# Autonomous greenhouse climate and crop control in high wire cucumber

Anja Dieleman, Anne Elings, Ilias Tsafaras, Anna Petropoulou, Guido Jansen, Bart van Marrewijk, Selwin Hageraats, Feije de Zwart, George Ntakos, Monique Bijlaard

AUTONOMOUS GREENHOUSES

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Good afternoon,

I am Feije de Zwart and I feel honored to represent this large group of people involved in autonomous control of a cucumber greenhouse in the AGROS-project.

# ‘My’ definition of autonomous cucumber growing

- Control of temperature, screening, lighting and CO2-dosing based on objective cost-benefit comparison.
- Automatic control of irrigation based on calculated transpiration in combination with feed back information.
- Automatically generated leaf and fruit pruning strategy based on automated (but now still manually) assessed crop status.

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Autonomous greenhouse control has not a clearly defined meaning, so it is good to start by stating what I mean with autonomous control right at the start.

It is clear that planting, winding the crop in the wire, re-arranging the hooks, de-leafing, selective young fruit removal, pest and disease control, fertilizer application and harvest are still human powered jobs. It is also clear that it requires important skills to do these things properly so in that sense, full autonomous control is still far away. Nevertheless, growers are feeling very much supported if this climate and watering control can be fully delegated to an autonomous system as it gives them more time to pay attention to the remaining management tasks.

# AGROS - “Towards an autonomous greenhouse”

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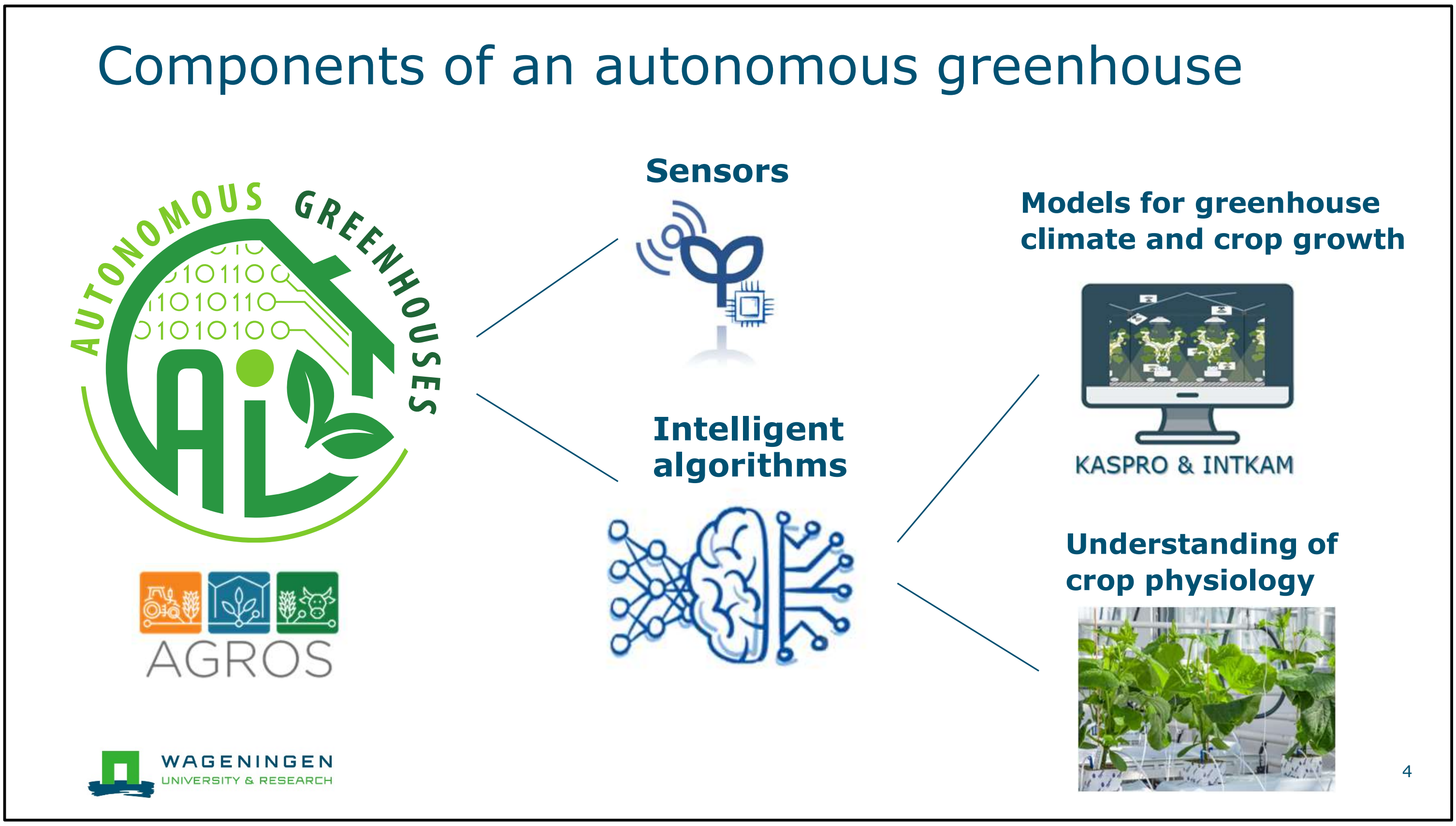
Besides the long list of colleagues, there were also many companies involved as a sponsor in this project.
The largest sponsor was the Dutch governmental funding from the Topsector. As horticulture is considered a vital and powerful area for innovation, the Topsector Tuinbouw en Uitgangsmaterialen supports developments in Horticulture and has a clear focus on data-driven approaches. The contributions of all companies together provided the other half of the project budget.




