Final report

1. Project details

Project title	Greenhouse Industry 4.0
File no.	64019-0018
Name of the funding scheme	
Project managing company / institution	Danish Technological Institute (Economy) HortiAdvice (Project Management)
CVR number (central business register)	HortiAdvice 32 30 51 64
Project partners	HortiAdvice, Teknologisk Institut, Aarhus Universitet, Senmatic, EnergyCluster DI, EnergiDanmark, Gartneriet bygrowers, Gartneriet Hjortebjerg og Gartneriet Knud Jepsen
Submission date	01 June 2023

2. Summary

English summary:

This project aimed to secure a position for the Danish horticultural greenhouse Industry as the world leader in energy-efficient and environmentally sustainable production. This is done by making the Danish greenhouse growers world-leading digital frontrunners by adopting and combining Industry 4.0 technologies, Io, AI, Big Data, cloud computing, and Digital Twins as integrated parts of their production systems.

The project has developed software with both a practical and a scientific purpose. Several software systems have been developed. Some are now used in several Danish greenhouse nurseries, while others are developed for research only.

The application InfoGrow 2.0 is now installed in seven Danish nurseries and one Finnish. With the software, the growers can save energy for both heating and the use of artificial light. A dashboard helps the growers overview the production and identify areas needing attention. The production can be followed with a user-friendly batch system. An app allows adding information about the production and the use of resources (energy, water, CO2, fertilizer, etc). With the new easy-to-use overview, the plant producers can secure optimal production while still focusing on utilizing energy-saving possibilities.

A simulation software (Universal Simulator) has been developed that is the model base of InfoGrow and Virtual Greenhouse, a greenhouse simulation software aimed as an advisory tool that advises growers on optimizing their greenhouse technology and climate strategy with a focus on energy savings.

Several research twins have been developed to explain and investigate research questions. With this development, the project has resulted in several master's and Ph.D projects.

InfoGrow 2.0 and Virtual Greenhouse is now commercially available from HortiAdvice. Several Danish and foreign plant producers are interested in the system for vertical farming, tunnel, and greenhouse production.

Dansk sammenfatning:

Projektet havde til formål at sikre den danske gartneribranche en position som verdens førende inden for energieffektiv og miljømæssigt bæredygtig produktion. Det sker ved at gøre de danske væksthusavlere til verdens førende digitale frontløbere ved at indføre og kombinere Industri 4.0-teknologier; Io, AI, Big Data, cloud computing og Digital Twins som integrerede dele af deres produktionssystemer.

Projektet har udviklet software med både et praktisk og et videnskabeligt formål. Flere softwaresystemer er blevet udviklet. Nogle anvendes nu i flere danske væksthusgartnerier, mens andre kun er udviklet til forskning.

Programmet InfoGrow 2.0 er nu installeret i syv danske gartnerier og en finsk. Med softwaren kan producenterne spare energi til både opvarmning og brug af kunstigt lys. Et dashboard hjælper med at overskue produktionen og identificere områder, der kræver opmærksomhed. Produktionen kan følges med et brugervenligt batchsystem. En app gør det muligt at tilføje oplysninger om produktion og brug af ressourcer (energi, vand, CO2, gødning osv.). Med det nye brugervenlige overblik kan producenterne sikre optimal produktion og samtidig fokusere på at udnytte energibesparende muligheder.

Der er udviklet en simuleringssoftware (Universal Simulator), der er modelgrundlaget for InfoGrow og Virtual Greenhouse. Det er et simuleringssystem der er målrettet rådgivningsvirksomheder. Systemet rådgiver om optimering af teknologi og klimastrategi med fokus på energibesparelser. Flere digitale tvillinger er blevet udviklet til at forklare og undersøge forskningsspørgsmål. Projektet har medvirket til at uddanne flere master og Phd studerende på flere danske universiteter

InfoGrow 2.0 og Virtual Greenhouse er nu kommercielt tilgængelige fra HortiAdvice. Flere danske og udenlandske planteproducenter er interesserede i systemet til både vertikalt landbrug, tunnel- og drivhusproduktion. En ny klimaovervågnings app er ligeledes tilgængelig fra Senmatic.

3. Project objectives

The project was organized into six work packages, as shown in Figure 1, and a demonstration package (WP7). Each of the twins is described individually in this report except for the dashboard (WP6) and demonstration (WP7), described together as InfoGrow 2.0/Virtual Greenhouse.

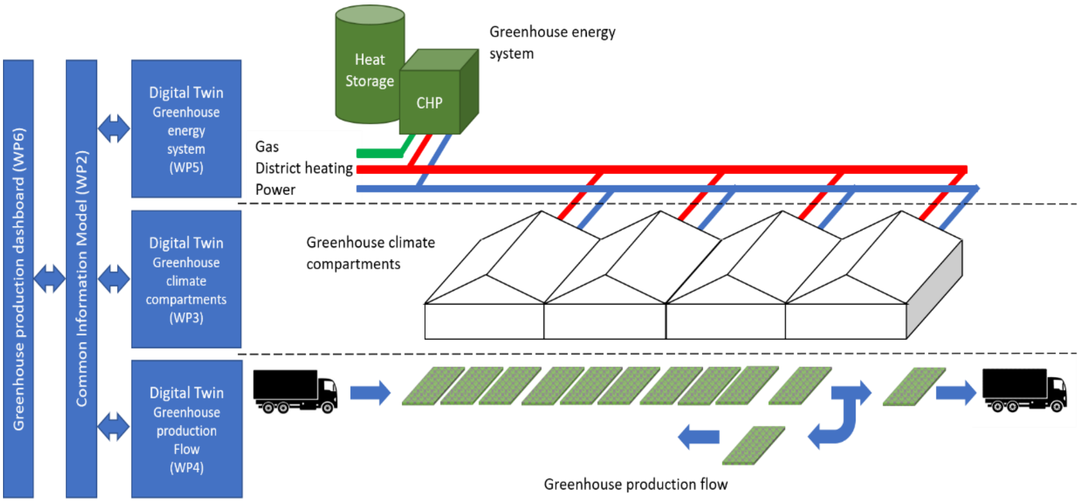

Figure 1. Greenhouse Industry 4.0 work packages.

3.1 Common information model for the Greenhouse Industry (WP2)

The aim of the WP2 Common information model for the Greenhouse Industry is to define a Common Information Model (CIM) that makes it possible in a defined and structured way to exchange information between different equipment and/or software solutions in the greenhouse industry.

Three objectives were conducted to achieve the WP2 aim:

- A Common Information Model for providing the necessary data exchange between greenhouse equipment and software used in the production.
- A unified software Application Programming Interface enables cost-effective integration of IoT-based sensors and existing greenhouse climate computers with the Digital Twin software platform.
- A Communication protocol for information exchange between digital twins supports bi-directional data flow and enables data sharing between the twins

3.2 Digital Twin - Greenhouse climate (WP3)

WP3 aims to develop a Digital Twin of greenhouse climate control (DT-GCC) system of individual greenhouse compartments for prediction-based actuator setpoint optimization to minimize energy consumption and production cost without compromising the production quality. The following objectives were conducted to reach the aim:

- Analyze the greenhouse climate system and identify the climate elements that significantly impact production quality.
- Design a Digital Twin framework for the greenhouse climate control system, including greenhouse digitalization and modeling-based optimization.
- Design digital counterparts to represent significant factors in a greenhouse system.

- Optimize actuator operation schedules to find the optimal solutions that can satisfy growing requirements, saving energy and minimizing production cost.
- Develop and evaluate the designed DT-GCC by standalone experiments and integration experiments on case studies.

Energy technologies demonstrated: WP3 applies the Digital Twin technology, Artificial Neural Networks (ANN), Multi-Objective Optimization (MOO) problems, and Genetic Algorithm (GA) to develop a Digital Twin framework for the greenhouse compartment climate control system for optimizing the actuator setpoints and minimizing the energy cost without comprising the production quality.

Specifically, concerning the virtual greenhouse climate control system, besides traditional mathematical formula functions, ANN methods are applied to model net photosynthesis, indoor temperature and, energy consumption. The level of net photosynthesis is a significant element to reflect the growing status of plants, and indoor temperature is the most influential climate element in the production flow in this project. Furthermore, the energy consumption forecast is provided as demands for the energy distribution. The features of these parameters are that they can be impacted by multiple factors and the relations between them are always highly non-linear and probably conflicting. Therefore, it is difficult to express these relations accurately with traditional mathematical methods. However, by training with historical data, ANN methods can handle non-linear relations for multi-input problems by mimicking the work strategies of dendrites and axons.

Regarding the energy optimization and actuator action schedule recommendation, the optimization problems are abstracted to MOO problems and GA is utilized to provide a Pareto Frontier (PF), and then the final optimal schedule plan is selected from the PF using Social Welfare (SW) through a Relatively Importance Graph (RIG). The optimization abstraction is defined and demonstrated in a climate control platform named DynaLight, and the optimization process is developed and implemented by a MOO platform called Controleum.

3.3 Digital twin - Greenhouse production (WP4)

WP4 aims to develop a digital twin for the greenhouse production flow encompassing the intermediary steps from plant propagation until the final shipment of plants. The digital twin provides a holistic opportunity for investigating decisions' impact on production flow and product deadlines. The digital twin was developed using generic agent-based modeling, which promoted reusability between the greenhouse facilities.

Energy technologies demonstrated: In WP4, digital twin technology for greenhouse companies was developed and demonstrated for simulating the production process. Using the digital twin for the greenhouse production process enabled quantifying the potential for energy flexibility and efficiency in the specific facility and examining potential risks to plant development. Therefore, WP4 also considers implicit demand response potentials for greenhouse growers as an energy technology. WP4 furthermore utilizes informatics principles for providing data-driven solutions in the greenhouse system that support decision-making for greenhouse growers. Incorporating the data-driven solutions in the simulation enables performing what-if scenario testing in the greenhouse production process with minimal impact on the physical production.

The digital twin was realized in AnyLogic using multi-agent systems. The simulation was developed utilizing multi-method modelling, including discrete-event systems, system dynamics, and agent-based modelling. Multi-method modelling enabled the realization of the digital system components' behaviour in alignment with the physical system counterpart.

3.4 Digital twin of the greenhouse energy system WP5

The objective of WP5 is to develop a digital twin of the greenhouse energy system, including energy generation and distribution networks and their components. The purpose of the energy system digital twin is to provide decision support for the cost-optimal operation of the greenhouse's local energy system.

The energy system of a generic greenhouse production facility is the basis of a mathematical model to be adapted to specific cases. This ensures the extendibility of the developed models. In addition, the modeling framework is modular, such as e.g. Modelica, for ease of model adjustment and model integration in optimization algorithms through the Functional Mock-up Interface. The energy system model, together with the common information model, constitutes a digital representation of the current state of the energy system and includes the capability to predict the demands and costs of future operation schedules.

In WP5, a digital twin for the generic greenhouse energy system was developed and demonstrated for greenhouse energy production, storage, and distribution. This digital twin covers the generic energy systems models within commercial greenhouses, i.e CHP (combined heat and power plant), HP (heat pump), GB (gas boiler), DH (district heating network), and TES (thermal energy storage). Using Modelica modeling language, the developed generic energy system models are parametrizable, scalable, and reusable, enabling easy adapting of the generic models to fit specific growers with specific data and information. Simulation of the generic energy systems was carried out complying with the typical commercial greenhouse energy system schematics. In combination with the common information model interface and multi-objective optimization framework (Controleum), the generic digital twin demonstrates the capability for optimal dispatch of greenhouse energy systems for cost reduction while taking into account the heat and electricity demand from greenhouse compartments and energy prices.

3.5 Greenhouse Industry 4.0 Demonstration WP6 and WP7

The aim of WP7 Greenhouse Industry 4.0 demonstration is to implement and demonstrate the Greenhouse Industry 4.0 Digital Twin concept at the participating industrial greenhouse growers. The objective was to develop a software system with these requirements:

- Use data from the main climate computer brands (Senmatic and Priva) in Denmark.
- Use models that describe greenhouse climate, plant climate, and plant photosynthesis.
- Estimate energy use for heating and artificial light from parameters collected from the climate computer.
- Possibility to time plant production and use existing knowledge of dynamic energy-saving control strategies.
- Dashboard that makes it easy to see if production and use of energy are within defined limits.
- Download collected data with possibilities for making advanced energy analyses of the productions.
- Develop an App that Senmatic greenhouse growers can use to overview production, adjust climate and make important alarms to secure production.

The dashboard was developed as an extension to the existing InfoGrow software from HortiAdvice utilizing the Universal Simulator software from the University of Aarhus.

To test some of the energy-saving climate control strategies, experiments were performed at Aarhus University. The aim was to test plant growth and plant quality in different climates.

Energy technologies demonstrated: Several energy technologies were demonstrated in the development. Use of big data, dynamic climate control strategies, mathematical modelling of energy use, IoT sensors, and nudging of growers to save energy.

4. Project Implementation

4.1 Common information model

WP2 started with a technology review of existing Common Information Models (CIMs) as background for creating a CIM which can be used to facilitate the data flow. Based on the technology review, a common information model framework and its main functionalities were defined, e.g., information exchange between different equipment and/or software solutions in the greenhouse industry.

WP2 investigated the OPC-UA (Open Platform Communications - Unified Architecture) standard developed by the OPC Foundation and designed and developed a unified software API (Application Programming Interface) based on this standard. Later, the developed CIM and software API was used in WP3 to integrate the existing IoT-based sensors and greenhouse climate computers with the Digital Twin of the greenhouse climate compartment.

WP2 also designed and developed a communication protocol. It was used and tested in WPs 3, 4, 5, and 7. The results show that the developed communication protocol can enable data exchange between digital twins, data storage and services (user Interface, weather data service, spot market, etc.), support bi-directional data flow and enable data sharing between the twins.

