Modeling, Calibration and Control of a Paper Machine Dryer Section

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Abstract

Following increased efforts during the last decade to formulate mathematical models for the paper drying process, this paper presents a Modelica library, `DryLib`, which enables users to rapidly develop complex models of paper machine dryer sections. In addition, parameter optimization, model reduction and moisture control by means of Non-Linear Model Predictive Control is treated. These applications have in common that they are based on numerical optimization schemes. Since the nature of the particular optimization problem dictates the requirements of the numerical code, the paper also serves as an illustration of the need for flexibility in terms of *i)* means for the user to express optimization problems, *ii)* and choice of numerical algorithms.

Keywords: paper machine, paper drying, parameter optimization, model reduction, non-linear MPC

1 Introduction

The topic of this paper is modeling, model reduction, parameter optimization and control of a paper machine drying section. The dryer section is the last part of the paper machine and consists of a large number of rotating steam heated cast iron cylinders. The moist paper is led around these cylinders and the latent heat of vaporization in the steam is used to evaporate the water from the web. The cylinders are divided into separate dryer groups where the steam pressure can be individually controlled in each group. By adjusting the steam pressure in the dryer groups, and thereby the heat flow to the paper, the moisture in the paper web is controlled.

Based on the work [11], a Modelica library, `DryLib`, has been developed. `DryLib` implements the physical phenomena involved in the drying process, as well as convenient components and connectors which enables rapid development of dryer section models. An important feature of `DryLib` is its ability to express models which are scalable, in the sense that the complexity of the models can be easily changed. This feature is quite useful, since the need for granularity depends on the application – a high fidelity model may be suitable for simulation, whereas a course model capturing the main behavior may be appropriate for control design.

The present paper gives three main contributions. Firstly, the Modelica library `DryLib` is presented. Secondly, important issues such as parameter optimization, model reduction and optimization based control schemes (Non-linear Model Predictive Control (NMPC)), are treated. Some of these topics have a general character, while others are dealing specifically with dryer section issues. Thirdly, the applications of the paper serves as examples of the wide range of relevant optimization problems that naturally follow the availability of high-fidelity models.

The paper is organized as follows. In Section 2 the structure and implementational details of `DryLib` are treated. The Sections 3, 4 and 5 treats parameter optimization, model reduction and moisture control by means of non-linear MPC. In Section 6, the software used to solve the optimization problems presented in the paper is described. The paper ends with with conclusions and future work in Section 7.

The current paper is a condensed version of [2], where additional details can be found.

2 `DryLib`

The model library, `DryLib`, that is developed and used in this paper is built upon physical relations in terms of mass and energy balances, in combination with constitutive equations for the mass and heat transfer. The objective is to obtain a non-linear model that captures the key dynamical properties for a wide operating range. The core of the model is based on [16] and [12], and it is also given in [11]. The model for the paper web is based on [16] whereas the model for the cylinder, and steam system is taken from [12]. The mathematical model used as a basis for `DryLib` is identical to the model described in the references, except that convective heat transfer from the paper web has been added.

The objective of building the Modelica library `DryLib` has been to create a user friendly and extensible platform for modeling of paper machine dryer sections. In particular, the aim has been to design the library so that, at the user level, the appropriate level of model detail can be easily selected. The current implementation of `DryLib` contains a few examples of components where the level of detail can be specified by the user. More importantly, the library classes are designed to enable advanced users to add new behavior to key components in order to extend the functionality of the library. An important concept in the design process has been that of *model scalability*, which means that the granularity of the model behavior should be easy to change, without the need to re-build the model.

2.1 Hierarchical Structuring

Having formulated a mathematical model for the paper machine dryer section, the issues of structuring the equations into Modelica classes and definition of interface classes (connectors) need attention. A paper machine dryer section model can be assembled using very few basic component types. In essence, there are only two fundamental entities, namely a steam heated cylinder and a sheet of paper. These two component types may then be combined, in large numbers, into a complete dryer section model. However, it is convenient to introduce additional hierarchical levels. As discussed above, the cylinders of a typical dryer section are organized into steam groups, in which a number of cylinders are operated at the same pressure. The introduction of steam groups into the library provides a convenient hierarchical level for the user, since many decisions regarding e.g. operating points and control design and evaluation are made at the steam group level. For basic usage of `DryLib`, it is also sufficient to utilize only classes defined at the steam group level in order to create a fully working dryer section model.

In order to increase the flexibility of the library, the boundary conditions of the physical entities have been factored out and modeled as separate classes. As an instructive example we consider a paper sheet, where the boundary conditions of the surfaces defining the sheet depends on the environment. For example, different boundary conditions are imposed on the surface if the paper is in contact with the air or a cylinder shell. The key to building a flexible Modelica libraries using this principle of separation is the design of generic connector classes. This topic will be discussed in detail below.