Basically, Autonomous greenhouses need sensors and Intelligent algorithms that transform the sensor data in suitable actions.
Although many new sensors are entering the market, the current project still made use of he standard greenhouse climate sensor data (temperature, humidity, $CO_2$ concentration, liter counters on irrigation and drain, outside weather data and weather predictions). On top of that, manual assessments of crop status were used.

The intelligent algorithms were developed and trained with the most recent developed integrated greenhouse climate and crop growth model.

# As a validation of the concept....

Three equal compartments growing cucumber were compared.

1 – A reference compartment controlled by experienced staff

2 – A compartment where climate was controlled by an AI-algorithm based on Reinforced Learning

3 – A compartment grown autonomously where control-actions were based on daily repeated scenario evaluations on a Digital Twin of the actual growing greenhouse crop.

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After two and a half years of preparative work, the AGROS project resulted in a validation trial where the performance of two types of autonomous greenhouse control was compared with the performance of a human operated reference greenhouse. As this human operated greenhouse was supervised by a group of very experienced cucumber growers it is fair to state the reference was operated by an above-average skilled team.

# For all, the same objective: maximum profit

Profit was calculated from
costs of variable consumables - benefit from the harvested cucumbers.

Costs:

- Heating energy (MJ/$m^2$) @ 0.09 €/kWh (0.80 €/$m^3$ natural gas)
- Electricity (kWh/$m^2$) @ 0.40 €/kWh for the on-peak hours
  0.30 €/kWh for the off-peak hours
- $CO_2$ use (kg $CO_2$/$m^2$) @ 0.30 €/kg.

Benefits:

- Class A cucumbers (350-400 gram) @ 0.65 € per piece
- Class B cucumbers (300-350 gram) @ 0.55 € per piece

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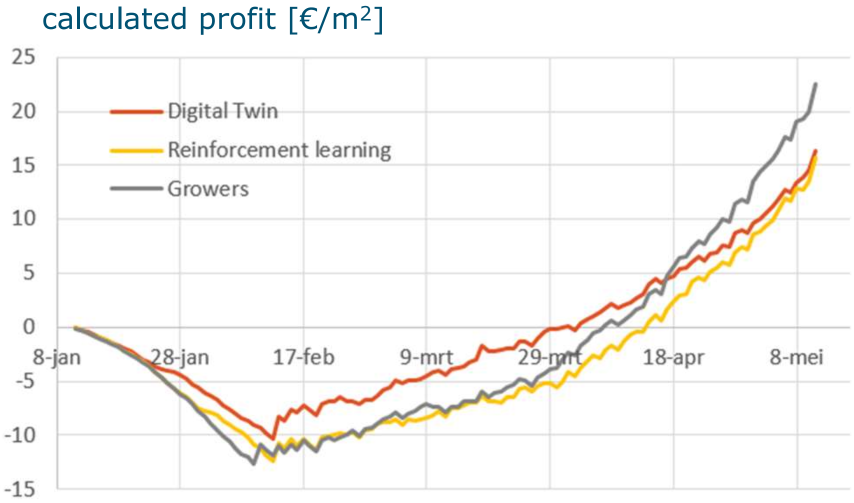
All three compartments aimed on the same goal

