Pre-study on the establishment of a research collaboration between industrial energy systems and process control at Chalmers

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Pre-study on the establishment of a research collaboration between industrial energy systems and process control at Chalmers

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SUMMARY

The aim of the project described in this report has been to create a platform for collaboration between the research areas of industrial energy systems and process control at Chalmers. The authors of this report, belonging to the division of Heat and Power Technology, the Automatic control group and to CIT Industriell Energi, are convinced that a close collaboration between these areas could generate benefits for the process industry including

- Improved efficiency with respect to energy
- Improved opportunities to ensure satisfying operability
- Improved process stability and product uniformity
- Intensified utilization of available process equipment
- Increased profitability

In accordance with the project scope, an inventory of relevant academic literature and of past and ongoing activities within the relevant research community has been conducted. Firstly, this inventory recognizes that researchers at Lehigh University (US), NTNU (Norway) and Carnegie Mellon University (US) have been strongly involved in the establishment of a research field commonly referred to as *Integrated design and control.* It is found that the research questions that are in the interest of the project partners largely can be attributed to this field. Other related labels used, and investigated as part of the project, are *plant-wide control* and *heat exchanger network control*. In a specific section of the report, definitions of important terms like operability, controllability and flexibility are given and commented on. Secondly, international research groups of special interest that has been identified are presented. In this category, I2C2 at University of Auckland and CAPEC at Technical University of Denmark can be mentioned. Relevant publications of the above mentioned research groups and their associates have been studied and are commented on in the report. Special emphasize has been put on review papers and on recent publications.

Furthermore, the project has mapped the competences, experience and interest of the project partners. On this basis, the following keywords were identified:

- Retrofit
- Bio-based processes
- Pulp and paper industry
- Real life case studies
- Industrial co-operation
- Economic evaluation
- Simulation
- Scale up challenges

This list was used during discussions on research questions and project ideas for future collaboration. This project has provided the partners an opportunity to obtain deeper insight into each other's knowledge and experiences, and, moreover, research areas of common interest have been recognized. To further develop the collaboration, the next step seems to imply joint participation in specific research projects. Research questions of interest and ideas for future projects are presented in the full report.

This relates to the prevailing possibilities to apply for research grant - an issue that is addressed lastly in this report. In relation to this it should be noted that there is a program on Industrial Process Automation, supported by Vinnova, the Swedish Energy Agency and Formas, that is soon to be launched. A strategy for monitoring calls from this program as well as other relevant programs was formulated. As a result of the work in this project, it has also been possible to formulate proposals for two specific PhD-student projects within the Preem-Chalmers cooperation. These proposals take the outcome of this project into account and include opportunities to further develop the collaboration between industrial energy systems and process control at Chalmers.

SAMMANFATTNING

Den här rapporten beskriver ett projekt vars syfte har varit att skapa en plattform för ett samarbete mellan forskningsområdena industriella energisystem och processreglering på Chalmers. Författarna till denna rapport, hemmahörande på Värmeteknik och Maskinlära, forskargruppen reglerteknik och på CIT Industriell Energi, är övertygade om att ett nära samarbete mellan dessa områden kan generera en rad fördelar för processindustrin såsom

- Förbättrad effektivitet med avseende på energianvändning
- Ökade möjligheter att uppnå tillfredställande körbarhet i processer
- Förbättrad stabilitet i processförhållanden och produktegenskaper
- Intensifierat utnyttjande av tillgänglig processutrustning
- Ökad lönsamhet

I enlighet med projektplanen har en inventering av relevant litteratur samt genomförda och pågående aktiviteter hos relevanta forskargrupper genomförts. Resultatet visar tydligt att forskare vid Lehigh University (US), vid NTNU (Norway) samt vid Carnegie Mellon University (US) starkt har bidragit till grundläggandet av ett forskningsområde som vanligen benämns *Integrated design and control*. Det står klart att de forskningsfrågor som intresserar projektets parter i stor utsträckning kan relateras till detta område. Flera närliggande områden har också studerats så som *plant-wide control* and *heat exchanger network control*. I ett särskilt avsnitt av rapporten ges definitioner av viktiga begrepp så som *operability*, *controllability* and *flexibility*. Vidare presenteras internationella forskargrupper som bedömts vara av särskilt intresse. Till denna kategori hänfördes exempelvis I2C2 vid University of Auckland samt CAPEC vid Technical University of Denmark. En rad relevanta publikationer relaterade till de forskargrupper som nämnts här ovan har studerats och deras innehåll kommenteras i rapporten. Särskild tonvikt har lagts vid översiktsartiklar samt vid artiklar som nyligen publicerats.

Vidare har projektet kartlagt parternas kompetenser, erfarenheter och intressen, och utgående från det identifierat följande nyckelord:

- Ombyggnationer
- Bio-baserade processer
- Papper- och massaindustri
- Verklighetsnära fallstudier
- Industriellt samarbete
- Ekonomisk utvärdering
- Simulering
- Uppskalningsaspekter

Den här listan användes som utgångspunkt för diskussioner om forskningsfrågor och projektidéer. Projektet har gett parterna tillfälle att erhålla en fördjupad insikt i varandras kunskaper och erfarenheter och framförallt har forskningsområden av gemensamt intresse kunnat identifieras.

Ett naturligt nästa steg för vidareutveckling av samarbetet vore gemensamt deltagande i specifika forskningsprojekt. Forskningsfrågeställningar av särskilt intresse och framtida projektidéer beskrivs mer ingående i rapporten. Detta relaterar till rådande möjligheter att söka forskningsmedel – en fråga som behandlas mot slutet av rapporten. I sammanhanget bör Processindustriell Automation nämnas. Det är ett program som stöds av Vinnova, Energimyndigheten och Formas, och som kommer att lanseras inom kort. En strategi för att bevaka utlysningar från såväl detta som från andra relevanta program har formulerats. Projektet medförde också att förslag till två specifika doktorandprojekt inom samarbetet mellan Preem och Chalmers kunde formuleras. Förslagen stödjer sig på projektets resultat och genomförande av dem skulle medföra mycket goda möjligheter till vidareutveckling av samarbetet mellan industriella energisystem och processreglering på Chalmers.

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1 INTRODUCTION

Energy efficiency is a central issue for all process industries today, regardless of whether well-established technologies and existing industrial plants are considered or if new processes are being developed. Process integration can be a successful strategy to achieve improved efficiency with respect to energy as well as other resources. In some applications, not at least regarding new processes for efficient utilization of biomass, integration with already existing process areas is necessary in order for desired efficiency and required profitability to be achievable.

An increased level of process integration, usually by recycle and other physical feed-back loops, can significantly increase the complexity of the process dynamics. This can unfortunately imply that the process becomes more difficult to control and that improvements that are desired, and otherwise reasonable to expect, become unachievable. A dynamic process analysis is therefore a necessary activity during process development to ensure satisfying operability. This is also vital with regards to attenuation of process disturbances, which in turn can generate possibilities of intensified utilization of available process equipment as well as reduced variations in product properties. Undoubtedly, the potential for increased energy efficiency and profitability is highly favored if dynamic properties and process control is considered already at the process design stage.

Globally, there are a handful of research groups that are prominent in the area of process control in combination with the area of industrial energy systems. One such group is found at NTNU/SINTEF in Trondheim, Norway. These groups are characterized by a close collaboration between the areas of chemical/process engineering and control. Sometimes process control is part of a larger department for chemical/process engineering. In other cases, collaboration is performed between different departments and/or institutes as in the case of NTNU/SINTEF. To be able to compete as well as to collaborate with these groups, increased collaboration at Chalmers is needed.

Significant research advantages can be obtained by the suggested collaboration between the areas of industrial energy system and process control –a combination that throughout this report referred to as "the research area". Besides research advantages, the competence and network of the project partners have the potential to generate substantial, positive effects for undergraduate education at Chalmers as well as for technology transfer to the industry.

1.1 Project goal

The project aim has been to create a platform for collaboration between the research areas of industrial energy systems and process control. Focus for this collaboration will be on energy systems in industrial processes and on their dynamics.

Within the project it has been considered important to identify:

- Relevant research questions and project ideas for future collaboration
- Suitable collaboration partners in academy, research institutes and industry, both nationally and internationally
- Possibilities to apply for research grants

The means to accomplish this have included the following activities:

- inventories of knowledge and experience of the project partners
- review of relevant academic literature
- inventory of the relevant research community, nationally and internationally, with regards to organization, research topics and on-going projects
- idea-generation for future project within the area of process control and industrial energy systems in a systems perspective

1.2 Definitions

In this section, some relevant and frequently used definitions are presented and discussed.

Plant-wide control

Luyben et al (1997): "Plantwide control involves the systems and strategies required to control an entire chemical plant consisting of many interconnected unit operations."

Simultaneous control and design

Yuan et al (2012): "When referring to simultaneous design and control for chemical process, the word "design" means process decisions regarding flow sheet topology, process design/operating parameter and nominal operating conditions based on the steady-state mathematical model. The word "control" on the other hand, refers to the design of control system resulting in optimal closed-loop dynamic performance. There is no guarantee that the conceptually designed optimal operating conditions and steady-state based economic objectives of a process flow sheet will still be optimal and/or has good plant-wide dynamic performance when met with external, disturbances and parametric/model uncertainties".

Operability

General definitions of operability have been formulated in different ways:

- "Operability is defined as the ability (goodness) of a system to be operated as required" (Michelsen et al., 2010).
- "The term operability is often referred to the ease with which a process can be operated and controlled." (Escobar et al., 2013)
- "The operability of a process is its ability to adapt to changes" (Yuan et al., 2011)
- "The ability of a process to cope with uncertainty and disturbances and also with issues of reliability and maintenance." (Yuan et al., 2011)

Geogakis et al. (2003) provide one of the most detailed descriptions of the concept of operability. Note that they explicitly state that operability refers to the inherent ability of the process and is independent of the controllers used.

- "It is the purpose of an operability analysis to facilitate the integration of design and control by systematically exploring the beneficial as well as detrimental interaction between process and control designs. An operability measure should quantify the *inherent ability* of the process to move from one steady state to another and to reject any of the expected disturbances in a timely fashion with the limited control action available. Consequently such a quantification of the process operability should be independent of the controllers to be used in the feedback loop. Moreover, it should also be identifiable from the information available at the design stage." (Georgakis et al., 2003).

Operability is often described and/or defined as a concept including several other properties of a process.

- "Operability includes flexibility, switchability and controllability as well as many other issues." (Larsson and Skogestad, 2000).
- "[Operability] includes both flexibility and controllability, and it is strongly affected by the network design." (Escobar et al., 2013)

While the above definitions are quite common, a few descriptions of operability present a much wider concept. For example, Marlin (2007) include the following topics:

1. Operating window
2. Flexibility (and controllability)
3. Reliability
4. Safety (and equipment protection)
5. Efficiency (and profitability)
6. Operation during transition
7. Dynamic performance
8. Monitoring and diagnosis

Some definitions explicitly describe how operability covers steady-state as well as dynamic considerations.

- "Steady-state operability is a necessary condition for overall process operability, which should be subsequently complemented by dynamic operability". (Lima et al., 2010).
- "Operability is the ability of the plant (together with its control system) to achieve acceptable operation (both statically and dynamically)." (Larsson and Skogestad, 2000).

Flexibility

Flexibility can be described as the steady-state part of the operability concept.