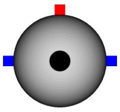
From a user's perspective, `DryLib` is intended to enable easy modeling of a dryer section. However, the user should remain in control of the implementational details of key components, e.g. paper sheets and cylinders. Also, advanced users should have the possibility to introduce new behavior of existing components. Two key features of Modelica have been used to satisfy these requirements. In the first case, extensive use of parametrized types (`replaceable`/`redeclare`) has been used to propagate type information downwards in the component hierarchy from the main user level (which is the steam group level) to lower level components. This strategy enables the user to easily select the appropriate level of detail for e.g. the cylinder dynamics. In the second case, inheritance has been used in order to simplify introduction of new component behavior. For the basic components such as cylinders and paper sheets, generic base classes have been introduced, which in turn serve as super classes for particular implementations. `DryLib` currently provides a few alternative implementations for key components, and additional behavior is easily added using the pre-defined base classes.

2.1.1 Connectors and Variable bindings

The interface structure in `DryLib` is based on three connector classes. While the connectors for heat flow and mass flow (for connecting components with steam flow) are straight forward, the connector class for a paper surface deserves to be discussed. The paper web is modeled by separate mass balances for water and fiber, and an energy balance, as described above. Natural flow variables are thus mass flow of water and fiber, q_w [kg/s] and q_f [kg/s], and energy flow Q [W]. As for the potential variables, there are several feasible choices. However, since `DryLib` is likely to be used by domain experts in the field of paper drying, it was decided to use the standard variables within this domain. The natural choices are then moisture ratio, u [kg water/kg dry substance], dry basis weight, g [kg/m^2] and temperature T [°C].

A particular feature of Modelica that has been used to simplify the propagation of parameters and variables between components in `DryLib` is name lookup in the instance hierarchy (`inner`/`outer`). For example, the machine speed is used in various components, but is common for the entire dryer section. Implementation using `inner`/`outer` constructs is thus convenient. Examples of variables that may be assumed to be shared by the components of a steam group are ambient temperature and air moisture, which are also implemented using `inner`/`outer`.

2.1.2 Cylinder Models



The (partial) cylinder base class `CylinderBase` contains mainly connector components and serves as a unifying class for particular implementations of dynamic behavior. The cylinder base class has two mass flow connectors corresponding to steam inlet and outlet, and one heat flow connector. Two particular implementations of the cylinder dynamics is included in `DryLib`.

2.1.3 Paper Models

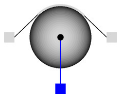
The paper web base class contains essentially four paper connectors corresponding to the cross section areas and the upper and lower surfaces. This design enables separation of the actual paper web behavior, and the physical phenomena defined by the boundary conditions of the paper.

2.1.4 Interfaces

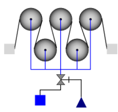
Having defined the connector structure and the basic cylinder and paper classes, modeling of the interfaces between components is straight forward. The `PaperPaperInterface` class models the interface between two paper cross section areas perpendicular to the machine direction. In `CylinderPaperInterface`, the heat transfer between a cylinder and a paper in contact is modeled. Finally, the evaporation of water from the paper surface is modeled in the class `Evaporation`.

2.1.5 Steam Group Models

The classes described above have the character of *specifying physical behavior*. We shall now turn our attention to classes which are mainly used as *structuring entities* in the sense that they introduce new hierarchical levels, and that they contain instances of behavior classes. Basic usage of `DryLib` may involve only classes introduced at this level.



In order to efficiently explore the strong repetitive character of a typical dryer section, the class `CylinderUnit` was introduced. This class combines a steam cylinder and a paper sheet which is attached to an evaporation component. While different cylinders may have different physical parameters, the structure of `CylinderUnit` is valid in most cases.



The actual control system typically consisting of a valve, a pressure sensor and a PID controller is encapsulated in the class `SteamGroup`, which also contains an array of `CylinderUnit` components. The `SteamGroup` class has four connectors corresponding to incoming and outgoing paper, the steam header and an input signal representing the reference value of the pressure controller.

2.1.6 Miscellaneous

Apart from the classes presented above, `DryLib` also contains classes which is used to drive a dryer section model, referred to as sources and sinks. In addition there are some miscellaneous classes for e.g. valves and sensors.