Risks associated with conducting the project: The Common information model (CIM) for the Greenhouse Industry developed in WP2 was expected to enable the data exchange between three digital twins of Digital Twin of Greenhouse Climate Control (WP3), Digital Twin of Greenhouse Production Flow (WP4), and Digital Twin of Greenhouse Energy System (WP5). Since each digital twin serves a specific purpose, and the diversity and complexity of the applied methods and data for each digital twin development and application vary, there were potential risks for the developed CIM in WP2 to realize the data exchange between the three digital twins. Furthermore, the development progresses of WPs 3, 4, 5, and 7 might create potential risks for the developed CIM in WP2 to be tested in these WPs. In the project, WPs 2, 3, 4, 5, and 7 closely collaborated, and the evolution of WP2 seamlessly aligned with WPs 2, 3, 4, 5, and 7. Therefore, no risks were exposed.

Did the project experience problems not expected: Several researchers had been involved in WP2, and some key staff left during the project. It resulted in workforce reallocation, but there was no significant impact on WP2.

4.2 Digital twin of Greenhouse Climate

The goal of WP3 is to develop an optimal model and multi-objective integration approach for greenhouse zone modeling in terms of speed, scalability, and robustness for delivering a complete digital twin of the greenhouse.

The activities that have been conducted to achieve the project goal can be summarized as:

1. Investigation of the greenhouse climate control system, including the climate elements, plant growth, actuator actions, etc.
2. Analysis and identification of data on the impact and relations between greenhouse climate, actuator action, and plant growth.
3. Selection algorithms for modeling and optimization based on the characteristics of individual factors in the greenhouse climate control system.

4. Development of DynaLight, which implements the functionalities of DT-GCC, including the virtual greenhouse and the optimization of actuator operation schedules.
5. Validation on the development of DynaLight in experiments based on scenarios.
6. Performance verification of the models in the virtual greenhouse and the optimization in the MOO platform in DynaLight with experiments based on scenarios.
7. Modification of the development of DynaLight based on the validation and verification experiments.
8. Update DynaLight for the Digital Twin integration with external Digital Twins (Digital Twin of Production Flow and Digital Twin of Energy System).
9. Integration testing with Digital Twin of Production Flow and Digital Twin of Energy System based on the case study of specific cultivars.

In conclusion, according to the evolution process of project, the developed DT-GCC is able to reach the goal of the project. That is, DynaLight, which finishes all the functionalities of DT-GCC, is validated to finish all expected functions of the project. Furthermore, the experiment results following scenarios based on case studies verify that the virtual greenhouse in DT-GCC can represent the physical greenhouse with high performance and the MOO platform of DT-GCC can provide actuator operation recommendations to trade-off between energy cost and growing quality.

Describe the risks associated with conducting the project: Three risks were identified related to the implementation at the start of the project:

1) Uncertainty of the data collection for establishing models in the virtual greenhouse, including data type, amount of data, data pattern, data quality, etc.
2) Uncertainty of the Digital Twin integration implementation: Due to DT-GCC needs to transmit data with other Digital Twins through the network, the uncertainties include communication data synchronization, network quality, etc.
3) Uncertainty of the external data collection: if required data are accessible in the external database, if the data collection resolution is suitable, if the connection with the external sources is stable, etc.

Did the project experience problems not expected: There are three main unexpected problems during the development due to the research scope at the beginning of the project:

1) Some critical data are missing because growers do not install the related sensors to collect the data.
2) The cultivar selection during experiments was changed a few times, which caused the changes in data understanding, data analysis, etc.
3) The definitions of data from growers are not clarified, which causes unexpected time consumption on the data understanding and analysis.

4.3 Digital twin of greenhouse production flow

The digital twin development for the greenhouse production flow was divided into multiple steps aligning with the WP4 objectives and milestones. A draft of the multi-agent simulation model was initially developed based on literature and state-of-the-art analysis. Following the development of the draft solution, selected participating growers were inspected and interviewed to determine the alignment of the developed solution.

The solution was adjusted through the onsite examination of the production flow facilities, and the commonalities and variabilities between production flow facilities could be determined. A generic multi-agent simulation model of greenhouse production flow could be developed to support the commonalities and variabilities between the facilities allowing the instantiation of the case-specific simulation model from the same underlying agents.

A common information model interface was established parallel to developing the digital twin for the greenhouse production flow. Initially, it was verified that the AnyLogic platform could support the implementation of the selected integration platform. The integration followed a horizontal approach with a bus for information exchange. The in-memory data grid Hazelcast was chosen as the platform, and a publish-subscribe pattern was implemented.

A methodology for developing a cultivar-specific development function for Kalanchoes was established to investigate the effects of co-optimizing the production flow. Initially, the collected data was cleaned to adjust for irregularities in the datasets. A climate timeline for each kalanchoe flower batch could be established by combining the climate and logistical data. Based on the climate timeline, the impact of the underlying climate parameters was examined and established through the development function. Using the development function enables approximating the development state of the plant at the desired deadline. The function enables detecting any deviations in the development state of the plant at desired product deadline.

With the digital twin for the greenhouse production process flow being established collectively through the established generic multi-agent simulation model, common information model interface, and the underlying plant development function, it was possible to perform simulation scenarios to validate and verify the performance of the digital twin. The potential for energy flexibility and efficiency could be examined after verifying the digital twin's performance.

Risks associated with conducting the project: Several risks are associated with conducting the tasks in WP4. The technical risks involved are that the digital twin solution may not work as expected due to technical issues with the software, hardware, sensors, data accuracy, reliability, or integration with existing systems. Developing a digital twin solution can be expensive, and there is a risk that the costs associated with development, demonstration, and deployment may be higher than expected. Furthermore, developing a digital twin solution can take a significant amount of time, and there is a risk that the development process may be delayed due to technical, cost, or other issues. There is a risk that the target users for the digital twin solution may not fully embrace the solution, either due to concerns about the technology itself or the costs and effort required to implement and use the solution. Lastly, data privacy and security risks may be a concern. Digital twin solutions often involve the collection, processing, and storage of large amounts of sensitive data, and there is a risk that this data may be vulnerable to cyberattacks, theft, or unauthorized access.

Did the project experience problems not expected: In (A4.3), the investigation of the effects influencing the production flow relied on collected data at the greenhouse facilities. It was evident that the data contained numerous errors, missing points, and uncalibrated values. In the data analysis, specific compartments had to be disregarded as these could not provide adequate data. Therefore, it became challenging to find an overlap between available logistical data and the observed climate values for creating a plant development function. Also, the development function can only hold in investigated compartments, and the ability to accurately determine plant development in disregarded compartments is, therefore, unproven. The development of the common information model interface (A4.2), experienced problems in determining the content of the exchanged information and the sequence of information exchange. Due to uncertainty, it was required to revisit the activity several times to reconfigure the operation mode.

4.4 Digital twin of the greenhouse energy system

The objective of WP5 is to develop a digital twin of greenhouse energy systems as an enabler for determining optimal energy system operating schedules for cost reduction.

In general, the project progressed in accordance with the plan. When writing this report, the defined task's milestones within WP5 have been completed. Throughout the project's lifetime, several bi-annual project meetings were held for project progress overview, where in-depth discussions took place on WP5's current status, future directions, and technical issues. In addition to project meetings, WP5 subtask leader held regular online work meetings monthly to check updates, discuss technical issues, and distribute detailed work tasks for the following month. Bilateral meetings between WP5 and industry partners were organized based on the need for collaboration for the work tasks, such as acquiring knowledge on energy system operating rules, data collection, cleaning, and analysis.

Complying with the WP5 objective and main activities (A5.1 - A5.4), the following research tasks were carried out with different timelines.

1) Mapping of the energy system with the primary grower (Kund Jepsen)
2) Control I/O strategy and architecture were selected.
3) The approach for developing component models for individual units was investigated and decided
4) The modeling approach for the emulator was investigated and decided (Modelica-based modeling)
5) Development of control component models for generic energy systems
6) Verification and validation of genetic control models
7) Customizing and instantiation of generic control models
8) Development and implementation of a generic emulator
9) Verification and validation of the emulator
10) Demonstrating optimization of the greenhouse energy system
11) Simulation of different energy compositions

Risks associated with conducting the project: The main risk related to the implementation at the start of the project is the uncertainty about the data collection for developing energy system models within commercial greenhouses. This uncertainty refers to data type, amount of data, data pattern, data quality, data resolution, etc.

Uncertainty about growers' willingness to apply the developed digital twin and multi-objective optimization framework for the cost-optimal operation of energy systems. The digital twin requires the installation of specific hardware and software, sensors for data collection, and actuators for control. This approach can be expensive, which might be a barrier to the wide application of digital twins within the greenhouse industry. In addition, data collection, storage, and sharing might bring up data privacy and security issue.

Project experience problems not expected: During the project implementation process, the project experienced three unexpected problems:

1) There are some key data missing for the energy system at the primary grower (Kund Jepsen), those data include water temperature and mass flow rate at key locations.
2) The current energy system dispatch rules are still unclear at the primary grower (Kund Jepsen), which forms the baseline for evaluating multi-objective optimization for cost-optimal operations.
3) The generic energy system digital twin is finished and has been tested in relation to the Knud Jepsen horticulture. The initial plan was to extend and tailor the digital twin to other growers. However, it has been difficult to get all the necessary data to be able to test in relation to all 3 participating nurseries. Therefore, the initial plan was replaced by carrying out a number of simulations of different energy compositions to demonstrate the use of the developed models for different greenhouse energy systems.

4.5 Greenhouse Industry 4.0 Demonstration (WP6 and WP7)

The objective of WP6 and WP7 was to develop UNISim and InfoGrow into new versions. Both software systems existed before the project, but both have been developed into totally new versions.

The InfoGrow 2.0 ecosystem is described in Figure 2. InfoGrow 2.0 Ecosystem. The hat in the cloud is an icon for UniSim's Virtual Greenhouse model system.Figure 2).

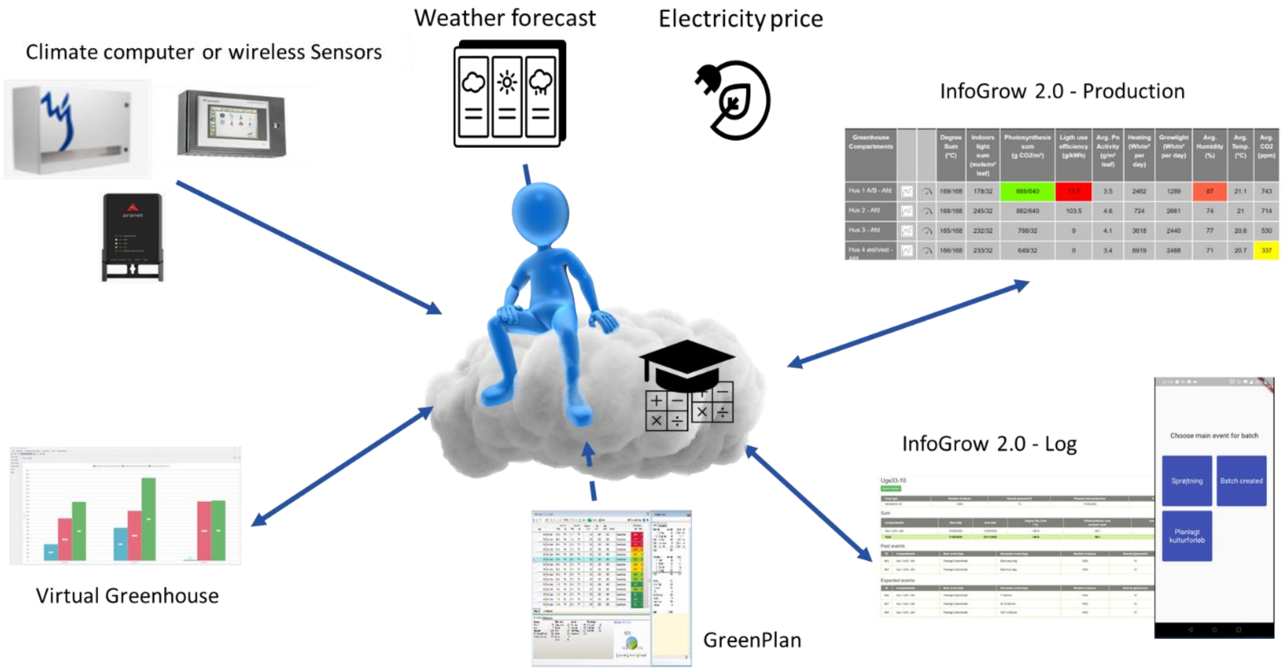

Figure 2. InfoGrow 2.0 Ecosystem. The hat in the cloud is an icon for UniSim's Virtual Greenhouse model system.

InfoGrow has been developed with a brand-new user interface and many new functionalities. Some of the main features are:

1. Interface to Priva climate computer
2. Summary table with Key-performance-indicators for the production
3. Color coding of the summary table to highlight challenges the grower needs to handle
4. Model that calculates use of energy pr department in small time step (10 min) utilizing data already existing in the climate computer
5. Possibilities to use weather forecasts and dynamic electricity prices in energy planning
6. A batch system that makes it possible to follow each new crop in production. A new crop has an attached QR code that identifies the batch
7. A log system that can log data observed by the grower and combine them with climate data.
8. An app that can scan batch QR codes and store data about the batch.
9. A desktop app (Virtual Greenhouse) that can simulate a year-round greenhouse production with different climate control strategies and different use of screens, lamps, covering material etc

Risks associated with conducting the project: The development demands many hours of programming. The main risk was, therefore, not having enough time to fulfill the programming. As we in the project were able to transfer resources from Senmatic to HortiAdvice/DTI we were able to finalize a version that is now used by several nurseries.