Probably people in the audience remark that all prices are really high.
This is because the prices had to be set in the middle of the peak-price period (end of 2022) due to the Ukrainien war and at that time it was simply not possible to assume the prices that we had one year before or the prices of today.
When using these prices while assuming cucumbers to be sold at the ‘normal’ prices it is very clear that glasshouse horticulture cannot be run economically at all.
Therefore, we agreed that the cucumber price should be set high as well.

# Result of the comparative trial




Growers made highest profit because the crop performed best

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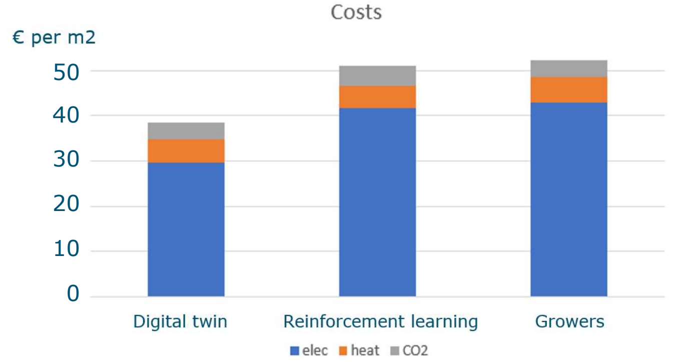
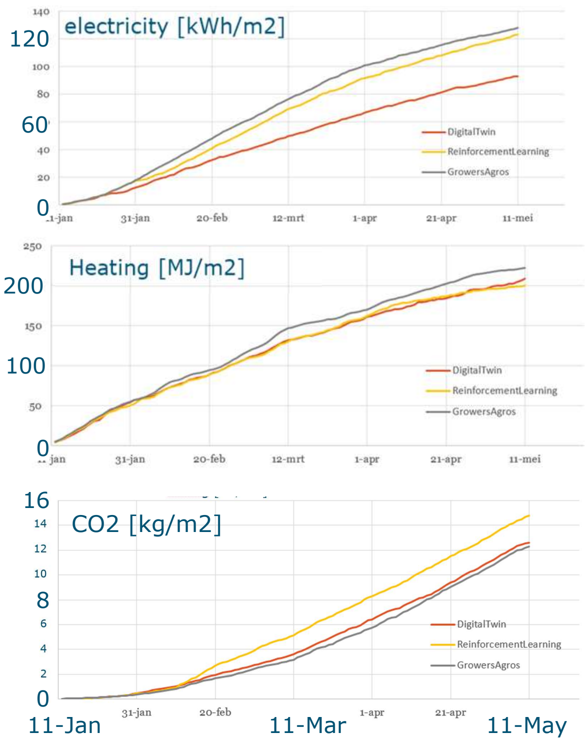
As you can see, all compartments ended with a high profit, but the growers-compartment performed best.

From this graph people might also remark that greenhouse industry must be an extremely profitable business.
However, the curves shown by far do not cover all costs, as they exclude te costs for capital, depreciation, management, planting fertilizers, crop protection etc.
These costs are relevant of course, but as the climate controller only has to deal with variable costs, the mutual comparison of climate control quality doesn't need to include these fixed costs.

