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***Abstract*—Greenhouse horticulture production is associated with high uncertainty and a long learning process due to its high dependency on the outdoor & indoor environment and plant types. Digital Twin (DT) technology enables a faster understanding of greenhouse horticulture facilities, obtaining insight into the production process flow and investigating the consequences of production decisions. However, no digital twin has been developed in this field due to the complexity of greenhouse production. Therefore, this paper presents a case study of a DT development for a Danish greenhouse production flow using multi-method modeling and multi-agent simulation. The results show that the developed DT can accurately represent the greenhouse production process and estimate the plant growth state with an absolute error of 0.31 days compared to the observed production. Furthermore, the developed DT can accurately predict deviations to the plant growth state corresponding to previously observed behavior at the facility. To capture the greenhouse production process flow at the top-level greenhouse DT agent, the underlying physical agents developed included: compartments, growth climate, conveyors, staff, tables, plants, soil machine, table loading, and packing station as well as the packing station. Lastly, the developed DT method supports agent re-usability for other case studies.**

Keywords— Digital Twin, Greenhouse, Production, Process, Horticulture, Multi-agent System

I. INTRODUCTION

A Digital Twin (DT) is to represent its paired physical counterpart [1] accurately. DTs have seen many application areas, from product design to business processes and healthcare applications [1]. With the introduction of Industry 4.0, DTs have been identified as a promising solution for optimizing industrial production, such as capturing the underlying uncertainties present in any production system [2]. A study on DTs in manufacturing assessed the drivers, enablers, and implementation barriers [3]. One of the primary drivers for DT implementation was the opportunity to improve quality and productivity and quality defects.

The development of industrial DTs relies on key enabling technologies; the predominant enabling technologies include cyber-physical systems, simulation, Big Data, the Internet of Things, modeling, and machine learning [4]. Most research has focused on DTs in discrete manufacturing, not process-type industries [5]. It is pointed out that an inherent challenge in process-type facilities is the high-level complexity associated with the development of high-fidelity models, which can pose a significant challenge in the development phase of the DT [5].

Simulation-based DT can provide process industries with decision support focusing on re-usability across specific industrial sectors to unlock energy and productivity benefits [6]. Furthermore, multi-agent-based simulation has been discussed in the literature for DT architecture development due to its ability to provide robust and resilient DT systems through a representation of the individual elements [7, 8].

Multi-agent-based simulation is characterized by the use of agents that are entities that react to changes in their environment through a given logic [9]; agent properties include the ability to communicate with and interact with its environment, the ability to perceive the environment, guiding objectives, and feedback behavior [10]. Through artificial intelligence methods, intelligent agents can be designed to appropriately handle tasks and changes in their environment [11, 12]. Multi-agent-based simulation development and application systems have previously been discussed for the greenhouse production process [13-15]. However, DT development for the greenhouse production process built upon multi-agent-based simulation is rarely discussed.

Commercial horticulture greenhouse production systems can be categorized as process manufacturing systems that utilize a flow of sequential steps for developing plants of sufficient quality [16]. The commercial greenhouse market can be subdivided into several crop-specific categories. Categories include the growth of vegetables, fruits, and flowers.

From a commercial greenhouse stakeholder perspective, it is essential to deliver the plants at the agreed deadlines with sufficient quality. The mix of Make-to-Stock (MTS) and Make-to-Order (MTO) operations is commonly adopted in the food process industries [17]. Commercial greenhouses use the MTO operation to sell the plants ahead of time, and the delivery deadlines are fixed. Ornamental greenhouse facilities adhere to seasonal deadlines delivering plats at specific dates, e.g., mothers' day and valentine's day. Insufficient quality or late delivery will result in significant economic loss.

The development of DTs within greenhouse horticulture predominantly focuses on control and monitoring, emphasizing climate control and cultivation [18]. Considering the associated production process is essential as indoor climate change will influence plants' development within the greenhouse. Linking the production process DT with existing climate control is expected to aid greenhouse facilities in realizing energy savings, reducing overall energy consumption by 5 - 15 % [14].

Furthermore, DT technology is expected to enhance product quality and yields while improving sustainability. As also pointed out in [18], there is a need for future research to address the design and implementation of DTs in horticulture greenhouses to obtain full advantage of the benefits while also improving the predictive capabilities of the DTs. Therefore, this paper aims to present a DT for a greenhouse horticulture production process with predictive capabilities enabled through process modeling and artificial intelligence that can represent the individual stages of the production process. The DT is developed using generic agents that are subsequently instantiated based on a case study to verify the ability of the agents to represent their physical counterparts. This paper contributes to state of the art for DT development by presenting a horticulture case study application of the production process, including verification and validation. Therefore, the paper's content enables realizing energy-saving potentials for greenhouse growers while maintaining deadline requirements.