Senmatic was part of the project, and communication with the Senmatic climate computer was easy to obtain. The risk was with the Dutch Priva climate computer used by about 50 % of Danish greenhouse producers. The communication is working, but the Dutch company has a newer and more reliable communication technology that we have not been allowed to use. In the future, this might be a risk for the developed system.

5. Project results

5.1 Common information model

A Common information model and OPC-UA (Open Platform Communications - Unified Architecture) server with a user interface for the Greenhouse Industry have been developed. The Common Information Model includes sensors, actuators, infrastructure (communication- and utility) and services (data storage, User Interfaces), weather data service, electricity market services, etc.) as well as IoT sensors. The OPC-UA server and the unified software Application Programming Interface were developed based on the OPC-UA standard. OPC-UA server with user interface integratesIoT-basedd sensors and existing greenhouse climate computers with the Digital Twin of the greenhouse climate compartment.

The developed Common information model and OPC-UA server with user interface were applied and tested in WPs 3, 4, 5, and 7. The results demonstrate that the Common Information Model for Greenhouse Industry 4.0 can support the OPC-UA compliant communication for integration of IoT sensors and existing climate computers; It can be used for standardizing the exchange of information between digital twins in the 4.0 industrialization of the greenhouse sector, therefore, it is possible to integrate with different brands of climate computers, IoT sensors or software used in the greenhouse production, and less time is needed to integrate with new software or hardware.

The testing results of applying the developed Common Information Model from WP2 in WPs 3, 4, 5, and 7 show *that* the original objective of WP2 was obtained.

Describe the obtained technological results. Did the project produce results not expected?

There are three main technological results obtained in WP2 according to the project design and plan:

1. A Common Information Model, which was applied and tested in other WPs and proved to be able to support data exchange between greenhouse equipment and software used in the production.
2. An OPC-UA standard-based unified software Application Programming Interface, which was applied and tested in other WPs and proved to be able to cost-effectively integrate IoT-based sensors and existing greenhouse climate computers with the Digital Twin software platform.
3. A Communication protocol that was applied and tested in other WPs and proved to be able to support information exchange between digital twins, support bi-directional data flow, and enable data sharing between the twins.

5.2 Digital twin greenhouse climate

This project aims to develop a Digital Twin of Greenhouse Climate Control systems of individual greenhouse compartments for prediction-based actuator operation setpoint optimization to minimize energy consumption and production cost without compromising the production quality. In order to achieve this aim, several objectives are realized based on case studies of this project.

- The climate control system is analyzed based on a typical commercial greenhouse to identify the critical climate elements that influence the plant growing quality.

By studying the impacts on the Net Photosynthesis of plants, three controllable factors - light irradiation, ambient air temperature, and CO_2 concentration - are determined to control in this research. Consequently, this research focuses on the modeling and optimization of these climate elements.

- The designed Digital Twin of the Greenhouse Climate Control system can virtually represent the greenhouse climate control system and optimize the actuator operation setpoints.

The entire Digital Twin system comprises four parts, including the Physical Twin of the greenhouse climate control system, the Digital Twin of the greenhouse climate control system, interconnection and External Source, and integration with other twins. The Digital Twin of Greenhouse Climate Control is designed by modularizing into a Virtual Greenhouse and a Multi-Objective Optimization based Climate Control platform, and a hierarchical Digital Twin implementation architecture is established in order to create the designed Digital Twin framework in practical case studies. This architecture can facilitate the practical development of a modulization structure and benefit the research management by dividing the fundamental system into multiple sub-sections. Additionally, the modular structure is able to isolate technical issues in a specific layer rather than influencing other layers.

- The developed Virtual Greenhouse can realize the digital counterparts of the significant factors in the greenhouse system, including the models of greenhouse climate, plant growth, and energy consumption.

Artificial Neural Network methods, including a Feedforward Neural Network and time-series methods, are designed and developed for modeling three factors in the Virtual Greenhouse. An architecture of Multilayer Perceptron with Back-Propagation training algorithm as a Feedforward Neural Network model is designed for Net Photosynthesis and Long Short-Term Memory, and Bidirectional Long Short-Term Memory are applied as time-series methods for indoor temperature and heating consumption models. Training and test datasets are based on feature engineering for individual Artificial Neural Network models. Through tuning the hyperparameters, the Artificial Neural Network models with the highest performance are selected as each model.

- The Multi-Objective Optimization platform, DynaLight, is refactored for the Digital Twin of Greenhouse Climate Control development and is compatible with the updated version of Controleum.

DynaLight is developed in Java on NetBeans in a modular architecture. The models in Virtual Greenhouse and the definition of the Multi-Objective Optimization problem of climate controlling are realized in DynaLight. In addition, DynaLight provides a Graphic User Interface for growers to monitor and configure growing and optimization parameters. The developed framework is applied to the case study of two commercial growers in Denmark with similar environments and can provide related data. Furthermore, multiple scenarios are designed from different perspectives, and the corresponding experiments are designed and developed to evaluate the performance of the developed Digital Twin of Greenhouse Climate Control.

- The implemented Multi-Objective Optimization based Climate Control platform can complete the Multi-Objective Optimization problem definition of climate controlling and the actuator operation optimization for the artificial lights and the heating system.

A Genetic Algorithm framework, Controleum, is adopted for the multi-objective optimization in the Multi-Objective Optimization based Climate Control platform in Digital Twin of Greenhouse Climate Control. The Genetic Algorithm is utilized to produce a Pareto Frontier with optimal operation setpoints for artificial lighting (Light Plan) and heating (Heat Plan). Relative Importance Graph Social Welfare metrics are used to select the final optimal solution from the Pareto Frontier.

Describe the obtained technological results. Did the project produce results not expected?

This research fills the gap that there is no comprehensive Digital Twin framework for greenhouse climate control in the literature. The literature only concerns either the digital counterparts of the physical system or the optimization of the actuator operations, while the DT framework in this research consider both aspects. In the current literature, the DT systems in the agriculture area only focus on the digitalization of a specific perspective during the production process, while this research covers multiple aspects of the greenhouse system, including greenhouse climate, plant growth, and energy consumption, so that the virtual greenhouse can represent the physical system comprehensively. The current DTs in the agriculture area tend to simplify the control system highly. As a result, these DT systems can only concern a specific perspective of requirements of the production. In this research, greenhouse climate control is abstracted as a MOO problem defined concerning requirements, including growing quality and speed, energy consumption, and production cost.

This research innovatively applies time-series ANN methods in greenhouse climate control. By analyzing the historical data on greenhouse indoor temperature and compartment heating consumption, they present the features of seasonality and cyclical patterns, and time-series ANN models are good at capturing these time-series correlation characteristics. From the experimental results, the proposed time-series ANN methods have a high prediction performance in the case studies.

This research fills the gap in the design of DT-GCC systems concerning the characteristics of the environment and electricity market of Nordic countries. The two case studies in this research are both from Denmark, which is with long and dark winters, and the electricity price fluctuates by hours. These features make the MOO problem of greenhouse climate control significantly different from many other countries because they request objectives focusing on distinct constraints. As a result, the MOO problem definition can be applied to the research of greenhouse control optimization problems in other Nordic countries.

This research fills the gap in the design and development of DT-GCC integrating with other DTs, such as the Digital Twin of Production Flow (DT-PF) and Digital Twin of Energy System (DT-ES)., The DTs for greenhouse climate control in the literature only focus on the specific DT rather than communicating with other DTs to constitute the entire greenhouse system. This research designs and develops the DT integration with other DTs, so that DTs can communicate and exchange information with each other to constrain the optimization in individual DTs. DT-GCC can respond to different requests from DT-PF to optimize the actuator operations to satisfy multiple requirements and objectives. The response sequence and the optimization performance of DT-GCC in DT integration are verified in experiments based on case studies.

This research also analyzes the benefits of applying the updated version of Controleum so that it can provide recommendations for algorithm design for similar MOO problems for future research work.

Describe the obtained commercial results. From the commercial perspective, DT-GCC in greenhouse systems is able to:

1) Dramatically reduce the electricity cost of artificial lighting meanwhile maintaining the plant quality.
2) Reduce the management cost of configuring the greenhouse climate parameters to fulfill the production growing requirements, such as setting up heating setpoints to meet the production delivery date.
3) Reduce the development cost because it is easy to apply the proposed Digital Twin framework to other greenhouse climate control systems.

Target group and added value for users: There are two targeted groups related to WP3:

• For commercial greenhouse growers, DT-GCC provides a MOO platform that can recommend optimal Light Plan and Heat Plan for the next 24 hours to minimize energy consumption and production cost without compromising the production quality. The MOO problem definition concerns the specific weather condition, horticultural growing logic, and the characteristics of the electricity market in Denmark. Additionally, through the GUI, Growers can input significant parameter configurations according to growing requirements and monitor the prediction and optimization results.

• For project managers, DT-GCC elaborates a hierarchical architecture for establishing and developing a Digital Twin system in a greenhouse system. The fundamental system is modularized into multiple sub-sections that are relatively independent but are also able to communicate with each other so that the development and management of individual modules can be synchronic.

5.3 Digital twin production flow

WP4 includes (A4.1) the Development of a multi-agent simulation model for greenhouse production flow; (A4.2) the Identification of a Common Information Model interface; (A4.3) Investigating the effects of co-optimizing factors influencing the production flow; and (A4.4) Simulation of energy efficiency and demand response potentials. All the above objectives were achieved. The objectives were realized through the case studies provided as a part of the project.

In (A4.1), the objective was fully achieved with a multi-agent simulation model of the greenhouse production flow being established. The multi-agent simulation was developed based on object-oriented programming principles with a modular and generic approach, enabling the developed agents' reusability across the project's case studies. Furthermore, the multi-agent system was developed using generics to facilitate ease of including case-specific variability subject to the underlying hierarchy of the generic multi-agent simulation.

(A4.2) was fully achieved with the information model interface being fully identified. It was realized through the in-memory data grid Hazelcast, and a publish/subscribe pattern was implemented as a horizontal integration approach. The horizontal integration approach for external communication eases the addition or removal of actors in the system and only emphasizes the communication content.

(A4.3) was achieved, but certain factors, such as quality grading requirements, district heating demand, and gas prices, could not be considered. Quality grading requirements were not precisely quantified but rather deemed complete when plants met the necessary level of quality. Therefore, an appropriate amount of time was allotted for plant development, with quality assumed to be sufficient at the time of recording. District heating demand was difficult to include with sufficient granularity, as it was only recorded for the facility as a whole and in specific compartments. Gas pricing was also not considered in the digital twin of the production process, as it had no direct impact on production flow.

(A4.4) was achieved through the communication architecture with the digital twin of the greenhouse climate compartment from WP3. The energy efficiency and demand response potentials could hence be found with the underlying restrictions imposed by the production process. The expected impact on the plant development can be examined through weather forecasts and hindcasts and any discrepancies adjusted as the plant progresses through production.

Describe the obtained technological results. The literature provides no solutions for creating digital twins for ornamental greenhouse production process flow. The literature primarily emphasizes identifying ideal growth conditions for greenhouse plants, energy management, and optimization solutions. The literature does not adequately consider multi-stage process facilities such as the greenhouse production flow in which the decision-making in one stage of the process may propagate to the adjacent processes and systems. Furthermore, the literature does not provide holistic solutions considering the impact of energy flexibility or efficiency on the production process flow. Therefore, the developed generic multi-agent simulation for greenhouse production process flow poses a novel solution for enabling digital twin development in greenhouse production process facilities. Through the developed solution, greenhouse growers can obtain insights into the underlying mechanisms of their production and perform what-if scenario testing and risk assessment.

In conjunction with developing a generic multi-agent simulation model for greenhouse production processes, a methodology was established for creating cultivar-specific plant development functions. This methodology can be used as a standalone function or in combination with the generic multi-agent simulation model for greater effectiveness. By utilizing this methodology to identify plant development functions, growers can assess whether the plant development matches the desired production time. This function can also help reveal any discrepancies between the desired and actual plant development, allowing growers to take corrective measures earlier in the production process. Moreover, it can be a planning tool for growers to determine when to initiate new batches of specific plant cultivars.

The generic multi-agent simulation model for the greenhouse production process and the methodology for identification of plant development function were verified and validated on the basis of the case studies of the project showcasing the applicability across different cases.

Describe the obtained commercial results. The digital twin for greenhouse production flow has several commercial benefits, including increased efficiency, cost reduction, and improved yields. By collecting data from greenhouse facility sensors, the digital twin provides a digital representation of the greenhouse and its systems, enabling growers to monitor and optimize conditions for plant growth. For instance, growers can use the digital twin to detect and troubleshoot problems with their greenhouse systems, such as temperature imbalances, and take corrective measures. Moreover, the digital twin can help ensure yields while reducing overall costs. As a result, greenhouse growers can improve their operations, increase productivity, and achieve a more sustainable and profitable business. To enhance the usability of the digital twin for growers, a user interface was developed to streamline data input and testing on the platform.

Overall digital twin for the greenhouse production process flow can improve key performance indicators (KPIs) related to the following areas:

- Production efficiency: this can aid in identifying opportunities for improving production efficiency. The twin can hence aid in improving production costs.
- Energy management: the digital twin can provide a testbed for examining the impact of energy management strategies to examine any unforeseen consequences on production.
- Ensuring quality: the digital twin can aid in planning and ensuring sufficient development of plants at a given production deadline.
- Maintenance schedule: the digital twin can be used to examine the impact of breakdowns or scheduled maintenance in production, e.g., change of artificial light system or reparation of machines.
- Regulatory compliance: through monitoring and collection of data, the digital twin can potentially aid in reporting and ensuring regulatory compliance.

