Master Thesis Projects in Controls and Machine Learning at Carrier, spring of 2022

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Carrier Introduction

Carrier Corporation is one of the world's largest provider of building technologies. Its fire safety, security, building automation, heating, ventilation, air conditioning and refrigeration systems and services promote integrated, high performance buildings that are safer, smarter and sustainable. Building systems, and HVAC systems in particular, are dynamic by nature. In addition, this type of equipment is subject to a number of hard constraints in operation due mainly to the protection of components including the compressor.

In this document we have listed several master thesis ideas in the fields of controls and machine learning. Most of the projects are, more-or-less, driven by Modelica models that well capture the physics of the real systems. Modelica is a language for building dynamical and steady state models of physical objects. Modelica has its roots in Lund and is now widely used in industry (https://www.modelica.org).

1. Chiller control using machine learning

Chiller control is a multi-variable control problem that typically utilizes classic feed-back control based on PID controllers tasked with protecting the equipment, maximizing the machine efficiency, and delivering wanted cooling or heating capacity. As the process under control is highly non-linear, and contains delays, this approach is not always efficient.

The purpose of this thesis project is to explore and evaluate the usage of machine learning control on chiller applications with the end goal of creating a controller that better handles non-linearities and delays of the system than the currently used algorithms. The project will include down selection of machine learning techniques to utilize, automation of data generation, testing and verification of the developed controller and benchmarking against current controllers. Detailed models will be used for both for the data generation and the verification and testing of the developed control algorithms.

Student profile: One or two motivated and skilled students with interest in machine learning, automatic control, modeling of dynamic systems, and programming. Experience with Modelica and thermofluid modeling is a merit but not required.

2. Chiller diagnostics using machine learning

Chiller problems at a customer site are usually not detected before the machine suffers critical failure and shuts down. The total down time is made worse by the fact that the diagnostics information made available to the service technician is limited which results in many man-hours before the root cause of the problem can be found and addressed.

The purpose of this thesis project is to utilize machine learning on a high-fidelity model to develop ways to diagnose the root cause of different problems and find ways of detecting problems before they happen. The project includes milestones to generate data to analyze for the machine learning, down selection of appropriate machine learning algorithms for the identification, training of the algorithms and testing and validation of developed models.

Student profile: One or two motivated and skilled students with interest in machine learning, automatic control, modeling of dynamic systems, and programming. Experience with Modelica and thermofluid modeling is a merit but not required.

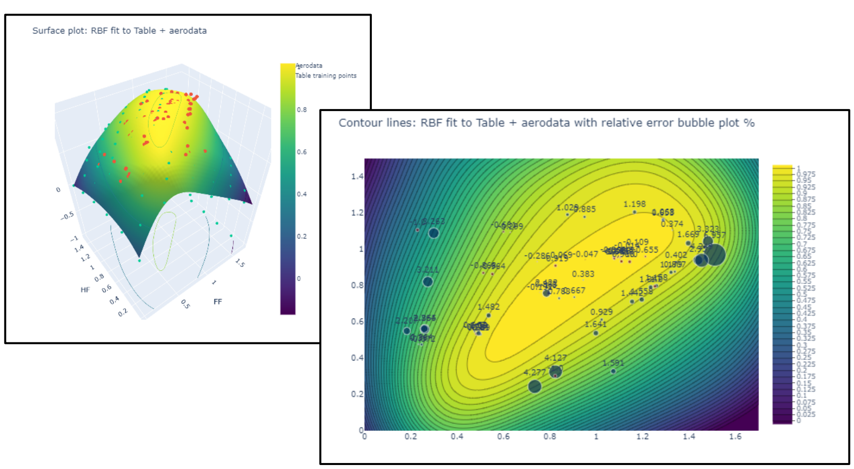
3. Machine learning for compressor efficiency map

The compressor efficiency maps are used to predict the compressor efficiency given a certain head and flow. Carrier does not have detailed/physical Modelica models for this and have historically generated these maps by collecting data from lab tests of the compressor and then generated simple polynomial input/output models based on this data. In most cases, the Modelica implementation has then been represented by a 2D-lookuptable, where bilinear interpolation is used between datapoints.