2.2 PM7, Husum, Sweden

To demonstrate the capabilities of `DryLib`, a dryer section model corresponding to that of PM7 located at the M-real mill, Husum, Sweden, has been developed. The PM7 paper machine is a multi-cylinder machine producing copy paper. The dryer section of the machine is divided into a pre-dryer and an after dryer section with the surface sizing in the middle. The objective of the after-dryer section is only to dry the mixture added by the surface sizing and it cannot take care of moisture problems from the pre-dryer section. Only the pre-dryer is modeled here. The PM7 drying cylinders are divided into six groups, consisting of one, two, two, three, ten and twelve cylinders respectively. For a detailed description of the plant, see [5].

In Figure 1, the top level of the PM7 dryer section model is shown, including six steam groups, a paper source, a paper sink, a mass flow source representing the steam header and a set point distribution for calculation of pressure set points for the groups. The final

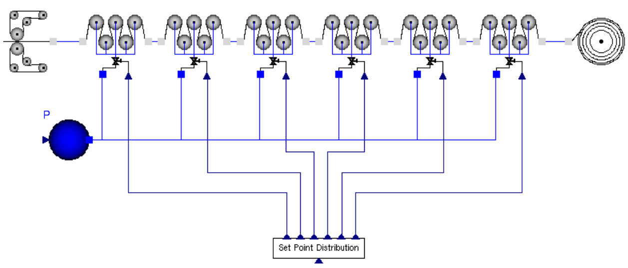


Figure 1: The top level of a complete dryer section model.

model consists of 7453 equations and 312 dynamical states when translated with Dymola.

2.3 Extensions

Possible extensions of `DryLib` can be sorted mainly into two categories. Firstly, the library may be extended by adding components modeling process equipment or physical phenomena not covered by the current implementation. For example, modeling of systems in direct connection with the dryer section, such as the condensate system, the steam production and the ventilation system would enable simulation of a larger part of the process. Also, adding this functionality would simplify connection of the dryer section model to models of other important parts of the paper machine, e.g. the press section, the wire section or other process units utilizing the same steam header.

Secondly, `DryLib` may be extended by introducing components which enables simulation of the drying process at an increased level of detail. The current design of `DryLib` is based on a particular choice of discretization of the underlying PDE:s (describing mass and energy transport), which yields a model with a reasonable level of detail, while maintaining acceptable simulation times. While this choice of discretization is suitable for analysis of moisture, temperature and pressure profiles in the machine direction, other applications may require different levels of detail.

3 Parameter Optimization

It is desirable that the behavior of the model is similar to that of the real plant, in order for results obtained from using the model to be applicable on the plant. A common method to minimize the plant-model mis-match is to select one or more parameters of the model, and then tune these until a satisfactory model response is obtained. This procedure of tuning parameters while leaving the structure of the model unchanged is referred to as gray-box identification, see [4]. Parameter tuning may in simple cases be done by hand, but more complex problems requires structured methods for finding the parameter set which yields the best result. One such method is parameter optimization, which, in addition to selection of parameters to optimize, also includes definition of a performance criterion to minimize.

When selecting parameters to optimize, parameters which are uncertain are attractive choices. However, it should be kept in mind, that the parameter optimization procedure does not necessarily produce the physically correct parameter values. Rather, the selected parameters are used to compensate for all types of model-data mismatch given a particular performance criterion. This implies that the actual parameter values obtained from optimization should not be interpreted as the true physical values, but rather those that achieves the best model-data match. On the other hand, it is usually desirable to ensure that parameters have physically feasible values.

3.1 Problem Definition

Setting up a parameter optimization problem requires insight into which aspects of the model are most important. In this case, both the dynamic and static model response is of importance. However, in a first step, only the static behavior has been considered. Specifically, cylinder and paper temperatures of the paper machine, as well as the output moisture, have been measured during stationary operation conditions. The aim of the optimization has been to improve the stationary response of the model in the sense that the difference between simulated temperatures and moisture and measured temperatures and moisture, should be minimized.

A reasonable cost function to minimize is then

$$\begin{aligned} J =&\gamma_{T_m}\sum_{i=1}^{N_{cyl}}(T^m_{m,i}-T^s_{m,i})^2+ \\ &\gamma_{T_p}\sum_{i=1}^{N_{cyl}}(T^m_{p,i}-T^s_{p,i})^2+\gamma_u(u^m_{out}-u^2_{out})^2 \end{aligned} \tag{1}$$

where N_{cyl} is the number of cylinders, super-script m indicates measured quantities, super-script s indicates simulated quantities and γ_{T_m}, γ_{T_p} and γ_u are weights. While the measurement method used to determine cylinder temperatures is reliable, the measurements of paper temperatures should be regarded as uncertain.

In particular, the paper temperature is varying considerably in the machine direction depending on the position, relative to a cylinder contact area, at which the measurement is done, [11]. Therefore, the weight γ_{T_p} was set to a small value. The moisture, on the other hand, is an important quality variable that should be matched with high accuracy. Accordingly, γ_u was set to high value.

