Challenges in Applying Optimization in the Design of Continuous Processes
Case: Collaborative Optimizing Design of Pulp Fractionation Process

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Abstract: In order to make pulp and paper facility design more effective, simulation and optimization could be used more comprehensively during design. The structure and the operation of the mill should be designed simultaneously, and therefore bi-level multi-objective optimization (BLMOO) is a feasible method. Applying BLMOO in pulp and paper facility design requires changes in business processes of organizations involved. In this research, projects of applying optimizing design in example cases have been followed and a multi-organizational design process is defined. The process is then evaluated by expert interviews.

1 INTRODUCTION

Profitability in paper making has decreased and therefore also the competition in paper mill design is getting harder. The mill should be constructed with minimal capital expenses and at the same time the facility should be optimal for the current market situation. Compared to other chemical processes, where the whole design can be simulation driven, modelling, simulation and optimization is currently not very efficiently used in pulp and paper sector.

As the design of a paper mill consist of both structural design and operational design of the mill, it is useful to apply bi-level multi-objective optimization (BLMOO) (Eichfelder, 2010) to the design. In our previous research, a process model for applying BLMOO in pulp and paper facility design has been presented. In this paper, this model is expanded with the multi-organizational aspects. Also the workflow has been developed and the model has been evaluated by expert interviews.

2 DESIGN PROCESSES

2.1 Optimization and Modelling in Pulp and Paper Mill Design

In paper mills the modeling has been usually used for two things: mass balance calculations and logistics problems. These simulations are similar in that sense, that the basic phenomena are simple and the challenge is to understand the system as a whole. (Dahlquist, 2008). Logistic problems are simulated with event based models, which are outside of the scope of this paper.

The dynamic process models can be divided into first principle models, statistical models and the combination of those. Also terms white model, black model and gray model are used (Blanco et al., 2009).

White, or first principle models are directly based on physical laws. For example the modelling of mass and energy flows is quite straightforward and they are also applicable outside the originally designed area if they are not excessively simplified (Blanco et al., 2009). A framework for representation of mathematical models in chemical processes has been developed in (Bogusch and Marquardt, 1997).

When modelling quality issues of paper or probabilities of web breaks, simplified statistical models, or black models are used. The downside of statistical data is that it is often gathered in normal operating situation, where some variables are kept constant. This can lead to omission of important variables in the model. Also the model cannot be extrapolated over the limits of the gathered data.

Hybrid, or gray models combine the physical model with the empirical, statistic model. As the hybrid model can be extrapolated, it is important to assess the validity of the model. In (Kahrs and

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Marquardt, 2007) two methods for validating hybrid models are presented.

Certain phenomena are difficult to model in process industry. For example quality properties of paper combined with the control of a mill are hard to model.

When using models in an optimization loop, the computational time can become too large. Computational time requirements have been tackled by using simpler surrogate models A model of the papermaking process can also be constructed of several types of sub models. The sub models have to be chosen in such a way that they meet the requirements of the optimization problem. A decision support system using a process line model consisting different types of sub models is presented in (Hämäläinen et al., 2004).

As both the process structure design and process control design are essential parts of the paper mill design, they should be designed simultaneously (Pajula, 2006). The problem can be formulated as a bi-level multi-objective optimization problem as in (Ropponen et al., 2011). The dynamic model of the papermaking line and the dynamic multi-objective optimization can be coupled (Linnala, 2010)

2.2 Conceptual Design of Continuous Processes

The optimizing design can be utilized in two kinds of project; in a product development project or in a conceptual design phase of a delivery project. The difference between these project types is that in product development project, the goal and timetable can be more freely defined. A product development project often has a stage-gate kind of process, which means that the project consists of several phases. After every phase, the feasibility of the project is evaluated and the project is continued only if certain criteria are fulfilled. Therefore, more risks can be taken at the early phases of the project.

In delivery project however, the delay or cancellation of the project often leads to substantial expenses. The goal of the project is a feasible concept of a functional plant.

Whereas in the product development project, there can be only one organization involved, the delivery project always have several. The customer asks bids for the project from one or several engineering enterprises. The bids can contain the whole project as a turnkey project, just the conceptual design phase or anything between. Before the bidding phase, there are usually unofficial negotiations between the participants about the higher level concepts. The bidding request should define the project so well that the bids can be made.

