twins and also regarding Digital Twins for pharmaceutical cannabis. However, domain enthusiasts remain largely positive regarding its potential and future uptake. Regarding the theoretical contribution of the use of XR with a Digital Twin, the technology combination has the potential to enhance the user's sense of presence and agency within the Digital Twin itself. For example, a combination of the two technologies allows users to experience and manipulate the system in a way that feels immersive and intuitive. This can lead to a greater understanding of the production processes involved and support improved decision making or problem solving.

6.2. Practical Relevance

The main practical value of the provided architecture in Section 4 is that it helps to model, in a timely, punctual and coherent way, specific information architectures for pharmaceutical cannabis production. As such, it can improve the quality, costs and lead time of architectural design processes. The architecture is especially designed for XR-based Digital Twins in this domain. Furthermore, since the viewpoints are adopted from generic architectural frameworks, the method presented in this paper, including the guideline for the application, can also be used to construct models in similar domains.

The developed prototype can be used for virtual enterprises that either study or provide consultancy services regarding pharmaceutical cannabis production strategies (input optimization, ERPS, etc.) or for educational institutions that focus on crop optimization cultivation strategies throughout digital smart farming. In a future (i.e., meta) concept, the virtual plants may represent the actual plants that, each time, are stored in a lot in the drying compartment. The user can browse through an interactive menu and have the ability to obtain valuable information regarding the products stored each time in real time in the physical facility.

In a future scenario, the meta greenhouse might provide information about the quantities processed from the Digital Twins of the machinery. Additionally, it can provide training for engineers focusing on higher technical educational engineering institutions. Tutorials on how to repair such machineries with hands-on training by an autonomous or non-autonomous virtual avatar can provide valuable information for future experts/farmers [47].

In addition to the domain-specific application, the scientific contribution of this proof of concept is the integration of XR technologies and Digital Twins. To the best of our knowledge, this article is the first to document the use of a Digital Twin concept coupled with XR specifically for pharmaceutical cannabis production. Moreover, also in the broader context of smart farming and greenhouse horticulture, we did not find any research that integrated XR technologies in a Digital Twin.

6.3. Limitations and Future Work

The proof of concept was implemented in an experimental greenhouse that is not utilised by a real-world pharmaceutical cannabis producer. We expect that the results of this study will help to convince growers of the benefits of participating in a future case study. Another limitation is that the Digital Twin focuses on monitoring the state of its physical counterpart. It does not yet include predictive and prescriptive capabilities, such as plant growth simulation and decision support for crop management. However, these functionalities build upon the capabilities that are included in the current proof of concept and are a natural next-stage addition to the Digital Twin.

The sensor data integrated into the proof of concept are provided from a real-world greenhouse, but not a cannabis greenhouse. However, this has little impact on the proof of concept case study as the API connection and overview of sensor data output are valid. At the same time, it is, of course, a limitation; however, use of an API from a cannabis greenhouse was restricted due to strict regulations regarding access. The authors, therefore, elected to use sensors from a related greenhouse that would also typically be found within a pharmaceutical cannabis production environment. The integration with the experimental greenhouse allowed us to use the open state of the art digital technology of 30 MHz, including sensors that are most relevant for modern cannabis greenhouses.

Regarding the architecture, a limitation is that a restricted set of viewpoints are included that focus on the design of XR-based pharmaceutical cannabis DTs. It does not yet cover the complete software lifecycle. The domain model can also be further expanded. For example, for coding software and for technical deployment, the architecture is still too generic. Furthermore, it does not include strategic viewpoints, e.g., for the definition of a (commercial) business model or the decomposition of key performance indicators (KPIs). However, we expect that new viewpoints can be integrated from existing architecture frameworks if needed. For example, in a future version, a variety of features can be included, such as a combination of services (prediction, recollection of data, autonomous control via actuators, etc.) to cater to controlling everything in the developed virtual world.

Finally, there is a risk of bias in the survey process. As the process took place during a Digital-Twin-themed conference, one can assume that the attendees have a natural or professional interest in the topic and, therefore, may be likely to communicate this enthusiasm in their survey responses. Moreover, VR is considered to be a computer-based matrix simulation environment providing a variety of features via smart gadgets and helping the end users to become immersed in it. Due to the recent COVID-19 pandemic, there was an accelerated transition from conventional in-person education to remote education that affected most students around the world and entailed resources and access to gadgets (laptops, tablets, phones, etc.). Conventional digital education (pre-recorded lectures, video, etc.) has demonstrated substantial limitations compared to hands-on practical and empirical knowledge from immersive experiences. There is great potential and there are challenges in generating VR technologies as an alternative means of education for the students of the future world for various domains of human activity [6]. Recent studies propose various models and future recommendations for integrating VR technologies into meta concepts for virtual education, thus enhancing active learning and practical information accumulation as it pertains to the stakeholders involved.

7. Conclusions

This paper has analysed how XR-based Digital Twins for pharmaceutical cannabis production can be designed and implemented. It has designed an architecture and implemented a proof of concept of such Digital Twins. The designed architecture includes a coherent set of predefined views that model recommended practices for pharmaceutical cannabis production. It applies widely used modelling views to the cannabis domain and uses existing generic reference architecture as a basis, including IoT-A for the Internet of Things and ISA95 for production automation. The implementation is verified through developing a proof of concept of Digital Twins based on XR technologies that integrates a 3D virtual model with sensors from a live greenhouse.

The Digital Twin architecture is designed to address basic design requirements based on the literature review, including a depiction of the interaction between the physical objects and the corresponding Digital Twin in the virtual environment. The model also includes the overall control of the physical twin's future or current state and behaviour and a visualisation of the processes and activities for the implementation of Digital Twin/VR for smart IoT remote monitoring management systems in modern or future pharmaceutical cannabis production. The Digital Twin architecture represents the activities, processes and features of such systems, including precise information regarding data acquisition, management integration and augmentation processes of the physical twin in real time.

By designing the architecture and implementing the proof of concept, this article has contributed to the promising research on combining XR and Digital Twin technologies that is still under exploration.

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Abbreviations

2D	Two Dimensional
3D	Three Dimensional
APK	Android Application Package
API	Application Programming Interface
AR	Augmented Reality
BPMN	Business Process Model and Notation
CO_2	Carbon dioxide
DT	Digital Twin
IoT	Internet of Things
KPI	Key Performance Indicators
MR	Mixed Reality
PAR	Photosynthetic active radiation
Ph	Potential of hydrogen
SDK	Software development kit
Temp.	Temperature and Humidity Dewpoint
UML	Unified Modelling Language
VR	Virtual Reality
VRCC	Virtual Reality Cannabis Crops
XR	eXtended Reality

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