The rest of the paper is structured as follows. The production process for a greenhouse is presented, leading to the presentation of the agent-based simulation governing the DT and the applied case study. Subsequently, the acquired results are presented with a discussion and conclusion

II. BACKGROUND

Modern greenhouse production facilities provide protected growth environments with the ability to control the environment, i.e., artificial lighting, control of windows and curtains, the addition of CO_2, and temperature control. Plants are grown in greenhouse compartments. A compartment is a delimited part of the greenhouse where the internal growth parameters can be controlled. The plants are placed on tables holding a specific cultivar. The plants follow pre-determined production steps necessary for developing plants with the correct quality. Commercial greenhouses typically focus on producing plants within a specific species and will not combine, e.g., flowers and crops, as these have varying requirements. There are several distinct production stages that a plant goes through. The production stages may be combined or omitted differently in various greenhouses. As seen in Fig. 1., the plants initially start at a rooting area where the plant establishes rooting. Subsequently, the plant is moved to a propagation area in which it develops more vegetation. Lastly, the plant is moved to a flower initialization area in which the plants are exposed to a climate that promotes the development of flower buds.

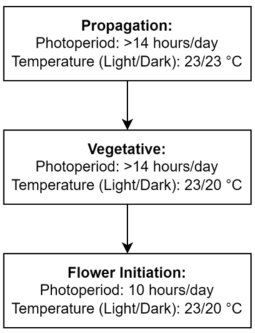

Fig. 1. Generic Kalanchoe Blossfeldiana crop development

Generally, the production process steps for different greenhouses vary slightly; however, the overall process remains unchanged and follows the general outline presented in Fig. 2.

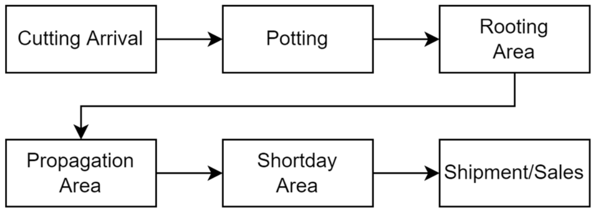

Fig. 2. The general production process for a horticulture greenhouse

As seen in Fig. 2., cuttings arrive at the greenhouse and are transported to the placement station. At the placement station, the cuttings are placed in pots. The pots are placed on tables and are transported by a conveyor belt to the rooting area. The pots are placed in the rooting area, in which the goal is to allow the cuttings to establish rooting that will provide a foundation for the plant and further growth. Once the cuttings finish developing sufficient rooting, they are transported to the propagation area. In the propagation area, the cuttings are placed to propagate from cuttings into small plants. Once the plants have grown sufficiently, they are transported to the short-day area for further growth. In the short-day area, the plants will spend most of the time in the production process, and it is in this area that the plants will be grown to a specific quality requirement, e.g., stem height, number of flowers, or buds. Once the growth in the short-day area is concluded, the plants will undergo a quality check. If the product does not meet product requirements, it is either transported back to the short-day area for further growth or discarded. If the product meets quality requirements, it will be transported by conveyor to the sales or stock section in the sales and stock section, and the product awaits final auctioning or pick-up to be delivered to the customer.

A. *Case Study*

The chosen case study is a Danish grower with multiple facilities, and the examined facility can be seen in Fig. 3.

Fig. 3. Overhead of the industrial greenhouse facility

The grower produces several cultivars of primarily Kalanchoe Blossfeldiana, which go through a series of predefined production steps corresponding to Fig. 2. in the specific case, no rooting area was used. The facility comprises 14 compartments, with two compartments used as propagation areas. For the DT development, specific compartments were selected to focus on the production flow for the Kalanchoe Blossfeldiana flowers. Approximately 65 % of the plants at the facility are produced MTO. Through an established facility, API data from the greenhouse could be collected in near real-time.

During the production process, a series of production decisions can impact the development of the plants, referring primarily to the choice of indoor climate and the movement of plants from one compartment to another. Currently, the production decisions are conducted based on the underlying tacit knowledge of the grower, and the impact of changes to the indoor climate is not clearly understood. Especially assessing the impact of indoor temperature changes is necessary as this has been observed to be the parameter with the highest impact on production time. Therefore, the DT requirement for the greenhouse stakeholder is a tool that can aid in assessing the impact of indoor temperature changes and provide recommendations for temperature set points required to meet the specified delivery date.