Target group and added value for users: The digital twin of the greenhouse production process flow benefits various groups, such as greenhouse operators, agricultural engineers, technology providers, technology consulting firms, and integrators who specialize in implementing digital twin solutions in industrial environments. However, to utilize the developed solution, the target groups must fulfill specific requirements. These requirements include having an established physical sensor network, installing an ERP or a similar system to monitor the flow of plants and the required production deadlines, and having a data storage and management system to store and manage the large amounts of data generated by the sensor network. Therefore, the primary target group for the solution is modern smart greenhouse facilities with the necessary infrastructure and technology to integrate and benefit from the digital twin of the greenhouse production process flow.

The target groups are:

- Greenhouse operators and managers: They can use the digital twin to monitor the real-time performance of their facilities, optimize the production process, and make data-driven decisions to improve efficiency and productivity. Also, they can use the digital twin to identify potential bottlenecks in the production process, optimize growing conditions, and monitor plant growth.
- Researchers and plant breeders can use the digital twin to experiment with different growing conditions and evaluate the impact on plant growth and development.
- Investors and stakeholders: They can use the digital twin to monitor the performance of their investments and make informed decisions about future investments in the industry.

The added value for the target groups includes:

- Improved efficiency and productivity: By monitoring the performance of the facilities and modeling the production process, the digital twin can help optimize resource allocation and efficiency.
- Increased yields and reduced costs: The digital twin can identify potential bottlenecks in the production process, allowing operators to address them proactively, resulting in increased yields and reduced costs.

- Better data-driven decision-making: By providing performance data, the digital twin can enable users to make informed decisions based on accurate and up-to-date information.

5.4 Digital twin energy system

In accordance with the WP5 objectives, the results of the project are detailed under each task as indicated below:

Mapping and identification of generic greenhouse energy system (5.1): Activity 5.1 aims at investigating the energy systems and current CHP operation for greenhouse production facilities in order to establish a generic model with optional choices for specific growers. It was decided that a Modelica library would be built and contain a collection of components that would each describe specific parts of the energy systems with simple mathematical models. The possible list of energy systems is provided. One of the growers involved in the project (Kund Jepsen) was selected as the primary grower to gather information about the specific systems in operation at Kund Jepsen. Meanwhile, it was decided that the list of all possible energy system components would be narrowed down to only a few components. The components that have been retained are:

1) Gas-fired CHP (heat/power)
2) Electrically driven heat pumps
3) Electric heaters
4) Thermal heat storage (water tanks)
5) District heating

Identification of Common Information Model interface (5.2): The interface (input/output structure) for the energy system model identified in A5.1 has been defined as shown in Figure 1.

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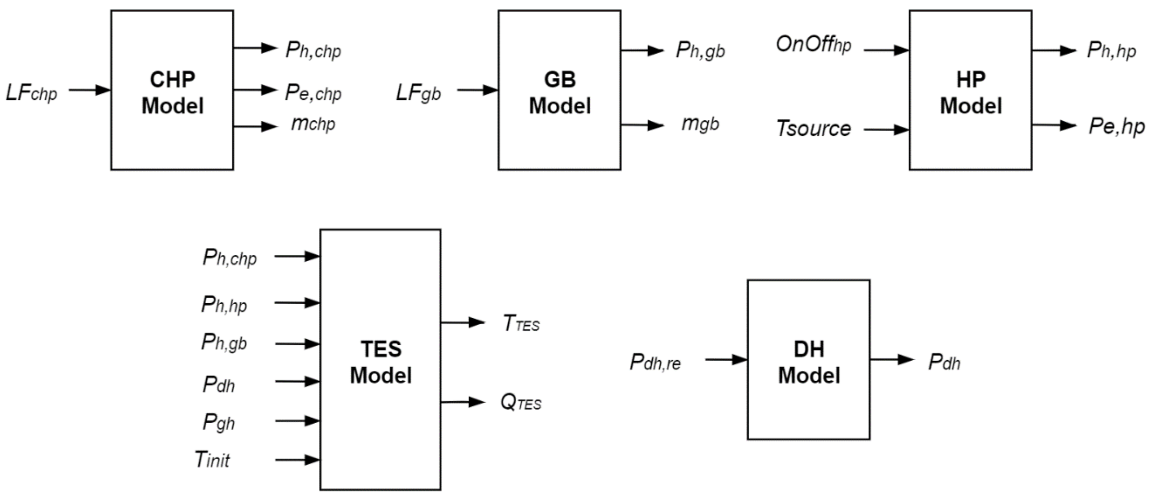


Figure 3 Inputs and outputs of the generic control models

Development of the energy system model (A5.3). Considering the inherent complexity and diversity of greenhouse energy systems at each grower site, a two-step approach is therefore adopted. Generic control and emulation models for greenhouse energy systems were first developed to demonstrate the application of multi-objective optimization for greenhouse energy system operation. Then, the emulation models were tailored to represent the specific energy systems of each grower.

In this context, simple generic components for individual greenhouse energy systems were created. The generic models are made simple, adaptable, and parameterizable, i.e., they can be customized to match new system sizes and characteristics, which allows them to be readily adapted to different types of greenhouse energy systems. Then, a generic emulation model of greenhouse energy systems was developed. An emulation model tailored specifically for the grower Knud Jepsen was implemented. Together with the generic control models, this emulator could be used as a virtual representation of Knud Jepsen's energy systems in an optimization framework.

Model parameter identification and validation on case study data from normal operation (A5.4) The development of generic control models consisting of typical greenhouse energy systems (combined heat and power plant, heat pump, gas boiler, district heating, and thermal energy storage) was completed. Measured data from the grower Knud Jepsen was used to estimate unknown parameters of the generic control models. The system identification was conducted using Modestpy. Figure 2 shows the simulation results of the model with estimated parameters as compared to measurements.

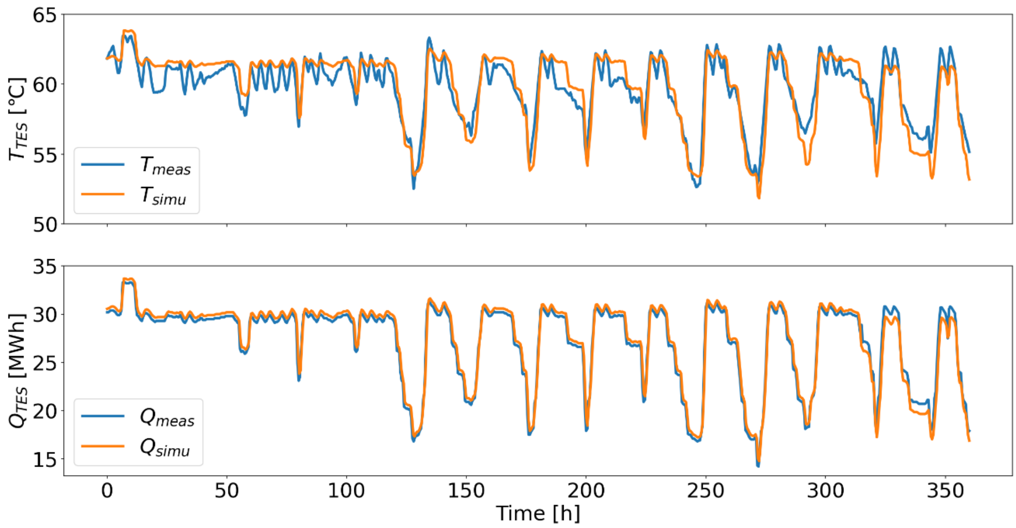


Figure 4 Measured vs. simulated TES temperature and stored energy (orange – model predictions, blue - measurements)

WP 5 also demonstrates the cost-optimal operation of greenhouse energy systems, where multi-objective optimization for greenhouse energy systems planning was implemented.

Besides, a model of greenhouse energy systems which includes seasonal thermal storage (aquifer) was developed as it is also part of the energy portfolio of one of the growers. A model predictive control strategy was used to demonstrate how greenhouses can operate their energy systems when using both diurnal and seasonal thermal storage in an energy- and cost-efficient way. It was demonstrated that using a seasonal factor for the aquifer can enable a model predictive controller to operate greenhouse energy systems in a cost and energy-efficient way.

Describe the obtained technological results. The research works in WP5 contribute to:

1) Generic greenhouse energy system models

Generic control and emulation models for typical greenhouse energy systems consisting of CHP, HP, GB, DH, and TES are developed. These models are built as generic, reusable and allow users to access and readily adapt them to their customized models. In this regard, this work contributes to providing Modelica models for greenhouse energy systems modeling, which allows potential users to quickly align to their specific energy systems and enables simulation and testing for conceptual design at the early stage.

2) A showcase of developing a detailed emulation model for greenhouse energy systems

Starting from the generic models, a step-by-step showcase of developing a detailed emulator tailored to a specific greenhouse grower is presented, which serves as a guide and reference for the potential model developers to build up their energy system emulator. In addition, the developed emulation model is partially validated against on-site measurements, simulation results are compared with the measurements to analyze model accuracy. Suggestions for attaining a high-fidelity emulator are recommended.

3) A demonstration of optimization for greenhouse energy system planning

An multi-objective optimization framework for greenhouse energy systems is proposed. The optimization aims to minimize operational costs while satisfying greenhouse heat and electricity demand and physical operation constraints. Through this study, the flexibility of utilizing TES is identified. The proposed optimization framework (Controleum), taking into account different energy resources and energy prices, demonstrates the ability to exploit economic benefits by smartly dispatching greenhouse energy systems. This demonstration verifies the viability of applying multi-objective optimization for greenhouse energy scheduling and highlights the potential economic benefits, which contribute to moving research simulation work toward real-life implementation.

Describe the obtained commercial results. WP5 developed a digital twin for generic greenhouse energy systems serving as the decision support for optimizing the co-generation of heat and electricity based on predicted greenhouse demand, weather, electricity, and district heating energy prices. The main commercial result with respect to the energy system digital twin is to enable reducing energy costs of energy system operation while delivering specific heat and electricity to greenhouse climate compartments. This commercial result can be achieved using Controleum as the multi-objective optimization framework. the energy costs are reduced by optimally dispatching different energy production and storage unit based on electricity price, gas price, and district heating price.

Target group and added value for users. The two main targeted groups are:

1) Greenhouse growers: the digital twin of the greenhouse energy system is a virtual representation of physical energy systems, enabling
   - Decision support for optimizing co-generation of heat and electricity based on predicted greenhouse demand, weather, electricity, and district heating energy prices
   - Analysis and visualization of past and current plant efficiency and performance
   - Plant diagnostics functionality based on comparison of ideal and real process performance indicators
   - Potential functionality for plant multi-objective optimal control for either greenhouse production optimization or participation in demand response event
2) Energy system modeling community: the developed digital twin for greenhouse energy systems consist of typical energy component (CHP, HP, GB, DH, and TES) These models are built as generic and reusable, which allows researchers within energy system modeling community to reuse and readily adapt them to their customized models.

5.5 Greenhouse Industry 4.0 Demonstration

Two software systems are developed with the aim of supporting growers to minimize their use of energy. InfoGrow is an online tool, while Virtual Greenhouse is a desktop application.

5.5.1 DGT App

Senmatic developed an app that makes it much easier for greenhouse producers to overview the climate and use resources on the distance. With the app, it is possible to follow the climate and adjust it for an optimal climate and use of resources. The app uses a hardware developed together with Consibio that transfers data from the Senmatic system to the Consibio cloud. The flow of data is shown in Figure 6. The greenhouse grower can follow the climate, change the setpoint, and make alarms that can help to secure production.