Four parameters were selected for optimization – three heat transfer coefficients and one mass transfer coefficient.

3.2 Solving the Problem

The minimization of (1) should be performed subject to the constraint constituted by the DAE representation of the model. Since the minimization is performed in stationarity, all derivatives may be set to zero, and the model is then represented by a purely algebraic constraint, $F(x,y,p) = 0$, where x is the state vector, y represents the algebraic variables and p are the parameters.

The problem was solved by a custom made application coded in C, which is based on the `dsblock` interface for accessing the model description generated by Dymola, and the NLP code IPOPT, see [14], which is dedicated to solving large scale algebraic optimization problems. The software is described in detail in Section 6.

3.3 Parameter Optimization Results

Minimizing (1) yields an optimal cost of 277, compared to the cost 61869 for the nominal parameter values. The optimal temperature profiles are shown in Figure 2. For comparison, the nominal profiles are plotted. As can be seen, there is a significantly improved fit between simulated and measured responses. In particular, the output moisture in the nominal case is unrealistically low too early in the dryer section. It can also be noted that the fit of the cylinder temperature profile is better than that of the paper temperature profile. This phenomenon is expected, since the weight of the paper temperature errors was set to a low value.

The matching of the profiles can be improved further by introducing additional optimization parameters. This strategy is explored in [1] for a slightly different parameter optimization problem.

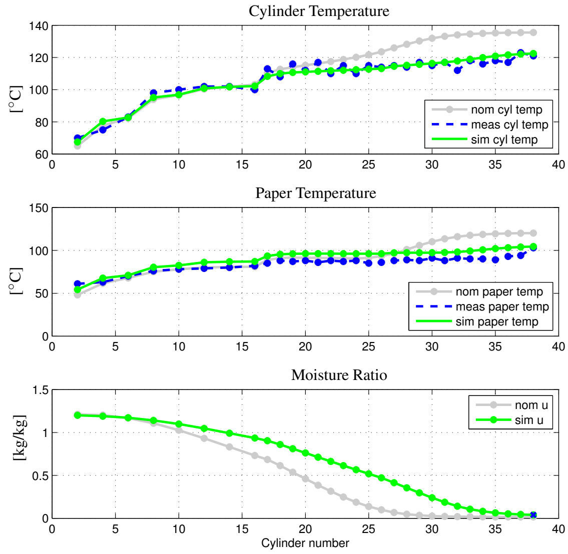


Figure 2: Stationary temperature and moisture profiles. The x-axis shows cylinder numbers.

4 Model Reduction

Dryer section models built using `DryLib` results in large scale models, even though a sparse discretization scheme for mass and energy balances has been applied. For control design and evaluation purposes, however, a model describing the dynamic relationship between the inputs and the quality variables at the last free draw is usually sufficient. In practice, low order models (e.g. KLT-models with a gain, a time delay and a time constant) valid at a specific operating point are commonly used for dryer section control. In this section, a reduced model targeted towards moisture control design is developed. Since the moisture measurement signal available for feedback control is usually obtained at the end of the dryer section, the aim of the reduction scheme is to develop a simpler model, which captures the non-linear dynamical behavior relating the steam pressure reference signal, input moisture, input temperature and dry basis weight (from the press section) to output moisture. Accordingly, accurate simulation of the paper temperature and the moisture profile can be compromised in order to obtain a lower order model, describing only the phenomenon of interest, i.e. the behavior of the moisture, accurately.

4.1 The Equivalent Dryer

In this paper, the structure of the dryer section will be exploited, in order to obtain a model of lower order.

A previously reported concept is that of the equivalent dryer, which is described in [10]. Instead of modeling each cylinder as a separate unit, the equivalent dryer concept suggests that one, larger cylinder can be used to approximate an entire steam group. This approach has several attractive features. *i)* It preserves the structure of the dryer section, since each steam group is replaced by its corresponding equivalent dryer, *ii)* each equivalent dryer has an intuitive physical interpretation *iii)* and the reduction potential is large, especially for large steam groups.

4.2 The Reduction Problem

At the steam group level, the reduction problem can be stated as *"Find the dimensions of **one** steam cylinder, including associated incoming and outgoing free draws and contact paper, which approximates as well as possible, the behavior of a given steam group"*. Given our experiences from simulation of dryer section models, we suggest that the dynamic and stationary response of the equivalent dryer cylinder may be treated separately. As for the dynamics, we assume that the mass and volume of the equivalent cylinder can be set to N_{cyl} times those of an individual cylinder in the steam group, where N_{cyl} is the number of cylinders. Now, simulation experiments reveal that the time constant of an equivalent cylinder, constructed based on this assumption, corresponds well to the time constant of the full steam group. However, the same result does not seem to hold for the stationary gains, where there is a significant mismatch. Intuitive ways to set the lengths of the free draw and contact papers, using the same reasoning as for mass and volume, does not produce acceptable results. A more sophisticated way of finding the physical dimensions and parameters is thus necessary.