- Flexibility commonly refers to "the range of operating conditions, normally steady-state conditions, which a particular process design can achieve". (Bogle, 1998)
- "Flexibility refers to the ability to obtain feasible steady-state operation at a given set of operating points. This is a steady-state issue, […]" (Larsson and Skogestad, 2000).
- Perkins and Walsh refer to flexibility as "the requirement of a process to handle uncertainty and variability from a steady state perspective while controllability refers to the dynamic perspective." (Bogle, 1998).

Some definitions do not refer to steady state explicitly, but talk about long-term variations.

- "Flexibility is a system's capability of absorbing long-term variations appearing at the inlet of the process" (Yan et al., 2006)
- "A flexible network is a system capable of absorbing long-term variations on inlet stream conditions or having the capability of changing stream temperature targets significantly" (Aguilera et al., 1998)

Some definitions define flexibility as an ability to operate under uncertain conditions.

- Dimitriadis and Pistikopoulos introduce flexibility analysis for dynamic systems where it is defined as the "ability to maintain feasible operation over a range of uncertain conditions" (Bogle, 1998).
- "The ability to accommodate uncertainties over a range of uncertain parameters" (Yuan et al., 2011)

More common is, however, to define it in relation to variations and changing conditions (uncertain as well as known).

- Closely connected to feasibility. Flexibility represents the range of operating parameters for which the process operation is feasible. (Lima et al., 2010).
- From Grossman and Morari (1983): "Flexibility is the ability of the HEN[1] to readily adjust to meet the requirements of changing conditions" "This implies that the HEN works at different

[1] HEN = Heat Exchanger Network

operating conditions that are normally attained by changing set points in the control system" (Tellez et al., 2006)

- Process flexibility is defined by Grossmann and Swaney (1985) as "the ability of a design to tolerate and adjust to variations in conditions which may be encountered during operation" (Chodavarapu and Zheng, 2002)

Note that the above definitions of flexibility differ with regard to how the process is desired to respond to the variations. Some definitions express this as "ability to adjust to variations", while others express it as ability to "accommodate variations" or "absorb variations", which can be interpreted quite differently. The common view seems to be the ability to maintain feasible operation.

Switchability

Switchability refers to the ability of a plant to move between alternative steady state conditions.

- "The ability of a process to move between operating points in a dynamically feasible and safe manner" (Yuan et al., 2011)
- "Switchability refers to the ability to go from one operating point to another in an acceptable manner usually with emphasis on feasibility." (Larsson and Skogestad, 2000)

Controllability

Within the process control area, controllability, as well as its dual, observability, is a well-defined concept. However, a number of different descriptions and definitions of controllability can be found in literature, partly depending on the field of study, but also depending on the size of the system analyzed. The most general definitions have formulations like:

- Rosenbrock definition: "A system is controllable if it is possible to achieve the specified aims of control" (Yuan et al., 2011)
- "Controllability may be viewed as a property of the process, which indicates how easy it is to control the process to achieve the desired performance" (Yuan et al., 2011)
- Controllability assessment deals with whether the plant is controllable, and ideally also with what is the achievable controlled performance of the plant. How the plant is actually controlled is subsequently dealt with during control structure selection and controller design. (Bogle, 1998).

Controllability usually refers to the possibility of keeping a process at steady state:

- "Controllability can be defined as the ease with which the process can be held at the specific steady state" (Weitz and Levin)(Bogle, 1998; Yuan et al., 2011)
- Ziegler and Nichols (1943) define controllability as "the ability of a process to achieve and maintain a desired equilibrium value" (Yuan et al., 2011)

However, definitions exist that also include switchability aspects into controllability, but they are not common.

- "…controllability is associated with short-term perturbations, stability, and safe transitions from one operating point to another" (Aguilera et al., 1998)

Some definitions are explicit about which parts of the system are included, and usually agree that it is a property of the process, including the location of sensors and actuators, but not the controllers:

- "Controllability refers to the ability of a particular design, *usually including the control system*, to maintain safe and stable operating conditions following disturbances". (Bogle, 1998)
- According to Skogestad and Postlethwaite (1996) "…controllability does not depend on controller type and is a property of the process that can only be altered by process modifications, which can involve changes in equipment type; location of sensors and actuators; addition of new equipment; addition of new process lines, such as bypasses; and redefinition of the control objective" (Oliveira et al., 2001)

Controllability indicators include RGA, condition number, controllability index (Georgakis et al., 2003) More specified controllability concepts have also been defined. For example state controllability, that was introduced by Kalman (Bogle, 1998) and is a more narrow concept than general controllability. State controllability is "the ability to bring a system from a given initial state to any final state within a finite time" (Yuan et al., 2011). Structural controllability on the other hand puts focus on the process design:

- "Structural controllability is based on the concept that structural information gives insights into the pathways of disturbances in the process. If each flow in a process is not interconnected and independent, then the disturbance in a flow does not propagate through other parts of the process, and thus this process is well controllable" (Yuan et al., 2011)
- "The following two statements, therefore, define the concept of structural controllability:

    1. A process is completely controllable structurally if disturbance does not propagate through it.
    2. A process is highly controllable structurally if undesirable propagation of intense disturbances does not occur in it." (Huang and Fan, 1992)

Finally, plantwide controllability is defined as a property of the process without a pre-defined control system:

- "A process is steady-state plantwide controllable if and only if there exists a plantwide control system to maintain a process at desired steady states in the presence of uncertainty and disturbances." (Chodavarapu and Zheng, 2002)

To summarize, controllability generally describes the dynamic properties of a process, including sensors and actuators, but not controllers. It describes how this process performs in the presence of short-term variations and disturbances. The last definition of steady-state plant-wide controllability is, however, although uncommon, interesting from a process design point-of-view since it does not require the manipulated variables and the controlled variables to be given.

It is common to state that controllability is a property of the process itself and independent of the control system. Note, however, that from a control perspective, the locations of sensors and actuators (controlled and manipulated variables) are generally considered to be part of the process. From the process design perspective, on the other hand, these are typically seen as part of the control system. The term control system should therefore be read and interpreted with care.

Resilience (resiliency)

Resilience is a term that historically has been used in the heat integration field for HEN design with consideration to operability issues. Generally, it is a rather "crude" concept that does account for energy balances and temperature differences, but not for the heat exchanger areas.

It mainly seems to refer to steady state operability (that is, something similar to flexibility), e.g.:

- "Thus HENS are often designed to operate at each extreme of an expected range of temperatures and flowrates, with the hope that the HEN will operate at all intermediate temperatures and flowrates (i.e. with the hope that the HEN will be resilient). " (Saboo et al., 1987)
- "For a rigorous formulation of the problem, the following definitions are adopted from Marselle et al. [6]. These definitions have been slightly modified [1] to make them more useful for practical situations.

  Definition 1. A network is called *feasible* if it meets the specified energy recovery target and stream target temperatures without violating any ΔT_{LM} requirement.

  Definition 2. A network is said to be *resilient* in a *specified disturbance range D* if and only if it is feasible for every operating point in D.

  Definition 3. A network is said to be *operable* for a *specified disturbance range D* if and only if it is able to meet the stream target temperatures without violating ΔT_{LM} (irrespective of utility requirements) for every operating point in D. " (Saboo et al., 1987)

However, other definitions might suggest that dynamic considerations are also included and that it is closely connected to controllability:

- From Grossman and Morari (1983): "Resiliency is the ability of the HEN to tolerate and recover from disturbances" (Tellez et al., 2006)
- Mathisen et al. (1991, 1992b) defined controllability as "the dynamic resilience of heat exchanger networks". (Varga et al., 1995)

Yet other definitions imply that there is both steady state resilience and dynamic resilience as two different concepts:

- "To avoid confusion between practical controllability and state controllability, Morari introduced the term dynamic resilience as the quality of the regulatory and servo behavior, which can be obtained by feedback" (Yuan et al., 2011)

Summarizing, resilience can probably be described as a flexibility and controllability concept that is specific for heat exchanger networks.

2 About the Project Partners

2.1 Heat and Power Technology at Chalmers

The Heat and Power Technology group conducts research and educational training within the industrial process energy engineering area. The research encompasses a wide span of activities including the development and application of methods and tools for identifying opportunities for improving energy efficiency and reducing CO_2 emissions from industrial processes. These methods are applied in real-life case studies and develop systemic knowledge about possible future development paths for industrial processes and the role that these processes could play in regional energy systems. The group conducts a significant number of research projects related to process integration of advanced biorefinery concepts, and is generally considered to be Sweden's leading group in this field. Our vision is to be a leading group in the development of new methods and tools for assessing the technical and economic performance as well as the carbon footprint impact of future development pathways for industrial chemical process energy systems.

Important methods and tools

An important tool developed in the research group and for evaluation of techno-economic and carbon footprint performance of industrial future technologies and systems is the energy market scenario tool called ENPAC. This tool is used for construction of consistent sets of data for energy prices, policy instrument levels and CO_2 emissions associated with the use of various energy carriers. Within the heat integration area, the group has a long experience of working with pinch analysis, both for method development and case studies in cooperation with industry. The methods and tools developed by the group, many times in collaboration with CIT Industrial Energy, are mainly focused on retrofit projects for existing industrial plants. They include the Matrix method for cost-effective energy savings projects in existing heat exchanger networks and advanced pinch curves for visualization of retrofit energy savings potentials. Other methods and tools that are used either to create input to the pinch analysis or to evaluate the results of a retrofit project include process modelling in Aspen, investment evaluation and energy systems optimization modelling.

Industrial partners and important networks and research centers

Heat and Power Technology has a long experience of close research collaboration with the pulp and paper industry. This includes pervious and ongoing projects together with Södra, Stora Enso, Holmen, Innventia and others, as well as within the national research programmes KAM (the eco-cyclic pulp mill) and FRAM (the future resource-adapted pulp mill). In later years, industrial collaboration has extended significantly into other sectors such as the oil refinery industry (Preem) and the petrochemical industry (the chemical industry cluster in Stenungsund – Borealis, Perstorp, Akzo Nobel, etc.).

Heat and Power Technology is part of the Chalmers Energy Area of Advance. In addition, the group is part of the national research and graduate research school ‘Programme Energy Systems’, which is an interdisciplinary programme in which five research divisions from four universities work in close cooperation. Other networks in which the research group is active include SFC (Swedish Gasification Center), f3 (Swedish Knowledge Centre for Renewable Transportation Fuels) and CPE (Centre for Chemical Process Engineering). The group is active in a number of international research forums, particularly the International Energy Agency’s Industrial Energy-Related Systems and Technologies.

Recent and ongoing projects connected to operability aspects of process integration

Difficulties to achieve the theoretical potential for advanced process integration projects due to practical and operational constraints have been mentioned in various projects from the research group. One example is the project about process integration in the petrochemical cluster in Stenungsund (Total Site Stenungsund). Within that project it is estimated that it should be economically reasonable to avoid 50% of the heat production currently supplied by purchased fuel in the whole industrial cluster. However, a number of technical barriers are brought up, such as the different operating times of the plants and the challenge of controlling the target temperatures in a system with many heat sources and heat sinks located at different plants. These issues have not yet been further investigated.

In Elin Svensson's doctoral project, a methodology for the optimization of investments in process integration was developed. A strategic perspective was considered, in which the large uncertainties connected to long-term changes in the energy and biorefinery markets were explicitly considered. The methodology was applied to pulp mills and their investment opportunities for energy efficiency and biorefinery implementation. Lessons learnt from model development and optimization results include conclusions about the value of flexibility, something that is also a core element of operability.