Figure 5 DGT APP

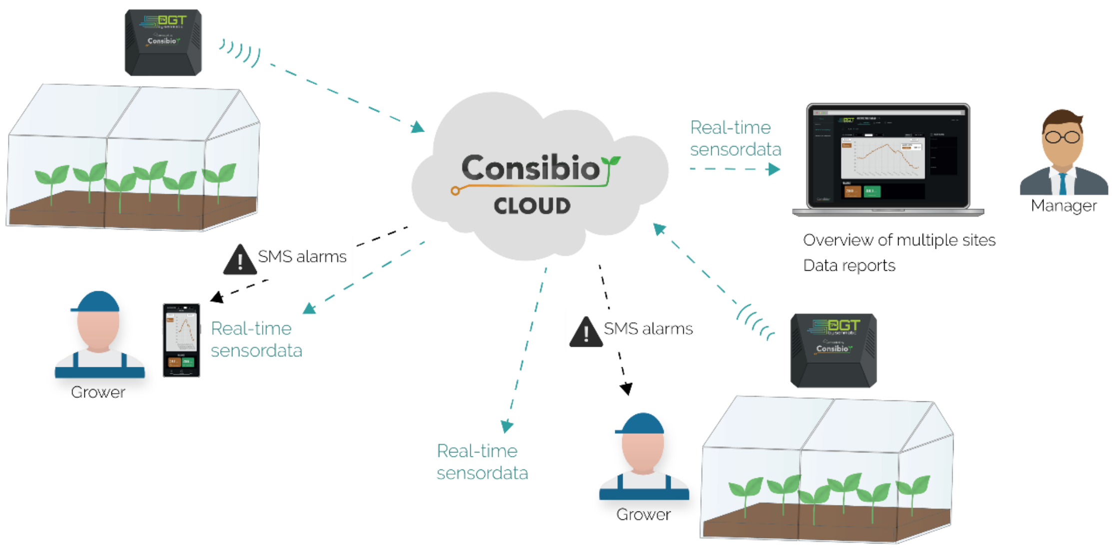


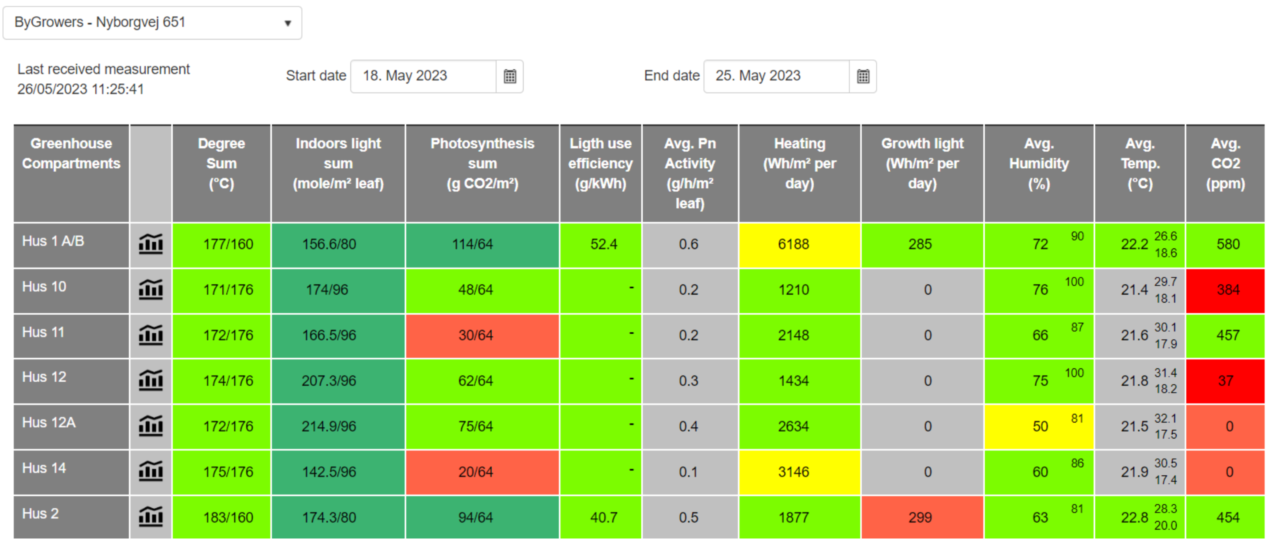
Figure 6 DGT App. Roles and data collection.

5.5.2 InfoGrow 2.0

InfoGrow 2.0 is a unique tactical tool that enables the grower to follow and optimize production in relation to the use of resources.

- It presents real-time information about plant growth, production time, and climate in relation to energy use.
- It models parameters such as photosynthesis, light use efficiency, carbon gain, and energy use based on data from the climate computer and sensors.
- Data are summarized for the entire greenhouse complex and detailed for individual departments or specific decision support parameters, showing deviations from relevant key point parameters.
- It offers a flexible and customized log system for event registration and reporting, e.g., the application of biological or chemical pest control.
- InfoGrow 2.0 is an online tool.

With InfoGrow 2.0, growers gain real-time performance indicators for plant photosynthesis and plant growth. With this information, growers can adjust set points for climate parameters to optimize plant production growth on a daily basis.


ByGrowers - Nyborgvej 651
Last received measurement 26/05/2023 11:25:41
Start date 18. May 2023
End date 25. May 2023

Greenhouse Compartments		Degree Sum (°C)	Indoors light sum (mole/m² leaf)	Photosynthesis sum (g CO2/m²)	Ligth use efficiency (g/kWh)	Avg. Pn Activity (g/h/m² leaf)	Heating (Wh/m² per day)	Growth light (Wh/m² per day)	Avg. Humidity (%)	Avg. Temp. (°C)	Avg. CO2 (ppm)
Hus 1 A/B		177/160	156.6/80	114/64	52.4	0.6	6188	285	72 90	22.2 26.6 18.6	580
Hus 10		171/176	174/96	48/64	-	0.2	1210	0	76 100	21.4 29.7 18.1	384
Hus 11		172/176	166.5/96	30/64	-	0.2	2148	0	66 87	21.6 30.1 17.9	457
Hus 12		174/176	207.3/96	62/64	-	0.3	1434	0	75 100	21.8 31.4 18.2	37
Hus 12A		172/176	214.9/96	75/64	-	0.4	2634	0	50 81	21.5 32.1 17.5	0
Hus 14		175/176	142.5/96	20/64	-	0.1	3146	0	60 86	21.9 30.5 17.4	0
Hus 2		183/160	174.3/80	94/64	40.7	0.5	1877	299	63 81	22.8 28.3 20.0	454

Figure 7 InfoGrow Dashboard with a summary table that presents key performance indicators for production. The summary view displays data from all climate zones and uses colors to indicate where the grower has to focus.

InfoGrow 2.0 uses data from the climate computer to model plant photosynthesis, climate, and energy. This makes InfoGrow 2.0™ unique, as there is no need for the costly installation of new sensors or fancy equipment.

InfoGrow 2.0 has been developed with many features important for greenhouse growers. To use the program, the departments (greenhouses) must be described in the program. This includes a description of covering material, used screens, vents, heat pipes, and artificial light. A greenhouse complex usually consists of several greenhouses, and each has to be described in the software. Each greenhouse is handled individually in InfoGrow, and data are presented for each greenhouse, as shown in Figure 8.

Figure 8 Data from each greenhouse are presented as rows in the summary table. The summaries are made over a period of dates that can be selected. If more detailed information's needed, charts can provide detailed data, or a detailed energy analysis can be made.

In the project, we have developed models for both uses of energy and photosynthesis. InfoGrow estimates the use of energy in 10 minutes time step using the inlet temperature of the hot water. Photosynthesis (plant growth) is estimated using climate data (temperature, CO2, radiation, and humidity). Using these values, values for the climate in the greenhouse and values for using the different actuators in the greenhouse (screens, vents, artificial light, etc.) InfoGrow presents greenhouse production in a new innovative way with possibilities for optimizing the production.

Several Danish and international projects have demonstrated ways to minimize energy use in greenhouse production. The main problem is to do it and still be sure to have plant production. This is one of InfoGrow's main features. Estimating light, photosynthesis, and temperature sums give the growers a unique possibility to secure production utilizing energy-saving possibilities.
The main features of InfoGrow are described in Table 1.

Table 1. InfoGrow main features

InfoGrow feature	Function	Description
Modeled parameter	Energy for heating	Estimate heat energy for heating from inlet temperature and information about the installed heat pipes
	Energy for artificial light	Estimate energy used for artificial light from the artificial light status
	Light at plant height	Estimate light at plant height from light measured outside the greenhouse and use of screens, artificial light, and properties of the covering material.
Dashboard	Summary table	KPI for the production. Information about the use of energy for heating and artificial light. Temperature sum, light sum and photosynthesis sums are important to ensuring optimal plant production.
	Production effectivity	Plant production per used kWh for heating and/or artificial light. Indicate where the production is most effective.
Modules	Collection of charts and tables	Modules with a presentation of energy, photosynthesis, light, and humidity in the production
Charts		Several charts present the production parameters (use of energy and photosynthesis) together status for actuators, setpoints, and climate
Weather forecast		Weather forecast developed for the agricultural industry provided by ConWx. The weather forecast provides ordinary climate parameters but also the radiation in W/m2
Light strategy	Light sum	The light sum is calculated for a specific number of days and estimated for the following days using the weather forecast. From this InfoGrow estimate the needed artificial light (in hours) for each of the nurseries departments.
Crop definition	Photosynthesis	Describe crops photosynthesis by several parameters
	Crop	Describe a specific crop's requirement for temperature, light, or photosynthesis sum for development.
Batch system	QR codes	Each batch is defined in the system with a start and expected end production day. A QR code is attached to each batch.
	Special software	Software is developed that makes it easier for the producers to create batches and QR codes.
Log System	System	A generic log system makes it possible to store information about almost anything in production. Examples are the use of resources, diseases, use of pesticides, etc.
	App	Android app that easily can store information in the log.

Several of the functions are described detailed on the InfoGrow.dk website. See Table 2.

Table 2. Links to www.InfoGrow.dk with extended information on the use of InfoGrow

Save energy	Save energy | InfoGrow website
Save energy for artificial light	Save artificial lighting | InfoGrow website
Production control	Production control | InfoGrow website
Description of log system	The log system | InfoGrow website
Humidity issues	Solve humidity problems | InfoGrow website

InfoGrow Example 1 – Unexpected high use of energy

The dashboard indicated a very high energy use for one of the departments. See the small dashboard snip in Figure 1.

Using the charts, we saw that the energy use increased from 0.3 kWh/m² on the 5th of October to 1.6 kWh/m² on the 9th of October (Figure 9 and Figure 10).

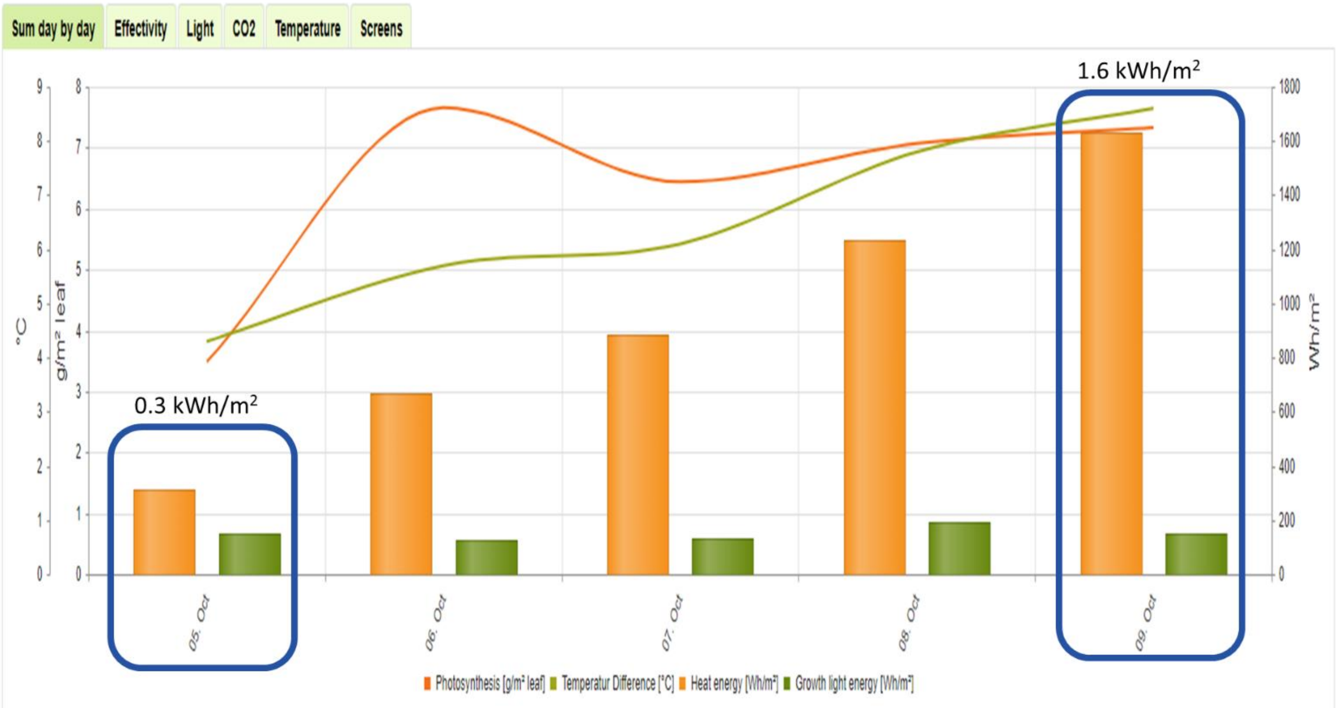


Figure 9 Daily energy use chart showing data from one greenhouse.

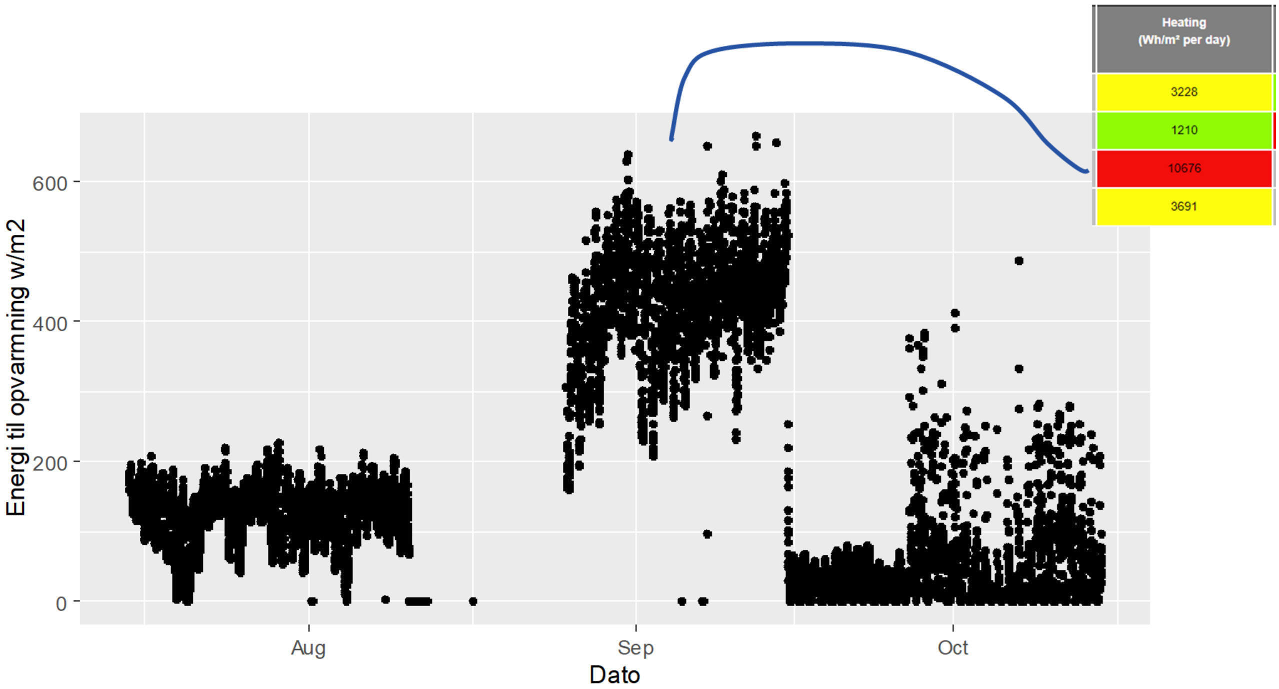


Figure 10 Use of energy for three months. A small clip from the dashboard indicates an important energy problem with the red color.