# Growers had highest costs

Electricity (light) is by far the largest component

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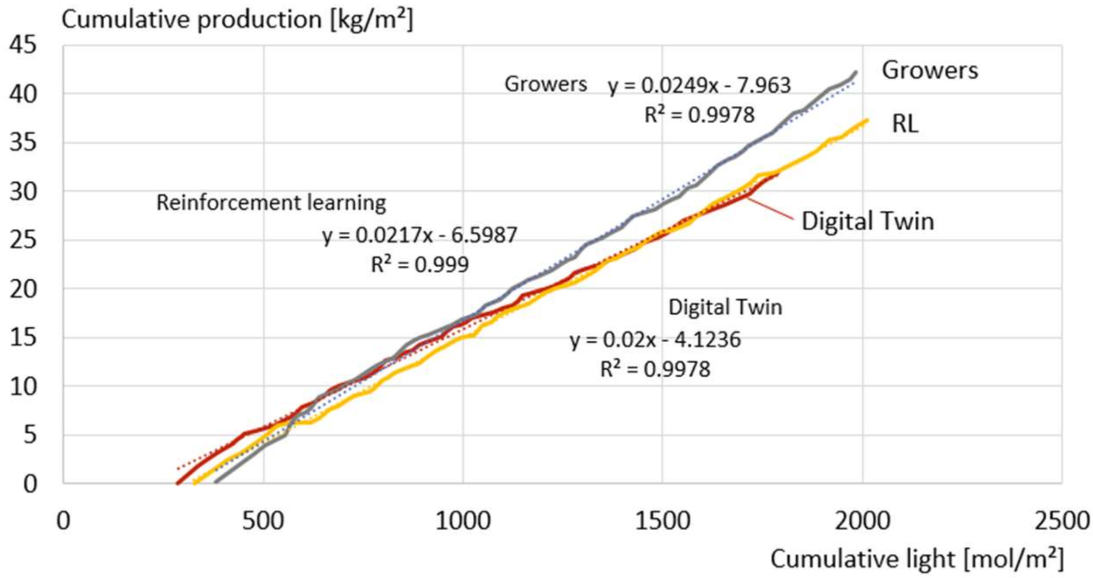
Remarkably enough, the growers even had the highest costs.

# ... but it was well compensated with highest LUE

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But they had also the highest LUE, so their crop was simply performing better.
It is hard to say what exactly caused this difference in performance.

# LUE determines if artificial illumination pays out

Compartments equipped with LED's with efficiency of 2.5 µmol/J

→ 1 mol of light costs 1e6/2.5/3.6e6 = 0.11 kWh
= 3.3 cents off-peak
= 4.4 cents on-peak

→ at a cucumber value of 1.73 euro per kg (@average 375 gram), 1 mol of light brings

3.6 cents @ LUE=21 gr/mol ← Assumed by Digital Twin

4.3 cents @ LUE=25 gr/mol ← Assumed by growers

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As electricity consumption has the highest impact on costs and the crop responses quite linearly on light, the LUE is very important in determining the lighting strategy.

# Conclusions based on LUE:

1) Lighting during off-peak hours always pays out
2) For growers assumption: on-peak lighting almost pays out so keep lamps on also during peak hours for the sake of stability.
3) For digital twin: on-peak lighting is actually too expensive, but run the lamps on 50% during peak hours for the sake of stability.

The Reinforced Learning algorithm was trained on simulations with also a high LUE and therefore decided for many lighting hours as well.

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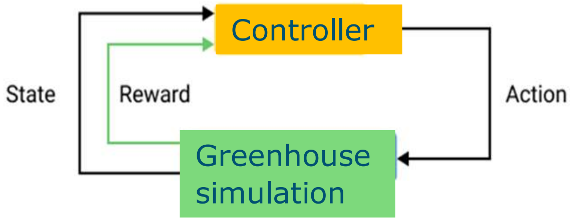
For the digital twin, expecting not more than 21 gr/mol based on previous cucumber cultivation, this meant that it kept the lamps at 50% during many hours.
The electricity costs therefore ended the lowest, but still the lower productivity of the crop yielded not a very high profit.