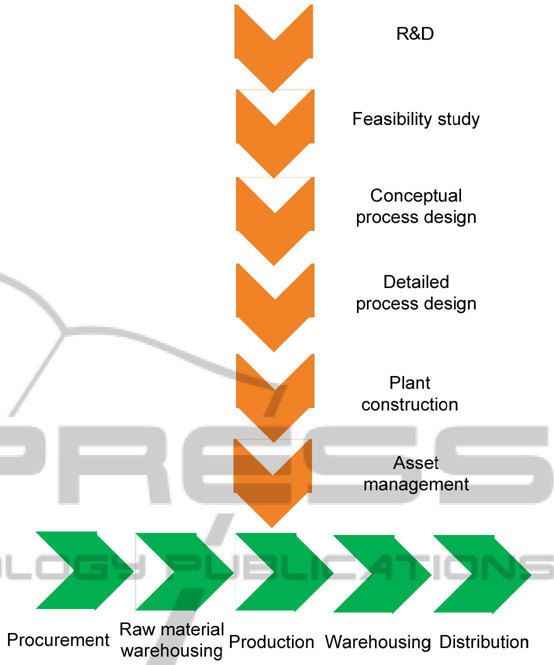

Figure 1: Two major business processes in pulp and paper industry. Modified from (Marquardt and Nagl, 2004).

At an aggregate level the business process of process industry can be modelled as a combination of two major processes; the one containing the manufacturing of the product and the other one containing the design of the product and production plant (Figure 1). The design process starts with a feasibility study containing economical impacts and is then followed by conceptual design and front-end engineering and design (FEED).

The early phases of the project are considered important, because the decisions made have a large impact on the life cycle costs of the plant. The nature of multidiscipline collaborative creative work makes it difficult to model the design process and to develop common tools. The process design approaches can be divided into three: 1) heuristic and engineering experience based methods, 2) optimization based methods and 3) case-based reasoning methods (Seuranen et al., 2001). The combination of the methods and the usability of a certain method should also be taken into account.

The conceptual design process has been researched by several research groups. In University of Edinburgh Bañares-Alcantara et al. have developed a design support system for chemical engineering (Bañares-Alcántara and King, 1996).

In RWTH University Aachen, the workflows of the conceptual phase has been studied as well as the modelling of the design process (Marquardt and Nagl, 2004), (Theissen et al., 2008). A specific modelling language, WPML, has been developed for modelling design processes (Theißen et al., 2011). Also requirements for tools in distributed collaborative engineering has been specified

Some researchers have emphasised the importance of creativeness in the conceptual design phase and therefore criticized too strict process definitions (Catledge and Potts, 1996). Without any documented process, the collaboration, common tools and the improvement of the process is though hardly feasible.

The usage of simulation and optimization methods have been researched before, but the effects of the usage of the methods in business processes is not so well studied.

2.3 Improvement of Collaborative Business Process of Design

Adopting a new method in process plant design can be seen as a business process re-engineering project. Kettinger and Grover present a Business Process Change Model, which divides the required changes in an organization into five areas: Management, IT, Business Processes, People and Organization Structure. (Kettinger and Grover, 1995)

In process redesign, a focus of development has to be chosen so that it is safe and productive enough. Schein (Schein, 1998) uses process consultation to define the focus. However, when introducing a significantly different new method in the process, the participants don't have experience of the new process beforehand. In such a change, the evaluation of the new method, workflow and tools have to be done by evaluating first the current method, process and tools, suggesting new process and evaluating the process in experimental pilot project. A framework for BPR presented in (Kettinger et al., 1997) divides the BPR process into six steps, namely Envision, Initiate, Diagnose, Redesign, Reconstruct and Evaluate.

The viewpoint of process improvement in general process improvement methods is often top down; the first step is to develop business vision, then the critical processes are being identified and after that, IT and methods are considered. e.g. in (Davenport, Thomas; Short James, 1990). When applying optimizing design, the starting point is the optimization method, but large parts of the process should be redesigned.

As the evaluation process is likely to be iterative, so is also this research: the initial version of the process described in this paper is published in (Strömman et al., 2011), and is updated and expanded according to the new knowledge gained from a new case study and expert interviews.