The chart indicates that something went wrong after the 5th of October. We downloaded data and made a more detailed analysis (Figure 11).

The greenhouse grower had changed the use of the greenhouse from an ordinary growing greenhouse to a storage facility with a lower temperature requirement. To obtain the lower temperatures, the valve controlling the inlet of hot water was closed, and the screens were withdrawn day and night. The problem was that the valve didn't stop the inlet of hot water. Therefore, the temperature was higher than expected, and energy use was much higher. The grower fixed the valve, and the system worked as expected. This is one example f how InfoGrow indicate for the grower when they need to act.

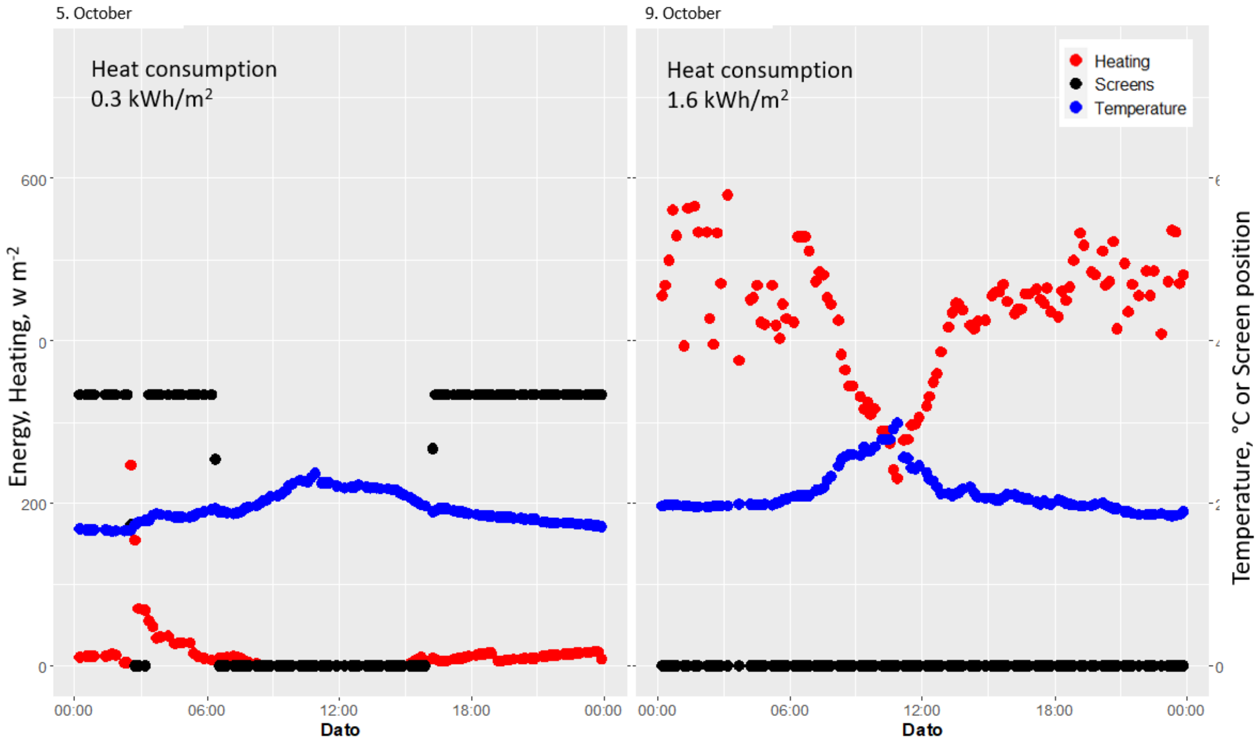


Figure 11 Temperature, Screen position, and heating energy use during two days of October.

InfoGrow Example 2 – Light sum-dependent use of artificial light

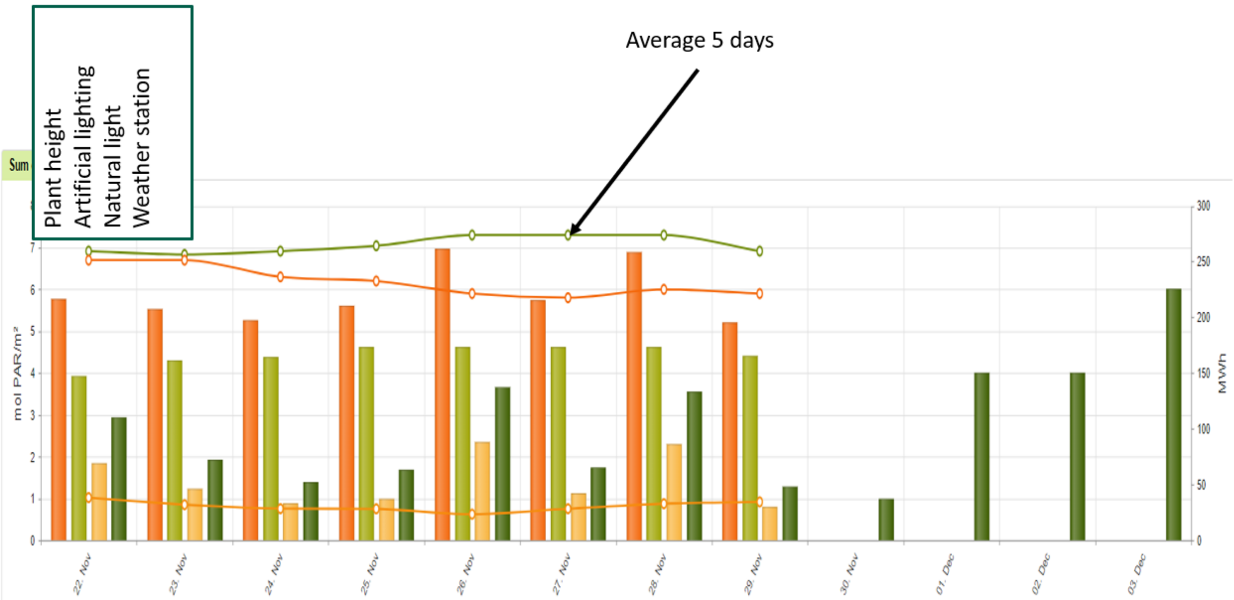


Figure 12 Estimated light level in the greenhouse at plant height (orange) and separated in the part from natural light (Green) or artificial light (light green). Green bars are light measured at the weather station or values from the weather forecast.

With information about the installed artificial light, requirements for the plant, light sum for the last days, and weather forecast InfoGrow calculates the need for artificial light for the following days (Figure 13).

Light strategy iG Info

Nbr. days for last period of time 5

All values are by day

Greenhouse Compartments	Target At plant height [mol PAR/m^2]	Indoors light At plant height [mol PAR/m^2]	Contribution Natural light [mol PAR/m^2]	Contribution Growthlight [mol PAR/m^2]	Growthlight Hour capacity [mol PAR/m^2/h]	01/12/2022	02/12/2022	03/12/2022	04/12/2022	05/12/2022	06/12/2022	07/12/2022
Sun [mol PAR/m^2] =>			2.5			4	4	5	5	7	6	7
Hus 5 - Øko	7	6.2	1.64	4.56	0.601	7 h	7 h	6 h	6 h	4 h	5 h	4 h
Hus 9	7	9.17	1.42	7.75	0.65	7 h	7 h	6 h	6 h	5 h	5 h	5 h

Figure 13 Artificial light needed to obtain the needed light sum the secure the optimal plant production.

The data are updated daily, and from this table, the energy manager decides when and how much light to use in the production. With this, a substantial amount of energy can be saved from March to May and September to November.

InfoGrow Example 3 – Advanced energy report

Once or twice a year, data is downloaded from InfoGrow and used in an advanced energy analysis of the production. In the analysis, the system identifies important factors for the use of energy. With the analysis, the energy manager gains information about the greenhouse facility, uses of the different technologies, and plant production.

Content of the energy report:

- Energy consumption and weather conditions
  - Overview of data with total energy consumption
  - Energy as a function of the difference between indoor and outside temperature
  - Energy consumption as a function of the dose between indoor and outdoor temperature and the importance of wind speed
- Greenhouse temperature control
  - Medium temperature with variation - Is the dynamic exploited?
  - Hours of ventilation at low outside temperatures
  - Humidity at hours of ventilation at low outside temperatures
  - Hours with curtain and varying outdoor light level
  - Hours without a curtain. Little light and rising temperature
  - Hours without a curtain. Low temperature and rising light
- Light in the greenhouse
  - Daily light sums at plant height
  - Daily energy consumption for artificial lighting and light sum achieved.
  - Medium temperature against light sum.
- CO2 in the greenhouse
  - Hours with artificial lights on and low CO2 levels
  - CO2 when artificial lights are used
- Humidity
  - Moisture distribution
  - Periods of high humidity
- Appendix

- Days with the highest deviation from expected energy consumption

During the project, the master's student Hongyuan Zhang developed a new procedure and model that made it possible to adapt the photosynthesis model to new crop species. This was done as part of his master's thesis with Eva Rosenqvist as supervisor. The model ad adaptation procedure is now implemented in InfoGrow and Virtual Greenhouse.

At the University of Aarhus, several test growing was performed. The aim was to test development with different light levels and the same temperature in order to investigate the effect of using less energy for artificial light. Several experiments were performed, and they will be published later in scientific journals. Figure 14 shows some of the first plant responses, which indicates that even though the temperature sum is the same, the effect of less light influences plant development significantly. It is, therefore, important not only to focus on the temperature sum but also the light sum.

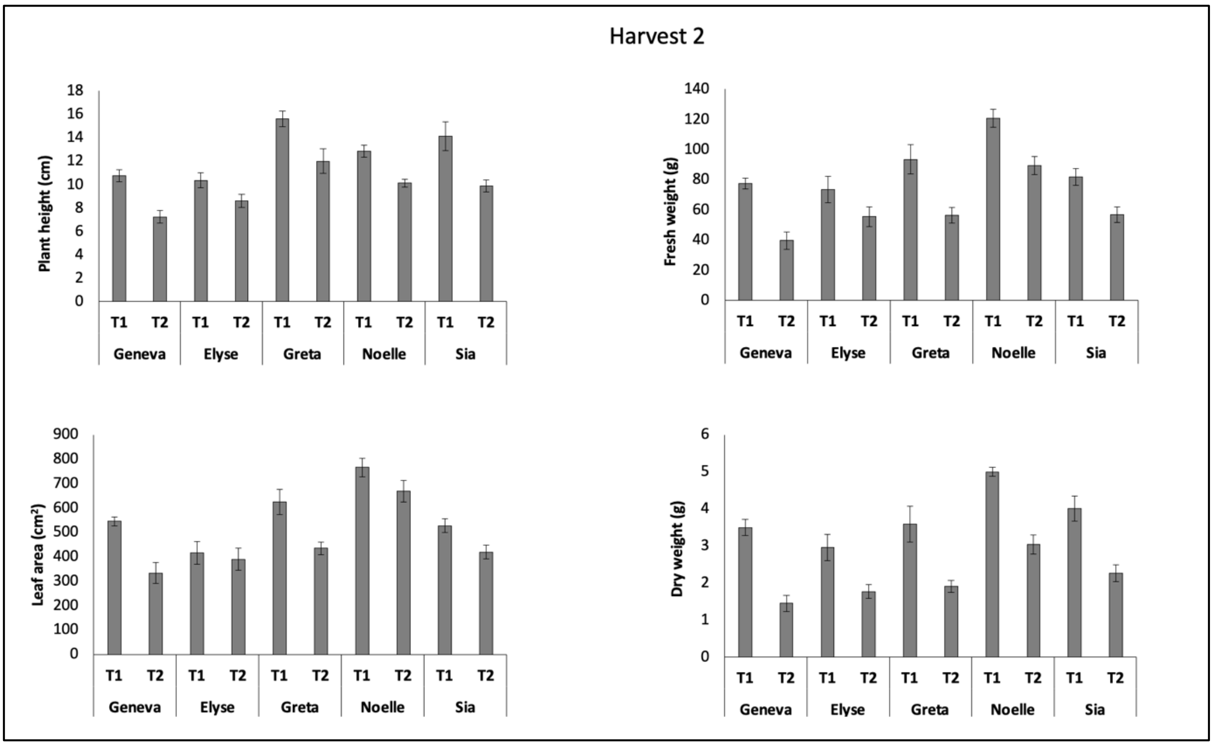


Figure 14 Plant responses (Kalanchoe varieties) to two light treatments. T1: 20°C and 150 µmol m^{-2} s^{-1}. T2: 20˚C and 75 m^{-2} s^{-1}.

5.5.3 Virtual Greenhouse

Virtual Greenhouse utilizes UNISim to simulate year-round greenhouse production. Virtual Greenhouse and UniSim are the digital twins of greenhouse production.