# AI – controller based on Reinforcement Learning fully relied on simulated greenhouse and crop




- It has 'learned' profitable responses on outside weather conditions, predicted few days ahead weather and 'observed' greenhouse and crop response by millions of greenhouse model simulations while rating the resulting calculated profit.
- It determined effective control rules for
  - Lighting
  - Heating (and also venting)
  - Screen deployment
  - CO2 setpoints

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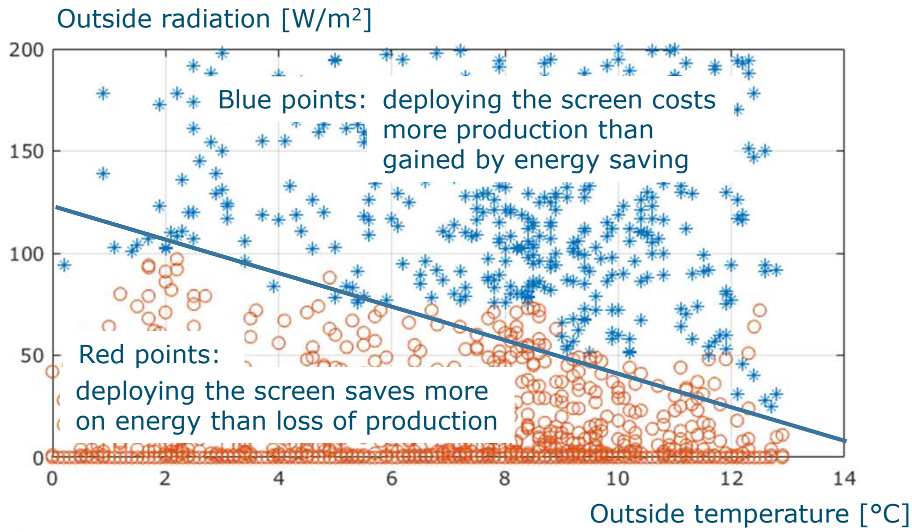
Different than the Digital Twin, the AI-controller did not learned the lighting control on crop observations but from a simulation model where the crop grows with a high LUE, resulting in similar light application as the growers.

Besides lighting, the RL compartment also learned a suitable heating strategy, screen deployment and CO2-setpoints.

I think it is amazing to state that:

1. The greenhouse climate simulation model is apparently close enough to reality for an algorithm without prior knowledge of a smart strategy to find a good working strategy
2. The algorithm is apparently smart enough to find a proper control strategy.

# The Digital-Twin based controller used the model to find a suitable screen-strategy




Rule:

Deploy the screen when

Iglob < 125 - 8.3 Tout

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Just like the lighting strategy was pre-defined for the digital twin (and not adjusted later on as the LUE in this compartment turned out to be around this 21 gr/mol indeed) the digital Twin calculated a screen-deployment strategy beforehand that weighs the pro's of screening against the cons.

# Temperature control

1) Growers sticked close to their RTR-setting

2) Digital twin control used RTR-approach as well, but allowed day-to-day up and down shifts to avoid high 24h temperatures at 'expensive' heating days, which were one or two days later compensated on 'cheaper' heating days.

3) The Reinforced Learning algorithm learned from the simulation model where the average greenhouse temperature needs to be and that it should be dependent on light availability.

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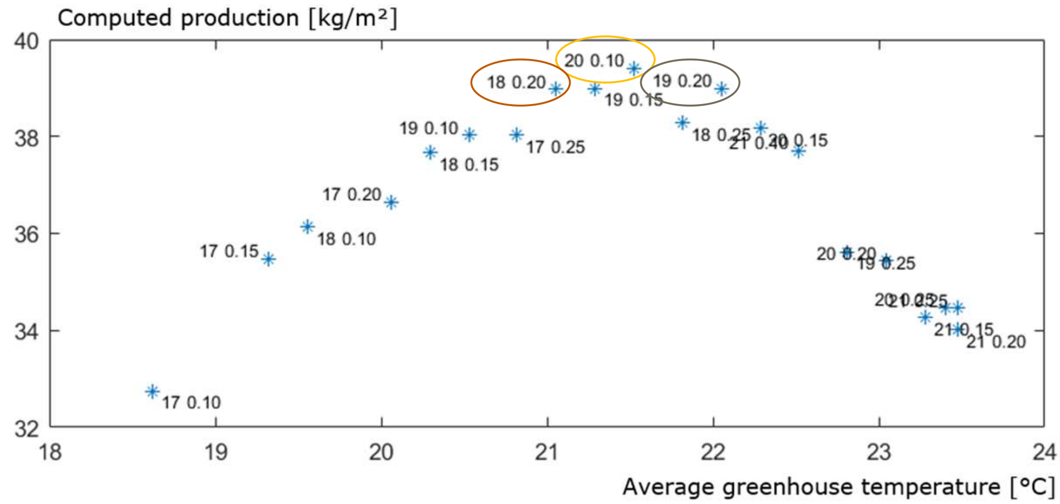
RTR means Ratio Temperature over Radiation.
This is a rather new concept stating that each crop is growing best when the temperature is adjusted based on the available light in the greenhouse.