This solution is neither smooth nor automatically differentiable and a recent push to upgrade to more advanced methods and solvers has made it unacceptable. We did work in the spring of 2021 to fit the lab data to an RBF function, which fulfils the requirements of a smooth and differentiable map to acceptable accuracy. However, the workflow is quite clunky, and we do believe there may exist better/simpler models that also fulfils our requirements.

The goal of this master thesis project is to evaluate what other types of machine learning models could be used for the compressor efficiency maps and to benchmark them against each other and the existing RBF solution.

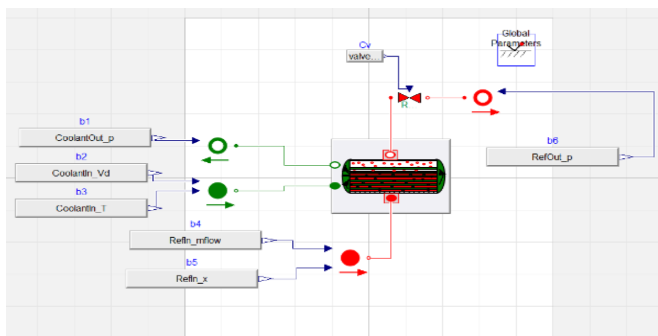
Student profile: One or two motivated and skilled students with interest in machine learning, automatic control and (Python) programming. Experience with ALAMO is a merit but not required.



4. Low-order nonlinear model of a chiller

A suitable dynamic model is necessary for a range of control-oriented tasks such as verification, tuning and when developing a model-based controller. The current dynamic models used at Carrier are built up of hundreds of states and non-linear equations which makes the models less than ideal for these tasks as they suffer from stability issues and are also usually very slow to simulate.

This project aims to reduce the current models as far as possible and at the same time keep the non-linear properties of interest in the model. The work will continue previous work done earlier in 2021 where one of the heat exchangers were reduced from 300 states to 1 while at the same time keeping the dynamics and non-linearities of interest. At the end of the project the aim is to have a full chiller model reduced to its simplest form giving a very fast and robust model that can be used for the control development and verification.



Student profile: One or two motivated and skilled students with interest in modeling of dynamic systems, machine learning and (Python/Modelica) programming.

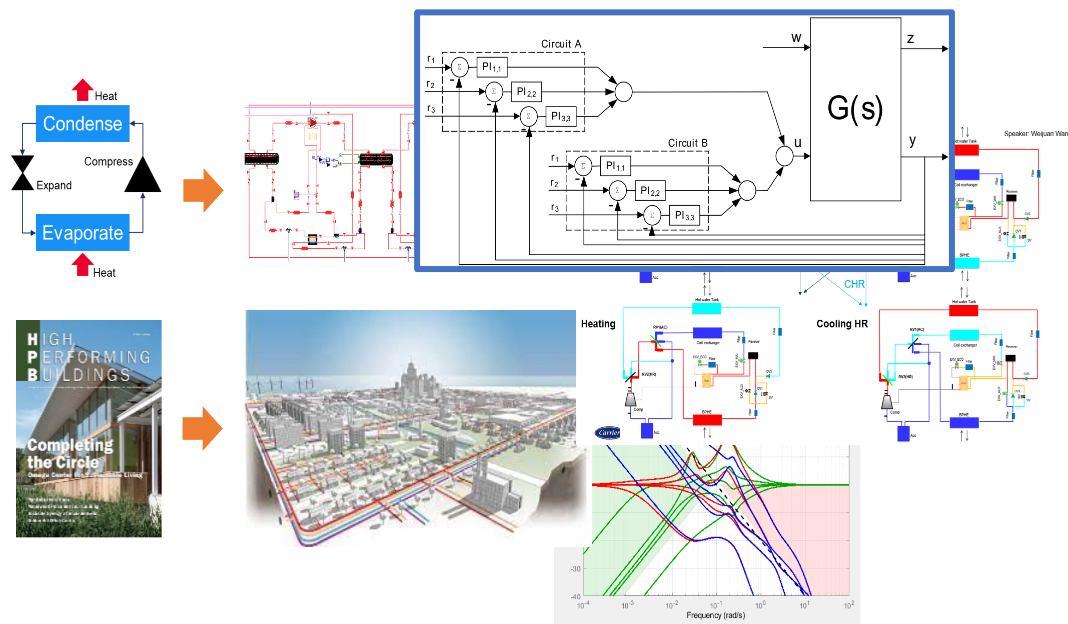
5. Multi-variable control of energy systems