A virtual description of the greenhouse production system is created and used by UniSim to simulate the production. The simulation is done in 3-minute steps, and more than 40 parameters are simulated, describing the use of energy, microclimate, plant production, and more.

The first step in a simulation is to define greenhouse and crop:

- Physical greenhouse setup
    - Geography
    - Size
    - Screens
    - Covering
    - Lighting
    - CO2
    - Heat pipes
    - Heat exchanger
    - Heat pumps
    - Humidification
    - Etc.
- Weather Data
    - Use weather data for more than 2100 locations or your own weather data.
- Define the climate strategy.
    - Climate strategy can be defined that mimics an advanced commercial climate computer from Senmatic.

A few of the calculated parameters

- Crop
    - Photosynthesis
    - Transpiration
    - Canopy temperature
- Energy:
    - Energy for heating
    - Energy for artificial lighting
- Climate:
    - Temperature
    - Humidity
    - Light at plant height
    - CO2 at plant height
- Efficiencies
    - Light use efficiency
    - Energy use efficiency
    - Photosynthetic efficiency

After the simulation, Virtual Greenhouse creates a detailed report about the simulation. The simulation system can be used to see what effect a new technology will have on production. Two or more greenhouse setups' can be compared to see the effect. Figure 15 is an example comparing an old LED lighting system with traditional HPS lights. The effect is using less energy for lighting and more for heating. While the total use only was slightly lower.

Text	Unit	Std	Led	Difference	Percent
Greenhouse area	m^{-2}	4,000	4,000	0	0.0
Total use of energy	MWh $Year^{-1}$	2,995	2,968	27	-0.9
Energy for heating	MWh $Year^{-1}$	1,902	2,183	-281	14.8
Energy for artificial light	MWh $Year^{-1}$	1,093	785	308	-28.2
Energy removed by water vapor (ventilation etc)	MWh $Year^{-1}$	-221	-153	-68	-30.8
Net Photosynthesis	g m^{-2}	4,762	4,580	182	-3.8
Light Use Efficency	mg CO2 J^{-1}	0.0149	0.0149	-0.0001	
Total energy used to produce 1 kg dry plant material	MW kg^{-1}	146	154	-8	5.5
Heating energy used to produce 1 kg dry plant material	MW kg^{-1}	100	119	-19	19.3
Light energy used to produce 1 kg dry plant material	MW kg^{-1}	57	43	15	-25.4

Figure 15 Main results from a simulation comparing an HSP artificial lighting system with a new LED system.

UNISim has been rewritten in the project with many new functionalities. Among the most important are that it is now component-based, so it is possible to test many new technologies. Another new possibility is to make a sensibility test with the system. The Virtual Greenhouse model has been documented, and the documentation can be found on the Virtual Greenhouse page of InfoGrow.dk.

6. Utilisation of project results

6.1 Common information model

Different greenhouse technology providers can utilize the obtained technological results from WP2 to integrate their technologies, e.g., climate computers, IoT sensors or software into the existing greenhouse systems.

The obtained technological results from WP2 can reduce the complexity and cost for digital twin solution providers, allowing efficient and effective data exchange among digital twins, sensors, and systems.

The data and system integration enabled by the obtained technological results from WP2 can benefit growers to have a better overview, management, and optimization of greenhouse production.

6.2 Digital twin greenhouse climate

The results of DT-GCC can be utilized by growers to collect the schedule recommendations for the artificial lighting switch and the heating setpoints for the next 24 hours. Growers only need to configure some parameters related to growing logic and strategies, then DT-GCC can automatically complete the artificial lighting optimization concerning minimizing the electricity cost without compromising the growing quality and finish the heating setpoint optimization to fulfill the growing requests and logic.

The results of WP3 contribute to realizing energy policy objectives by:

- Artificial lighting optimization

Regarding the experimental results for minimizing electricity cost, the optimal Light Plan based on the proposed MOO problem concerning the objective “Satisfy day light integral” with designed RIG structure can satisfy the Day Light Integral (DLI) requirements in most situations and can also dramatically reduce the electricity cost during the experiment period in both long-day and short-day compartments.

- Heating setpoint optimization

In the standalone experiments of DT-GCC, the optimal Heat Plan (optimal heating setpoints for the next 24 hours) can reproduce the setpoints that follow growers’ operation logics and strategies.

In the Digital Twin integration experiments, the predicted indoor temperature based on the optimal Heat Plan can satisfy the expected daily accumulated temperature on top of the growers’ operation logics and strategies. Meanwhile, the predicted heating consumption based on the Heat Plan can be an energy demand recommendation to benefit the energy allocation in Digital Twin of Energy System (DT-ES).

The following PhD has been part of WP3:

> Qu, Y. (2023). A Digital Twin Framework for Commercial Greenhouse Climate Control System. [Ph.D. thesis, SDU]. Syddansk Universitet. Det Tekniske Fakultet.

6.3 Digital twin production flow

Multiple stakeholders can utilize the obtained technological results in the future. Greenhouse growers are expected to use the digital twin of the greenhouse production process. The growers will use the digital twin to optimize the greenhouse production process, including monitoring plant growth, predicting crop yields, and adjusting environmental conditions to optimize plant development and productivity.

Supply chain managers can use the digital twin to monitor inventory levels, predict demand, and optimize production schedules based on data from the greenhouse. Researchers may use the digital twin to study the greenhouse production process and to develop new methods and technologies to improve energy efficiency and reduce greenhouse gas emissions.

Regulatory bodies and government agencies could potentially use the digital twin to monitor and regulate the greenhouse industry, e.g., tracking greenhouse gas emissions or evaluating the potential response of new legislation. Likewise, investors or greenhouse owners may utilize the digital twin to evaluate investment opportunities in the greenhouse industry, including assessing greenhouse operations' financial and environmental performance.

Within the energy system domain, the digital twin may be used by utility companies to monitor and optimize greenhouse facilities' energy consumption and identify opportunities to reduce energy costs and improve energy efficiency. Similarly, energy service providers may use the digital twin to analyze greenhouse facilities' energy consumption patterns and identify opportunities to improve energy efficiency, reduce energy costs, and integrate renewable energy sources. Energy technology providers may use the digital twin to develop and demonstrate new energy technologies, such as energy storage systems and energy-efficient lighting, to improve the energy efficiency of greenhouse facilities.

The market for digital twins for greenhouse production process flow is relatively new and growing, but competition is increasing as more players enter the market. No actors have provided a solution that resembles the digital twin for the production process flow; however, key actors, including startups and established technology companies, provide partial or similar technologies that could pivot into the digital twin domain. Some of the key players in this market include:

- CropX: A digital agriculture company that provides a platform for optimizing crop growth through soil sensing and machine learning.
- Priva: A global leader in sustainable and energy-efficient solutions for the horticulture industry, offering a wide range of products and services for greenhouse management.
- Fluence: A horticulture lighting solutions and services provider offering digital twins for greenhouse production as part of its broader solution portfolio.
- PrecisionHawk: PrecisionHawk offers a platform for greenhouse growers that includes aerial imaging, machine learning algorithms, and predictive analytics. The platform provides growers with real-time data and insights to help optimize their operations and reduce energy usage.
- Arable Labs: Arable Labs provides a platform that integrates with various sensors and data sources to provide greenhouse growers with real-time data and insights into their operations. The platform includes tools for data visualization, predictive analytics, and decision-making support.
- Opti-Sci: Opti-Sci offers a platform that integrates with various sensors and data sources to provide greenhouse growers with real-time data and insights into their operations. The platform includes tools for data visualization, predictive analytics, decision-making support, and support for renewable energy systems.

These companies are generally focused on providing greenhouse growers with the data and insights they need to optimize their operations, reduce energy usage, and promote sustainable agriculture. By providing real-time data and predictive analytics, these companies aim to help greenhouse growers make more informed decisions and take more effective actions to achieve their goals.

In addition to these established players, many new and smaller startups are also entering the market, offering solutions associated with digital twin solutions for the greenhouse production process flow.

The key factors determining the competitiveness of digital twin solutions for greenhouse production process flow include the accuracy and reliability of the data, the ease of use and integration with existing systems, the level of customization and flexibility, and the availability of technical support.

The market for digital twin solutions for greenhouse production process flow is continuously evolving, and the competition is increasing, with more players offering similar solutions. Therefore, to remain competitive, a digital twin solution must provide robust and reliable data processing, be user-friendly and customizable, and offer technical support to ensure the system's smooth operation.

A digital twin of greenhouse production flow can help realize the Danish climate goals by providing greenhouse growers with the tools and information they need to reduce greenhouse gas emissions and promote sustainable agriculture. Denmark has set several climate goals, including reducing greenhouse gas emissions by 70% by 2030 compared to 1990 levels and achieving carbon neutrality by 2045. Some of the ways that a digital twin can contribute to Danish climate goals include:

- Energy efficiency: By utilizing data-driven methods and predictive analytics, a digital twin can help greenhouse growers identify inefficiencies in their energy usage and take corrective action, reducing energy consumption and emissions.
- Renewable energy: By integrating with renewable energy systems, such as solar panels or wind turbines, a digital twin can help greenhouse growers reduce their dependence on fossil fuels and transition to cleaner, more sustainable energy sources.
- Smart grids: By integrating with smart grid systems, a digital twin can help greenhouse growers participate in demand response programs, balancing energy supply and demand to improve the overall efficiency of the grid.

- Sustainable agriculture: By optimizing their operations and reducing energy usage, greenhouse growers can improve the sustainability of their operations and reduce their environmental footprint.

Overall, a digital twin of greenhouse production flow can help Denmark achieve its climate goals, including its target to reduce greenhouse gas emissions by 70% by 2030 and achieve carbon neutrality by 2045. The project aids the transition by providing greenhouse growers with the tools and information to reduce their energy usage and promote sustainable agriculture. A digital twin can help Denmark transition to a more sustainable, low-carbon future by promoting energy efficiency and renewable energy. Furthermore, with the Danish government agreement from 2022, companies will be taxed according to their carbon emissions starting from 2025. The digital twin for the greenhouse production process can also aid in identifying reduction potentials or optimization of the emission factors associated with electricity consumption.

The results from developing the digital twin for the greenhouse production process flow have been used in several dissemination and teaching activities. From a teaching perspective, the results have been used as a real-world application of data collection, cleaning, and analysis. The lessons learned, and applicability have been emphasized for students. Furthermore, the behaviour and production process flow has been used as an example of industrial energy consumption in relation to the underlying production process for which requirements and limitations must be addressed when considering industrial facilities for energy flexibility.

Besides teaching, other dissemination activities have been conducted on WP4. Relevant results and findings have been presented at conferences and meetings. Domain experts have attended conferences and meetings within various directly or indirectly related domains to the digital twin of the greenhouse production process. The meetings and conferences have aided the development of the digital twin through discussions and suggestions with field experts.

The following PhD has been part of WP4:

(Expected) Daniel Anthony Howard (2023). Developing a Generic Digital Twin Framework for Enhancing Energy Efficiency and Flexibility in Industrial Production Processes. [Ph.D. thesis, SDU]. Syddansk Universitet. Det Tekniske Fakultet.

6.4 Digital Energy system

The obtained technological results can be utilized by greenhouse growers to accelerate the digitalization of the greenhouse industry and implement digital twins for the greenhouse energy system, allowing data collection, system monitoring, and cost-optimal planning based on predicted greenhouse demand, weather, electricity, and district heating energy prices. The digital twin framework and multi-objective optimization for greenhouse energy systems will help growers to reduce energy costs for operations while ensuring favorable plant growth conditions (temperature, lighting, etc.) by meeting greenhouse heat and electricity demand.

Denmark committed to phasing out fossil fuels and reaching Net Zero Emissions (NZE) of CO2 by 2050. Enhancing energy efficiency for energy systems plays an important role in the green and sustainable transition. On the other hand, the energy-efficient operation of systems will benefit energy end-users economically as it cut down energy consumption, thus reducing energy bills.

WP5 has developed a digital twin for generic greenhouse energy systems and demonstrated the optimal scheduling of the generic greenhouse energy system in combination with the multi-objective optimization framework (Controleum). The optimization can recommend optimal operation schedules for greenhouse energy systems according to the defined objectives, e.g. reducing energy costs, and minimizing CO2 emissions.

It has therefore contributed to accelerating the green energy transition in greenhouse industry and Danish green energy goals.

The following PhD has been part of WP5:

1) Yang, T. (2022). Analysis and Application of Model Predictive Control in Energy Systems. [Ph.D. thesis, SDU]. Syddansk Universitet. Det Tekniske Fakultet. https://doi.org/10.21996/r826-bq49

In the Ph.D. research, the generic greenhouse energy models and a detailed emulation model tailored to a specific greenhouse grower are used for teaching activities for the master course "Data- and component-based energy system modeling". Apart from teaching, the results are also presented and disseminated through meeting, where in-depth discussions within greenhouse industry experts were involved.

6.5 Greenhouse Industry 4.0 Demonstation

InfoGrow 2.0 and Virtual Greenhouse are now owned by HortiAdvice and part of the services from HortiAdvice. After the project, HortiAdvice stated to sell license to InfoGrow in Denmark and abroad. When this report is been written (end May 2023) InfoGrow is installed in 7 nurseries and there are negotiations with several others. The first installation outside Denmark is also made in Finland.

The system has been extended with possibilities for using wireless sensors from Aranet (Smarter Horticulture - Aranet) in Letvia. With those sensors InfoGrow can also be used in Vertical Farming and Tunnel production (berries). HortiAdvice has partnered with Aranet in order to use their sensors in our InfoGrow software. This is demonstrated in our InfoGrow installation in Finland. Here Aranet sensors are usen in a tunnel production pf strawberry and Raspberry together with InfoGrow. InfoGrow is used to optimize the production and to obtain a sustainable production.