Another completed project at the division studied process integration under varying ambient conditions with application to the hot and warm water system of a pulp mill. The focus was on how the potential for energy savings was affected by considerations to seasonal and more short-term variations in inlet temperatures and heat flows. However, the variations were only modelled in steady state.

Elin Svensson is currently working in a project with a wide view on operability connected to process integration. The aim of the project is to investigate and concretize the need of better knowledge and new methods within the process integration field, with connection to practical feasibility, reliability, flexibility and operability of process integration measures and new system solutions in the energy-intensive industry. Within the project, the problem areas most crucial for practical implementation of process integration measures and for strategic decisions about such measures should be identified. State-of-the-art methods and tools in this area should be surveyed and the need for method development should be defined.

A new project proposal is currently discussed with Preem. This involves a new case study based PhD project in co-operation with CIT Industrial Energy for investigation of the technical potential for energy recovery through heat integration. The aim of the project will be to get a better view on what the actual difficulties are with strongly integrated plants. Based on a case study of the Preem refinery in Lysekil, the objective is to map and concretize the gap between the theoretical potential and the practically feasible potential. The goal is to find concrete examples of controllability difficulties, safety issues and other factors that might be considered as barriers in achieving the full energy savings potential.

Finally, it is worth mentioning the recently completed master thesis about the operation of the secondary heat system at the pulp and board mill Skoghall. This master thesis has been studying the operation and general control principles of the hot water production at the mill, and seems to be a good ground for further case studies on controllability, control system design and operation optimization in a heat-integrated system.

2.2 Process Control at Chalmers

The Automatic control group at Chalmers part of the Division of Automatic control, Automation and Mechatronics that is found at the Department of Signals and Systems (S2). To a large extent the department deals with dynamic modelling and development of efficient systems for extracting, processing and acting on signal information. These systems often represent the essential functions in high-technological products, and can be regarded as the built-in intelligence in operating systems. Possible application areas can be found in almost all kinds of devices and advanced technology with integrated electronics. At S2, fundamental research projects in automatic control, automation, signal processing, information theory, and communication systems are conducted. The applied projects are found in a wide range of areas and these are often carried out in close collaboration with industry and/or researchers from other fields.

Research in the Automatic control group concerns both fundamental questions in control methodology and applications of control in areas of industrial and societal interest. Currently, the application areas of particular interest are in environmental and biological systems, in transportation and vehicle technology, and in systems and control aspects of electric power systems. Moreover, automatic control is part of the curriculum in many of Chalmers educational programmes, with several levels of consecutive courses for deepened understanding of dynamical systems and control. Courses are provided at both undergraduate and graduate level, and the master's programme Systems, control and mechatronics is one of the largest programs at Chalmers.

Retrospectively, there has been numerous research projects related to process industry conducted at the Automatic control group. To exemplify the PhD-projects of Torsten Wik, Anders Karlström and Karin Eriksson, who all participated in the project that this report concerns, can be mentioned. The dissertation of Torsten Wik considered dynamic modelling of biofilm reactors; Anders Karlström considered an application in packed-bed distillation and Karin Eriksson considered the production process of thermomechanical pulp. In connection to these projects and applications there have been numerous other PhD and Licentiate projects at the group.

Torsten Wik is a professor in the Automatic control research group. The focus of his research and teaching is mainly on process control, involving methods and theoretical aspects as well as direct applications. Methods include optimal control, dynamic modelling of distributed parameter systems, model reduction, hysteresis and methods for systems with model uncertainties. The applications are in general energy saving, environmental and biological systems such as waste water treatment, re-circulating aquaculture systems (RAS), and LED lighting in greenhouses. Torsten is also involved in vehicle applications, aiming at reduced fuel consumption and increased use of electric propulsion. During a couple of years, 2005-2007, he worked as a senior researcher at Volvo Technology developing model based control systems for engine test cells and units combining catalytic diesel reformers and fuel cells for electricity production (today owned by Power Cell).

Anders Karlström has been adjunct professor at the Automatic control research group since 2011. During this period, as well as at his earlier positions, Anders has initiated and participated in a range of research and development project and program. His research interest covers on-line modelling approaches for use in process control and the related development of new measurement technologies needed for model verification. The specific applications, which can be exemplified by new process units in the oil industry and new biorefinery concepts related to the pulp and paper industry, have in common that process engineering and advanced process control should be simultaneously considered to obtain desired performance and profitability. Furthermore, Anders strongly promotes cross-disciplinary approaches incorporating collaboration and interaction between scientists and specialist in different fields as well as efforts to strengthen the collaboration between academia and industry.

2.3 CIT Industriell Energi

CIT Industriell Energi (CIT IE) is a consultancy and development company at Chalmers Industriteknik. CIT IE arose from, and has active knowledge exchange with, the chemical and energy technology research environment at Chalmers University of Technology. CIT IE has developed extensive competence within industrial energy efficiency and related policy measures, process integration, technical analyses and syntheses of technical information and international collaboration within all these areas. During the last ten years, the organization has also broadened its experience substantially within areas such as strategic energy planning, project management, research-industry-policy networking, and dissemination and communication of technical information.

Projects at CIT IE

CIT IE conducts projects in collaboration with academia, industries and governments in which systematic analyses of complex energy systems and energy techniques are performed. The analyses will:

- identify economically and functionally advantageous solutions
- highlight consequences for the environment, energy, and economics due to different development alternatives
- formulate bases for action plans and decisions
- include advanced energy-engineering calculations.

Projects with both short term and long term perspectives are conducted. The short term project can consider direct implementation of results and readily applicable measures by means of

- Expertise for government authorities and industries
- Energy efficiency
- Identification and usage of excess heat
- Analysis of alternative process lay-outs
- Process control
- Energy management

The long term projects consider systems perspectives, new process paths and products. Here, the areas of bio-refineries and fossil free fuels can be mentioned, as well as the development of legislative instruments for industrial energy usage.

The following list reflects recent and ongoing project activities:

- Management of the Swedish Knowledge Centre for Renewable Transportation Fuels, f3
- Secretariat for IEA Industrial Energy-related Technologies and Systems (IETS)
- Technical expertise in projects within the Chalmers-Preem collaboration (in Chalmers Energy area of Advance)
- Implementation of the EU energy efficiency directive - Energy audits and energy management systems
- Total site analysis for the cluster of chemical industries in Stenungsund
- Vinnova financed project Skogskemi (Forest chemistry) for development of sustainable chemicals and materials
- Possibilities for improved energy efficiency in wood refining processes by use of process control
- Process analysis of implementation of Chemical Looping Combustion for CO_2 capture
- Supervision of PhD-projects

3 ESTABLISHMENT OF THE RESEARCH AREAS: RESEARCH GROUPS AND LITERATURE

This section presents a few research groups and a book that have been strongly involved in the establishment of the research fields "plantwide control", "integrated design and control" and "heat exchanger network control". The research groups are heavily cited in literature. The book contains chapters written by various researchers with experience of integrated design and control and covers a wide range of research topics in that field and is therefore an important reference work.

3.1 Center for process modeling and control, Leigh University

This center is part of the department of Chemical Engineering at Lehigh University, Bethlehem, US. It is a co-operative Industry-University center that was founded in 1985. The mission of the center is to collaborate with industrial partners for their benefit through the application and advancement of research in the areas of model development, dynamical systems analysis and control, design, synthesis, and development of a broad range of manufacturing process systems.

The co-director of the center is Professor William L Luyben. He is an authority in the field of process control and he expresses special research interest in recycle system and in design and control of coupled reactor-column processes. Regarding dynamics, design and control of recycle systems he has produced numerous well-cited papers during the 1990´s and 2000's. In the last ten years Luyben has been very productive with publications of a more application specific nature, in which earlier developed analysis tools are utilized.

Examples of publications by W.L. Luyben and co-workers at Lehigh University and some comments on their content:

Luyben, W. L. (1993a). Dynamics and control of recycle system: 1. Simple open-loop and closed-loop system, *Industrial Engineering and Chemistry Research, 32*, 466-475.

Luyben, W. L. (1993b). Dynamics and control of recycle system: 2. Comparison of alternative process designs, *Industrial Engineering and Chemistry Research, 32*, 476-486.

Luyben, W. L. (1993c). Dynamics and control of recycle system: 3. Alternative process designs in ternary system, *Industrial Engineering and Chemistry Research, 32*, 1142-1153.

The above series of paper

- illustrates some dynamic phenomena that occur in recycle systems
- shows recycle system with conditional stability
- compares different designs with focus on plant-wide effects of recycle
- discusses how the choice of design parameters affect the process dynamics
- proposes a variable-volume control strategy of the reactor to eliminate what is referred to as "the snowball effect", i.e. the large amplification of disturbances in the recycle flow rate
- proposes a generic rule for recycle systems: one flow rate somewhere in the recycle loop should be flow controlled

Luyben, M. L., Tyreus, B. D., & Luyben, W. L. (1997). Plantwide Control Design Procedure. *AIChE Journal, 43*(12), 3161-3174.

- Describes a nine-step procedure for plantwide control design
- Applies the procedure to three different, fairly complex, processes

- "Plantwide control involves the systems and strategies required to control an entire chemical plant consisting of many interconnected unit operations."
- "the fundamental principles of plantwide control: energy management; production rate; product quality; operational, environmental and safety constraints; liquid-level and gas-pressure inventories; makeup of reactants; component balances; and economic **or** process optimization."

Georgakis, C., Uztürk, D., Subramanian, S., & Vinson, D. R. (2003). On the operability of continuous processes. *Control Engineering Practice, 11*(8), 859-869.

- Provides a literature review on operability analysis (emphasize on theoretical measures)
- Steady-state operability framework with terms like operability index, available input space, available output space, desired input space, desired output space, expected disturbance space
- Dynamic operability: extension of the above, dynamic desired operating space, dynamic achievable operating space
- Visualizations with regions in plots

Link to the center website:
http://www.che.lehigh.edu/blog/2007/01/center_for_process_modeling_an.html#more

3.2 Norwegian University of Science and Technology (NTNU) Norway

At NTNU there is one research group that is a major player in the field of process integration (Industrial Process Technology, Department of Energy and Process Engineering) as well as a strong group in process control (Process Systems Engineering, Department of Chemical Engineering). Connected to these two are also other technical institutes in Norway (Telemark Institute of Technology, Porsgrunn and Institute for Energy Technology, Halden). In addition, they have a close collaboration with SINTEF which is the largest research institute in Scandinavia. Worth noting is also that the Process control group, in difference to the organization at Chalmers, belongs to the Chemical Engineering department, while the Process integration group belongs to the department of Energy and Process Engineering.

Truls Gundersen and Sigurd Skogestad lead these two research groups which have had a well-established cooperation, at least during the 1990's. The main results of that cooperation were to doctoral theses on the topic of Heat exchanger network control and dynamic modelling: Mathisen's (supervised by Skogestad with Gundersen as a co-supervisor) and Glemmestad's (supervised by Gundersen with Skogestad as a co-supervisor).

With a general objective of developing a systematic procedure for plantwide control from process design to regulatory control the research topics include:

- Degrees of freedom analysis that has later formed the basis for others work on controllability of heat exchanger networks (see e.g. Section 5.1).
- Control structure selection based on controllability analysis.
- Guidelines for design of good control structures.
- Optimal operation of HENs for given design and control structure.
- Studies developing or applying the concept of self-optimizing control.

There does not seem to be any ongoing collaboration between the groups. The group of Skogestad has a few current and recent projects of interest (see Section 5.1), but not with a direct application to energy.