4.3 Reduction of One Steam Group

A static model for a paper sheet in contact with a steam cylinder, can be formulated using algebraic versions of the dynamic mass and energy balances of the mathematical dryer section model. The algebraic systems of equations for each cylinder and paper web may then be duplicated and put together to formulate a static model for a steam group.

As stated in the introduction of this section, the most important quality variable, at least for moisture control, is paper moisture. Therefore, a reasonable objective is to minimize the deviation between the moisture in the last free draw of the cylinder group, and the moisture in the outgoing free draw of the equivalent cylinder. In addition, as a secondary objective, it was decided to minimize the deviation in steam consumption. This objective was added since it may be desirable to limit the steam consumption during moisture control. Performing this minimization for a single operating point is not sufficient, however. In order to obtain a good fit over a wider operating range, a set of operating cases was introduced, over which the optimization was performed. Each case consists of a specification of the operating point in terms of steam pressure, input moisture, input temperature and basis weight.

It remains to define the optimization parameters, over which the minimization is performed. Six parameters of the equivalent dryer were selected for optimization, namely the length of the free draws, the length of the contact paper, and in addition two heat transfer coefficients and one mass transfer coefficient. The number of variables that are actually needed to obtain a good fit is not unambiguous, however. For small steam groups, or if few cases are used, some of the suggested optimization variables may well be fixed, without any increase in the approximation error. In fact, it is desirable to find an appropriate trade-off between the number of optimization variables and optimization performance, in order to avoid over-parametrization.

4.4 Reduction of a Dryer Section

A straight forward approach for deriving a reduced order dryer section would be to simply apply the method described in the previous section for each individual steam group. Recalling our main objective, which is to predict the moisture in the last free draw, this approach would not explore the full potential of the method. Instead, a larger optimization problem, incorporating all groups, may be formulated where most attention is given to minimizing the deviation of the last group. This means that *all* groups are reduced at the same time, and that the full reduction potential is used according to the main objective, which is to predict the final moisture. It may, however, be advantageous to include the deviations, with small weights, of all groups in the optimization criterion, in order to avoid a physically unrealistic model.

4.5 Solving the Optimization Problem

The resulting algebraic optimization problem is challenging, both due to its size and its non-linear character. The final problem consists of 9536 free variables and 9504 equality constraints, of which 8568 are non-linear. Efficient solution of large scale NLP problems of this type require state of the art numerical algorithms, exploring the sparse structure of the problem as well as analytical Jacobian and Hessian information.

The problem definition was programmed in AMPL, which is a language for mathematical programming, [6]. AMPL enables encoding of linear and non-linear algebraic optimization problems, using optimization oriented language constructs. The problem description, i.e. the AMPL code, is then executed within the AMPL tool, which in turn interfaces several numerical solvers. In this application, the NLP code KNITRO, [15], has been used. The combination of AMPL and KNITRO is extremely powerful, since the AMPL interface to numerical solvers offers analytic evaluation of Jacobians and Hessians as well as sparsity information. This enables KNITRO to operate in its most efficient mode, resulting in acceptable execution times also for large systems. The reduction problem formulated in the previous section is solved in about 2-5 minutes, depending on initial starting point.

The proposed method has the distinct drawback of requiring complete re-encoding of the the model description. This was necessary, however, in order to enable utilization of the appropriate symbolical and numerical algorithms.

It is important to note, however, that the problem is non-convex, and that only local optimality can be expected. However, in this case, the solution to the reduction problem seemed to be robust with respect to different starting points. Also, the obtained solution is reasonable in the sense that the optimized parameter values lies within physically feasible limits.

4.6 Model Reduction Results

As mentioned above, a set of operating conditions need to be specified, in order to complete the problem formulation. Clearly, the operating range over which the reduced model is valid, is influenced by this choice. As the nominal case, values for steam pressures, input moisture, input temperature and dry basis weight corresponding to a typical grade were chosen. Based on the nominal case, additional 35 cases were defined by varying the nominal parameters.

