AGROS: Towards an autonomous greenhouse

Final report of the AGROS project

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Referaat
In de afgelopen tien jaar zijn glastuinbouwbedrijven steeds groter geworden en werd de bedrijfsvoering steeds complexer: telers moeten rekening houden met productie, leveringscontracten, kwaliteit, energiegebruik, gewasgezondheid en water en nutriënten. Daarbij is het ook nog eens lastig om voldoende geschoolde arbeidskrachten te vinden die alle complexe processen in een kas kunnen overzien. Dat betekent dat het wenselijk is de beslissingen die moeten worden genomen in de teelt op gebied van klimaatregeling, gebruik of levering van energie en gewasbeschermingsmaatregelen te ondersteunen met slimme regelingen op basis van data. In het AGROS project is door de business unit Glastuinbouw van Wageningen University & Research samen met bedrijven succesvol gewerkt aan de ontwikkeling van een autonome kas, waarin kasklimaat, irrigatie en teelthandelingen aangestuurd worden door intelligente algoritmes op basis van continue, geautomatiseerde sensor informatie.

Abstract
Over the past ten years, greenhouse horticulture companies have grown increasingly larger, and their operations have become more complex: growers need to take into account production, supply contracts, quality, energy use, crop health, and water and nutrients. Moreover, it is also challenging to find enough skilled workers who can oversee all the complex processes in a greenhouse. This means that it is desirable to support decisions in their cultivation regarding climate control, energy use or supply, and crop protection measures with intelligent systems based on data. In the AGROS project, the business unit Greenhouse Horticulture of Wageningen University & Research, together with companies, have worked successfully on developing an autonomous greenhouse, in which greenhouse climate, irrigation, and crop management are controlled by intelligent algorithms based on continuous, automated sensor information.

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Summary

Current greenhouse horticulture is facing a number of challenges. Companies are growing larger, supplier contracts get more complicated, energy prices have risen sharply, and finding qualified workers is a constant concern. For an individual grower, it is almost impossible to oversee all these processes. Thus, there is a need for systems that can support growers in their decision making. In the AGROS project, Wageningen University & Research collaborated with the private sector to develop intelligent algorithms that allow cultivation to be controlled remotely via artificial intelligence, based on measurements of crop properties with the help of intelligent sensors to achieve a sustainable and profitable cultivation system.

In the first years of the AGROS project, building blocks for an autonomously controlled cultivation in cucumber were generated: plant traits essential in decision-making, the sensors to determine these traits, a Digital Twin and a trained artificial intelligence algorithm based on Reinforcement Learning. The building blocks were assembled, and the results were demonstrated in a successful validation trial, in which three cucumber crops were grown, controlled by a group of crop and irrigation experts, the Digital Twin, and the Reinforcement Learning algorithm. The Digital Twin made explicit use of variations in electricity prices, resulting in the lowest price per kWh electricity used. The Reinforcement Learning algorithm successfully controlled the climate autonomously, resulting in a healthy, well producing cucumber crop. In the crop controlled by the cultivation experts, the number of fruits harvested very closely matched the production predicted in the cultivation plan. Investing in the crop, proved to be a favourable strategy, since the net profit in the cultivation experts' compartment was the highest one. PAR line sensors and weighting gutters could be used as proxy for light absorption respectively water uptake of the crop. The cameras used to determine leaf initiation rate showed good functionality for detecting and tracking leaves, but data might be improved by measuring a larger crop area. Vision technology could also be used to determine fruit growth duration and predict yield, which could also be applied in hand-held sensors.

To reduce emission of nutrients in soil-grown crops, chrysanthemum crops were grown in containers under two irrigation strategies, where plant and substrate sensors monitored plant weight, plant temperature and drain. Sensors for soil moisture proved to be very effective in controlling (reduced) irrigation strategies, preventing drain in the "low irrigation" strategy. Transpiration, determined by a soft sensor corresponded well with water uptake and plant weight. Treatments did not affect stem length and weight of chrysanthemum shoots, indicating that crop control based on sensors is feasible, allowing the next steps towards autonomous cultivation.

1 Introduction

1.1 Problem statement

Greenhouse horticulture plays an important role in the year-round production of fresh and healthy products with a continuous, high product quality. Worldwide, the area of protected cultivation is increasing. The production of vegetables in greenhouses must be efficient in the use of natural resources, economically viable, and produce a high quality product. This can be achieved very well in protected cultivation. However, the limiting factor is becoming the availability of sufficient highly qualified staff with knowledge of cultivation of a high-quality product and who can oversee all aspects of an efficient production system with minimal use of resources. Therefore the step to more automation in cultivation is required. In the AGROS project, we aimed to work on the realization of the 'autonomous greenhouse' in which cultivation is controlled remotely via artificial intelligence, based on measurements of crop properties with the help of intelligent sensors and in which crop handling is supported or realized through automatic systems in order to achieve a sustainable and profitable cultivation system.

Modern high-tech greenhouses are equipped with active control of actuators (for example heating, lighting, fertigation) to create the desired greenhouse climate for the crop. These intensive cultivation systems require a high use of natural resources such as energy, water and nutrients. Current practice is that growers determine the set points for their greenhouse climate based on the crop status and their experience on how crop growth is affected by the climate. Actuators are operated based on these set points and sensors provide information on the realized climate to control the greenhouse. Automated greenhouse climate control algorithms were developed decades ago. Nowadays, advanced crop growth models are also used to generate advise on the climate set-points. The aim of this project is to further integrate climate and crop growth models and to link them to the sensors and actuators of the greenhouse, and thus to steer the greenhouse climate based on self-learning algorithms that receive their information from crop and climate sensors. This requires further knowledge about the reactions of the crop to changing environmental conditions.