3 COLLABORATIVE DESIGN PROCESS WITH USAGE OF LIMITED MODELS

3.1 Research Focus

As the use of collaborative optimizing design in industrial projects is not straightforward, the applicability has been researched in case studies. Our previous publication (Strömman et al., 2011) presented a process model for optimizing design. In our recent research, the model has been widened to taking organizational interfaces into account. This expansion was made because the comments from industrial experts showed that the optimizing design is likely to change also the customer interface.

Here the design process is represented according to the classification by (Kettinger and Grover, 1995). The management and IT parts have been left out here and left for further research. It should be pointed out that before applying collaborative optimizing design in enterprise, it is extremely important to define e.g. process measuring and risk propensity and IT tools.

3.2 Collaborative Optimizing Design

3.2.1 People and Organization Structure

A typical organization in a delivery project is shown in Figure 2. The decision making in customer organization is divided into business decision making and technical decision making. Depending on the size of the investment, the business decision making can be in corporate level or on local site. Business decision makers are interested mostly in return of the investment, but also in some other issues which have direct or indirect influence on earnings like good image, the green values of the corporation, investment risks taken, future of the markets and prices of the raw material and energy etc. Technical decision makers are interested on the feasibility of the design, life-cycle costs, easiness of maintenance and flexibility for the changes.

The end-user organization purchases such

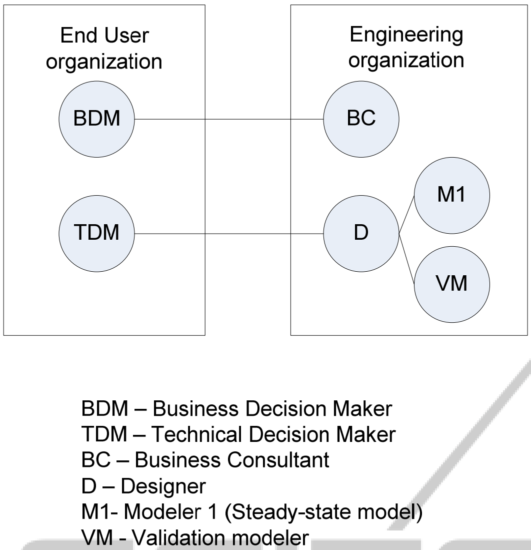

Figure 2: Organizations and roles in traditional design.

services it doesn't have. As the end-user organizations have become trimmed, in investment projects they are more dependent on the engineering organizations than before. The business decision makers need consulting services about market situation, risks and expectation about future development. Large engineering enterprises can offer also the business consulting services or they can be bought elsewhere.

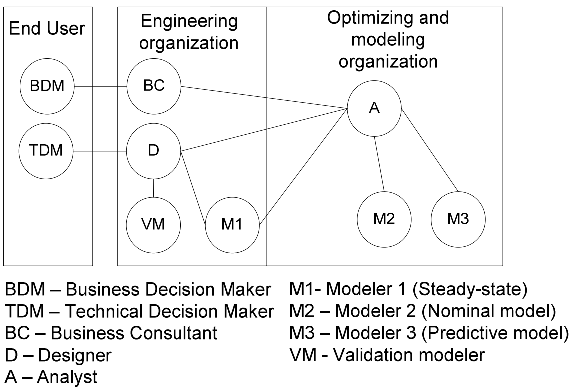

Figure 3: Workflow in optimizing design.

The actual engineering organization consists of designers from different disciplines. In the conceptual design phase, the main responsibility is on process designer. The process is modeled e.g. with flow chart containing the static balances of mass and energy flows in a typical operating point.

In Figure 4 the optimizing and modeling organization is added. Though these roles can also be in the same organization they are here separated from the engineering organization in order to emphasize the interfaces between these roles. The added organization consists of an analyst and modeler roles. In optimizing design, the designer has the main responsibility for the design. He also is in the key role in identifying possible optimization targets. The analyst is responsible for mathematical representation of the optimizing problem, coordination of the model building and for solving the optimization problem.

3.2.2 Business Processes

The optimization activities take place in a few stages as an extension to conceptual process design phase as illustrated in Figure 3. The process starts from a feasibility study, where economical and technical possibilities and limitations are evaluated. Then, a conceptual design phase can be started by giving the design task to the engineering organization. When the designer and/or business consult identifies a need for optimization in his conceptual design, he initiates cooperation with the analyst. As a result of this cooperation, a definition of an optimization problem is made. The analyst is responsible for the mathematical formulation of the problem as well as finding a solution to it using models he chooses.