# Indeed, the simulation model values RTR-control

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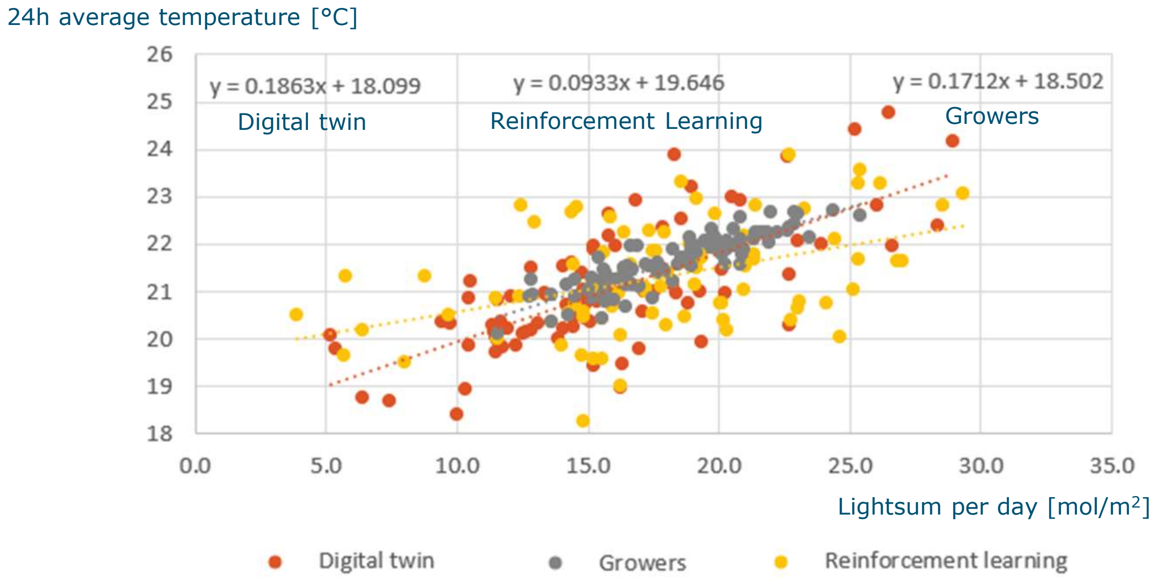
As stated before, the cucumber crop model of the simulator was apparently good enough to value a suitable RTR-strategy.

Here you see the computed crop production at different settings of the RTR-parameters. The three regression-equations on the observed RTR’s are indeed all in the top of the model responses.

# Radiation - Temperature Relation (RTR)

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Here you can see that the Growers were always close to the RTR-line The graph also shows that the differences in daily light sums were small.

Both autonomous controlled compartments show a similar average temperature, but a much wider range of temperatures and DLI’s.

As this is the most prominent difference with the growers’ compartment, this might be a reason for the lower LUE of both autonomously controlled greenhouses.

# CO2-dosing

1) Growers just applied the strategy they always apply

2) Digital twin used an explicit computation that each 5 minutes compared the costs of a higher CO2 concentration with the benefits based on CO2-response curves and acted on this with an increased or lowered CO2 concentration setpoint

3) The Reinforced Learning algorithm learned from the simulation model what CO2 concentration should be kept best.