1.2 AGROS: Towards an autonomous greenhouse

In the AGROS project, the business unit Greenhouse Horticulture of Wageningen University & Research worked on the first steps towards an autonomous greenhouse in cooperation with Topsector Horticulture and Starting Materials and the private companies 2Grow, BASF Vegetable Seeds, Delphy, Engy, Gennovation, Greenport West-Holland, Hortilux, IMEC/ One Planet, Mechatronix, Philips, Ridder, Roullier, Saint-Gobain Cultilene, Signify, Stichting Kennis in je Kas and Van der Hoeven.

Project activities were organised in three work packages:

WP 1. Understanding crop physiology in response to changing environmental conditions
In greenhouse cultivation, intelligence is used by growers to determine how climate conditions should be altered to generate the desired crop status, and thereby to realise the cultivation goals. In this project, we aim to develop artificial intelligence algorithms that can optimise based on goal functions (e.g. a continuous level of production over time). In order to do so, it is important to know which plant traits are relevant and should be measured, and how these plant traits are affected by changes in the greenhouse climate. In this work package, the crop response to changes in environment was investigated and these effect were incorporated into the crop models. The control algorithms developed in WP3 was then validated in a greenhouse trial, where cucumber crops were controlled by a Digital Twin, AI algorithm and expert growers.

WP 2. Translation of data from sensors to crop parameters and crop responses
In this work package, plant characteristics were measured by sensors using optical and imaging techniques, so that the plant itself can act as a sensor of its own biological status and its environment. The translation of these raw sensor data into biologically relevant plant characteristics is complex and required the help of artificial intelligence algorithms. These algorithms are self-learning, so that when more data becomes available, the performance of these models will improve. Artificial intelligence algorithms that link sensor data to plant physiology were developed for cucumber and chrysanthemum. For both crops, greenhouse experiments were conducted, and both sensor data and manual scores were measured. Results were ultimately validated on this data.

WP 3. Autonomous greenhouse control through (climate-plant) sensor-driven-intelligent algorithms
The greenhouse control aims to provide optimal climate conditions for plant growth and development while raising resource use efficiency. In modern high-tech greenhouses it is growers' task to define the climate, irrigation and crop management strategies. This is done with the aid of a climate process computer, sensor information, long-term accumulated experience and intuition. However, the greenhouse systems present a high-degree of complex and interactive processes of physical, chemical and biological nature which makes it challenging for human intelligence to control. Even if that was possible, the greenhouse industries have to deal worldwide with a lack of sufficiently qualified personnel with knowledge on growing high-quality products and able to oversee all aspects of efficient production with minimum use of resources. Different model-based algorithms have been developed decades ago aiming at a more efficient and autonomous climate control. More recently, with the evolution of computer science and sensor technology, Artificial Intelligence (AI) has undergone comprehensive development and reached breakthrough in several fields (healthcare, finance, media and e-commerce etc.). This work package focused on the development of intelligent algorithms for autonomous control of the greenhouse climate, irrigation and advice on crop management under a pre-defined goal function.

1.3 Reading guide

The knowledge that was developed in the work packages of the AGROS project was integrated in two validation trials for the two model crops, i.e. cucumber and chrysanthemum. In chapter 2, the control algorithms, vision technology, experimental set-up and results of the validation trial of cucumber are summarized. In chapter 3, the results of the chrysanthemum cultivation strategy are presented. In chapter 4, the results of the AGROS project are summarized and discussed, and chapter 5 gives an overview of communication activities.

2 Validation trial cucumber

2.1 Introduction and goals

The increasing complexity of horticultural production system necessitates the step to a more data-driven approach. In AGROS, we aimed to realize an 'autonomous greenhouse' in which cultivation is controlled remotely by intelligent algorithms, based on data from non-invasive crop, climate and substrate sensors. In the first two years of the project, the building blocks for autonomously controlled cultivation of cucumber were constructed. The plant traits essential in decision-making for crop management and climate control were determined, as well as the sensors to measure these traits. To control the greenhouse autonomously, algorithms based on two approaches were developed: a mechanistic model-based digital twin, and a trained Reinforcement Learning algorithm. In the third year of AGROS, these approaches were applied in a greenhouse trial to evaluate their performance, together with the control by a group of cultivation experts, based on a cultivation and irrigation plan.

The goals of the cucumber trial were:

- To gain experience with managing a cucumber production system using two autonomous control approaches (i.e., mechanistic model forecasts and reinforcement learning), and to compare them with one approach based on expert knowledge.
- To gain experience with sensors and imaging technology which provide automated data flows.
- Evaluate, learn and document the lessons learned to identify future steps to improve autonomous greenhouse control.

To establish a clear basis for evaluating the two autonomously controlled compartments and compare them with the human-operated reference, the results of a four-month cucumber crop were assessed using a net profit calculation. Of course, the real costs of running an experiment in a small research compartment are not comparable to costs of commercial enterprises, but the resource use of the three compartments is realistic. In the trial, net profit was defined as the difference between the economic value of the harvested product and the costs for heating, lighting (electricity) and CO_2-dosing. For the sake of better interpretability of results, all cost and revenue components are kept constant in time.

This validation trial was not a competition between controls, but a learning experience, where the entire consortium could learn from the observations and results in the three compartments, to gain experience towards autonomous cultivation. During the validation trial, AGROS partners were updated weekly on the crop status, climate, production and realized net profit.

2.2 Cucumber trial: set-up

A high-wire cucumber crop (cv. Hi-Power) was grown in three identical 96 m^2 greenhouse compartments of in the research facilities of the business unit Greenhouse Horticulture of Wageningen University & Research in Bleiswijk, The Netherlands (Figure 2.1). The trial started with planting on 11 January 2023 and the final fruit harvest was done on 11 May 2023. Each compartment contained standard high-tech greenhouse equipment's, including heating, ventilation, movable screens, LED lighting, fogging, and CO_2 supply systems. The crop was grown at a density of 2.3 plants m^{-2} on rockwool substrate in an effective cultivation area of 77 m^2.

