Applying the systems thinking and modelling toolbox to industrial symbiosis

Andrew Simons[1], Shane Carnohan[1], Rickard Fornell[1], Andreas Nicolaidis Lindqvist[1], Elin Wallin[1]

1) RISE – Research Institutes of Sweden, Energy and Resources Department

Background

Industrial symbiosis (IS) is focused on the use of waste and by-product streams between actors to improve resource efficiency in an industrial cluster. The Swedish lighthouse in the Horizon 2020 funded project CORALIS has involved the development of a symbiosis in Frövi, Sweden, the result of which is the use of residual heat from pulp and paper production for heating an industrial greenhouse to produce tomatoes. WA3RM AB was the developer of the industrial symbiosis, with RISE working to support the development as part of the CORALIS project, including performing system modelling.

Greenhouses are highly dynamic in nature due to both their reliance on prevailing weather and the complexity of the control systems allowing for a large amount of variation in operation from hour to hour. In advanced greenhouses it is possible to control lighting levels, temperature, humidity and carbon dioxide concentration through the use of various systems such artificial lighting, heating pipes, venting, thermal screens, shading screens, and dehumidification systems.

While there is knowledge on greenhouse design and operation available, greenhouses in a symbiosis context may not adhere to typical rules of thumb that can be used when exploring design and performance of a new greenhouse. For example, the greenhouse may need to be in an atypical location due to the need to be near an IS anchor industry. The use of nontraditional heat and/or electricity sources may also impact operational decisions in unexpected ways with respect to economic and sustainability aspects. The IS aspect may also impact broader aspects than the greenhouse itself, for example local development or changes in the market for the crop produced.

Discussion between WA3RM and RISE highlighted that establishing a detailed understanding of the technical system was critical before expanding into wider system perspectives. Given this, detailed modelling of a greenhouse behaviour in IS contexts was selected as a starting point to anchor exploration of the wider system. The model boundaries for Frövi are shown in Figure 1.

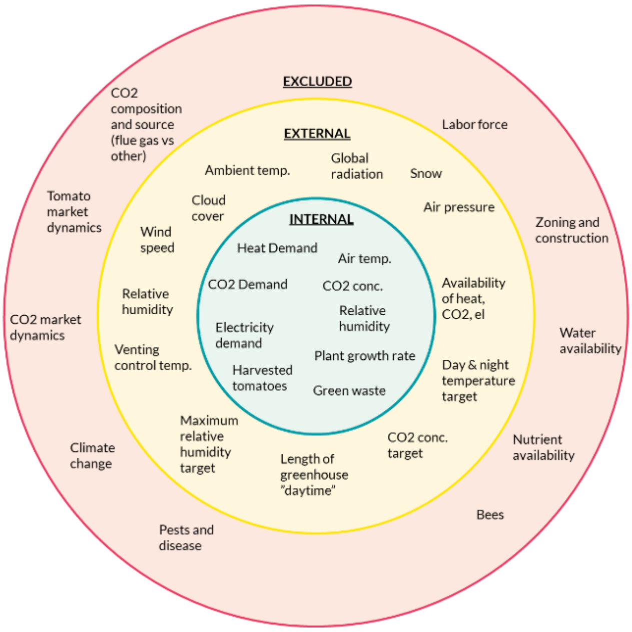

Figure 1 Bullseye diagram showing what the model calculates (internal) what input information the model uses (external) and what is excluded from the model (largest circle).

Method

The models in this work are based on a series of papers that have incrementally improved and validated a set of dynamic models for exploring greenhouse design choices and performance over a wide range of climates (De Zwart, 1996; Katzin et al., 2020; Naseer et al., 2022; Naseer et al., 2021; Vanthoor, de Visser, et al., 2011; Vanthoor, Stanghellini, et al., 2011). A drawback of the existing models is a lack of interpretability as they are available as equations or Matlab code. In this project the model was built in the Stella Professional environment to aid in model exploration and development with non-modelling experts involved in the project.

Broader exploration of the IS was conducted in a workshop using nominal group technique to develop scenarios of interest from the many different perspectives within WA3RM, such as technical operation, sustainability, economics, and business models for IS.

Results

Workshop outcomes

Twenty-two scenarios were collected from the workshop, which fall into four main categories:

- **Multiple operation.** Effects of operating the technical system in different ways. This includes the impact of the grower operating the greenhouse in ways that are different to the design expectations, or the impact of the symbiosis on operation decisions compared to conventional greenhouses.
- **System flexibility.** The greenhouse not reaching its "full potential" for sustainability due to a lack of flexibility. For example, in the future a different crop may be a more sustainable option, but may not be able to be grown due to early design decisions.
- **Effects of disruption.** Impact of disruptive events. For example, a loss of heat from the anchor industry, a disease event, or a labour shortage due to a pandemic or policy change.
- **Local market impacts**. Economic effects from increases in labour costs or reductions in tomato price due to the IS changing the local market.

An example of using the greenhouse model to explore broader IS aspects

Greenhouses have different temperature, light, humidity and carbon dioxide concentration targets between daytime and nighttime. In an advanced greenhouse, where all these factors can be controlled, the operator is able to set the length of the daytime and nighttime periods. The workshop identified that greenhouse daytime is often long (up to 18 hours) to maximise tomato yield.