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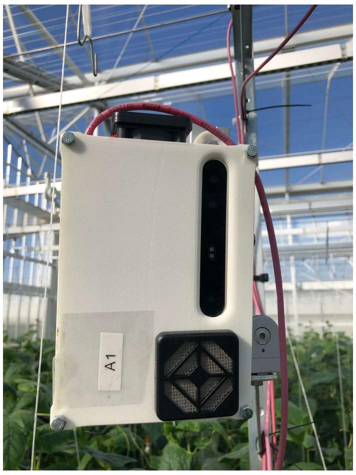
The Digital twin approach computed for each 5 minute's how much CO2-dosing was needed to maintain the elevated CO2-concentration in the greenhouse. Part of this dosing is needed to compensate the losses due to bridging the concentration difference between inside and outside of a leaky, or even venting greenhouse. Another part of the dosing is, of course taken up by the crop.
Knowing the losses at the current concentration it can be calculated how much the losses would grow if the concentration difference would be enlarged, but by having a photosynthesis-response curve on light, temperature and CO2-concentration, it can also be calculated how much the benefits would be from an elevated CO2-concentration.
The digital twin algorithm was equipped to auto-calibrate the photosynthesis-response curve, based on the observed fresh production and did optimize the CO2-dosing accordingly.
The algorithm was based on "An Algorithm for Optimal Fertilization with Pure Carbon Dioxide in Greenhouses" (Stanghellini et.al., 2012) and for the purpose of this autonomous control project extended with this auto-calibration functionality.

# New sensor: camera to obtain leaf formation rate

- Segmenting images to detect new leaves coming
- Difficult because:
  - mainly green-in-green
  - distinguishing front side from background
  - plants are growing fast

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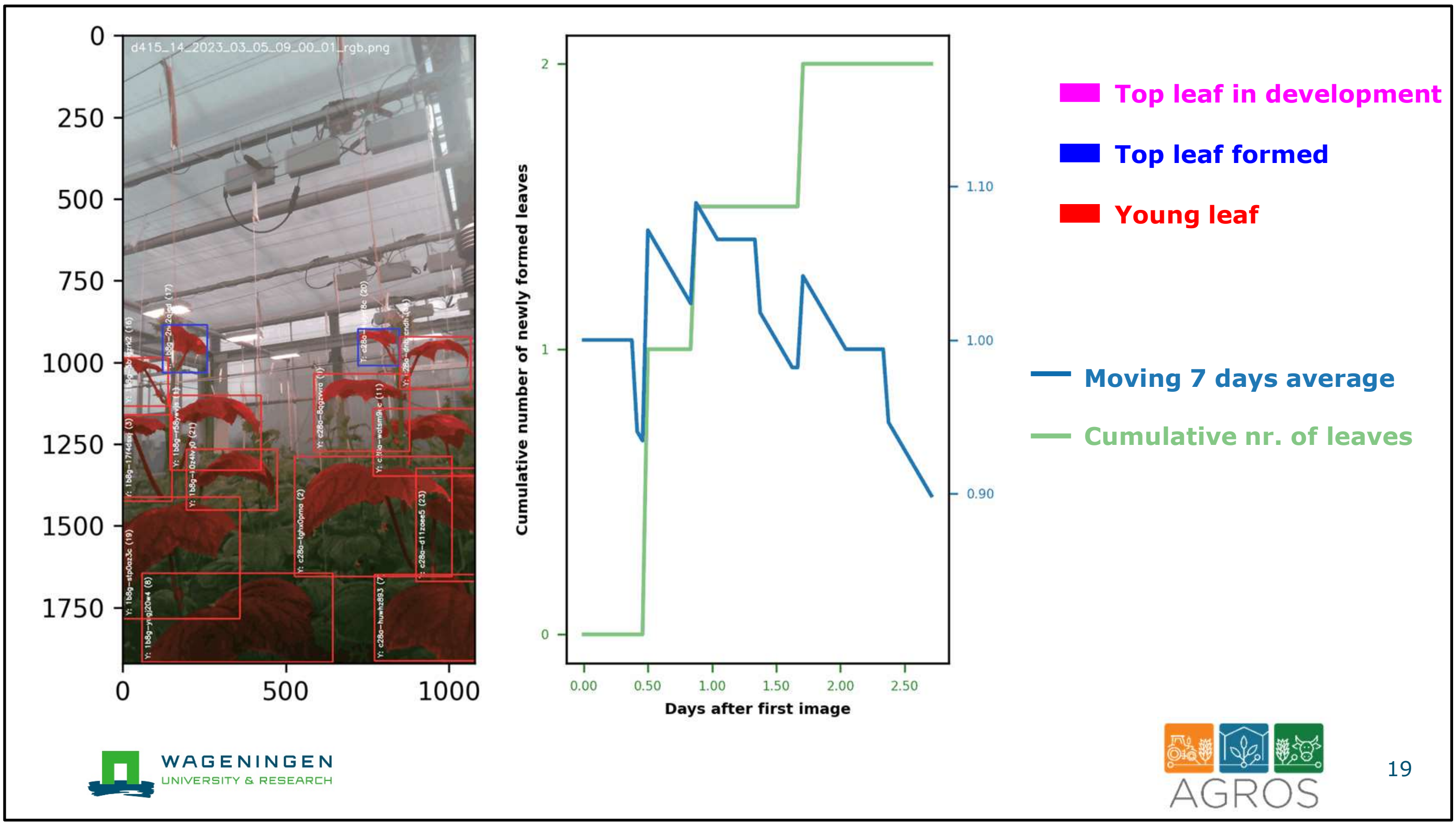
Next to work on autonomous climate control, the AGROS-project also worked on new sensors.