Publications:

Mathisen, K. W., Skogestad, S., & Wolff, E. A. (1992). Bypass selection for control of heat exchanger networks. *Computers and Chemical Engineering, 16*(1), S263-S272.

Mathisen, K.W. (1994). Integrated design and control of heat exchanger networks. PhD thesis, Norwegian University of Science and Technology, Norway.

Glemmestad, B., Mathisen, K. W., & Gundersen, T. (1996). Optimal operation of heat exchanger networks based on structural information. *Computers and Chemical Engineering, 20*(SUPPL.2), S823-S828.

Glemmestad, B., Skogestad, S., & Gundersen, T. (1997). On-line optimization and choice of optimization variables for control of heat exchanger networks. *Computers and Chemical Engineering, 21*(SUPPL.1), S379-S384.

Glemmestad, B., Skogestad, S., & Gundersen, T. (1999). Optimal operation of heat exchanger networks. *Computers and Chemical Engineering, 23*(4-5), 509-522.

Glemmestad, B. (1997*). Optimal operation of integrated processes – Studies on Heat Recovery Systems*. PhD Thesis, Telemark Institute of Technology, Norway

3.3 Center for Advanced Process Control Norwegian University of Science and Technology (CAPD) Carnegie-Mellon University,

Carnegie Mellon University (CMU) has been a major contributor to the introduction of computer and systems technology into process engineering.

Early interdisciplinary collaboration within the University, with significant participation by chemical engineers led to the development of core methodologies for Process Systems Engineering, such as optimization algorithms and formulations and operations research methods.

Today, the Center for Advanced Process Decision-making (CAPD) provides an umbrella organization for interactions with industry in the Process Systems Engineering area. Companies that are currently members of CAPD include: ABB, AspenTech, Bayer, BP, Dow, Eastman, ExxonMobil, GAMS, Honeywell, IBM, Kraft, Neste Eng., Petrobras, and Total. The CAPD consortium was recently renamed the Center for Advanced Process Decision-making (previously Computer-Aided Process Design). Research efforts within the CAPD have led to strategies and tools for process design and operations such as: commercially available mathematical programming software, design strategies for process synthesis, advanced modeling environments for process simulation and analysis, and management of the entire design process.

Currently, the research activities are in the areas of process synthesis and analysis, process operation, process planning, and scheduling. Moreover, process control has become an active area of research.
The center has been active in the field of process integration since its early expansion through Professor Ignacio Grossman. However, the research in Process Systems Engineering at CMU is strongly relying on mathematical models and tools. As such the CAPD research center has been an important contributor to the development also in the Optimization community, but has no real connection with the heuristic and graphic method of Pinch Technology that is the core process integration method used at Heat and Power Technology at Chalmers.

Link to the center website: http://capd.cheme.cmu.edu/index.html

3.4 The integration of process design and control

A wide yet comprehensive discussion on the challenges involved when considering process design and process control is given in the following textbook

Seferlis, P., & Georgiadis, M.C. (Eds.) (2004): ***The Integration of Process Design and Control***, Amsterdam, The Netherlands, Elsevier.

The book is published by Elsevier as part of the series Computer Aided Chemical Engineering. It includes 24 papers from invited researchers organized into four different parts:

A. Process characterization and controllability analysis
B. Integrated process design and control – Methods
C. Plantwide interactions of design and control
D. Integrated process design and control – Extensions

The different papers provide literature reviews, theoretical definitions, descriptions of methods and frameworks as well as discussions on practical considerations together with relevant industrial examples. In the preface the editors expresses their aim of bringing together the developments in a variety of topics related to the integrated design and control. We believe that this is successfully accomplished and that selected parts of the book would be of interest for any engineer, practitioner or researcher that whose work relates to the area.

For this project, selected part of this textbook was studied. Some of these are listed below together with selected citations and comments.

Seferlis P. and Georgiadis M.C.: The integration of process design and control – Summary and future direction

"The integration of process design and control aims at identifying design decisions that would potentially generate and inherit possible trouble to the dynamic performance of the control system. Furthermore, it aims at exploiting the synergistic powers of a simultaneous approach to ensure the economical and smooth operation of the plant despite the influence of disturbances and the existence of uncertainty."

"The simultaneous design and control involves decisions that will carefully balance multiple competing objectives. Operational specifications arising from environmental protection and energy savings requirements needs to be directly associated with the design problem."

"It is quite obvious that the main research trends will be towards a higher degree of integration dictated by the need for increased competitiveness in a fast changing business environment. Integration of energy, safety, and environmental issues will be necessary to satisfy tighter quality assurance specifications in a plant-wide basis."

"Opportunities for further process integration and intensification in existing plants will be persistently sought. Greater interaction with planning and scheduling levels in the company is also expected leading to issues related to supervisory control of expandable plants and the ability to manage efficiently large manufacturing systems."

"The design of flexible plats and units that can quickly and efficiently absorb and utilize technological innovations, and adapt to varying product specifications reflecting customer demand set the new frontier in the integration of design and control."

Alhammadi H.Y. and Romagnoli J.A.: Process design and operation Incorporating environmental, profitability, heat integration and controllability considerations

In this paper, the below figure is presented and in relation to this the following is stated:
"There is a lack of work that looks at integrating the four objectives, economical, environmental, process integration and operational, simultaneously. This area of integrated design procedure remains an open and challenging research field. "

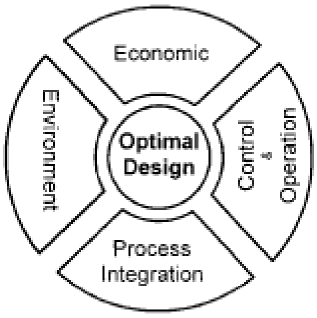

Figure: Relevant objectives in design and operation

"In general, the success of an integrated design is measured based on the agreement with its ability to be controlled and operated safely and profitably. Therefore, a systematic procedure is required to evaluate the controllability issues of the integrated designed processes."

Furthermore this paper stresses the need for multi-objective optimization and usage of process modeling and simulation for validation and testing performance (both steady state and dynamic). A plant-wide process control and dynamic modeling framework, originally formulated by Luyben and co-workers, is proposed. The procedure is demonstrated for a case study for a vinyl chloride monomer plant and it follows the general steps listed below:

1. Establish control objectives
2. Determine control degrees of freedom
3. Establish energy management system
4. Set production rate
5. Control product quality and handle safety, operational and environmental constraints
6. Fix a flow in every recycle loop and control inventories
7. Check component balances
8. Control individual unit operations
9. Optimize economics or improve dynamic controllability

"There are inherent uncertainties associated with both the plant model as well as the environmental model. Designing chemical processes under uncertainty has been a common class of problems in synthesis and design and has received considerable attention in recent years. A natural extension in the formulation proposed in this thesis is the incorporation/addition of uncertainty in the formulation of the optimization problem. This, however, would naturally increase the computational complexity as the presence of uncertainty would lead to semi-infinite optimization problems."

Carlemalm H.C. and Jacobsen E.W.: Design for controllability of integrated plants

This paper stresses that “controllability concerns the ability to provide acceptable dynamic performance of a process system by means of feedback control, and is a property of the process itself only”, “controllability is independent of the control system, and a property of the process only.”

“If there exist a conflict between the required and achievable performance, this conflict can only be resolved by modifying the process design.”

It describes an approach to separate dynamics resulting from interactions from those that can be attributed to single process units only as a strategy when analyzing existing plants.

Luyben M.L.: Design of industrial processes for dynamic operability

[….] “controllability and control strategy design should not be simply an afterthought of the process design. Further, this viewpoint believes well-designed processes (in a way that inherently eliminates variability) can often be controlled by relatively simple, straightforward, decentralized control strategies that are robust, easily understood by operators and plant engineers, and easily maintained. It seeks to avoid poorly designed processes that need "advanced" control schemes that too often turn out to be complicated and fragile, are not understood by operators and plant engineers, and require constant attention and maintenance.”

“Luyben et al. [3] published a nine-step procedure to aid in the design of the regulatory control strategies for a complex integrated process that hold the system at the desired operating condition (called plantwide control). The plantwide control structure must take into account the effects of material recycle, energy integration, and the inventory of the chemical components, which are commonly not issues when focusing on the control of an individual unit operation. From this perspective, five major objectives can be listed for any plantwide control system:

- stabilize the process
- cope with imposed constraints (safety, environmental, equipment, operational)
- balance the inventory of material and energy
- satisfy the economic objectives (including on-aim product quality) of the plant
- control the recycle structure”

“There is no general mathematical algorithm or approach that can be used for all processes since they have different issues, requirements, constraints, technologies, etc. The complexity of real processes prevents us from being able to come to a single solution. What is important is the process understanding and insight required to do an effective analysis. Without such understanding, any approach (based on heuristics or rigorous optimization) will have only limited effectiveness. Although some general understanding exists about how process design affects controllability and product variability, future academic research can certainly provide training and develop methodologies that better quantify such interaction.”

Skogestad S.: Integration of optimal operation and control

“It should also be noted that many plants are not operated at the conditions they were designed for. The reason is that the economic conditions are often such that it is optimal to operate the plant at higher capacity than what it was designed for. This usually involves operating one or more units at capacity constraints, and the active constraints may change on a daily basis, or as various units are "debottlenecked". In any case, this means that one needs to rethink the control strategy, so in most plants there will be an ongoing need for interactions between the design and control people.”

4 RELEVANT ACTIVITIES IN SWEDEN

In the beginning of 2012, a number of organizations and stakeholders, including Kempestiftelserna, ABB, Boliden, LKAB, SCA, SSAB and ProcessIT Innovations, presented a report with the English title "National pooling of resources for Industrial Process Automation" (Swedish title: Nationell kraftansamling för Processindustriell Automation". The work behind the report was partly financed by VINNOVA within the program "Strategiska innovationsområden-Agendor" (English translation: Strategic innovation areas – Agendas).

In the report summary it is written: *"we are proposing an agenda where we:*

1. *Establish an industrial national leadership and a national collaboration platform for the area.*
2. *Coordinate projects and networking activities with university and college based RDI environments that are identified as particularly strong and relevant to the area.*
3. *Coordinate and implement combined skills development initiatives with both business community and research partners.*
4. *Make substantial investments in National RDI programs in this area.*

To make a difference in the long term and fulfil the vision of the agenda is of key importance to the implementation of a major investment in national RDI programs. The investments that are based on assessments made within the scope of this work involve government investments of about SEK 200 million per year with a corresponding funding amount from industry/the business community."

The report has an appendix in which an overview of RDI environments, clusters and initiatives within the area of process industrial automation is presented. Focus in this overview is on Sweden and activities in for example universities, institutes, science parks and different organizations are listed and commented on. Relevant RDI environment in our neighbor countries are also given besides a number of examples of other international environments.

The information presented in the report and its appendices is relevant also for this project as it presents activities in the field of control (automation) in process industries. It stresses the need for a closer collaboration between process design and process control, clearly on line with the views and statements that are highlighted in this report. Moreover, among the expected benefits of the collaboration within the suggested program, clearly energy related issues are highlighted like improved efficiency in production processes and long-term involvement in the development of sustainable and efficient solutions for the climate challenges of the future.

Rather than repeating all the information, we refer to the other report with its appendices that can be downloaded from this web-site: http://processindustriellautomation.se/?page_id=22. The report is available in both English and Swedish, while the appendix section is in Swedish only and with some parts in English.