HortiAdvice has also started a cooperation with a Danish vertical farming technology provider (Viemose DGS, Viemose DGS (viemose-dgs.dk)) and a Italian greenhouse builder (Lucchini, Idromeccanica Lucchini | Perfect ecosystems for your growth (lucchiniidromeccanica.it)). Together we have offered a vertical farming setup in Japan. We expect to receive the order late this summer and start the construction this autumn. Together the three companies also participate in the US horticultural trade faire Cultivate 23 in Columbus Ohio in July 2023. HortiAdvice has great expectations to the cooperation.

HortiAdvice are partly owned by the world-leading Dutch horticultural advisory company Delphy (Home (EN) - Delphy). This connection will be used to spread the knowledge of the system and specially to test the system in a Dutch greenhouse production. The Netherlands is world leader of the horticultural industry, and it is therefore important to test the software at that marked.

We expect that more than 15 nurseries will use InfoGrow before the end of 2023 and about the double the year after. First year will mainly be in Denmark but later we will focus on the export marked.

Several IT-systems exist with the aim of supporting growers in there in production. Most of the systems have another focus than InfoGrow, but many have some of the features also found in InfoGrow. InfoGrow is from the beginning developed for greenhouse production of pot plant but is now also in test for production of greenhouse vegetable (lettuce, cucumber, and tomato). Most of the competing software is developed for vegetable production. On example for a competing software is the Pylot system (PYLOT & Tomatoes -). Pylot has a strong focus on registration of what happens in the production. Many of the same features we have in InfoGrow Log. Pylot does not have any focus on energy which is the main focus of InfoGrow. Another competing software is Letsgrow (LetsGrow.com - Worldwide experts in Data Driven Growing). Letsgrow is also developed with focus on vegetable production. There are several competing software systems, but InfoGrow is the only one with a strong focus on optimizing the use of energy. We therefore see great possibilities for InfoGrow in the future.

Project conclusion and perspective

6.6 Common information model

WP2 developed a Common Information Model and OPC-UA server with a user interface for the greenhouse industry. The developed Common Information Model and OPC-UA server with a user interface have been applied and tested in other WPs and have proven to be able to support data exchange between greenhouse equipment and software used in production, cost-effectively integrate IoT-based sensors and existing greenhouse climate computers with the Digital Twin software platform, and support information exchange between digital twins with bi-directional data flow and enable data sharing between the twins. These technological results obtained from WP2 can benefit greenhouse technology providers, digital twin solution providers, and growers, enabling efficient and effective data exchange, reducing complexity and cost, and providing better management and optimization of greenhouse production.

6.7 Digital twin Greenhouse climate

In conclusion, a Digital Twin of the Greenhouse Climate Control framework is designed to establish a virtual greenhouse and optimize the operation schedules of artificial light and heating systems. The framework is validated and verified by experiments following multiple scenarios based on case studies. The experimental results indicate that the developed Digital Twin can achieve all the designed objectives in order to minimize the energy cost without compromising the growing quality.

Next steps for the developed technology: The historical data collected from Bygrowers A/S for training the models in VGH are comprised of two periods, which are divided by 2020-04-03. The collection strategies and resolutions of these two periods are quite different, which probably influences the quality of the training and test datasets so which introduces inaccuracy into modeling. In future work, more historical with consistent characteristics can be collected for establishing datasets to improve the prediction performance of models.

Regarding the optimization of compartment heating, it is based on the prediction results of the heating consumption model. However, Bygrowers A/S does not collect the heating-related data, so the heating data from Knud Jepsen A/S are utilized for establishing the model. Although the two companies apply similar heating strategies, there are probably some differences between them that can impact the accuracy of the model in practical application. Therefore, sensors can be installed in Bygrowers A/S to collect heating-related data, so the heating consumption models can be trained using the new data to enhance the practical performance of the model.

With regard to the modeling methods, although the proposed ANN methods can provide high performance on the case studies, there are probably new methods or some other ANN methods that are also with potential characteristics for this research background. These methods can be tested and comparing the results with the proposed methods in this research to select better models.

Concerning the artificial lighting optimization for the greenhouse compartments with multiple lighting systems, the asynchronous optimization of individual systems can be considered in DynaLight in future work. This can make the optimization of the energy efficiency more accurate to ensure sufficient light supplement for growing but without over-lighting in some hours.

How the project results may influence future development: The designed Digital Twin framework and the Digital Twin architecture can be applied for future Digital Twin development. The hierarchy and modulization structure can benefit the research management by dividing the system into multiple sub-sections and isolating technical issues in a specific layer rather than influencing other layers.

Concerning the modeling results in the virtual greenhouse, the proposed time-series ANN methods present better performance than traditional static modeling methods on the prediction of indoor temperature and heating consumption. These results can give recommendations on method choosing for related factor modeling in future similar projects, so that time-series methods have a higher priority for such climate elements and energy consumption parameters.

Regarding the optimization results for actuator operation schedules, the optimization results using Genetic Algorithm can provide converged Pareto Frontiers, and the final solution selected using the Relative Importance Graph and Social Welfare can satisfy the operation logic and strategies. This optimization procedure has been applied successfully on the artificial lighting and heating schedules, and it can be utilized for other control objects in the future.

6.8 Digital twin Production flow

The development of the digital twin for the greenhouse production process flow has the potential to bring significant benefits to the horticulture sector. Providing a virtual representation of the greenhouse environment can help growers better understand and optimize their production processes, improve energy efficiency, and reduce carbon emissions. The digital twin can also help support research and development in the horticulture sector, encouraging innovation and collaboration between growers, researchers, and other stakeholders.

It is essential to consider the challenges and risks associated with developing and demonstrating a digital twin, including data collection and management, data accuracy, and that the solution can be customized to ensure usefulness to growers with various setups. Despite these challenges, the benefits of a digital twin are evident.

The developed generic multi-agent simulation model was verified and validated using the case studies from the participating growers. It was found that the generic multi-agent simulation model could represent the production process flow at various facilities. Furthermore, the underlying methodology for establishing plant development functions for use in the digital twin was successfully showcased across various cultivars from different growers providing a structured approach for identifying required data and building the development function. The internal communication within the digital twin for the greenhouse production process was developed using an observer pattern. This pattern allows for the further decomposition of individual parts, which enables the exchange of an alternative model or digital twin of a plant or process component with the current implementation if needed.

In the future, the use of digital twins in the greenhouse production process will likely become increasingly common, aiding growers in sustainably producing plants. The proposed technology presented in this project presents a novel addition to realizing the impact that digital twin technology will have on the horticulture sector in the future.

Next steps for the developed technology: The developed multi-agent simulation model for the greenhouse production process flow currently considers a single batch of plants when examining the impact of production process decisions on the process flow. However, for future development, the simulation must consider the development of all plants across production since they are stored in compartments exposed to similar climate conditions. Therefore, optimizing one batch may influence the completion of another batch, making the decision horizon non-trivial. A robust methodology has been developed for obtaining plant development functions for Kalanchoe Blossfeldiana cultivars across different growers, but there is a need to improve the input and output of the model.

In addition, future development may explore the potential for including carbon capture systems in greenhouse facilities to increase their sustainability. Currently, greenhouse facilities combust natural gas to raise CO2 levels inside the greenhouse, but a carbon capture system can be installed to examine its impact on production using the digital twin for the greenhouse production process.

Finally, an edge-based or cloud-based deployment of the solution at the grower facility would be beneficial for long-term usage and inclusion in the facility's daily operation. By incorporating these technologies, the digital twin for the greenhouse production process will become more sophisticated and provide a more comprehensive view of the greenhouse production process, leading to improved energy efficiency, cost reduction, and growth of the renewable energy industry. This will also enable stakeholders to make informed decisions and better understand the interplay between energy consumption, plant growth, and environmental conditions.

Perspective how the project results may influence future development: The WP4 also reveals the importance of a data management plan to ease the project's development and ensure that the needed data is available. A data management plan would aid in ensuring that the data collected and used by the digital twin is accurate, complete, and consistent. Furthermore, it would ensure proper handling, integration, and retention of the data. A detailed metadata description should accompany the data management plan to ensure a shared understanding of the collected data points. A preliminary data management plan could also potentially reveal any missing data points for additional sensors.

Furthermore, it was evident that even though a digital twin may operate automatically and perform direct actions within the system, it was beneficial to design the digital twin as a recommender system instead. Essentially the system requires a human-in-the-loop that can critically appraise the results and output from the digital twin and use it as a tool for further decision-making. The growers remain in complete control of their production process but can choose to implement the recommendations outputted from the digital twin. It is expected that digital twins in the industry may largely become recommendation systems in the short term until the technology has matured and proven its robustness over time.

6.9 Digital twin energy system

Conclusions made in the project: With respect to the overall objective and the specific research tasks, the WP5 has:

- Developed generic control models for greenhouse energy systems.
- Developed a generic emulator for greenhouse energy systems complying with typical energy system schematics in greenhouse industry.
- Developed a detailed emulator tailored to a specific grower (Kund Jepsen), the emulator model was partially validated against measured data. Suggestions for attaining a high-fidelity emulator are recommended.
- Developed and demonstrated the optimal scheduling of the generic greenhouse energy system in combination with the multi-objective optimization framework (Controleum).
- Disseminated project results through various forms of activities including bi-annual project meetings, monthly WP coordination meetings, and master teaching activities.

At the time of writing this final report, all the tasks and milestones defined in WP5 have been completed. Over the project period (2019-2022), plenty of deliverables have been achieved consisting of several publications, a Modelica-based library for greenhouse energy systems, multi-objective optimization development, etc. It can be concluded that WP5 has advanced the knowledge of applying digital twins for greenhouse energy systems to enhance energy efficiency and reduce operating costs in greenhouse industry. The objective of WP5 is therefore considered to be accomplished.

Next steps for the developed technology: For modeling the generic control models and generic emulation model, current Modelica-based library consists of combined heat and power plan, heat pump, gas boiler, and thermal energy storage (water tanks). Through these are typical energy systems in greenhouse industry, potential energy system models including solar collectors, PV, and aquifer thermal storage can be developed to enrich the diversity of the library, which will extend the applicability of the developed energy system library in various greenhouse facilities.

For validation of the detailed emulator tailored to energy systems at Knud Jepsen, future works center around data acquisition in relation to the water temperature and mass flow rate at critical locations. The insufficient accuracy of the current tailored emulator has emphasized the importance of data on model fidelity.

In addition, the assumptions made for the tailored emulator should be verified with access to more data and information. The water-based thermal storage tank in this emulator was modeled as a five-layer stratified water tank, where 25 layers are monitored in reality. Choosing a proper number of layers for the TES models can potentially lead to the accuracy improvement of the emulator. The returning water temperature from greenhouse compartments is assumed to be the same as the bottom layer water temperature of the TES. However, the grower has three main greenhouse compartments, and each of them has an individual returning water branch with a specific temperature and mass flow rate.

For the digital twin test and demonstration of multi-objective optimization, the generic energy system digital twin has been tested in relation to the Knud Jepsen horticulture. Future work is to extend and tailor the digital twin to other involved growers in this project ranging from data collection, control, and emulation model development and validation, and demonstration of utilizing digital twin for cost-optimal scheduling of energy systems.

How the project results may influence future development: This project developed a digital twin for generic greenhouse energy systems used for cost-optimal optimization and decision-making for greenhouse energy system operating schedules. The project results demonstrated the benefits of applying the digital twin approach in the energy-intensive industry sector in terms of reducing energy costs considering dynamic energy prices. This has verified the benefits of the digital twin in greenhouse industry and serves as a convincing case study that aids in accelerating digitalization in energy sector and motivating stakeholders to implement digital twin for their energy systems.

The energy systems developed in this project are modular, parametrizable, and reusable. This is achieved using Modelica modeling approach, allowing the extendability of the developed models and ease of model adjustment and model integration in optimization algorithms through the Functional Mock-up Interface. The results achieved in this project will attract potential model developers and boost the use of Modelica modeling communities for energy systems.

The Genetic Algorithm (GA)- based optimization framework (Controleum) enables multi-objective optimization for the energy systems in this digital twin. This framework allows users to customize and prioritize different objectives according to scenario-based requirements. This optimization framework is transferable to different industry sectors.

6.10 Greenhouse Industry 4.0 Demonstration

Conclusions made in the project: InfoGrow has been developed and tested in several nurseries during the project. At the beginning of the project, we had a specific focus on optimizing the use of energy, but we realized very fast that we needed a more holistic focus on greenhouse production. Energy is important, but optimal plant production is curial. Both with respect to production time, size, and quality. We, therefore, decided to improve InfoGrow with the log system to register plant development and use of resources and with a batch system to control plant development. The combination of energy management, registration, and bath control has been found to meet the demands of many growers.

As the energy prices increased dramatically due to the war in Ukraine, we also developed a system for controlling the use of artificial light depending on the light sum. This was not planned initially, but the development was possible as HortiAdvice's budget increased after one of our budget changes.

Next steps for the developed technology: The Danish greenhouse industry is too small to pay for the future development of InfoGrow and Virtual Greenhouse. There will, therefore, in the future be a focus on the international market. We will therefore integrate with other climate computer brands and also adapt the software to requirements from other countries (electricity prices etc.). When writing this report, this is in process, and we hope to have many more installations abroad in the future.

To extend the market, we will also focus on the use of the system in tunnel production and greenhouse production of vegetables. This is also started but needs to be extended with better production models for tomatoes and cucumbers.

DGT App will be further developed, and the possibilities for making an easier installation of InfoGrow when using the Consibo Cloud will be examined.

7. Appendices

7.1 Phd Research from the project

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- GreenTech 2022, 13-17 June 2022, Amsterdam, The Netherlands
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