Carrier products involve interconnected components at multiple scales (size and temporal), and with an increased need to reduce energy consumption and increase product performance, these components need better coordinated control. The scales involve components at a machine level – this includes valves, pumps, heat exchangers, vessels, etc. as well as components at a district level – buildings, cooling or heating plant, district supply. The time scales involve decisions made in seconds and over months or longer as weather changes and equipment ages.

The inherent physical coupling of these systems is difficult to control and because of this, the equipment often performs below its targeted performance – wasting energy and making occupants uncomfortable. As in many cases each system is slightly different from one another, robust design techniques are needed to provide a way to quickly develop interactive controllers for energy equipment.

Master thesis projects 2022

In this study, students will be paired with a global business unit to develop better control design approaches for highly coupled multivariable systems. Different business units around the world are associated with different products and scales (e.g. controlling buildings, small air conditioners, or larger cooling equipment). The control design approaches will be tested and developed in unison with engineers currently designing controllers for these systems.



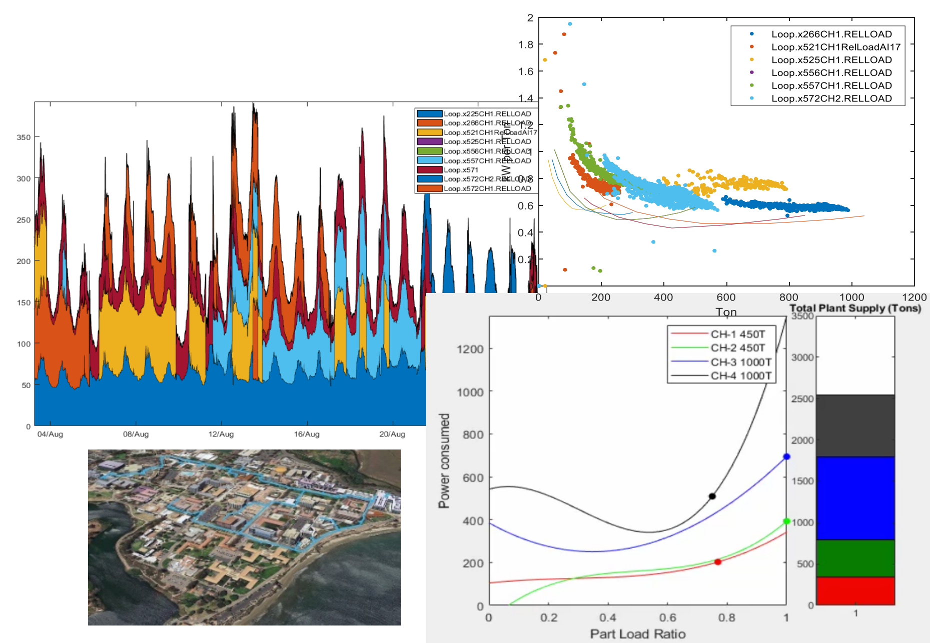
6. Energy system operation optimization

Energy systems are a driving consumer of global energy resources and subsequently contribute to the production of significant pollution. Energy optimization is the process of coordinating and using these systems *just enough* to achieve objectives without waste.

Carrier sells energy equipment and the control systems that make decisions on how they are operated. Optimizing these decisions and operations can lead to significant energy savings and less pollution – yet they are fairly complex in how they respond to such commands and the environment they interact with is very uncertain. To add to this, Carrier's products are increasingly being integrated at larger scales with other equipment resulting in networks of energy systems that are challenging to control and optimize.

In this project the student will use low order models of chiller equipment in an optimization framework to identify how a group of chillers should work together and harmonize to prevent the waste of energy and create excess pollution (when to turn individuals on or off, and at what throttle to use different contributors to the network). This may include selection of different products to add to the network to redesign it to be more efficient.