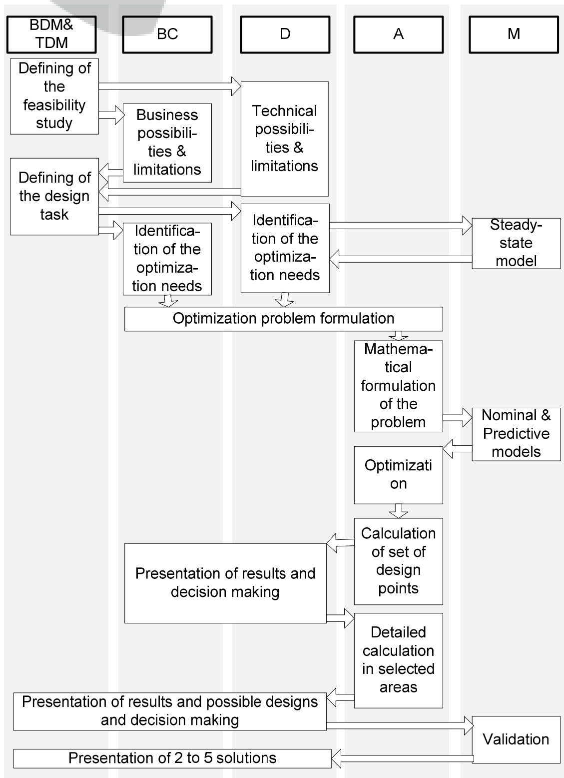

Figure 4: Organizations and roles in optimizing design.

In this process, computation and presentation of results are divided into two phases. In the first phase, the results are presented according to the objective functions that were originally set as primary objective functions. When the solution is limited by selecting the values of primary objective functions, the solution according to the secondary objective functions are the calculated. Depending on the amount of objective functions, there can be more phases that can also be iterative, because it can turn out that some of the objective functions e.g. correlate or have very little influence on the solution.

The knowledge needed in each role and the data the roles are producing, updating and using is described in (Strömman et al., 2011).

3.3 Model Usage in Collaborative Optimizing Design

In current design practice, the pulp and paper process is modeled first with a flow diagram, which describes the main material flows. Then, a steady-state model is constructed in a typical operational state. Steady-state model is used to decide the size of process equipment and the amounts of raw materials. In current design practice dynamics of only some unit processes can be modeled. Sometimes a dynamic model of mass and energy balances is actually constructed for verification purposes. In addition to a steady-state model and a verification model, the optimizing design needs another, somewhat more limited, models that are efficient to calculate.

When applying collaborative optimizing design, also the models for optimization have to be constructed. The models are built according to the optimization problem taking the computational requirements also into account. First, a nominal model of the process is built. The nominal model describes the essential functionality of the process. The control variables of the nominal model are solved with a predictive model, which optimizes the control variables in every time step by calculating all of the control parameters over a prediction horizon and then implements the first calculated step.

Because the models used in optimization are built exactly for the needs of the optimization problem and they are simplified for computational reasons, the verification of the optimization has to be done with a different simulation model. The verification model should be constructed independently of the optimization work.

The modeling requires much work and the management of models is difficult; a change in the design requires changes in every model and in the cases in this project, the changes are made manually in each model.

4 ASSESSMENT OF THE MODEL WITH A CASE STUDY AND INTERVIEWS

4.1 Case Study

The presented design method was studied on a example of a paper machine design project including pulp storages and mixing. (Ropponen and Ritala, 2012). The paper machine is designed to have two headboxes, one for the base of the paper and one for the surface. (Figure 5) The raw materials consisted of chemical and thermomechanical pulp. Also a small dose of nanocellulose was used to make the base of the paper stronger. The thermomechanical pulp was fractionated so that the largest fibres are used in making of the base of the paper in first headbox and the finest fibers were used in the surface layer to make the surface of the paper smoother. Nanocellulose was used to compensate the strength of the paper in base layer.

The scenario of this design project is applicable to a product design project or a conceptual design of a renewal delivery project. The optimizing design was used for minimizing the deviation of the strength and fast changes in the controls. In addition, there are constraints in flows and volumes of the towers.