On the website it is described that after the report on the agenda had been presented, the project has applied and received grants for the next step which had the objective to establish the proposed program. That work has been carried out during 2013 but has not yet been reported on. However, in relation to this the following press release from June 2013, the decision by VINNOVA, Energimyndigheten and Formas to support this program and four others is expressed:

http://www.vinnova.se/sv/Aktuellt--publicerat/Pressmeddelanden/2013/130627-Miljardsatsning-for-att-starka-Sveriges-konkurrenskraft/

Specifically, with regards to the program on Industrial Process Automation, the following is stated (translated from Swedish): *IT and Automation for industrial process is an area where several Swedish companies have world leading positions on development, delivery, integration and usage of technology. The goal is that in 2022 Sweden is to be recognized as world leading for development and usage of innovative and competitive solutions within the area. The project is led by Luleå Tekniska Universitet (grant recipient SICS, Swedish Institute of Computer Science)*

5 International research groups of special interest

This section presents a number of research groups that are currently active in the field. Groups have been selected based on the interest of their research topics or for having organizations that are inspiring as collaborative research environments.

5.1 Process control group, Process Systems Engineering, NTNU, Norway

The process control group led by Sigurd Skogestad is part of the Process Systems Engineering Group at the Department of Chemical Engineering, NTNU, Trondheim (see Section 3.2).

The research group is part of the 40-member Strong Point Center in Process Systems Engineering in Trondheim, PROST. PROST consists of people from Chemical Engineering, Electrical Engineering and Mechanical Engineering (both at NTNU and SINTEF) and is the second largest process systems engineering center in Europe (after Imperial College). At least, this has been the case until 2010. Today, PROST is focused more specifically on process control and lives on in the form of a so-called Gemini-center in co-operation with SINTEF.

Examples of research areas:

- Plantwide control and optimization (including self-optimizing control)
- Controllability of processes (achievable control performance)
- Control structure design (including decentralized control)
- Model-based control system design

Research in the 90's involved the collaboration with Truls Gundersen's group in process integration that was described in Section 3.2.

Following the period of that collaboration, Skogestad's group has continued with their contributions to plantwide control studies. To summarize, lately there has been an increase in applications and development of the self-optimizing control concept, which is established by the group (see publication list below). Based solely on the paper titles, there is no direct connection to energy, but parallels to process integration are probably indirectly present in many of the studies anyway.

Larsson, T., and Skogestad, S. (2000). Plantwide control - a review and a new design procedure. *Modeling, Identification and Control*, 21(4), 209-240.

Skogestad, S. (2000). Plantwide control: The search for the self-optimizing control structure. *Journal of Process Control*, 10(5), 487-507.

Skogestad, S. (2000). Self-optimizing control: The missing link between steady-state optimization and control. *Computers and Chemical Engineering*, 24(2-7), 569-575.

Skogestad, S. (2002) Plantwide control: Towards a systematic procedure. *Computer Aided Chemical Engineering*, Vol. 10 (pp. 57-69).

Lersbamrungsuk, V., Srinophakun, T., Narasimhan, S., & Skogestad, S. (2008). Control structure design for optimal operation of heat exchanger networks. *AIChE Journal*, *54*(1), 150-162.

Downs, J. J., & Skogestad, S. (2011). An industrial and academic perspective on plantwide control. *Annual Reviews in Control*, 35(1), 99-110.

Link to website of Process control group of Skogestad:
http://www.nt.ntnu.no/users/skoge/prost/Process_Control/

5.2 Industrial Information and Control Centre (I2C2), University of Auckland

There has been a close collaboration between a group of researchers at the Department of Chemical and Materials Engineering at University of Auckland and the Department of Chemical and Petroleum Engineering, University of Calgary, Canada. This collaboration also involves people at Aspen Technology (former AEA Technology-Hyprotech that later were merged into the Aspen suite) and at Jacobs Canada.

A number of interesting papers have been published within this Auckland-Calgary research group. A reason for the interest is that Aspen is involved, which suggests that the methods presented in the papers are likely to be (or already are?) implemented in commercial software.

Research topics are centered on controllability analysis of heat exchanger networks, e.g.:

- Easily calculated measures of controllability to be used in conceptual design phase
- Screening process using controllability measures to determine a more controllable HEN
- Heuristic rules to be used in the design phase to achieve controllable HENs
- Determination of failure possibility (HEN resiliency) and hence need for modification in design or strengthened control system requirement.

It is also worth mentioning that the work of Westphalen (Calgary) on a controllability index for heat exchanger networks is largely based on the degrees of freedoms analysis developed at NTNU (see Section 3.2)

Disregarding a few later contributions from Munir (see below), the last article from this specific research collaboration and research area is from 2008. At the University of Calgary, there does no longer seem to be any significant activity within the field.

The unifying link between Auckland and Calgary seem to be Professor Brent Young, who is Professor at University of Auckland, but also Adjunct professor at Calgary where he previously was Associate professor. He is also Director of the Industrial Information and Control Centre at University of Auckland (see below).

Energy and Environment, Department of Chemical and Materials Engineering, University of Auckland

"In the area of oil & gas processing, the technical focus is on the development of energy management tools for eco-efficient design, operation and control. […] and also the application of the fundamental thermodynamic concept exergy for determining the energy efficiency and controllability of processes for sustainability. Partners in this work include the University of Calgary […]. At an economic level, we are also interested in risk based economic options for sustainable energy generation in New Zealand and collaboration exists with the Faculty of Business."

Industrial Information and Control Centre (I2C2), Faculty of Engineering, University of Auckland

"Automatic control, plant-wide management of production and resources, and process simulation play a major role in New Zealand's future. Our ability to compete globally can be boosted by the enhanced management of processes and resources and more efficient energy utilization, the result of turning data into industrial information for control. […] a national focal point for research, postgraduate study, graduate training, continuing education and industry consultation in industrial information and control."

Selected ongoing projects at I2C2:

- Exergetic, eco-efficient process control.
- Modelling of integrated energy generation.
- Model predictive control, optimization & steam utility modelling.

Publications

Earlier contributions in Auckland-Calgary co-operation:

Westphalen, D. L., Young, B. R., & Svrcek, W. Y. (2003). A controllability index for heat exchanger networks. *Industrial and Engineering Chemistry Research*, 42(20), 4659-4667.

Tellez, R., Svrcek, W. Y., & Young, B. R. (2006). Controllability of heat exchanger networks. *Heat Transfer Engineering*, 27(6), 38-49.

Young, B. R., Tellez, R., & Svrcek, W. Y. (2006). Towards integrated process and control system synthesis for heat-integrated plants. *Canadian Journal of Chemical Engineering*, 84(2), 219-229.

Young, B. R., Westphalen, D. L., & Svrcek, W. Y. (2006). Heat exchanger network dynamic analysis. *Developments in Chemical Engineering and Mineral Processing*, 14(3-4), 505-514.

Tellez, R., Svrcek, W. Y., Ross, T. J., & Young, B. R. (2006). Heat exchanger network process modifications for controllability using design reliability theory. *Computers and Chemical Engineering*, 30(4), 730-743.

Later contributions from Auckland:

Munir, M. T., Yu, W., & Young, B. R. (2013). The relative exergy-destroyed array: A new tool for control structure design. *Canadian Journal of Chemical Engineering*.

Munir, M. T. (2012). *The development of a controllability index based on RGA and exergy for plant-wide control problems*. PhD thesis, University of Auckland, New Zealand.

Link to website of Energy and Environment, Department of Chemical and Materials Engineering, University of Auckland:
http://www.ecm.auckland.ac.nz/uoa/home/about/our-research/research-areas/energyandenvironment

Link to website of I2C2, University of Auckland: http://www.i2c2.auckland.ac.nz/uoa/

5.3 Computer Aided Process Product Engineering Center (CAPEC), Technical University of Denmark

CAPEC was founded in 1997 by professors Rafiqul Gani and Sten Bay Jørgensen. The activities at the center are development of computer aided systems for chemical and biochemical product-process modelling/simulation, synthesis, design, analysis and control/operation for chemical, petrochemical, pharmaceutical, agrochemical, and food and biochemical industries. Professor Gani is Director of the center.

The research interest of the center includes the following topics:

- Modelling of chemical processes and their operations, chemical products and their behavior/properties
- Synthesis, design and analysis of chemical products and their processes
- Process integration (sustainable process design)
- Tools integration and software architecture
- Design and analysis of chemical processes including nonlinear analysis; batch processes and bio-reactors
- Control of chemical and biochemical process and product operation
- Process Integration, i.e. efficient usage of materials and energy for ensuring environmentally benign and sustainable processes and products

Examples of publications and comments on their content:

Li, H., Gani, R., & Jørgensen, S. B. (2003). Process-insights-based control structuring of an integrated distillation pilot plant. *Industrial and Engineering Chemistry Research, 42*(20), 4620-4627.

- Identifying a set of variables that have important roles in design as well as in control structure definition
- Purpose of optimizing control by exploiting interactions between plant design and control
- Refers to Russell at al 2002 for description of the model analysis approach used

Alvarado-Morales, M., Hamid, M. K. A., Sin, G., Gernaey, K. V., Woodley, J. M., & Gani, R. (2010). A model-based methodology for simultaneous design and control of a bioethanol production process. *Computers and Chemical Engineering*, *34*(12), 2043-2061

- two methodologies for simultaneous design of process and control system are presented:
- the integrated process design and controller design (IPDC) methodology
- the process-group contribution (PGC) methodology
- tests methods on two case studies
- evaluated in terms of energy consumption

Yuan, Z., Chen, B., Sin, G., & Gani, R. (2012). State-of-the-art and progress in the optimization-based simultaneous design and control for chemical processes. *AIChE Journal, 58*(6), 1640-1659.

- comprehensive review paper written together with Yuan and Chen from Tsinghua University in Beijing (see Section 6.4)
- simultaneous plant-wide process design and control is defined as the development of a plant-wide process by considering both steady-state economics and dynamic operability at all stages of flow sheet synthesis
- process design decisions define the inherent process and the control performance of the chemical process
- the economic optimization was defined as a function of design variable, model parameters and external specified disturbances to minima the process cost

- Classifies different methods, for example
    - controllability index approaches
    - Mixed integer dynamic optimization-based approach: here, the simultaneous design and control problem is cast as a mixed integer dynamic optimization problem where discrete (flow sheet topology structures, number of control loops) and continuous variables (design/operating parameters, controller tuning parameters etc.) are incorporated into a single optimization framework
- Classifies studies under five different themes depending on their solution approach, these are illustrated and discussed

Suggestions for future work given in this review paper:

"There is a strong need for new methodological and engineering approaches that ensure efficient, predictable, safe and secure behavior of large-scale highly nonlinear systems."

"the use of the advanced control is especially attractive since once multivariable controllers are used the control structure selection step may not be necessary"

"in order to further bridge the gap between the theoretical development and industrial development requirements, and substantially, the application of optimization-based simultaneous design and control frameworks for highly nonideal and realistic industrial plant-wide process should be given more emphasis."

"It is hoped that this article will stimulate future academic researchers and industrial practitioners with the research in developing fundamental theory, optimization-based frameworks and commercial computational tools for process design and process control design simultaneously."

Link to CAPEC website: http://www.capec.kt.dtu.dk/

6 SOME EXAMPLES OF OTHER INTERNATIONAL RESEARCH GROUPS

6.1 *Research institute of automation, China University of Petroleum, Beijing*

At this University there is emphasis on chemical process engineering, but it has also other faculties. There is a Department of Automation and a Research institute of automation which are part of the Faculty of mechanical and electronic engineering. The information provided on their website is however sparse and no project descriptions are provided.