Methods and algorithms for controlling such networked systems can be used today in Carriers building control products, the student will work with engineers in the Buildings Solution Group to learn the problems in this area and to deliver solutions to save energy and reduce pollution.



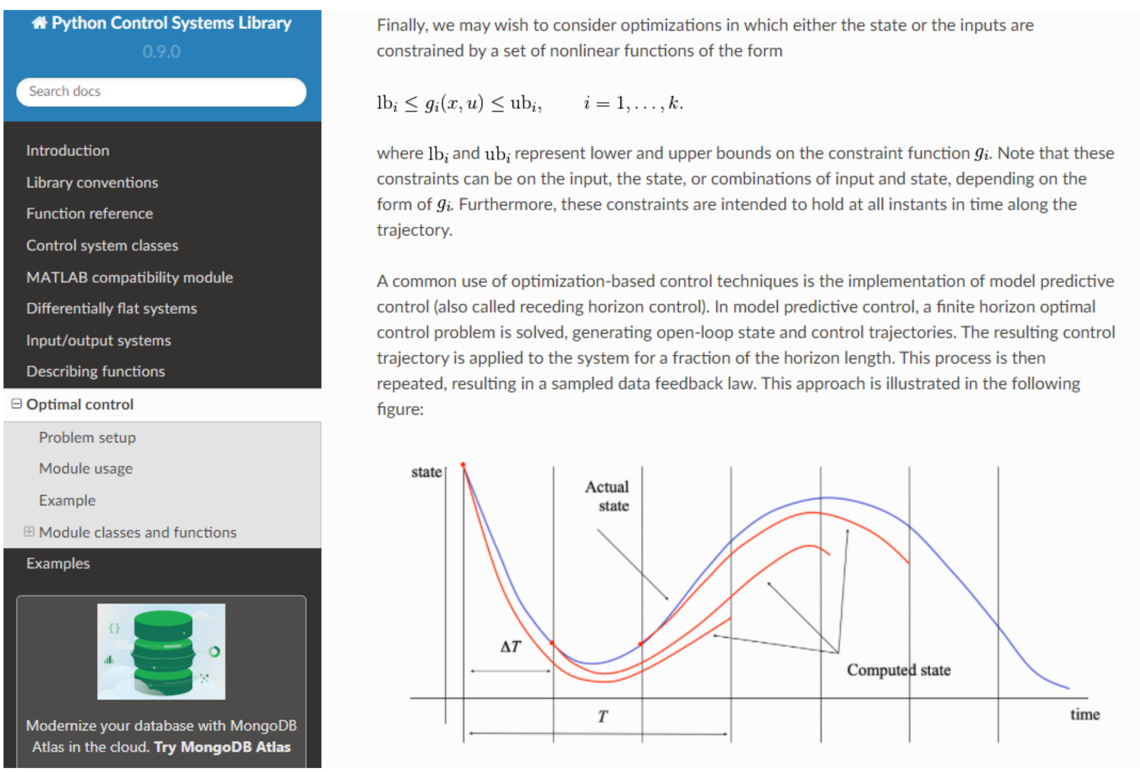
7. Python controls tool development

Python has become a globally accepted and versatile computing environment for engineers. Computations related to control design and verification are extremely important to the product development process in all industries. Although there are some tools that have matured recently (i.e. related to learning and data analysis), controls design tools in python are still minimal.

The python-control package (https://python-control.readthedocs.io/en/0.9.0/) that is publicly available is a great baseline for controls teaching and some design threads of a controls analysis and design workflow. The intention of this project to further mature and harden the python-control package.

A detailed list of functionality that is needed to further its adoption in industry will be discussed at the onset of the thesis project. Collaboration will be with a variety of engineers in different design centers at Carrier as well as with the package developers (at Caltech, Princeton, and others).

Students will benefit from having documented code commits to a well-respected python package, gain a good understanding of specific workflows and controls tools used in industry, and meet and collaborate with other coders at different universities around the world.



Python Control Systems Library
0.9.0
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Finally, we may wish to consider optimizations in which either the state or the inputs are constrained by a set of nonlinear functions of the form

$$\mathrm{lb}_i \leq g_i(x, u) \leq \mathrm{ub}_i, \qquad i = 1, \ldots, k.$$

where lb_i and ub_i represent lower and upper bounds on the constraint function g_i. Note that these constraints can be on the input, the state, or combinations of input and state, depending on the form of g_i. Furthermore, these constraints are intended to hold at all instants in time along the trajectory.