III. METHODOLOGY

The growth of plants within a greenhouse represents an inherently uncertain process in which an array of external and internal parameters can affect the overall flow and development of the plants. A simulation environment eases uncertainty quantification, which allows for including variable data [19]. Furthermore, simulation enables the developing and testing of the production process DT in a risk-free environment allowing to test scenarios before applying them. Simulation furthermore provides a visual presentation of the environment for a more natural understanding and verification of DT concepts. The simulation allows for observing system behavior at any time, supported by a higher level of detail with increased accuracy and forecasting potential.

The greenhouse production process can be characterized as a heterogeneous system in which the individual parts correspond to individual modeling paradigms, e.g., processes may adhere to a discrete-event modeling paradigm. In contrast, the plant's growth may correspond to a system dynamics paradigm [20]. Agent-based modeling (ABM) is chosen as the fundamental modeling approach as it allows for building a flexible solution that can be altered and adjusted based on varying inputs to the system. This furthermore allows focusing on the most appropriate behavioral modeling for the individual agent, i.e., discrete or dynamic. Hence, the greenhouse multi-agent DT behavior becomes a product of the individual agent communications, i.e., emergent phenomena. Based on the biennial survey on simulation software comparison conducted by The Institute for Operations Research and the Management Sciences, AnyLogic was chosen for developing the DT based on its support for multi-method modeling capabilities, as the greenhouse production flow incorporates a mixture of inherent modeling methods and paradigms [21].

The agents were developed according to the similar event-driven architecture modeling framework presented in [22] to improve the re-usability and general application of the developed solution. By imploying interface and role interactions combined with the defined agent architecture, the solution can be instantiated to the chosen case study.

A. Digital Twin Development Process

The development process of the greenhouse DT represents an outline of the general steps and considerations taken to obtain the final operational DT setup. Understanding the production setup and production sequence logic was done through collaboration with the grower.

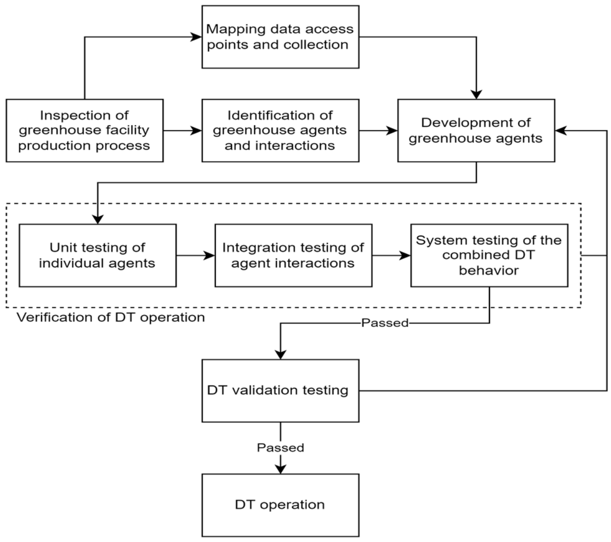

Fig. 4. Greenhouse production process flow DT development process

As shown in Fig. 4, the DT development is started by inspecting the facility. The inspection is preceded by initial considerations of the data requirements and an examination of the literature for a background understanding of the facility production process. After the inspection of the facility, the relevant agents within the DT should be identified, and their underlying interactions be understood. Simultaneously the available data access points within the facility should be mapped, leading to the development of the greenhouse agents. The combined multi-agent system constitutes the production process DT with data assimilation and conditions handled by the individual agents.

To ensure the capabilities of the developed DT can accurately represent the greenhouse production process, the DT should be verified and validated. Verification and validation ensure that the DT meets the requirements and specifications necessary for the DT to fulfill its purpose. Verification refers to the process which ensures that the DT behaves according to the specifications, ensuring the integrity of both individual agent behavior and the system behavior as a whole correspond to the expected outcome [22]. For multi-agent systems, the emergent phenomena should correspond to the system's expected behavior. Validation refers to the process which ensures that the DT meets the needs and acceptance of the greenhouse stakeholders. Following the greenhouse stakeholder needs, verifying the DT should examine if the DT can accurately represent current and historical production. The validation should prove that changes to the indoor temperature are accurately reflected in the change in the system's future states, i.e., the final plant growth state.

B. Digital Twin Development Environment

An underlying necessity for DTs is the ability to communicate with the outside world and its physical twin and other surrounding DTs [1]. The indoor climate data and compartment parameters were extracted through a facility API. The indoor environment data is collected through a sensor bucket. Static historical data relating to production planning was stored in a database. The exchange of information with other DTs was enabled through a horizontal integration bus using an in-memory data grid (Hazelcast). The climate control agent is the primary communication integration point that handles the current and historical indoor climate.