The result of the reduction procedure was evaluated by means of step responses in input moisture, dry basis weight and pressure set point, see Figure 3. As can be seen, there is a good match between the stationary responses of the original and reduced models. Also, the (slow) dominating time constant is captured well by the reduced system. A detailed study of the initial part of the step response reveals that the reduced model does not fully capture the transport delay of the original model. This is, however, to be expected. The original model consists of a large number of paper components, which together forms a high dimension compartment system. The reduced model consists of significantly fewer segments, and cannot approximate the time delay with the same accuracy

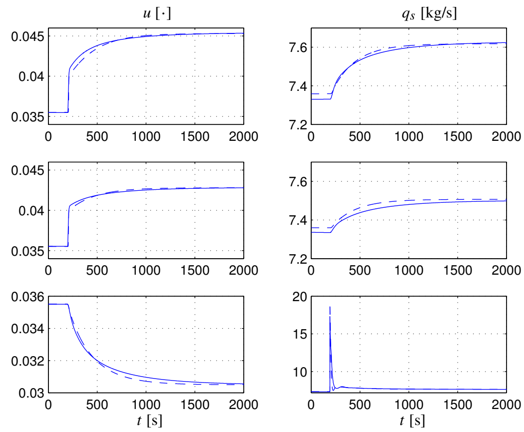


Figure 3: Step responses for moisture (left) and steam flow rate (right) of the original (dashed) and the reduced (solid) models. The responses corresponds to, from above, steps in input moisture, input dry basis weight and pressure reference, applied at 200 s.

The original motivation for performing the model reduction was to obtain a model of lower complexity. Indeed, the reduced model has fewer dynamical states, namely 85, as compared to 318 for the original model. Also, the simulation time for a typical scenario was approximately 85% shorter for the reduced model.

5 NMPC of Output Moisture

Paper moisture is usually controlled using a cascade structure, where the inner loop controls the steam pressures and the outer loop controls the actual moisture. The controllers of the inner loop are commonly PID-controllers, whereas the outer loop is controlled by a Model Based Control (MBC) scheme, e.g. IMC (Internal Model Control), a Dahlin controller, or linear MPC (Model Predictive Control).

The MBC controller is usually based on a low order linear model of the dryer section. While a well tuned controller works well at a given set-point, the non-linear character of the dryer section dynamics results in degraded performance if the set-point is changed. Since the plant is operated at several different set-points, corresponding to different grades, a traditional control system maintains several parameter sets for the MBC controller. Switching of controller parameters is then done after a grade change.

In this paper, we consider a different approach to moisture control. Based on the reduced non-linear dryer section model derived in Section 4, a basic Non-Linear Model Predictive Control (NMPC) scheme is implemented. The main benefit of using a non-linear model in the control design is that the operating range of the controller may be increased. Also, successful implementation of a controller which achieves good performance in a wide operating range may serve as a unifying strategy for stationary and transition (grade change) control, whereas common practice today is to use separate controllers for these two control modes.

A realistic implementation of an MPC controller consists of tree main parts – reference target calculation, state estimation and solution of the optimal control problem. In this paper, the problem of solving the optimal control problem is addressed. The resulting controller is evaluated under the assumption of full state information.

5.1 Model Predictive Control

MPC refers to a family of controllers which are based on the receding horizon principle. At each sample, a finite horizon open loop optimal control problem is solved, and the first part (corresponding to the first sample) of the resulting optimal control profile is applied to the plant. At the next sample, the procedure is repeated and a new optimal control problem with the horizon shifted one sample is solved. Two of the most important advantages of using MPC is that it works well for MIMO plants and that it takes state and control bounds into account *explicitly*. However, an MPC controller, including the on-line solution of an optimization problem (at least in the case of a non-linear model), is computationally demanding, which makes application to processes with fast dynamics troublesome. During the last decade, MPC has emerged as a major control strategy, mainly in the process industry, see [9] for an overview.

5.2 Dynamic Optimization

Traditionally, optimization problems incorporating constraints imposed by dynamic systems have been addressed by dynamic programming, or the maximum principle. During the last two decades, however, a new family of methods, referred to as direct methods have emerged. These methods are based on discretization of the original optimization formulation, transforming the infinite dimensional problem into a finite dimensional one. The discretized problem is then solved by means of algebraic non-linear programming, see [13] and [3] for two examples of direct methods.

Optimization of Dymola models has previously been considered in the work [7], where the Simulink interface provided with Dymola was used to access the model. The main difference between the approach used in [7] and this work lies in the methods of accessing the model, where the `dsblock` interface has the advantage of offering evaluation of an analytical Jacobian.

The algorithm used to solve the dynamic optimization problem described in this section is a straight forward implementation of a sequential single shooting algorithm, see [13].