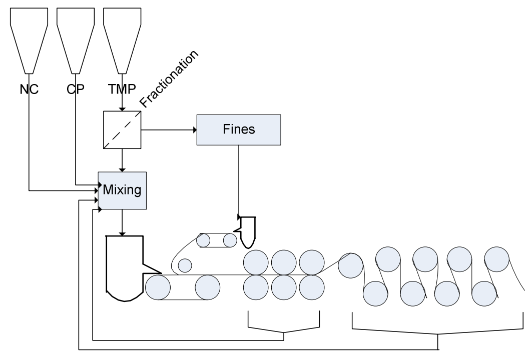

Figure 5: Simplified Flow Chart of the Case Process.

When designing a new facility, and there is no previous measurement data of the target process, all assumptions made of the system are based on physical laws, statistics of another processes or expert knowledge. Part of the process can be modeled accurately based on physics. Such issues in this facility are e.g. the flows between process equipments. Some phenomena are more difficult to model, but there are models that are detailed enough for the optimization needs. For example the outflow of a tower can be modeled as a plug flow, ideal mixture or a combination of those. The accuracy of the model can be grown with more detailed physical models or by adjusting the model parameters according to the available statistical data.

The difficulty in paper making is that there are phenomena that are quite poorly understood and can only be modeled statistically. Such issues in this case are the relations between the process design and control and the quality properties of paper, e.g. the effect of changes in material flows to the probability of breaks.

4.2 Interviews

A set of interviews was performed in order to evaluate the presented model of collaborative design and model usage. The interviewees included experts from both paper and pulp industry and vendors of process systems. The primary objective of the interviews was to find out opinions of the industrial experts about the feasibility of the design process. A secondary objective was to identify necessary development targets for design process and process models required in optimization.

The general comment from the interviewees about the feasibility of the model of collaborative design was that it is feasible in principle, but there are some important reservations. Particularly, the applicability of optimization in a design process depends on the characteristics of the project. For small projects, where the possible benefits of optimization are smaller and time constraints also can be quite tight, the presented model of a design process is quite likely too heavy. However, for large greenfield projects the situation is different. The proper stage for optimization in such a project would be the pre-feasibility stage, i.e. before a contract between the vendor and a customer is made. The customers typically want to have an exact estimate of the costs of an investment before coming to one. Another possible situation where the presented model could be applied in a somewhat modified form is a product development project of a vendor.

The most important development target for the design process identified during the interviews was development of a more light weight model for utilizing optimization during delivery projects. Such a model would make it feasible to utilize optimization also in smaller projects. In order to do this, part of the optimization related work has to be moved into a phase preceding individual customer projects, e.g. into product development projects. The question how optimization work should be divided between product development and delivery projects is maybe the most important further development target for the model of collaborative optimization.

The general observation during the interviews concerning the modeling required for optimizing design was that it is exactly the challenging part of the whole approach. There are well-known and important phenomena in paper and pulp processes for which models usable for optimization do not exist. In addition to this, in design projects there are situations when there is not enough usable data even when applicable models would exist. However, on the other hand there are also some other design tasks for which models and data are available. As a conclusion, taking into account the currently availability of process models and data, optimization should be applied to selected parts of the design problem and combined with other design methods. Identifying the limits of optimization in the design of paper and pulp processes is on-going research and combination of optimization with other design methods an essential topic for further development.

There are a few different ways how the challenges concerning the model usage in optimizing design could be approached. First, the utilization of the existing models could be developed. Optimization studies during R&D projects could be used to update design knowledge, which is then utilized during customer projects, e.g. in a form of design rules. Another option is to develop new optimization methods and models for restricted targets during R&D projects and apply them during customer projects. A third option is to build a library of process models and more systematically utilize them for optimization in delivery projects. A fourth option is to develop new optimizing methods that require less effort on process modeling even at the expense of higher computational requirements.

5 CONCLUSIONS

We have presented a business process model for utilizing optimization in the design of continuous processes. The model is applicable to the conceptual design phase. The model includes organizational boundaries, roles, knowledge, data and a coarse workflow. The model has then evaluated with a case study from the paper industry and a set of expert interviews. The model should be considered as a start point when defining a design process for an enterprise. The process is intended to be fitted and specified for the needs of a particular organization.