IV. RESULTS

A part of the visual representation of the DT can be seen in Fig. 5. The visual representation can show different compartments (1) with plant tables (2) placed on conveyors (3) and the Danish trolleys in the right corner (4). The DT mimics the production process based on logistical information recording movement between the facility processes.

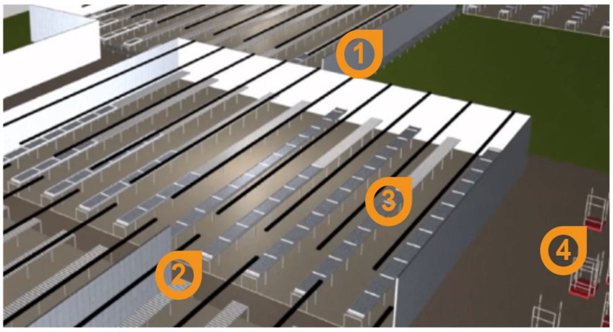

Fig. 5. 3D visual representation of the greenhouse DT.

The production flow logic associated with the 3D presentation shown in Fig. 5. can be seen in Fig 6. The agents shown in Fig. 6 are production process flow-specific agents representing the production steps the plants should complete to be ready for sale. The non-process-specific agent handles the plants' movement and containment, enabling the flow between the agents shown in Fig. 6.

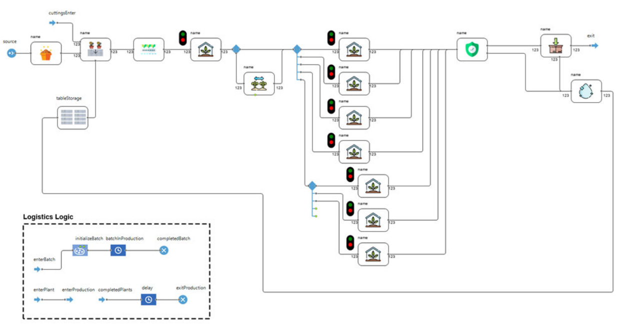

Fig. 6. Greenhouse DT production process flow

A. Greenhouse Agents

The developed agents and their prescribed functions can be seen in Table I together with the number of agents in the population; the individual agents in a given population may have varying characteristics, e.g., different compartments may have various numbers of artificial lighting installments and types of lamps.

TABLE I. AGENT FUNCTIONS AND POPULATION SIZES IN THE DT

Agent	*Function*	*n*
Greenhouse	Top-level agent containing the other agents constituting the combined production facility. Adheres to a static location that determines external parameters, e.g., weather forecasts.	1
Compartme nt	Represents the physical compartments within the greenhouse and holds information such as available space and installed artificial light.	8
Growth Climate	Represents the physical environment in the greenhouse in terms of photosynthetic active radiation, CO_2 concentration, temperature, and humidity.	8
Plant	Represents the behavior of the crops within the system and is an agent that is only influenced by its surroundings; the agent does not communicate with other agents in the system but merely reacts to the states other agents present.	D[a]
Conveyor	Represents the conveyors placed throughout the production and adheres to parameters such as length, speed, and capacity. The conveyor agents can represent accumulative or fixed-distance conveyors.	
Staff	The staff at the facility is subject to working schedules and union agreement constraints.	D[a]
Table	Represents the table container used for moving a collection of plants throughout the production. Parameters include width and length.	D[a]
Pot	Provides the growth medium for the plants and requires filling with soil from the soil machine before it can be used	D[a]
Pot tray	Hold multiple pots together; the pot tray may be omitted depending on the pot size.	D[a]
Danish Trolley	Represents the trolley container on which the plants are transported once they finish packing.	D[a]
Batch	Reference for a group of specified plant agents. Manages the logistical information constant for all plants in the batch, e.g., deadline.	D[a]
Planner	Contains information on the production planning of specific batches. Manages the timely movement of plants and tables throughout production.	1
Climate Control	Handles the planning of the artificial light schedule for the individual compartments and temperature set-points.	8
Table Loading Station	Once the pots have been prepared for production, they are loaded onto the table at the table loading station which is represented in this agent.	1
Table Washing Station	After using a table in production, it should be washed before being used again. The agent represents the table washing station.	1
Soil Machine	Represents the soil machine in the facility that handles the preparation of the pots and filling them with soil	1
Packing Station	Once the plants have finished production, they are handled in the packing station where they are prepared for sale; this includes packaging.	1

a. Dynamic population size, changes during DT operation

B. Digital Twin Agent Identification and Interaction

The developed agents interact through the simulation environment and react to changes from the environment and the other agents in the system. The interactions between the individual agents are presented in Table II.