5.3 The Optimal Control Problem

An integral part of an NMPC controller is the formulation of the open loop optimal control problem to be solved in each sample. Since the aim of the control scheme in this application is to control the moisture ratio, it is natural to penalize deviations from the target moisture. The control trajectory in the optimization problem is parametrized by a piece-wise constant function with N_u segments. In order to avoid violent control moves, which may introduce disturbances in the steam system, a term penalizing the deviation between two successive control moves is introduced in the cost function. In addition, there are hard limits acting on the control variable. This yields the following optimization problem

$$\begin{aligned}&\min_{\hat{p}_i^{sp}} \int_0^{T_f} \gamma_u (u_{out}^{sp} - \hat{u}_{out}(t))^2 dt + \sum_{i=0}^{N_u-1} \gamma_p (\Delta \hat{p}_i^{sp})^2 \\ &\text{subject to} \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (2)\\ &F(x, \dot{x}, y, p^{sp}) = 0 \text{ (DAEdynamics)} \\ &466 \text{ kPa} \leq p^{sp} \leq 596 \text{ kPa (control constraint)}\end{aligned}$$

where T_f is the prediction horizon, u_{out}^{sp} is the target moisture, $\hat{u}_{out}(t)$ is the predicted moisture profile, $\hat{p}_i^{sp}$ is the predicted pressure set point trajectory and $\Delta \hat{p}_i^{sp} = \hat{p}_i^{sp} - \hat{p}_{i-1}^{sp}$. γ_u and γ_p are weights. In the simulation, the parameters were set to $\gamma_u = 10000$, $\gamma_p = 0.01$, $N_u = 4$ and the sampling interval to 5 s.

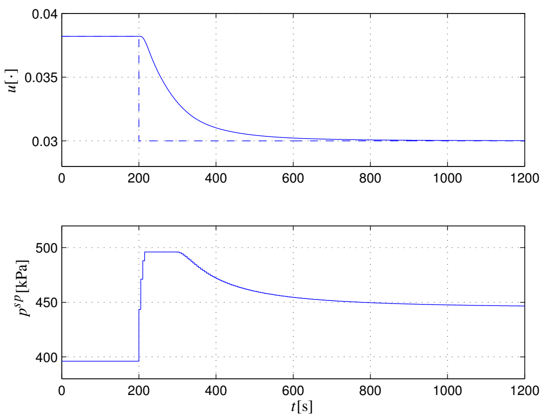


Figure 4: Step response of the NMPC controller.

5.4 Results

A simulation where the NMPC controller is applied to the reduced dryer section model derived in Section 4 is shown in Figure 4. In the simulation, a reference step, from $u_{out}^{sp} = 0.038$ to $u_{out}^{sp} = 0.03$ is applied at $t = 200$ s. As can be seen, the moisture reaches the desired set-point, while the control signal respects the specified constraints.

An important, and often limiting, factor when using MPC controllers, is the execution time for solving the on-line optimization problem. In this case, execution times ranged from 10 s to 80 s, with a mean of 13.5 s. Typically, execution times are longer when reference changes and disturbances occur, while shorter and more predictable execution times are obtained during stationary operation. Assuming a sampling interval of $h = 5$ s, it is clear that the execution times must be decreased. There are several approaches to reducing execution times, e.g. modifying the lengths of the control and prediction horizons, reducing the complexity of the model or using a more efficient optimization algorithm. This is, however, beyond the scope of this paper.

In addition, the problems of reference target calculation and state estimation needs to be solved in order for the control scheme to be useful in practice.

6 Software Tools

The dryer section model has been implemented, as mentioned above, in Modelica and Dymola. The parameter optimization problem and the NMPC problem, however, were solved by integrating several software packages into custom applications, which utilized the C-code representing the model generated by Dymola. The results were then fed back to Dymola and verified on the original simulation model.

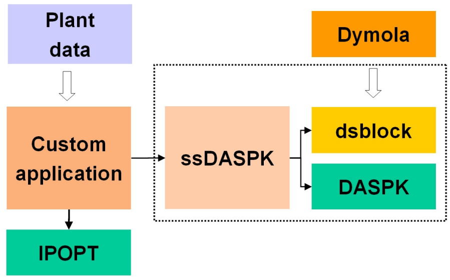


Figure 5: Software application structure.

The software packages used in the development of the custom applications are: *i)* A **C programming interface** which enables access to routines generated by Dymola, `dsblock`. Using this interface, custom applications can be developed for e.g. simulation or like in this case, optimization. The interface provides basic routines for acquiring information about model parameters and initial state, evaluation of the right side of the resulting ODE (DAE) and the associated Jacobian. *ii)* A DAE-solver, **DASPK 3.1** [8]. This code solves DAE:s as well as calculates sensitivities required for optimization. The code is written in Fortran and was translated to C using `f2c`. *iii)* An NLP-code, **IPOPT** [14]. This code implements a primal-dual interior point method and was used to solve the NLP resulting from the parameter optimization and NMPC problems. *iv)* A package for managing the communication between the Dymola C interface and DASPK, which was developed in order to enable convenient development of optimization applications based on models generated by Dymola. This package, referred to as **ssDASPK**, provides e.g. simulation and sensitivity calculation for use in custom applications.