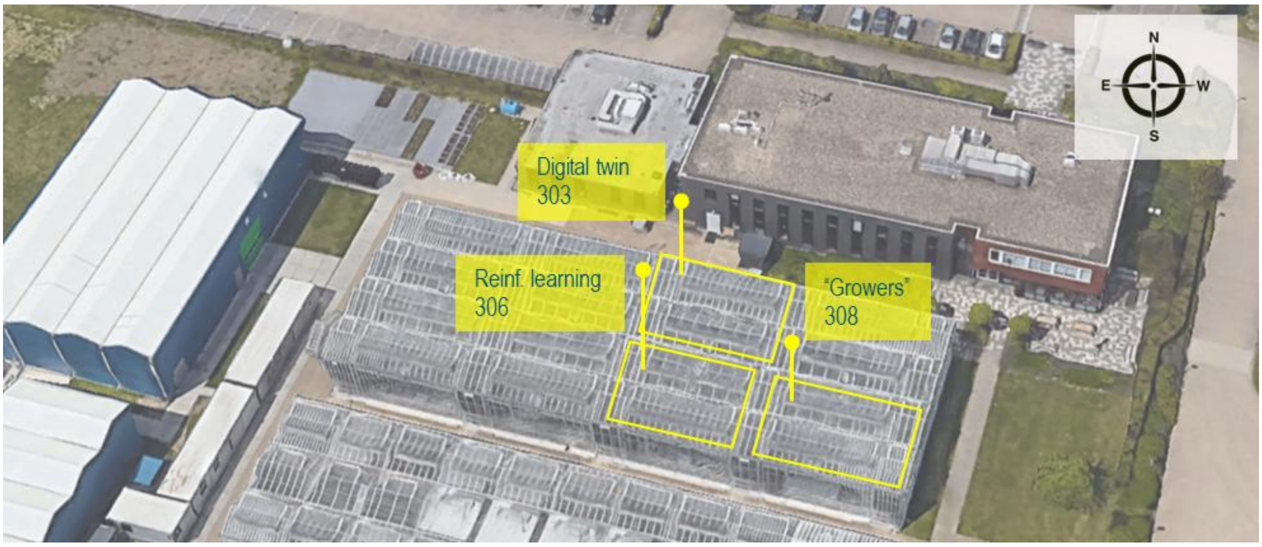

Figure 2.1 *Satellite image of the greenhouse compartments of the cucumber trial 2023. Source: Google earth.*

In all compartments, sensors and cameras were installed (Figure 2.2), data flows and processing were automated, and manually taken data were digitized. LetsGrow services were used for greenhouse control. In addition, a number of plant traits were measured weekly to determine the growth and development rates of per compartment.

Figure 2.2 *Each compartment was equipped with: climate measuring boxes for measuring temperature, relative humidity and CO_2 concentration (a); PAR sensors (b); sap flow and stem diameter sensor (c); camera's for vision technology (d); weighing gutters for measuring crop transpirations and fresh weight growth of the crop (e); slab sensors to measure EC, volumetric water content and temperature of the root-zone environment (f).*

One goal of AGROS was to develop and test sensors that can measure crop characteristics to keep crop models aligned with reality. Two key traits, leaf initiation rate and cucumber fruit growth, were expected to be measurable automatically with computer vision. Leaf initiation rate determines potential leaf and fruit number (needed for the fruit pruning strategy), while fruit weight and growth rate influence harvest potential and strategy. Thus, part of the project focuses on continuously estimating leaf initiation rate and cucumber growth using cameras and computer vision (Figure 2.2, d).

Pest and disease management was preventive and biological, as far as possible, and not part of the comparison. The nutrient composition of the irrigation was predetermined and adjusted if necessary based on advice of the group of cultivation and irrigation experts controlling the reference compartment.

Each of the three compartments was managed independently with respect to climate, irrigation, and crop management. One compartment was operated by a team of experienced greenhouse growers, representing the current state-of-the-art (Dutch) practice. In the other two compartments, the AGROS project explored the potential of data-driven control by using available models to develop two intelligent algorithms, referred to as "Digital Twin" and "Reinforcement Learning."

2.3 Description of the 3 control approaches

2.3.1 Control by cultivation experts ("reference")

One compartment was managed by a member of the WUR greenhouse staff, following the guidance of a group of cultivation experts (the "supervision group") and with the aim of realizing a balanced crop growth and production. Before the trial began, this group prepared a cultivation plan and an irrigation plan for the reference compartment, reflecting commercial best practices in cucumber production. The supervision group consisted of specialists from the project partners, including a crop physiologist, a cultivation expert, and an irrigation expert.

Decisions regarding setpoints and crop instructions were taken by the growers, utilizing:
- Actual weather data and weather forecasts.
- Manually taken crop observations.
- Cultivation and irrigation plan based on experience.

2.3.2 Control by Digital Twin

In the AGROS project, the Digital Twin (DT) is a virtual version of the greenhouse and cucumber crop that closely reflects how the real system behaves. It combines a greenhouse climate model (Kaspro, WUR) with a crop growth model for cucumber (Intkam, WUR) to simulate the key processes that drive cultivation. Because the DT is grounded in transparent, process-based models, it can simulate how the greenhouse and crop will respond to different climate and irrigation strategies. This enables the system to evaluate multiple scenarios and select the action that best meets a predefined cultivation target.

Decisions regarding setpoints and crop instructions were determined by the digital twin, utilizing:
- Actual weather data and weather forecasts.
- Manually taken crop observations, translated to node formation rate and Light Use Efficiency.
- Greenhouse climate sensors as a feed-back signal to adjust the daily re-evaluated temperature and irrigation strategy.

2.3.3 Control by Reinforcement Learning

The last approach examined in the AGROS project uses machine learning to develop a controller that learns to operate the greenhouse through repeated interactions within a simulated environment. This method, known as Reinforcement Learning (RL), teaches an artificial "agent" to make decisions that steer the greenhouse toward a predefined goal. During a training phase, the agent explores different action (such as adjusting climate settings), receives feedback on whether these actions move the system closer to the goal, and gradually learns which decisions work best. Because this learning process requires millions of attempts, it is carried out entirely in simulation rather than in a real greenhouse.