TABLE II. IDENTIFIED AGENTS AND PRIMARY INTERACTIONS

Agent	*Interaction content*	*Receiver*
Greenhouse	Outdoor weather conditions	Growth climate
	Staff working schedule	Staff
Compartment	Artificial light level	Growth climate
Growth climate	Temperature, photosynthetic active radiation, CO_2, humidity	Plant
Plant	Plant growth state	Planner
Conveyor	Movement	Table
Staff	Operation	Table Loading Station, Danish Trolley, Packing Station, Soil Machine, Table Washing Station
Table	Capacity	Table loading station operator
	Container	Pot tray
Pot	Provide growth medium	Plant
Pot tray	Container	Pot
Danish trolley	Capacity	Staff
Batch	Logitstics information	Planner
Planner	Movement	Batch
Climate control	Artificial light schedule and temperature set-points	Compartment
Table loading station	Loading of pot trays on the table	Pot tray, Table
Table washing station	Washing	Table
Soil machine	Input of soil	Pot
	Pot placed in pot tray	Pot tray
Packing station	Packing	Plant

C. Verification result

To verify an accurate representation of the physical twin, i.e., the greenhouse production process, the DT should be able to operate similarly. Several historical batches of plant cultivars were inputted into the DT to compare the recorded historical data with the measured output of the DT. Table III shows that three batches are selected to compare the historical data with the observed DT operation. Table III shows cultivars with various production start times. The start date represents the date at which the plants enter production, and the recorded days are the measured number of days it took the specified cultivar to become ready. The DT estimation of the plant's readiness should be comparable to the recorded days.

TABLE III. PLANT READINESS STATE ESTIMATION FROM DT

#	*Cultivar*	*Start Date*	*Recorded Days*	*DT Readiness Estimation [Days]*
1	Rubio	09/07/2019	76	75.57
2	Nolin	17/04/2018	79	79.50
3	Demeter	08/11/2017	89	88.992

D. Validation result

Based on the DTs' previous verification, the impact of specific production decisions can be examined for the plant readiness state. The ability of a DT to accurately predict future states based on deviations ensures the robustness of the DT solution for future what-if scenario testing. Based on previous experiments conducted at the facility, it had been observed that an average decrease of one degree Celsius during the production time of the plants would increase the time required for the plant to be ready by approximately one week. Table IV shows the response to a lowered indoor temperature, represented in the readiness deviation. The readiness deviation shows that a lowered temperature will have plants lack development at the completion time, corresponding to approximately 5.34 days, depending on the cultivar.

TABLE IV. DEVIATION OF FINAL PLANT READINESS STATE IN RESPONSE TO LOWERED INDOOR TEMPERATURE

#	*Cultivar*	*Recorded Days*	*DT Readiness Deviation [Days]*
1	Rubio	76	4.17
2	Nolin	79	4.65
3	Demeter	89	7.20

V. DISCUSSION

As can be seen from the results in Table III, the DT can accurately represent the production of three different plant cultivars in various seasons. The estimated plant readiness deviates absolutely by approximately 0.31 days and is therefore considered sufficiently close to the observed number of days. The movement times of the batches aligned with the historical decisions to move the plants at specific dates, as this information was captured in the underlying production plan associated with each batch. Based on the initial verification, the validation results presented in Table IV shows the plant's response to an average one-degree change throughout its production, the readiness state of the plant at the deadline, on average, deviates by 5.34 days. As there is only staffing in the greenhouse Monday to Friday, it is seen that the compliance of the readiness of the plants corresponds to the observed deviation stated by the greenhouse domain experts.

VI. CONCLUSION

This paper presents a case-specific application of a Digital Twin for a Danish horticulture greenhouse production process. The DT was created using multi-method modeling and multi-agent systems for a simulation environment. The individual agents in the developed DT could represent the underlying production stages, allowing the correct product flow for the specific case study. Using agent-based modeling, the individual processes and actors within the facility could be modeled based on their inherent behavior. The DT logic resulted from emergent phenomena of the facility production process. The results show that the DT could accurately represent the historical operation. Using historical data, the behavioral logic of the DT was verified to ensure correct and comparable operation between the DT and the physical twin. Introducing production decisions regarding temperature change reflected observations by greenhouse domain experts. The DT could be decoupled to examine the impact of production decisions and ensure its robustness. This paper contributes to state of the art by addressing the implementation of a case-specific greenhouse DT with predictive capabilities. The findings of this paper may be relevant for greenhouse stakeholders and researchers within greenhouse horticulture and DT technology.

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