These packages were compiled and linked with the code representing the model generated by Dymola, into applications which was used to set up and solve the particular optimization problems. The structure of the applications is shown in Figure 5.

In addition, AMPL and KNITRO was used to solve the model reduction problem, as described above.

7 Summary and Conclusions

In this paper, modeling, model reduction, parameter optimization and NMPC control design for a paper machine dryer section has been considered. It has been demonstrated how Modelica models of high complexity can be used for purposes other than simulation. The resulting optimization problems are challenging and require state of the art numerical solvers. In particular, solution of the model reduction problem, which has more than 9000 free variables, is dependent on algorithms exploring the problem structure. Our experience from this project is that there is no single tool or software that can address all problems arising in simulation and optimization. Rather, in order to solve problems effectively, it is essential that Modelica tools are designed to be interfaced with software for solution of optimization problems. In general, it is highly desirable that software for complex systems is provided with interfaces so that they can be combined.

There are several possible extensions of the paper. The `DryLib` library may be extended as outlined in Section 2, and the parameter optimization scheme would benefit from including also time series data. Regarding the model reduction scheme, it may be desirable to derive models with further reduced complexity valid over a wide operating range. Finally, the NMPC scheme outline in Section 5 needs to be further elaborated in order to be applicable to the real plant.

References

[1] J. Åkesson and J. Ekvall. "Parameter optimization of a paper machine model." In Proceedings of Reglermöte 2006, Stockholm, Sweden, May 2006.

[2] J. Åkesson and O. Slätteke. "Drylib - a modelica library for paper machine dryer section modeling, and some applications of dynamic optimization." Technical Report, Department of Automatic Control, Lund University, 2006.

[3] L. Biegler, A. Cervantes, and A. Wächter. "Advances in simultaneous strategies for dynamic optimization." Chemical Engineering Science, **57**, pp. 575–593, 2002.

[4] T. Bohlin and A. J. Isaksson. "Grey-box model calibrator and validator." In 13th IFAC Symposium on System Identification, Rotterdam, The Netherlands, August 2003.

[5] J. Ekvall. "Dryer section control in paper machines during web breaks." Licentiate thesis ISRN LUTFD2/TFRT--3236--SE, Department of Automatic Control, Lund Institute of Technology, Sweden, November 2004.

[6] R. Fourer, D. Gay, and B. Kernighan. AMPL – A Modeling Language for Mathematical Programming. Brooks/Cole — Thomson Learning, 2003.

[7] R. Franke, M. Rode, and K. Krüger. "On-line optimization of drum boiler startup." In Proceedings of Modelica'2003 conference, 2003.

[8] T. Maly and L. R. Petzold. "Numerical methods and software for sensitivity analysis of differential-algebraic systems." Applied Numerical Mathematics, **20:1-2**, pp. 57–82, 1996.

[9] S. J. Qin and T. A. Badgwell. "A survey of industrial model predictive control technology." Control Engineering Practice, **11**, pp. 733–764, 2003.

[10] M. Rao, Q. Xia, and Y. Ying. Modeling and Advanced Control for Process Industries – Applications to Paper Making Processes. Springer-Verlag, New York, 1994.

[11] O. Slätteke. Modeling and Control of the Paper Machine Drying Section. PhD thesis ISRN LUTFD2/TFRT--1075--SE, Department of Automatic Control, Lund Institute of Technology, Sweden, January 2006.

[12] O. Slätteke and K. J. Åström. "Modeling of a steam heated rotating cylinder - a grey-box approach." In Proc. 2005 American Control Conference, Portland, Oregon, USA, June 2005.

[13] V. Vassiliadis. Computational solution of dynamic optimization problem with general differnetial-algebraic constraints. PhD thesis, Imperial Collage, London, UK, 1993.

[14] A. Wächter and L. T. Biegler. "On the implementation of an interior-point filter line-search algorithm for large-scale nonlinear programming." Mathematical Programming, **106:1**, pp. 25–58, 2006.

[15] R. Waltz. KNITRO User's Manual, Version 4.0. Zienna Optimization Inc., 2005.

[16] B. Wilhelmsson. An experimental and theoretical study of multi-cylinder paper drying. PhD thesis, Department of Chemical Engineering, Lund Institute of Technology, Lund, Sweden, 1995.