Once trained, the RL controller can independently translate the current situation (for example, indoor climate conditions or outside weather) into an action. Unlike the Digital Twin approach, the RL controller operates as a "black box", meaning its internal reasoning is not transparent. However, this flexibility allows it to develop complex control strategies with minimal human input and to adapt effectively to uncertainty in the environment.

Decision regarding setpoints were determined by the reinforcement learning algorithm, utilizing:
- Actual weather data and weather forecasts.
- Greenhouse climate sensors as a feed-back signal to adjust the setpoints.

2.4 Results

2.4.1 Crop performance

In all three compartments, cucumber fruits developed and were harvested from February 8 onwards. Total fresh fruit production was highest in the Reference compartment, both in number and in total fresh weight (Figure 2.3). Average fruit weights were comparable between treatments, with an average fruit weight of all harvested fruits of 400-401 g $fruit^{-1}$. During the course of the validation trial all approaches resulted into an average fruit growth period of 14 days, although the Reinforcement Learning and the Digital Twin had a higher fruit growth duration at the start of the trial than at the end. The fruit growth duration in the Reference/growers compartment was relatively stable.

Light Use Efficiency (LUE) was calculated as the ratio of cumulative production (kg m^{-2}) to the total light sum (mol m^{-2}). The Digital Twin achieved an LUE of 20.1 g mol^{-1}, the Reinforcement Learning approach 22.2 g mol^{-1}, and the reference compartment 24.5 g mol^{-1}. These differences indicate that the control strategy may influence LUE, potentially due to variations in climate conditions or differences in fruit load resulting from the pruning strategies used.

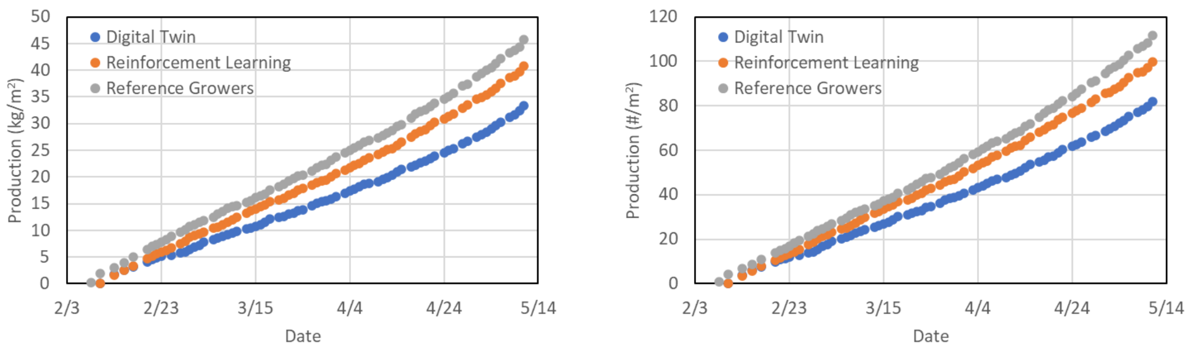

Figure 2.3 *Pattern of total cucumber production (left) in kg per m^2 and number per m^2 (right).*

2.4.2 Control approaches

The operational controls that were determined by the three control systems are summarized in Table 1.

Table 1 *Summary of the operation controls of climate and crop management strategies by the "growers", the Digital Twin and the Reinforcement Learning.*

Climate/crop control	Growers	Digital twin	Reinforcement Learning
Heating temperature setpoint	✓	✓	✓
Lighting (on/off, dimming)	✓	✓	✓
CO2 setpoint	✓	✓	✓
Screen setpoints (energy and blackout	✓	✓	✓
Irrigation strategy	✓	✓	x
Fruit pruning strategy	✓	✓	x
Leaf picking in the top of the canopy	✓	x	x
Alternative strategies to reach setpoints (change of heating system, use of fogging system)	✓	x	x

Growers

The basis of the strategy was the crop's demand for assimilates, provided by sun light, additional lighting, the temperature and CO_2 supply strategy. The irrigation strategy resulted in a strong growing crop at the beginning of the cultivation. When the first flowers appeared, the fruit pruning strategy was determined based on the number of newly formed leaves and the expected light availability in the weeks ahead. The concept of the control of the experts was to grow a vigorous crop, with the assumption that its production would compensate for the costs of electricity, heat and CO_2 (which turned out to be the case) (Figure 2.4).

The compartment managed by the cultivation experts performed very well. The cultivation plan predicted a production of 94 cucumbers per m², while the actual yield reached 119.5 cucumbers per m² (Figure 2.3). This higher production was mainly due to keeping more fruits on the plant during the final 5–6 weeks to maintain good plant balance. Of the harvested fruits, 94% were class A, 3% class B, and 3% class C. The class C fruits were picked on the final harvest day, indicating that fruit pruning after topping could have been more cautious; retaining all flowering fruits 10 days before the final harvest was slightly late, and doing so 11–12 days earlier likely would have prevented class C fruits.

Climate realization closely followed the intended targets. Early in the crop cycle, fruit should have been harvested more frequently (ideally daily rather than three times per week) to avoid overly heavy fruits. Fine-tuning of climate and crop management took place every 14 days, which was appropriate except during the first six weeks, a crucial period for plant development and initial fruit set when growers must respond more actively to changes in plant balance.

Digital twin

The Digital Twin algorithm ran from the very first day of the experiment until the end of the evaluation trial. In a close-to-real virtual environment (based on climate and crop models), the Digital Twin determined the ideal control strategy based on the responses of the simulated climate and virtual cucumber crop. It used real-time data from climate sensors and manual crop measurements to self-calibrate and refine its control strategy during the trial. The Digital Twin applied an objective control approach, balancing actual costs against expected benefits: the cucumbers projected to be harvested in the following two weeks. With this strategy, the DT achieved the lowest expenditure on electricity, heat, and CO_2 per m² of greenhouse. The reduced production due to the lower amounts of inputs was taken into account, but because the Light Use Efficiency of the crop was lower than in the other compartments (20.1 g mol^{-1}), the profit was also less than in the other compartments (Figure 2.4).