According to publication search in databases, there are ongoing or recent research activities in control with application to heat exchanger network. A couple of publications from 2013 have been studied and their features can be summarized as

- Considers control of the network by selection of by-pass location and by-pass adjustment
- States that both controllability and capital investments are considered
- Uses the term structural controllability and non-square (ns) RGA
- Refers also to a paper on structural observability, but this is in Chinese

Publication examples:

Luo, X., Xia, C., & Sun, L. (2013). Margin design, online optimization, and control approach of a heat exchanger network with bypasses. *Computers and Chemical Engineering*, *53*, 102-121.

Sun, L., Luo, X., Hou, B., & Bai, Y. (2013). Bypass selection for control of heat exchanger network. *Chinese Journal of Chemical Engineering*, *21*(3), 276-284.

Link to the university website: http://department1.cup.edu.cn/~waisb/cupb.htm

6.2 *National University of Singapore*

At the Department of Chemical and biomolecular engineering, Chemical Engineering Science at National University of Singapore there are researchers working on plant-wide control for chemical processes. The leading person seems to be Professor Gade P. Rangaiah. In relation to his research interest the following is stated

- Works in progress include multi-objective optimization of bio-fuel processes, heat exchanger networks, petroleum refining and polymerization reactors
- Plant-wide control perspective is essential to address the challenges in controlling chemical processes with material and energy recycles. We developed an integrated framework for plant-wide control and successfully applied it to selected processes.

Heat and Power Technology at Chalmers has established contacts with this group after that Simon Harvey spent a teaching sabbatical there during the autumn 2012. During that period he gave a course together with Professor Rangaiah, who co-authored many of the papers cited below.

Examples of publications:

Konda, N. V. S. N. M., Rangaiah, G. P., & Krishnaswamy, P. R. (2005). Plantwide control of industrial processes: An integrated framework of simulation and heuristics. *Industrial and Engineering Chemistry Research, 44*(22), 8300-8313.

Konda, N. V. S. N. M., Rangaiah, G. P., & Lim, D. K. H. (2006). Optimal process design and effective plantwide control of industrial processes by a simulation-based heuristic approach. *Industrial and Engineering Chemistry Research, 45*(17), 5955-5970.

Konda, N. V. S. N. M., & Rangaiah, G. P. (2007). Performance assessment of plantwide control systems of industrial processes. *Industrial and Engineering Chemistry Research, 46*(4), 1220-1231.

Vasudevan, S., & Rangaiah, G. P. (2010). Criteria for performance assessment of plantwide control systems. *Industrial and Engineering Chemistry Research, 49*(19), 9209-9221.

Vasudevan, S., & Rangaiah, G. P. (2011). Integrated framework incorporating optimization for plant-wide control of industrial processes. *Industrial and Engineering Chemistry Research, 50*(13), 8122-8137.

Link to professor Rangaiahs website: http://www.chbe.nus.edu.sg/people/faculty_rangaiahgp.html

6.3 Centre for Process Systems Engineering (CPSE), Imperial College, UK

CPSE is probably the largest centre for Process Systems Engineering worldwide. The centre members are researcher from both Imperial College and University College in London. CPSE is a good example of a research centre which is a collaboration between several universities and is closely connected to an industrial consortium.

During the 90's primarily, CPSE conducted research within the field of design and control of heat exchanger networks. It is, however, difficult to find any ongoing projects that are directly connected to industrial energy use in combination with considerations to operation and control. Today, their research in the field concern more general methods for optimization of industrial processes, with regard to design (also retrofit) and operation. The methods are more or less exclusively based on advanced mathematical programming models with an emphasis on the solution of the optimization. Even if the research within the centre covers a broad spectrum of design and control issues, to the major part it seems to concern either operation and control or design and supply chain management, without much integration of the two fields.

Professor Pistikopoulos is the author behind most of the papers from CPSE that are relevant for us. They are on the topic of synthesis of HENs including their control structure, considering flexibility, structural controllability and dynamics. Pistikopolous is still active and on his webpage his research interests are described.

"The objective of my research programme is to develop fundamental theory and optimization based methodologies and computational tools that enable process engineers to analyze, design and evaluate process manufacturing systems which are **economically attractive**, **energy efficient** and environmentally benign, while at the same time exhibit good performance characteristics like **flexibility, controllability,** robustness, reliability and safety. Our research involves three main strands:

- Process synthesis and the environment: Here we are concerned with the development of process integration and pollution prevention strategies for the design and operation of plant-wide sustainable processes. […]
- Integration of operability objectives in process design and operation: Our work here has centered on the development and implementation of novel analytical tools to simultaneously assess process flexibility, controllability, robustness, reliability and availability of complex process manufacturing systems and the systematic incorporation of these tools at the design and operational level.
- Process optimization under uncertainty - theory, algorithms and applications: […] "

However, it is difficult to find any ongoing project that actually fits the descriptions above.

Publications:

Papalexandri, K. P., & Pistikopoulos, E. N. (1994). Synthesis and retrofit design of operable heat exchanger networks. 1. Flexibility and structural controllability aspects. *Industrial and Engineering Chemistry Research, 33*(7), 1718-1737.

Papalexandri, K. P., & Pistikopoulos, E. N. (1994). Synthesis and retrofit design of operable heat exchanger networks. 2. Dynamics and control structure considerations. *Industrial and Engineering Chemistry Research, 33*(7), 1738-1755.

Papalexandri, K. P., & Pistikopoulos, E. N. (1994). Synthesis of cost optimal and controllable heat exchanger networks. *Chemical Engineering Research and Design*, *72*(A3), 350-356.

Gao, W., Yang, Y., & Pistikopoulos, E. N. (2003). Retrofit and control of heat exchanger networks. *Huagong Xuebao/Journal of Chemical Industry and Engineering (China), 54*(7), 965-971.

Link to CPSE website: http://www3.imperial.ac.uk/centreforprocesssystemsengineering

6.4 Process Systems Engineering, Tsinghua University, Beijing, China

At Tsinghua, Process Systems Engineering is an area of research under the Department of Chemical Engineering. The group has a collaboration with CAPEC in Denmark (see Section 0).
Researchers from Tsinghua have quite recently published papers on the topics about controllability of chemical processes that we are interested in. They propose a systematic method, discuss the influence of a higher degree of process integration on controllability, and conduct case studies. Note the recent review papers (from 2011 and 2012).

The papers illustrate an approach for how to clarify the roots of the poor controllability that arise in the design and operation of a large scale chemical process. They provide guidance both for deciding the optimal operation conditions and selecting the most suitable control structure. One paper outlines, reviews and discusses the main methodologies developed for controllability analysis and improvement of controllability. The papers also include definitions and explanations of various concepts such as operability, flexibility, dynamic resilience, functional controllability.

Publications:

Yuan, Z., Chen, B., & Zhao, J. (2011). Effects of Manipulated Variables Selection on the Controllability of Chemical Process. *Industrial & Engineering Chemistry Research*. 50, 7403-7413.

Yuan, Z., Chen, B., & Zhao, J. (2011). An overview on controllability analysis of chemical processes. *AIChE Journal*, 57(5), 1185-1201.

Yuan, Z., Zhang, N., Chen, B., & Zhao, J. (2012). Systematic controllability analysis for chemical processes. *AIChE Journal*, 58(10), 3096-3109.

Yuan, Z., Chen, B., Sin, G., Gani, R. (2012). State-of-the-art and Progress in Optimization based Simultaneous Design and Control for Chemical Processes. *AIChE Journal*. 58, 1640-1659.

Link to Department of Chemical Engineering, Tsinghua:
http://www.chemeng.tsinghua.edu.cn/en/default.jsp

6.5 University Politechnica of Bucharest, Romania

According to a translated version of the website for Department of Chemical and Biochemical Engineering at University Politechnica of Bucharest, there is a center called Centre for Technology Transfer in Process Industries (Centrul de Transfer Tehnologic pentru Industriile de Proces). This center is also mentioned in the affiliations of several publications. Unfortunately, no further information on activities or organization of this center is found and the only link provided will not work. An attempt to contact the center by email has been made, but at present no response has been obtained.

In publications found from data base searches it was shown that research projects have been carried out in cooperation with Akzo Nobel Research, Development and Innovation in the Netherlands, as well as with University of Amsterdam and Delft University of Technology.

Publication examples:

Dimian, A. C., Groenendijk, A. J., Kersten, S. R. A., & Iedema, P. D. (1997). Effect of recycle interactions on dynamics and control of complex plants. *Computers and Chemical Engineering, 21*(SUPPL.1), S291-S296.

Altimari, P., & Bildea, C. S. (2009). Integrated design and control of plantwide systems coupling exothermic and endothermic reactions. *Computers and Chemical Engineering, 33*(4), 911-923.

Bildea, C. S., & Kiss, A. A. (2010) Plantwide control of a biodiesel process by reactive absorption. *Computer Aided Chemical Engineering, Vol. 28* (pp. 535-540).

Kiss, A. A., and Bildea, C. S. (2011). Design and control of an energy integrated biodiesel process. In E. N. Pistikopoulos, M. C. Georgiadis & A. C. Kokossis (Eds.), *21st European Symposium on Computer Aided Process Engineering*, Vol. 29, pp. 186-190.

Nikačević, N. M., Huesman, A. E. M., Van den Hof, P. M. J., & Stankiewicz, A. I. (2012). Opportunities and challenges for process control in process intensification. *Chemical Engineering and Processing: Process Intensification, 52*, 1-15.

Link to the department website (Google translate version):
http://translate.google.com/translate?sl=auto&tl=en&js=n&prev=_t&hl=en&ie=UTF-8&u=www.chim.pub.ro

6.6 INTEC, Argentina

INTEC is an abbreviation for Institute of Technological Development for the Chemical Industry (El Instituto de Desarrollo Tecnológico para la Industria Química). The institute depends on the Universidad Nacional del Litoral and the National Council for Scientific and Technical Research, CONICET (Consejo Nacional de Investigaciones Científicas y Técnicas). Its purpose is to develop technology related to chemical processes, materials physics, computational mechanics and applied mathematics. They claim to give priority to projects of national importance, for example the use and conservation of natural resources. INTEC has also activities in training of researchers and technical level personnel. They collaborate with local industries in research and technology transfer.

The website is somewhat out-of-date as it refers to the year 2007 as today. At that point they had a staff of about 250 employees including 74 researchers and they had 126 research projects. According to the Spanish website, the organization has a group called Process control laboratory working in the following areas of predictive control applied to industrial processes, identification oriented MPC, and monitoring and statistical process control.

Publications linked to INTEC were studied. Some of these were on projects conducted together with researchers at Department of Chemical Engineering, University of São Paulo, Brazil. Some publication examples with comments on their contents are given below:

Aguilera, N., Marchetti, J. L., & Marchetti, J. L. (1998). Optimizing and controlling the operation of heat-exchanger networks. *AIChE Journal*, *44*(5), 1090-1103.

- General goal: not lose steam temperature targets while keeping the highest energy integration
- Uses linear and non-linear programming techniques (LP, NLP)
- Associates the term controllability with short-term perturbations, stability, and safe transition from one operating point to another
- Assumes that all necessary heat exchangers, utility units, and the connecting structure are completely defined, as well as the heat-transfer areas
- Considers an objective function in terms of minimizing utility consumption or maximization of energy integration

Giovanini, L. L., & Marchetti, J. L. (2003). Low-level flexible-structure control applied to heat exchanger networks. *Computers and Chemical Engineering*, *27*(8-9), 1129-1142.