One of them is a camera system to measure the leaf formation rate in real time.

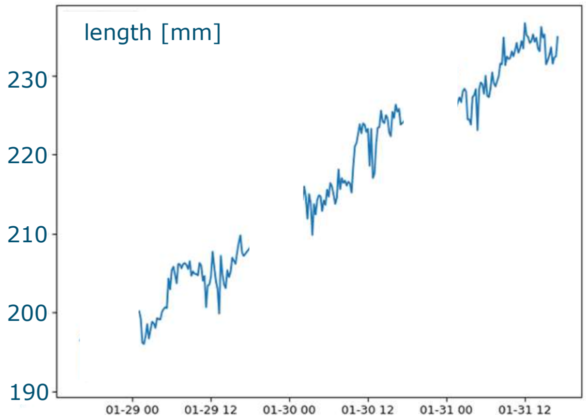
Leaf formation rate is an important parameter in cucumber growing as each new leaf is in principal also a potential new fruit (or for snack cucumbers a bunch of 2 to 3 fruits). In many situations, (and for the 400 grams ‘European’ cucumber in all situations), the fruit load of a crop would become to high when all potential fruits would be allowed to start developing and therefore it is good practice to remove a certain fraction of the new formed fruits.
In order to autonomously determine which fraction should be removed the algorithm should combine the leaf formation rate with the near future maximal bearing capacity of the crop.




The leaf formation rate is the number of occasions that a ‘Top leaf in development’ changes to a ‘Top leaf formed’ per unit of time.
The value will normally vary between 6 to 9 new leaves per week.

# Also a vision system for fruit growth estimation

- Algorithm automatically finds cucumbers
- Automatically calculates the length and width
  - Coverts length and width to fresh weight
  - Observes lowest cucumbers → gives short term harvest prediction




As this camera observes the weight (gain) of the lowest hanging fruits it can provide an advice on the target-harvest weight on days before the workers will have a day off. As after a day without harvest, cucumbers easily become too heavy, it is advisable to harvest a little lighter fruits on the day before.

# Conclusions

- Autonomous control of a cucumber greenhouse is ready to be used.
- Maybe the lower Light Use Efficiency of the autonomously controlled compartments is caused by the larger day-to-day variation.
- Vision techniques are coming to maturity to provide on-line leaf formation rate data and fruit growth speed.
- Having software that controls along clear reasoning allows systems to really learn and improve the strategy.

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And with this I come to my conclusions from this interesting project.

There are not many occasions where we as researchers had the opportunity to have a real parallel running experiment where greenhouses are equal except for the control strategy. In that sense the AGROS-validation trial is quite unique.

It is encouraging to see that the crop growth model for cucumber is good enough for a black box control optimizer to figure out a suitable way of growing.

And as a last point I would like to mark that the clear reasoning applied by the digital twin approach allows for very effective step-wise improvement of the control strategy. For the former generation of controllers there was no 1-to-1 relation between setpoints and result. This new Digital-Twin approach simply realize what you define so that you can better test the effect of defining refinements on your strategy.

# Thank you for your attention

Thanks to the contributors

Cultilene
imec OnePlanet Research Center
GenNovation
Greenport
Delphy
Stichting Kennis in je Kas
Signify
BASF nunhems
Topsector Tuinbouw & Uitgangsmaterialen
Philips
MechaTronix
Roullier
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