Reinforcement learning

In the third greenhouse compartment, the climate was controlled by a Reinforcement Learning (RL) algorithm that was trained on virtual data sets of cucumber crops and climate. The model could control actuators like lighting, screen use, CO_2 concentration and heating, but was not trained to control irrigation and fruit pruning (Table 1). Control in the first three weeks of cultivation was copied from the "growers" compartment. After the first fruits were set, the RL took over control. This "black box" model resulted in a greenhouse climate that differed considerably from the other two compartments. However, the crop proved to be able to integrate the larger fluctuations in temperature well, resulting in a good fruit production (Figure 2.3), which was even limited by a pre-set fruit pruning strategy.

During the trial, the Reinforcement Learning approach was able to grow cucumbers with a Light Use Efficiency of 22 gram mol^{-1}, which was lower compared to the Reference/Growers compartment. However, observations of the model were limited to only weather observation and realized climate reading with no feedback on the crop itself. The absence of crop feedback in the model's observation space is a major limitation of the approach. Next to that, more research in incorporating long-term effects in either the reward function or profit maximization of the digital twin approach are required.

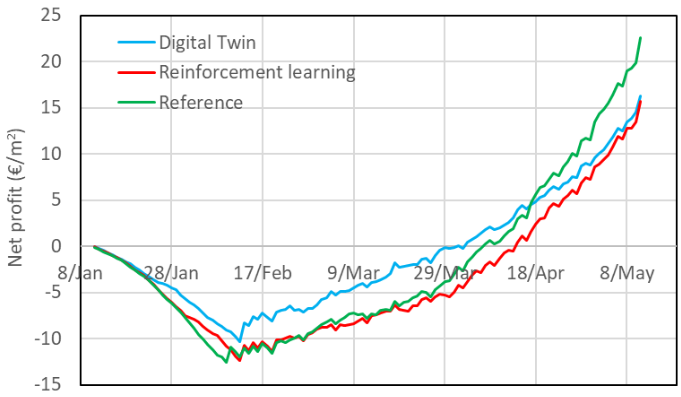

Figure 2.4 *Course of net profit during the validation trial for the three control treatments applied.*

2.4.3 Sensors

In the validation trial, a number of commercially available sensors were installed.

- PAR line sensors could be used as a proxy for the fraction of incident light that is absorbed by the crop automatically and continuously, thereby replacing the labour intensive measurements of canopy leaf area.
- A weighting gutter provides a reliable measurement of crop water uptake, which could be used as a proxy for transpiration. An alternative might be measurements with sap flow sensors, which might be used to control and evaluate the irrigation strategy. Furthermore, weighing gutters provide data on the increase in fresh weight of the crop, which might provide an accurate estimate of crop yield.
- For traits that cannot be measured with commercially available sensors, computer vision technology was developed. The system for leaf initiation rate showed good functionality for detecting and tracking leaves, but data might be improved by measuring a larger crop area. Vision technology could also be used to determine fruit growth duration and predict yield, which could also be applied in hand-held sensors.

Ideally, all controls should have been based on climate and crop sensors providing continuous, automated, objective data. However, in the validation trial, inputs for crop management were still based on manual measurements to ensure that crop management decisions would not be hampered by system failures. Also the feedback on drain percentage was inserted into the control loop with human intervention for this reason.

The next step in the development of autonomous greenhouse control is to incorporate also sensors for crop traits and a robust observation of drain measurement or slab moisture sensors in the control loop. This would require robust sensors, supported by soft sensor-based solutions checking the validity of the sensor readings.

Please note that a more detailed technical report (Validation trial AGROS 2023, Dieleman et al., 2023) has been published and is available upon request.

3 Effect of irrigation strategies on chrysanthemum

3.1 Introduction and goals

Chrysanthemum is the largest soil-grown greenhouse crop in the Netherlands, but rising energy costs for soil steaming and stricter EU water-quality regulations are driving interest in chrysanthemum cultivation outside the soil. This can be water cultures, but also cultivation in boxes with soil mixtures, where irrigation can be controlled precisely based on the crop's demand. Another advantage of this system is automation, since the boxes can be transported to a harvesting area, which would facilitate autonomous cultivation.

For chrysanthemum, stem length and shoot weight are important quality traits, that largely determine price of the product. To understand how these traits are influenced by climate and management is essential for autonomous cultivation. Within the AGROS project, cucumber and chrysanthemum are the model crops. In autumn 2023, a chrysanthemum experiment was carried out to study the crop's water balance using container-based cultivation.

The goals of the trial were:
- Determine crop characteristics that are essential to grow chrysanthemums autonomously
- Determine the effect of irrigation strategy on water uptake, transpiration and quality of chrysanthemum
- Determine which sensors can be used best to determine instantaneously water uptake and transpiration of chrysanthemum.

3.2 Chrysanthemum trial: set-up

Chrysanthemum varieties Baco and Bonus (Dekker Chrysanten) were grown in a greenhouse compartment at Wageningen University and Research, Business Unit Greenhouse Horticulture, in Bleiswijk, The Netherlands. The trial started on 27 September 2023 and lasted for two months.

Plants were grown on 12 tables in containers filled with a substrate mix (30% peat litter, 40% peat moss and 30% cocopeat). One cultivar was placed on the left six tables and the other on the right six tables (Figure 3.1).

The cultivation strategy resembled commercial practice. A long-day (LD) phase of 8 days (20-hour photoperiod) was followed by a short-day (SD) phase (11:45-hour photoperiod). Plants were harvested once they reached harvestable quality, defined as an average of 4.9 open flowers per stem. Temperatures were set at 19.5 °C during LD and 18.5/18.0 °C during SD.