- Uses the term FSC = flexible-structure control scheme
- Considers combinations of by-passes and utilities and thereby form pairs of manipulated variables

González, A. H., Odloak, D., & Marchetti, J. L. (2006). Predictive control applied to heat-exchanger networks. *Chemical Engineering and Processing: Process Intensification*, *45*(8), 661-671.

- Presents a two level control structure:
  - Low level constrained MPC
  - High level supervisory online optimizer (real-time)
- States that the control variables in a HEN system are
  - Process stream bypasses around HE
  - Utility stream flow rates in service units
  - Splits of process streams
- MPC by quadratic programming (QP), steady-state optimization by NLP

González, A. H., Odloak, D., Marchetti, J. L., & Sotomayor, O. A. Z. (2006). Infinite horizon MPC of a heat-exchanger network. *Chemical Engineering Research and Design*, *84*(11 A), 1041-1050.

- Method taking both control objective and economic objective into account
- Coordinated decentralized MPC
- Assumes fixed structure of HEN
- Same control structure as the above
- States that there are usually more control inputs than outlet temperatures to be controlled, set of input values satisfying output targets is not unique
- Two-step optimization:
- first step determines the inputs that produce the lowest service-cost (steady-state)
- second step defines how to dynamically guide the process towards the optimal point

Link to INTEC website: http://www.intec.unl.edu.ar/en/

6.7 Process integration in the pulp and paper industry, Ecole Polytechnique, Montreal, Canada

The NSERC Environmental Design Chair – Process Integration in the Pulp and Paper Industry at Ecole Polytechnique in Montreal is held by Paul Stuart. The research is mainly applied to the pulp and paper industry and biorefineries integrated to pulp and paper mills. However, it covers a wide range of topics from life cycle analysis to process simulation, process integration and process control.

A former PhD student, Ilich lama, worked on the project "Plantwide Controllability Analysis of TMP-Newsprint Process", which is close to the topic of Karin Eriksson's PhD project. However, there is no close connection to energy efficiency.

There are good contacts between Paul Stuart's group at Ecole Polytechnique and Heat and Power Technology within the process integration area. During the spring 2013, a PhD student, Jean-Christophe Bonhivers, was here for two months as a visiting researcher. Also Paul Stuart has plans for coming here as a guest Professor for a couple of months. Another former PhD student, Matty Janssen, is now Assistant Professor at Environmental Systems Analysis (working with Life Cycle Analysis) at Chalmers and participates in several projects together with Heat and Power Technology.

Publications:

Lama, I., Perrier, M., & Stuart, P. R. (2003). Applying controllability techniques to analyze a white water network for improved productivity in integrated newsprint mills. Resources Conservation and Recycling, 37(3), 181-192

Link to NSERC Environmental Design Chair of Process Integration in the Pulp and Paper Industry, Ecole Polytechnique Montreal:
http://www.polymtl.ca/recherche/rc/en/unites/details.php?NoUnite=27

6.8 Process Systems Engineering, University of New South Wales, Sydney, Australia

The process control group at UNSW department for Process Systems Engineering has a lot of recent and ongoing research projects on plantwide process control considering interaction effects such as heat integration. The literature review did not identify a very big number of publications from this group. It could be a matter of terminology, or that the research is not yet resulting in accepted papers.

Examples of current/recent PhD projects (from their homepage):

- Dissipativity based Distributed Model Predictive Control for Complex Industrial Processes
  Based on the behavioral approach to systems and dissipativity theory, this project aims to integrate nonlinear control theory with distributed optimization to develop a novel distributed predictive control approach for complex industrial processes. In this approach, the global objectives (i.e., the plantwide stability and performance) are converted into the local constraints of dissipativity conditions for non-cooperative optimization performed in the distributed controllers. The outcomes will include a framework and the fundamental control theory for distributed autonomous model predictive control that achieves improved scalability, flexibility and robustness compared with existing distributed predictive control approaches.
- Plantwide Control of Modern Chemical Processes from a Network Perspective
  To achieve high economic efficiency, modern chemical plants are becoming increasingly complex, to an extent that cannot be effectively managed by existing process modelling and control techniques. By exploring the physical fundamentals in thermodynamics and their connections to control theory, this project aims to develop a new modelling and control approach that can be applied to complicated nonlinear processes. In this approach, processes

over the entire plant are analyzed and controlled from a network perspective using the dissipativity control theory. The outcomes of this project will form the cornerstones of a new process control paradigm that offers more robust and reliable process operation at any scale.

- A Behavior Approach to Optimization based Controller Coordination for Complex Process The complexity of plantwide chemical systems is steadily increasing, driven by the gain in economic efficiency offered by more complex and interactive plant designs. This project aims to develop a new framework of complex process control using coordinated optimization-based controllers. Control systems based on online optimization are often most suitable for complex systems and can be applied to a large ranges of control problems. An interaction analysis approach for plantwide complex processes and the stability conditions for coordinated controllers based on their historical behavior will be developed. This will lead to a new control approach that can be applied in many modern complex engineering applications including control of renewable energy networks.
- Dynamic Controllability Analysis for Plantwide Process Design and Control Based on the concept of passive systems, this project aims to develop a new quantitative measure for dynamic controllability for design of plantwide process systems. Integration of process design and control has been widely recognized as an effective approach to improving process performance to meet increased economic, safety and environmental demands. Controllability evaluation plays an important role in this approach. The outcome of this research will be an easy to use controllability analysis method for nonlinear plantwide multi-unit systems, which can be used in early stages of process design to explore better opportunities for process improvements. World-wide chemical plants represent many billions of dollars of investment. Improvements to the process designs in terms of controllability would have the potential to provide large economic benefits, as it implies improved productivity, reduced operating costs and product variability. This proposed research will be a step towards integration of process design and control, which has been widely recognized as the key to this improvement. […]

Publications:

Setiawan, R., & Bao, J. (2011). Analysis of Interaction Effects on Plantwide Operability. *Industrial & Engineering Chemistry Research, 50*(14), 8585-8602.

Link to website of Process Control group, UNSW:
http://www.ceic.unsw.edu.au/processcontrol/processcontrol.htm

6.9 Babes-Bolyia University, Cluj-Napoca, Romania

At Babes-Bolyai, the center for research on computer aided chemical engineering, there are ongoing project on control (MPC) of a heat integrated FCC process. Two rather recent PhD theses covers this topic:

Iancu (2010)"Advanced control of the heat integrated complex plants"

Roman (2007)"Mathematical modelling and advanced control of a fluid catalytic cracking process".

Besides looking at both heat integration and MPC control, it should be noted that they also consider retrofit applications.

The website is not available in English. From the literature search it is, however, possible to see that their most recent research is based on a quite long history of modelling (dynamic as well as process integration) of the FCC process specifically.

Publications:

Iancu, M., Cristea, M.V., & Agachi, P. S. (2013). Retrofit design of heat exchanger network of a fluid catalytic cracking plant and control based on MPC. *Computers and Chemical Engineering*, 49, 205-216.

7 RESEARCH QUESTIONS AND PROJECT IDEAS

A number of research questions can be formulated for introducing controllability, control system design, etc. on different stages into the applications of industrial energy systems. To make the following examples more clear, they consider the application of a heat exchanger network, HEN. However, a wider perspective on process integration involving a larger part of the industrial energy system could also be applied.

- CONTROL SYSTEM DESIGN
  How to design the control system of a HEN (the placement of bypasses, heaters and coolers, but also buffer tanks)?
- OPTIMAL OPERATION
  How to optimally operate a given HEN design (including a given control system design) for minimum energy use?
- CONTROLLABILITY ANALYSIS
  How to evaluate/compare controllability (operability) of different HEN designs (both with and without the placement of measurements and actuators given)?
- INTEGRATED DESIGN AND CONTROL
  How to design a HEN for good operability (flexibility and controllability)?

Most of these questions have been covered to various extents by others, but there are gaps remaining. From a review of our special competences, experience and interest, the following keywords can be listed:

- Retrofit
- Bio-based processes
- Pulp and paper industry
- Real life case studies
- Industrial co-operation
- Economic evaluation
- Simulation
- Scale up challenges

Therefore, it looks as an interesting opportunity to investigate the above questions for a real life case study, preferably for an existing process (retrofit), or for a new bio-based process, and to thrive at evaluating process performance in economic terms.

Below, a number of potential projects are listed and discussed. These are not necessarily independent; depending on the source of funding, the research ideas presented could be grouped differently.

Operability in the hot and warm water system of a pulp mill. This is a heat exchanger network, a system for which quite easily applied methods of controllability and control system design have been developed. However, the hot and warm water system of a pulp mill does not straightforwardly fit into the generic heat exchanger network models which bypass valves as actuators and stream target temperatures as manipulated variables. Instead streams are mixed to a large extent in tanks. The temperatures and levels of the tanks are target values used for control (often manually). Hence, method development would probably be needed. Besides evaluation of controllability and control system design it would be interesting to look at how the system is optimally operated under varying conditions, for example, variations in fresh water temperature or hot water demand.

Economic value of controllability in industrial process energy systems. How large are the (economic) effects of variations and disturbances in different processes? There are quite few examples from real life case studies presented in literature. To try to put an economic value on control and dynamics is not entirely straightforward. This area would require efforts with regard to choice of methods, system boundaries and scope. Furthermore, if succeeding to apply such methods to selected real life case studies, the resulting measures of profitability or cost savings can be important for motivating a greater focus on energy efficiency during process operation. Case studies can be found from previous industrial projects on chemical and mechanical pulp mills, dairy processes, oil refineries, etc.

Effects on controllability of higher degree of process integration. There are examples in literature of how process integration affects the controllability of a process plant. They are, however, quite few, and the analysis is many times performed from the automatic control perspective. From the view of process integration design, the analysis can be presented in a clearer way. To ensure scientific novelty in this kind of work it will be important to find a case study from an industry that has not been studied extensively in this regard. Examples could be pulp mills or dairies, while refineries should probably be excluded. It will also be important to make some contribution with regard to methodology. An idea here could be to develop the approach for how to trade-off controllability against heat recovery, for example, using multi-objective programming and Pareto curves.

Effects of reduced driving forces for flexibility and controllability of heat exchanger networks. In heat exchanger network design, the minimum temperature driving force, ΔT_{min}, is a central decision variable that sets a level for the trade-off between energy savings and network heat transfer area, that is, the trade-off between energy costs and capital costs. With higher energy prices, this trade-off tends towards increased focus on minimizing energy use, leading to lower and lower value of ΔT_{min}. The question is at which point the reduction in temperature driving forces starts to have a significant influence on heat exchanger and heat exchanger network operability. With temperature differences as low as a few degrees Celsius, there is a risk that the variations in inlet temperatures are greater than the driving force, which might lead to heat temperature crosses, instability and difficulty of control. When the trade-off between operating and capital costs suggests the use of very low temperature differences, it is therefore motivated to also consider operability (reliability, flexibility and controllability) for the selection of $\Delta Tmin$. A development of systematic procedures for this optimization could definitely be beneficial.

8 POSSIBILITIES TO APPLY FOR RESEARCH GRANTS

A closer collaboration between the research areas of industrial energy systems and process control could preferably be established during the conduction of one or two joint research projects. The first suggestion at hand is PhD-student projects in which the partners of this pre-study together form a group of supervisors. The idea of having parallel projects with one PhD-student placed at the Division of Heat and Power and one PhD-student at Process Control, Automation and Mechatronics have been discussed. Clearly, both positive and negative experience from similar project constellations should be considered in order to promote and maintain the focus of a fruitful collaboration.