This research has revealed that applying optimizing design for pulp and paper facilities not only requires development of optimization methods and tools but also changes in the business processes of design organizations and also customers. An enterprise offering collaborative optimizing design can't compete with traditional design enterprises, if the customer is not aware of the different approach with different time and budget requirements. Therefore, the design organization has to be able to convince the customer that optimizing design will benefit the project.

One great challenge is the trustworthiness of the models. In order to convince the customer to invest in a separate optimization project or to allow longer and more expensive conceptual phase, the models have to match with experiential data. The optimizing design has the greatest potential, when the solution is outside the conventional solution area. Therefore the models should be proved to be valid also when extrapolated outside the area where the data for the model has been gathered.

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REFERENCES

Bañares-Alcántara, R., King, J.M.P., 1996. Design support systems for process engineering—III. Design rationale as a requirement for effective support. *Computers & Chemical Engineering* 21, 263–276.

Blanco, A., Dahlquist, E., Kappen, J., Manninen, J., Negro, C., Ritala, R., 2009. Use of modelling and simulation in the pulp and paper industry. *Mathematical and Computer Modelling of Dynamical Systems* 15, 409–423.

Bogusch, R., Marquardt, W., 1997. A formal representation of process model equations. *Computers & Chemical Engineering* 21, 1105–1115.

Catledge, L. D., Potts, C., 1996. Collaboration during conceptual design. *IEEE Comput. Soc. Press*, pp. 182–189.

Dahlquist, E., 2008. *Use of modeling and simulation in pulp and paper industry*. EU COST and Malardalen University Press, Sverige.

Davenport, Thomas; Short James, 1990. *The new industrial engineering : information technology and business process redesign*. Massachusetts Institute of Technology.

Eichfelder, G., 2010. Multiobjective bilevel optimization. Mathematical Programming 123, 419–449.

Hämäläinen, J., Miettinen, K., Madetoja, E., Mäkelä, M. M., Tarvainen, P., 2004. *Multiobjective decision making for papermaking*. CD-Rom Proceedings of MCDM.

Kahrs, O., Marquardt, W., 2007. The validity domain of hybrid models and its application in process optimization. *Chemical Engineering and Processing: Process Intensification* 46, 1054–1066.

Kettinger, W. J., Grover, V., 1995. Special section: toward a theory of business process change management. *J. Manage. Inf. Syst.* 12, 9–30.

Kettinger, W.J., Teng, J.T.C., Guha, S., 1997. Business Process Change: A Study of Methodologies, Techniques, and Tools. *MIS Quarterly* 21, 55–80.

Linnala, 2010. Dynamic simulation and optimization of an SC papermaking line - illustrated with case studies. *Nordic Pulp and Paper Research Journal 2*5, 213–220.

Marquardt, W., Nagl, M., 2004. Workflow and information centered support of design processes—the *IMPROVE perspective. Computers & Chemical Engineering* 29, 65–82.

Pajula, E., 2006. *Studies on Computer Aided Process and Equipment Design in Process Industry.* Helsinki University of Technology.

Ropponen, A., Ritala, R., 2012. *Operational Optimization of Flow Management in Papermaking.* Presented at the Papercon 2012, New Orleans, USA.

Ropponen, A., Ritala, R., Pistikopoulos, E.N., 2011. Optimization issues of the broke management system in papermaking. *Computers and Chemical Engineering* 35, 2510–2520.

Schein, E., 1998. *Process Consultation Revisited: Building the Helping Relationship*. Prentice Hall.

Seuranen, T., Pajula, E., Hurme, M., 2001. Applying CBR and Object Database Techniques in Chemical Process Design, in: Aha, D., Watson, I. (Eds.), Case-Based Reasoning Research and Development, Lecture Notes in *Computer Science*. Springer Berlin / Heidelberg, pp. 731–743.

Strömman, M., Seilonen, I., Peltola, J., Koskinen, K., 2011. Design process model for optimizing design of continuous production processes, in: SIMULTECH 2011 - *Proceedings of 1st International Conference on Simulation and Modeling Methodologies, Technologies and Applications.* pp. 492–501.

Theissen, M., Hai, R., Marquardt, W., 2008. Design Process Modeling in Chemical Engineering. Journal of *Computing and Information Science in Engineering* 8, 011007.

Theißen, M., Hai, R., Marquardt, W., 2011. A framework for work process modeling in the chemical industries. *Computers & Chemical Engineering* 35, 679–691.