Two irrigation strategies were applied to assess differences in transpiration and to evaluate how water balance affected stem diameter, elongation, and fresh weight. The reference treatment received sufficient water, while the reduced-water treatment received 25% less than the reference. Plants were irrigated using a drip system with one dripper per plant. Drip irrigation was applied with one dripper per plant, and treatments varied only in the amount of water supplied per irrigation event. During the LD phase, both treatments received the same irrigation to ensure adequate rooting and initial growth. At the beginning of the short day period (SD), when flowers were induced, the irrigation treatments started.

Figure 3.1 *Greenhouse setup on 18 October 2023. Variety Baco was grown on the left tables and variety Bonus on the right. Half of the tables received the reference irrigation strategy and the other half the reduced-water treatment. Each treatment–variety combination was replicated three times.*

Sensors and measurements
During the cultivation, climate conditions (temperature, relative humidity and CO_2) were recorded every 5 minutes using a Hoogendoorn climate box. Irrigation was logged by registering the number and volume of each irrigation event, and daily drain volumes were collected per table. Soil moisture content fluctuations were monitored with eight sensors (Teros 12). Changes in plant weight and transpiration were monitored using four scales, each holding one container per treatment–variety combination.

Plant temperature was measured using two infrared thermometers (Heitronics CT11.GH) to calculate transpiration based on the crop energy balance. Sensor positions were adjusted during the trial to monitor both varieties and treatments. Two 2grow sensors were used to monitor the stem diameter of Baco for both treatments in 2 repetitions.

The following crop measurements were recorded:
- Stem length (measured twice per week) to determine stem elongation as well as the dates and concentrations of the growth retardants to be used.
- Shoot fresh weight, stem length, leaf characteristics, flower numbers and biomass distribution during destructive measurements at harvestable stage of the crop.
- Quality indicators such as shoot firmness, leaf quality (based on a green-yellow color scale), leaf thickness (via specific leaf area), unwanted side shoots at the bottom of the crop (“sprot” in Dutch).
- A vase life test on two bunches per table (the test started nine days after harvest), carried out by Dekker Chrysanten.

3.3 Results

3.3.1 Effect of the irrigation strategies on crop performance

Applying 25% less water did not significantly affect stem length (Figure 3.2), number of internodes or total fresh weight of the plants (Figure 3.2). However, for Baco, a smaller proportion of shoots met the high-quality standard (at least 90 g $shoot^{-1}$) under the reduced-water treatment (54% vs. 67%). Total shoot dry weight was also similar between treatments for both varieties. No significant effects of reduced irrigation were found for shoot firmness, leaf area per plant (942 cm^2 for the reference vs. 926 cm^2 for reduced water), or specific leaf area (37.7 vs. 37.1 $m^2\ kg^{-1}$). Leaf colour scores also showed no differences between treatments. The vase-life test performed by Dekker Chrysanten indicated an average vase life of 17 days for Baco and 16 days for Bonus. Light use efficiency (LUE), calculated as total plant dry weight per unit of cumulative PAR received, was similar across treatments and varieties, ranging from 0.78 to 0.83 g DW mol^{-1}.

The two varieties differed in several parameters (such as internode number, dry-matter partitioning, unwanted shoot formation, shoot firmness, SLA and leaf quality), although varietal comparison was not the main objective of this study.

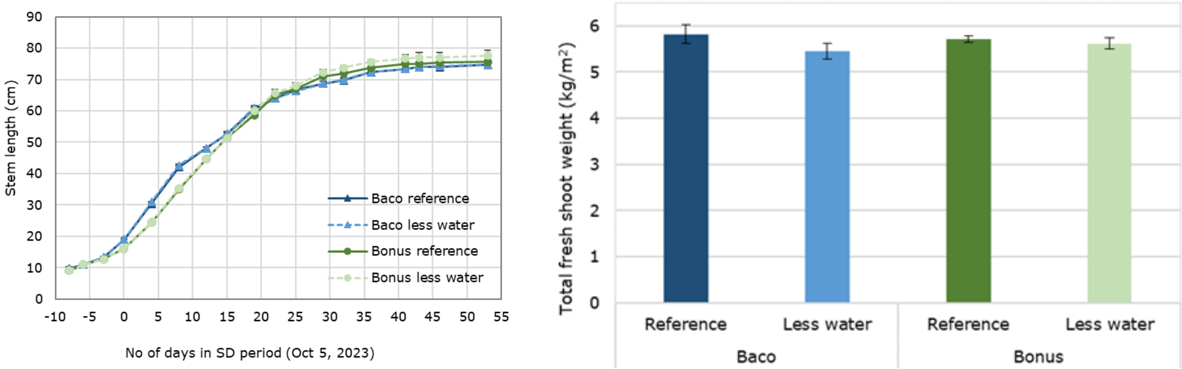

Figure 3.2 *Effect of the reference and reduced-water treatment on the development of the stem length (left) and on the total shoot fresh weight (right), for Chrysanthemum cv. Baco and Bonus. The error bars show standard error of the mean (n=3).*

3.3.2 Sensors

- The volumetric water content values in absolute numbers deviated comparably between the different sensors, making it hard to use the absolute values for control. Therefore the volumetric water content values were normalized. After normalization a clear difference was found in the reference and the reduced water treatment. Moreover, the irrigation moment is clearly visible. During the trial the normalized volumetric water content numbers were used to determine the moment of watering.
- Scale measurements showed expected weight loss patterns, with lower weights in the reduced-water treatment and clear irrigation events, comparable with the volumetric water content measurements.
- Transpiration estimates from plant temperature and scales had similar magnitudes and day–night trends, though the temperature-based method showed sharp peaks at lights on/off and occasional zero night values, while the scales method showed smoother patterns, clearer treatment differences, daytime peaks, and occasional negative values due to watering or disturbances.
- Stem diameter measurements also required normalization due to sensor-to-sensor variation; after normalization, no clear treatment effect was found. A strong daily pattern appeared, with stem diameter decreasing after lights-on and reaching a minimum around midday, then increasing rapidly after lights-off. Light intensity influenced stem diameter more than air temperature, and irrigation had no clear effect. Tests on plastic sticks showed remaining fluctuations but no clear relation to PAR or temperature.