In this context it should be noted that the Division of Heat and Power have had a number of PhD-student projects in which CIT Industriell Energi has participated with both co-supervision and research. This collaboration has been considered valuable by both parties.

As a natural part of this project, the current status of calls for research grants applications was reviewed. For the purpose of this report it is not motivated to provide details on this given its ever-changing nature. To summarize, the following activities/actors should be monitored for possibilities to apply for research grants

- On-going industrial collaborations of the project partners
- The Swedish initiative for Industrial Process Automation (recall Chapter 4 above)
- VINNOVA
- The Swedish Energy Agency
- Chalmers Energy Area of Advance

Added, as appendix to this report, are proposals for PhD-projects within the collaboration between Preem and Chalmers Energy Area of Advance. These proposals were sent for consideration in October 2013 and they describe parallel PhD-projects in line with the discussions of this report.

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Giovanini, L. L., & Marchetti, J. L. (2003). Low-level flexible-structure control applied to heat exchanger networks. *Computers and Chemical Engineering, 27*(8-9), 1129-1142.

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Projekttitel: Analys av skillnader mellan teoretiska och tekniskt uppnåbara potentialer för värmeintegration

Projektansvarig: Simon Harvey (huvudhandledare)
Utförare: Doktorand, Elin Svensson (bihandledare) och CIT-IE
Projektledare: Elin Svensson

Bakgrund och motivation för projektet

Välutformade integrerade systemlösningar är en förutsättning för energi- och kostnadseffektiv implementering av nya processer i befintlig industri. Men för att ta beslut om att investera i omfattande processintegration krävs en stor kunskap om risker och möjligheter med sådana lösningar. Hur drift och säkerhet påverkas i är en del av detta. Det behövs generellt bättre kunskap om hur kostnader och energibalanser för olika processintegrationsåtgärder påverkas när man tar hänsyn till förutsättningarna i driftskedet.

Genom att i en fallstudie utgå från olika förslag på processintegrations-åtgärder och utreda eventuella tekniska svårigheter kan man jämföra den teoretiska processintegrationspotentialen med den nivå som faktiskt anses genomförbar. Det blir då möjligt att konkretisera i vilken mån och på vilket sätt säkerhetsaspekter och andra driftsfrågor (som t.ex. säsongsvariationer) påverkar möjligheterna till processintegration. Detta ger kunskap om vad som krävs för att minska gapet mellan teoretisk och teknisk potential samt bättre underlag för bedömning av ekonomi och miljöpåverkan för olika framtida integrationsprojekt, t.ex. vid införande av en biomassebaserad process i en befintlig anläggning.

Tidigare Preem-finansierade forskningsprojekt på Värmeteknik och maskinlära (Daniella Johansson, Viktor Andersson och Jean-Florian Brau) har alla behandlat integration av olika nya processer i raffinaderiindustrin. De antaganden som gjorts om nivån på värmeintegration mellan den nya processerna och raffinaderiet bygger, i alla de nämnda studierna, på teoretiska potentialer. Möjligheterna och riskerna med att förverkliga dessa potentialer i praktiken har dock inte utretts i tidigare studier. Under hösten 2013 arbetar CIT Industriell Energi (CIT-IE) (med medverkan från Elin Svensson) med att ta fram ett antal förslag på hur värmeväxlarnätverken skulle kunna utformas för att faktiskt uppnå en del av de tidigare identifierade teoretiska energibesparings-potentialer. CIT-IE blir en naturlig resurs även i det här föreslagna projektet genom att bidra med beräkningsstöd och kunskapsöverföring från tidigare genomförda projektfaser.

Industriell relevans

Resultaten från projektet kan bidra till en ökad förståelse för hur de potentialer för processintegration som presenteras i olika projekt kan översättas till mer praktiskt uppnåbara mål. Genom en bättre kunskap om hur processintegration påverkar driften kan man också se vilka åtgärder som faktiskt kan genomföras utan att riskera problem i driftsfasen. Därigenom minskar förhoppningsvis också ogrundade tveksamheter till att implementera sådana åtgärder. Ett mervärde av projektet blir att det bidrar till ökad erfarenhet av hur olika metoder för retrofit av värmeväxlarnätverk (t.ex. ’matrismetoden’ och ’bridge analysis’) kan användas för energisystemanalys vid omfattande processintegration i industrier som består av en mängd olika delprocesser. Detta gäller såväl vid energieffektivisering i en befintlig anläggning som vid integration av nya ”gröna” processer.

Projektmål

Projektet avser att, utifrån faktiska förslag på processintegrationsåtgärder, kartlägga och konkretisera skillnaden mellan teoretiska potentialer och vad som är praktiskt genomförbart. Projektet har som mål att:

- Genom intervjuer och diskussioner med personer som innehar en god teknisk kunskap om drift och säkerhet i raffinaderiet, utreda i vilken mån de tidigare föreslagna energibesparingsåtgärderna är genomförbara.
- Komplettera tidigare framtagna förslag på energibesparingsåtgärder för att tydligt kunna visa på olika typer av implementeringssvårigheter.
- Förklara hur stora skillnaderna är mellan de teoretiska och tekniska potentialerna och vad som ligger bakom det gapet. Översiktligt analysera hur gapet kan påverka energibalanserna för olika bioraffinaderikoncept.
- Föreslå en metod för att analysera avvägning mellan potential och risk med avseende på energieffektivisering och drift (gärna uttryckt i ekonomiska termer).
- Utifrån fallstudiens resultat för processintegration mellan befintliga delprocesser generalisera kunskapen till integration mellan befintliga och nya processer, i exempelvis olika bioraffinaderikoncept.

Projektet är tänkt att genomföras som ett doktorandprojekt kopplat till tidigare påbörjad fallstudie av Preems raffinaderi i Lysekil.

Förväntat slutresultat

Projektet förväntas resultera i en ökad kunskap kring möjligheter och hinder för omfattande processintegration för såväl Preems raffinaderi i Lysekil som för processindustrin i allmänhet. På så sätt förbättras beslutsunderlaget för energieffektiv integration av nya processer i befintlig industri vilket i förlängningen kan bidra till att mer åtgärder genomförs.

Datum: 2013-10-15

Projekttitel: Reglertekniska konsekvenser och strategier vid effektivisering av industriella energisystem

Projektansvarig: Torsten Wik S2(huvudhandledare)
Utförare: Doktorand på S2, Karin Eriksson CIT-IE (bihandledare), Elin Svensson VOM (bihandledare), Torsten Wik
Projektledare: Torsten Wik

Bakgrund och motivation för projektet

Flera Preem-finansierade doktorandprojekt har genomförts vid Värmeteknik och maskinlära och nu söks medel för en doktorand med projekttiteln *Analys av skillnader mellan teoretiska och tekniskt uppnåbara potentialer för värmeintegration.* Doktorandprojektet är tänkt att innefatta arbete där drifttekniska aspekter kring föreslagna processmodifikationer analyseras. Här finns en naturlig koppling till dynamiska processhänsyn och därmed till processreglering. Därför föreslås en fördjupning genom ytterligare ett projekt med en doktorand på Reglerteknik.

Just nu pågår ett projekt med syftet att bygga upp ett samarbete mellan forskningsområdena Industriella energisystem och Reglerteknik på Chalmers. Projektet finansieras av Styrkeområde Energi och ett av dess mål är att identifiera relevanta forskningsfrågor och projektidéer för vidare samarbeten. Projektet pågår fortfarande men flera resultat har redan framkommit. Önskvärda komponenter som framtida samarbetsprojekt bör innehålla har identifierats och det står klart att en satsning på ett samarbete som detta ligger helt rätt i tiden.

Kompetens och intresse för forskningssamarbetet finns på Chalmers vid avdelningen för Reglerteknik, automation och mekatronik (på Signaler och system, S2), på Värmeteknik och Maskinlära, samt på CIT Industriell Energi. Samtliga parter är övertygade om att ett bra sätt att starta upp samarbetet vore kring doktorandprojekt som kopplar till en specifik processanläggning varifrån relevant underlag och frågeställningar kan hämtas, och där förhoppningsvis erhållna resultat i förlängningen kan testas och utvärderas. I förhållande till omvärlden och tidigare genomförd forskning bedöms en av Chalmers styrkor vara våra goda industriella kontakter och samarbeten.

Industriell relevans

VINNOVA, Energimyndigheten och Formas startar nu ett program kallat Processindustriell Automation (i detta sammanhang är benämningen automation synonymt med reglerteknik). Programmet grundar sig på en strategisk forskningsagenda i vilken utvecklandet av ett nära samarbete mellan processindustrin och akademin framhålls som avgörande för Sveriges konkurrenskraft såväl i näringslivet som i akademin. Listan med positiva effekter som ett välutvecklat samarbete kan generera är lång och innefattar klart energirelaterade aspekter så som ökad resurseffektivitet, tillgänglighet och driftssäkerhet i processindustriella anläggningar. Programmet har i dagsläget inte startat ännu, men baserat på den tillgängliga informationen bedöms det vara positivt för Chalmers och våra industrella samarbetspartner att påbörja aktiviteter som möjliggör framtida deltagande i programmet.

Projektmål

Fokus för det föreslagna projektet är reglertekniska frågeställningar kring processmodifikationer för ökad energieffektivitet. Projektet är tänkt att starta med att en noggrann styr- och observerbarhetsanalys med traditionella reglertekniska verktyg genomförs. Lämpliga systemgränser sätts i samråd med Preem. Erfarenheter och resultat från projekt som tidigare genomförts på CIT-IE och VOM inom Preem-samarbetet utgör ett värdefullt underlag.

Först görs en kartläggning av dagens processutformning och därefter analyseras konsekvenser av föreslagna processmodifikationer för ökad energieffektivitet. Analysresultatet blir utgångspunkt för val av reglertekniskt fördjupningsområde inom vilket projektet sedan går vidare. Tänkbara områden är dynamisk modellering och simulering, robusthetsegenskaper för styrbarhet och observerbarhet, koppling av olika modeller (exempelvis dynamiska och stationära), modellbaserad styrning samt flermålsoptimering.

Projektet utgår ifrån en tidigare genomförd fallstudie av Preems raffinaderi i Lysekil och erbjuder en reglerteknisk fördjupning till ett doktorandprojekt som VOM nu söker finansiering för. Ett parallellt genomförande av de båda doktorandarbetena förutses generera gynnsamma synergieffekter. Möjligheten att gemensamt utvärdera hur de olika forskningsområdenas traditionella analysverktyg fungerar tillsammans bedöms vara av stort intresse, särskilt när det appliceras på data från en verklig process.

Förväntat slutresultat

Inom det föreslagna projektet finns en betydande potential för att praktiskt formera ett samarbete mellan forskningsområdena Industriella energisystem och Reglerteknik på Chalmers. Därigenom kan Chalmers tillsammans med industriella samarbetspartner knyta sig till det aktuella forskningsprogrammet Processindustriell Automation. Inom det föreslagna Chalmerssamarbetet såväl som inom forskningsprogrammet framhålls nyttiggörandeaspekter som högprioriterade.

Det aktuella projektet förväntas kunna generera resultat för Preem med avseende på fördjupad kunskap kring de förutsättningar som styr- och reglersystemen ställer på implementering av energieffektiviserande åtgärder. Vidare finns en potential att nya reglerstrategier kan formuleras inom ramen för projektet.