A common use of optimization-based control techniques is the implementation of model predictive control (also called receding horizon control). In model predictive control, a finite horizon optimal control problem is solved, generating open-loop state and control trajectories. The resulting control trajectory is applied to the system for a fraction of the horizon length. This process is then repeated, resulting in a sampled data feedback law. This approach is illustrated in the following figure:

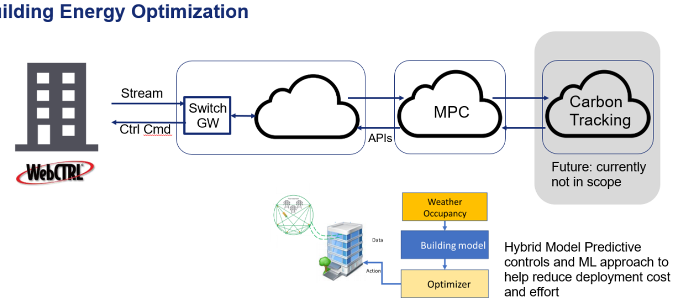
8. Physics-enhanced machine learning of energy systems

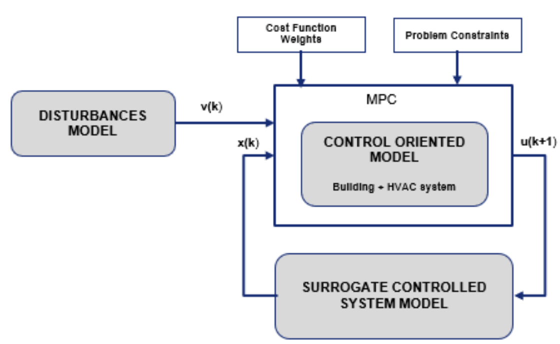
Model predictive control (MPC) is a leading opportunity for the Carrier service business as operating buildings' energy equipment safely and efficiently is a market differentiator. Although state-of-art MPC algorithms consider accuracy and robustness in the design process, initial implementation of such control approaches has illustrated that the uncertainty in building design, operation, and disturbance (e.g. weather and climate change) make effective control a challenge.

Current modeling approaches for MPC range from detailed whole-building physics based models – that are often nearly too slow to calculate in the time needed for predictive updates to low order resistor-capacitor models with empirically tuned coefficients from data (greybox models). Creating detailed models is not scalable, every building in the world is different in how it is constructed and used, and hence not realistic to use for every MPC project. Initial use of greybox models has found that they are often not accurate enough given the uncertainty in the building performance.

In this work, current trends in AI will be leveraged to test and implement next generation greybox models that are enhanced using machine learning and AI. Carrier has current implementation of MPC based building control that can be used as a testbed in the USA, students will work with engineers that are designing this system and help provide new algorithms for control.

Building Energy Optimization





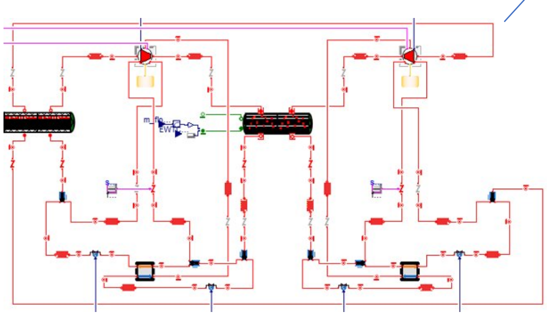
9. Abstraction of industry-secret physical models to publicly accessible models with a story

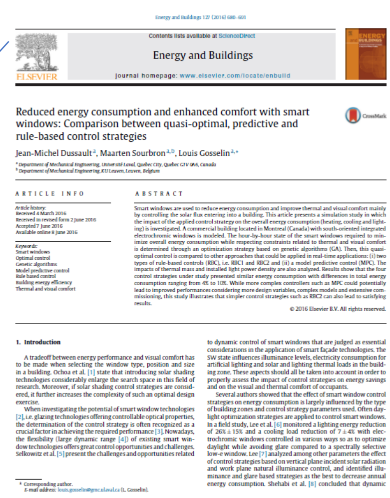
Many industries including Carrier use detailed physics-based models for designing their products and systems – their products and by association their models hold key intellectual property that can't be shared widely. They include physical relationships (equations) that have been pulled from textbooks and open resources, as well as very specific parametric information and performance curves or trends that need to be secret from competition.