Please note that a more detailed technical report (Effect of irrigation strategies on chrysanthemum cut flowers, Dieleman et al., 2024) has been published and is available upon request.

4 Discussion, conclusions and recommendations

4.1 Cucumber trial

Key conclusions

- The Digital Twin controlled the entire cultivation cycle, including climate, irrigation, and crop-related decisions.
- The reinforcement learning agent autonomously managed the climate and maintained a productive crop, confirming that RL can be used in real greenhouse conditions.
- The expert-led reference compartment followed the predefined cultivation and irrigation plans with only limited adjustments and achieved a high yield, serving as a strong benchmark.
- The validation trial clearly demonstrated that autonomous control of greenhouse crops is feasible in semi-commercial settings.
- Communication around the AGROS trial helped raise awareness within the greenhouse industry about the potential and future role of autonomous growing.

The trial allowed to gain experience with managing the cucumber production using the two autonomous control approaches as well as sensors and imaging technologies. The remaining gaps, recommendations, and future outlook are summarized below.

Digital twin (DT)

Digital twins offer growers a virtual representation of their greenhouse that can mimic real-time behavior and evaluate decisions before they are applied in practice.

In AGROS, the Digital Twin used WUR's crop and climate models to simulate past and future greenhouse states, enabling objective decision-making based on expected crop responses and future production.

Recommendations: looking to the near future, the Digital Twin is the approach closest to real-world application in commercial practice. It has the potential to take objective decisions in complex greenhouse systems, balancing variable resource costs with fluctuating product prices and supporting fully autonomous cultivation.

To further advance digital-twin-based control, several gaps remain. Current models lack detailed descriptions of nutrient management, product quality, and pest and disease dynamics. Future work must determine the necessary model complexity to ensure robust autonomous control, while keeping parameterization practical for real greenhouse systems.

Reinforcement Learning (RL)

RL has proven its value in many domains, and this trial confirmed its potential for greenhouse horticulture. The RL agent in AGROS autonomously controlled the climate and produced a strong fruit-producing crop.

The application of AI in greenhouse horticulture is still in its infancy, and this was one of the first times a greenhouse was controlled fully autonomously by a Reinforcement Learning algorithm.

Recommendations: several challenges remain before RL can become commercially viable. The control space must be expanded beyond climate to include ventilation, irrigation, and crop-management decisions. Additionally, incorporating feedback from the crop would greatly enrich the information available to the agent when making decisions. This would allow an RL algorithm not only to learn the conditions under which the crop performs best, but also to "read" the crop itself and adjust the environment accordingly. Such feedback would enable the model to calibrate itself on the go and correct for differences between expected and actual production. This is an important step, as there is always an inherent gap between performance in simulation and behaviour in the real greenhouse.

Finally, because RL often operates as a "black box", it is important to focus on explainable AI for autonomous control. In a greenhouse with living organisms, even small changes in climate settings can have serious effects on crop status. Understanding the decisions made by a black-box RL model is therefore a crucial priority.

Sensor technology
Autonomous control relies heavily on accurate and reliable sensor data. Although sensor technology is advancing rapidly, not all relevant crop and climate indicators can yet be measured cost-effectively or with sufficient stability. Human oversight is still required to verify sensor accuracy and maintain hardware.

In the AGROS trial, manual crop measurements were deliberately used to avoid risks from sensor failure.

Recommendations: future development will focus on seeking autonomous alternatives to remaining human tasks in the control loop:
i) advancing computer vision and deep learning models to perform automated plant measurements and replace time-consuming manual registration.
ii) employ a soft sensor approach where key traits are inferred using data from sensors already common in greenhouses (and that have already been verified in the first AGROS project). Soft sensors are software models that utilize computational algorithms to estimate physical or chemical parameters based on indirect or incomplete measurements. Crop traits such as development rate, LAI, transpiration rate, and photosynthesis rate are hard or costly to measure directly, so soft sensors provide a practical way to track them continuously.
iii) Developing algorithms that assess the reliability of data from physical sensors, ensuring smoother and more reliable autonomous greenhouse control.

4.2 Chrysanthemum

Key conclusions
- Chrysanthemum production is moving toward soil-less, automated, low-emission systems; growing in substrate-filled trays is a promising solution.
- A 25% reduction in irrigation did not significantly affect stem length or fresh weight, indicating that chrysanthemum can tolerate more efficient water strategies.
- Crop, climate, and substrate sensors show strong potential for autonomous control, but data processing and normalization remain essential for accurate use.

Irrigation strategies
The research compared two irrigation strategies: a reference strategy and a reduced-water strategy, which involved a 25% reduction in water supply. The findings indicated that the reduced water strategy did not significantly affect the stem length or the overall fresh weight of the chrysanthemum plants. This indicates that irrigation can be reduced to some extent without harming the crop, and that crop and substrate sensors offer promising control options, an important step toward autonomous chrysanthemum cultivation. Moreover, the research showed that it is quite possible to grow chrysanthemums in trays with substrate.

Sensors and measurements
During the cultivation, different crop, climate and substrate characteristics were measured to steer the growth. In the current research part of the characteristics were measured by hand and partly by sensors.

Another important cultivation measure is the irrigation moment and amount. In the current trial soil moisture content sensors were used to steer this process. The soil moisture sensors required normalization to provide accurate data, highlighting the need to process the data in practical applications. Growers are also always very interested in the transpiration of the crop to prevent abnormalities such as bulbous leaves, mainly caused by calcium deficiency due to a lack of transpiration.