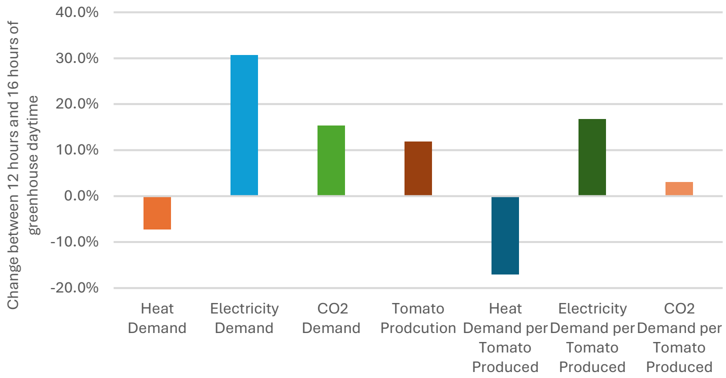

Figure 2 Change in resource demands and tomato production when the greenhouse daytime is changed from 12 to 16 hours.

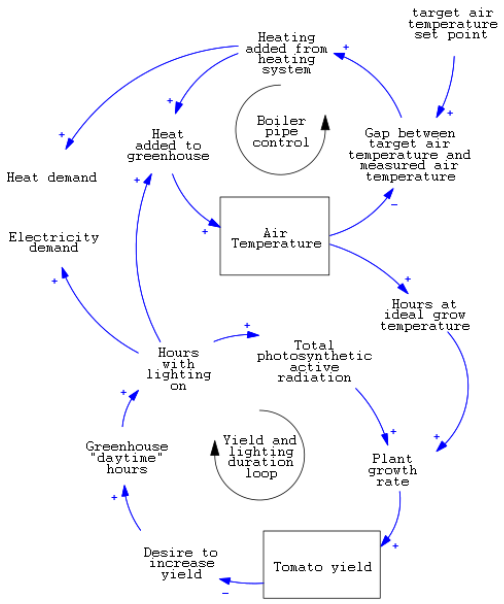

Figure 3 Causal loop diagram showing the relationship driving greenhouse daytime length and its impact on heat addition via the heating and lighting systems.

This impact of daytime length is confirmed by the model with longer days increasing yield (Figure 2). Carbon dioxide demand (tonnes) and electricity for lighting (MWh) are also increased to maintain the longer greenhouse daytime conditions. Interestingly heat demand is decreased from this change even though the greenhouse needs to be operated for a longer time at the daytime temperature set point (2 °C higher than nighttime). Investigation of the model showed that this is due to heat being provided to the greenhouse from the lighting system, which would need to be on for longer periods and in turn reduce demand from the heating system in that time. A causal loop diagram of this is shown in Figure 3.

When the length of greenhouse daytime is increased, heat demand is decreased, and electricity demand is increased. Likewise, decreasing greenhouse daytime hours has the opposite effect on these variables (Fig 3). This has implications for the carbon footprint and economic viability of the greenhouse depending on the heat and electricity source, thus making operational choices highly context dependent - for example IS with waste heat and grid electricity or co-generation of heat and electricity with natural gas. Given this, targeting maximum growth by increasing daytime length may not always be the best strategy depending on local conditions and desired outcomes. This example highlights the complexity of the greenhouse system and shows how a dynamic technical model can be used to support systems thinking.

Next steps

With the technical model validated, the final steps in the project focus on broadening the scope of discussion through simulation of socio-economic trends and uncertainties, in line with the scenario categories. The results will be presented to WA3RM to provide feedback on the parameters representing key assumptions, and the final results will be presented and discussed in a final workshop. Semi-structured interviews with WA3RM employees and founders will be used to evaluate the impact of the application of SD modelling and systems thinking within the 4-year CORALIS project.

References

De Zwart, H. F. (1996). Analyzing energy-saving options in greenhouse cultivation using a simulation model.

Katzin, D., van Mourik, S., Kempkes, F., & van Henten, E. J. (2020). GreenLight – An open source model for greenhouses with supplemental lighting: Evaluation of heat requirements under LED and HPS lamps. Biosystems Engineering, 194, 61-81. doi:10.1016/j.biosystemseng.2020.03.010

Naseer, M., Persson, T., Righini, I., Stanghellini, C., Maessen, H., Ruoff, P., & Verheul, M. J. (2022). Bioeconomic evaluation of extended season and year-round tomato production in Norway using supplemental light. Agricultural Systems, 198. doi:10.1016/j.agsy.2022.103391

Naseer, M., Persson, T., Righini, I., Stanghellini, C., Maessen, H., & Verheul, M. J. (2021). Bio-economic evaluation of greenhouse designs for seasonal tomato production in Norway. Biosystems Engineering, 212, 413-430. doi:10.1016/j.biosystemseng.2021.11.005

Rezvani, S. M.-E.-D., Shamshiri, R. R., Hameed, I. A., Hamid Zare, A., Godarzi, M., Davood, M., & Balasundram, S. K. (2021). Greenhouse Crop Simulation Models and Microclimate Control Systems, A Review. In R. S. Redmond (Ed.), Next-Generation Greenhouses for Food Security (pp. Ch. 6). Rijeka: IntechOpen.

Vanthoor, B. H. E., de Visser, P. H. B., Stanghellini, C., & van Henten, E. J. (2011). A methodology for model-based greenhouse design: Part 2, description and validation of a tomato yield model. Biosystems Engineering, 110(4), 378-395. doi:10.1016/j.biosystemseng.2011.08.005

Vanthoor, B. H. E., Stanghellini, C., van Henten, E. J., & de Visser, P. H. B. (2011). A methodology for model-based greenhouse design: Part 1, a greenhouse climate model for a broad range of designs and climates. Biosystems Engineering, 110(4), 363-377. doi:10.1016/j.biosystemseng.2011.06.001