It is very useful to be able to share technical challenges and problems between industry and academia, while on the other hand, it is not possible to reveal secrets of the systems that may be very key to the performance.

In this project we will find a balance point between secrecy and openness of a few key Carrier products and archive a transient model that captures the difficulty in designing these systems, while being open and abstracted so that they can be freely used in Academia. Included with each model will be a *story* of the system, and some of the typical challenges that engineers are met with in the design.

The students will pair with different business units throughout the world (North America, Asia, Europe) depending on the specific product addressed.





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Reduced energy consumption and enhanced comfort with smart windows: Comparison between quasi-optimal, predictive and rule-based control strategies

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ABSTRACT

Smart windows are used to reduce energy consumption and improve thermal and visual comfort mainly by controlling the solar flux entering into a building. This article presents a simulation study in which the impact of the applied control strategy on the overall energy consumption (heating, cooling and lighting) is investigated. A commercial building located in Montreal (Canada) with south-oriented integrated electrochromic windows is modeled. The hour-by-hour state of the smart windows required to minimize overall energy consumption while respecting constraints related to thermal and visual comfort is determined through an optimization strategy based on genetic algorithms (GA). Then, this quasi-optimal control is compared to other approaches that could be applied in real-time applications: (i) two types of rule-based controls (RBC), i.e. RBC1 and RBC2 and (ii) a model predictive control (MPC). The impacts of thermal mass and installed light power density are also analyzed. Results show that the four control strategies under study presented similar energy consumption with differences in total energy consumption ranging from 4% to 10%. While more complex controllers such as MPC could potentially lead to improved performances considering more design variables, complex models and extensive commissioning, this study illustrates that simpler control strategies such as RBC2 can also lead to satisfying results.

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1. Introduction

A tradeoff between energy performance and visual comfort has to be made when selecting the window type, position and size in a building. Ochoa et al. [1] state that introducing solar shading technologies considerably enlarge the search space in this field of research. Moreover, if solar shading control strategies are considered, it further increases the complexity of such an optimal design exercise.

When investigating the potential of smart window technologies [2], i.e. glazing technologies offering controllable optical properties, the determination of the control strategy is often recognized as a crucial factor in achieving the required performance [3]. Nowadays, the flexibility (large dynamic range [4]) of existing smart window technologies offers great control opportunities and challenges. Selkowitz et al. [5] present the challenges and opportunities related to dynamic control of smart windows that are judged as essential considerations in the application of smart façade technologies. The SW state influences illuminance levels, electricity consumption for artificial lighting and solar and lighting thermal loads in the building zone. These aspects should all be taken into account in order to properly assess the impact of control strategies on energy savings and on the visual and thermal comfort of occupants.

Several authors showed that the effect of smart window control strategies on energy consumption is largely influenced by the type of building zones and control strategy parameters used. Often daylight optimization strategies are applied to control smart windows. In a field study, Lee et al. [6] monitored a lighting energy reduction of 26% ± 15% and a cooling load reduction of 7 ± 4% with electrochromic windows controlled in various ways so as to optimize daylight while avoiding glare compared to a spectrally selective low-e window. Lee [7] analyzed among other parameters the effect of control strategies based on vertical plane incident solar radiation and work plane natural illuminance control, and identified illuminance and glare based strategies as the best to decrease annual energy consumption. Shehabi et al. [8] concluded that dynamic

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Logistics and application

The projects listed in this document will be carried out at the new Carrier office space @ Ideon Gateway in Lund, under the supervision of Magdalena Atlevi, Kristian Tuszynski and/or Bryan Eisenhower from Carrier as well as a supervisor from the Department of Automatic Control at Lund University.

Please submit your application, including a CV and a course transcript, to magdalena.atlevi1@carrier.com. Don't forget to specify which project/-s you are applying for.