In the trial different sensors, plant temperature, scales and stem diameter, were tested to monitor transpiration and water stress in the plant. In general, both the plant temperature and scales method showed comparable numbers of transpiration. The scales method showed differences in nigh transpiration between the reduced water treatment and the reference. The plant temperature method is less accurate during nighttime, this was most probably caused by the measurement accuracy of the plant temperature. The drawback of the scales method is that the method can’t be used by ebb and flow irrigation and you need a very accurate scale to measure the night transpiration.

The stem diameter measurement showed differences in stem diameter over time. It mainly reacts on changes of the light intensity and less on changes of air temperature. Before proper use the data needs to be normalized. All tested sensors had in common, that data processing is needed to get information.

5 Communication and project output

One of the aims of AGROS was to involve the horticultural sector in the developments towards data-driven and autonomous cultivation via extensive dissemination via events, professional journals, videos, websites, newspapers and local television. A selection of communication activities of AGROS is listed below.

5.1 Events organised

During the course of the project, three events were organised with the AGROS use cases dairy and arable farming:

- AGROS Networking and knowledge exchange meeting on May 31, 2022, Lelystad.
- Network and knowledge event AGROS “Data and intelligence in arable farming, horticulture and dairy”, 5 April 2023, Bleiswijk, The Netherlands.
  See https://www.linkedin.com/feed/update/urn:li:activity:7039151769393750016/.
- Final AGROS event, “AGROS: towards a sustainable, data-driven agriculture and horticulture”, Wageningen, 24 April 2025. See AGROS: towards sustainable, data-driven agriculture and horticulture - WUR.

5.2 Presentations

Researchers involved in AGROS presented their results and their vision on autonomous cultivation at a number of events:

- “Knowledge event for growers: challenges for the next 15 years”, October 5, 2021, Bleiswijk, The Netherlands.
- Knowledge session “autonomous cultivation” with growers, organized by Glastuinbouw Nederland: Naar een autonome kas: voorbij groene vingers. May 25, 2022.
- At the International Autonomous Greenhouse Event: PPP AGROS “Towards an autonomous greenhouse”, July 1, 2022, Bleiswijk. See: https://www.youtube.com/watch?v=s2Ap7HcGPiI.
- Session “Autonomous cultivation: how far are we”, at EnergiekEvent, organized by Glastuinbouw Nederland, Delphy and Wageningen University & Research, May 17, 2022.
- Future Trends & Innovations. The Next Step in Horticulture Technology.
  “AI in Horticulture - de gamechanger voor de sector?” World Horti Centre, Naaldwijk, 12 December 2023.
- Knowledge session “Towards an autonomous greenhouse, beyond green fingers”, DigitaliseringsEvent Gameren, 4 October 2023.
- “Autonomous greenhouse and crop control in cucumber” at the Greensys symposium, Cancun, Mexico, October 24, 2024.
- “Towards autonomous cultivation: automated plant phenotyping in a greenhouse environment” at the CIGR conference, Japan.
- “AGROS: Towards an autonomous greenhouse” at the GreenTech Amsterdam, session “Tools and vision in data and AI to create a better crop result”, 11 June 2024.

5.3 Television and video

- Local television: https://rtvlansingerland.nl/2023/08/18/slimme-technologie-in-de-kas-komkommers-telen-met-kunstmatige-intelligentie/. RTV Lansingerland, Augustus 2023.
- Sensor use in AGROS. https://youtu.be/JJXkvZg55nk.
- AGROS validation trial: sensors and vision technology. https://youtu.be/GSeGTbhzEx.
- AGROS validation trial: control by Digital Twin and Reinforcement Learning. https://youtu.be/JV_zaco9lRc.
- AGROS validation trial: control by growers – cultivation and irrigation plan. https://youtu.be/RXt4QaqJzUo.

5.4 Articles in professional journals

- Onderzoek en bedrijfsleven pakken ontwikkeling autonome kas samen op. Mensen met groene vingers worden steeds schaarser. Onder Glas (2010) 10: 36-37. https://www.onderglas.nl/magazines/?wur=true#dflip-df_42661/36/.
- Industry and research join forces to develop autonomous greenhouse. In Greenhouses (2021) 10(5): 20-21. https://edepot.wur.nl/547057.
- Sensors play key role in collecting up-to-date crop information: Automatic crop steering using measurement processes. In Greenhouses (2021) 11(3): 48-49.
- ‘We streven naar een volledig autonome kas’. Vergelijking digital twin, zelflerend algoritme en referentieteelt. Onder Glas (2022) 19(11); 36-37.
- Ontwikkelingsvisie en stand van zaken data-gedreven en autonoom telen. Digitale ecosystemen versnellen de route naar Tuinbouw 4.0. Onder Glas (2022) 18 (11): 17-19 https://edepot.wur.nl/559261.
- Fully autonomous greenhouse with self-learning algorithms. In Greenhouses (2023) 12 (1): 36-37 https://edepot.wur.nl/586284.
- Bepaling van snelheid van bladvorming belangrijke stap voor autonome teelt. Volledig autonoom aansturen kas cruciaal voor toekomst. Onder Glas (2023) 20(9): 13-15.
- Determining leaf formation rate key step in autonomous growing. Fully autonomous greenhouse control crucial for future. In Greenhouses (2024) 13 (1): 26-27.
- WUR onderzoekt twee watergeefstrategieën. Proef legt basis voor overstap naar autonome chrysantenteelt. Onder Glas (2024) 21(4): 22-23.
- Onderzoek watergeefstrategie en wortelverdeling. Intering mat heeft geen invloed op gewasgroei en productie. Onder Glas (2024) 21(11): 24-25.
- Veel minder mensen in de kas, AI moet het mogelijk maken (fd.nl). Financieel Dagblad (2024) (https://fd.nl/tech-en-innovatie/1505793/veel-minder-mensen-in-de-kas-ai-moet-het-mogelijk-maken?utm_medium=social&utm_source=linkedin&utm_campaign=earned&utm_content=20240207).

To explore the potential of nature to improve the quality of life

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