Profitability and Re-usability: An Example of a Modular Model for Online Optimization

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Abstract: In this article, we describe the development of a modular online optimization solution. This solution can be configured to deal with different plant layouts and therefore allows for a re-usable and hence profitable advanced optimization solution. The industrial process for which the model was developed is divided into separate stages. Each stage represents a production step, which may or may not be present in a particular plant. Inputs and outputs of each stage are defined in a flexible way to ensure that the sequence of the production stages can vary and can be easily connected. Optimization results are shown for two alternative plant configurations and are discussed together with the benefits and cost that come with the pursuit of a modular solution.

Keywords: Online optimization, modularity, advanced solutions, nonlinear optimization, multi-stage processes, configuration.

1. INTRODUCTION

Most advanced industrial control and optimization solutions are developed on a case-by-case basis and are tailored to a production process at a particular plant. A large part of the implementation is spent on expert manpower; to model the plant behaviour with a deterministic or stochastic model and to adjust the control algorithm of the model (Bauer and Craig, 2008).

From a vendor's point of view, the business case of developing advanced solutions will often only achieve a breakeven if the model and the control algorithm can be re-used and installed multiple times without long and tedious adaptation of the model and algorithm. The development cost can then be split between the several implementation projects and the solutions is offered at a price that will result in an acceptable net present value (NPV) – both for the vendor and the customer.

Achieving re-usable and thus profitable advanced control and optimization solutions, however, are as rare as hen's teeth. Darby and White (1988) point out that this can be a question of modelling the process with one single model or in a decentralized approach. A modular approach is often easier to implement and maintain, especially when model updates are required.

In some industrial plants, production stages resemble each other and show enough common features to be generalized by a basic building block. A modular approach is achieved by configuring and connecting the basic building blocks. Other processes might be constructed by the same basic building block with different parameterization that is configured to adjust to the plant layout, including the use of a different number of blocks.

In this article, we describe a modular nonlinear real-time optimization approach that maximizes the throughput in a production process. Nonlinear online optimization is still not applied as widely as linear optimization problems in industry but some applications have been reported (De Gouvea and Odloak, 1998, Jockenhövel et al., 2003). The approach has been developed for an industrial environment to be implemented for online application.

Here, we describe an example of a production process for which a modular model will be developed. This model is derived using the following steps.

- Identify a basic building block;
- Define the block equations;
- Define the block connections;
- Define the process' objective function;
- Package the basic building block.

If a model is available in such a way, it significantly reduces the effort required to adapt the model to a new plant configuration. The solution can be re-used once implemented on an appropriate platform. One of the keys to a profitable advanced solution is furthermore the easy configuration and implementation of any modelling approach. An example is ABB's Expert Optimizer that provides the framework for implementing hybrid model predictive controllers. An example of such an implementation is given by Stadler and co-workers (2007).

The paper is structured as follows. In the next section, the process is described and two examples of possible configur-

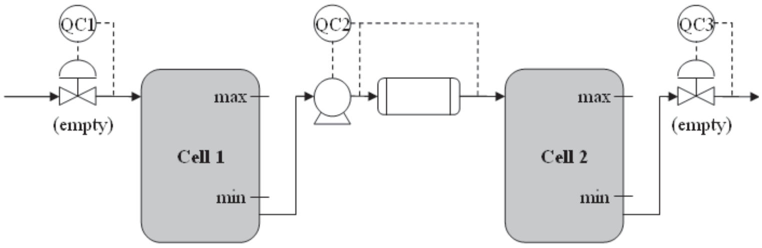

Fig. 1. Process schematic of Configuration I consisting of two cells.

ations are given together with the objective of the optimization problem. The different types to which the basic building block can be configured are identified and listed. Section 3 describes the model derivation along the steps stated above. Results are given in Section 4 together with a discussion on the advantages and disadvantages of the modular solution.

2. PROCESS DESCRIPTION

The continuous process under consideration consists of a set of sequential cells. An example of a configuration of this process is shown in Fig. 1. The medium flows from one cell with a certain flow rate. Valves or pumps control the flow rate into each cell. The flow rate is limited and so is the volume contained in the cell. What makes the process particular and difficult to control is the fact that the medium to be processed changes almost completely and abruptly. The medium consists, in fact, of different separate products with different attribute affecting the flow rate. The products do not mix but instead are processed successively. Thus, the flow rate changes whenever the next product enters a cell. A sensor therefore measures the consistency at the entry of the cell and the flow rate is adjusted accordingly.

The particular are characteristics concerning the operation of the two cells. The first cell has to be emptied before a new product enters it. Thus, the valve or alternatively pump is closed off for a period of time until the tank has been emptied to a certain level. The second cell is preceded by a heat exchanger that warms up the medium before it enters the cell. While the first part of the medium is in the heat exchanger, the heat has to be adjusted to a certain temperature and the flow rate has to be lower than its normal maximum. In any configuration, an outflow valve controls the last flow in the process. The outflow is interrupted as one product is filled into a container, the container is sealed off, removed and a new container is placed in this position.

Altogether, there are four basic cell types, each with or without a heat exchanger and/or emptying during transition, as listed in Table 1. A plant can consist of a number of sequential cells, ranging from two up to about eight cells.

The process is very difficult to control as all cells interact and disturbances directly travel through the process. Minimum and maximum constraints of the level in the cells and of the flow rate are hard and cannot be violated without causing a complete shut-down of the plant. An important process characteristic is that the flow rates have to be constant while one product is filled into a cell. The level is therefore constantly increasing or decreasing, depending on the difference between the in- and outflow of the cell. If in- and outflow are identical for a certain period of time the level stays constant for that period of time. Determining the optimal set-points is therefore crucial for an uninterrupted operation of the process that also maximizes the throughput.

2.1 Configuration 1

The process can have different setups of the basic cell types described in Table 1. The one such configuration is shown in Fig. 1 and, as described earlier, consists of two cells where Cell 1 has to be emptied before the next product can enter it (Case B). During this period, the valve is closed off. Cell 2 is preceded by a heat exchanger (Case C). The consistency is measured before and after the heat exchanger so that a product change is noticed thereafter so that the flow rate can be adjusted when the medium enters and exits the heat exchanger. The opening and closing of the cells in- and outflow depends on the different material and the control is indeed already very complex when considering only these two cells.

2.2 Configuration II

Fig. 2 shows the process schematic of the second configuration to be investigated in this paper. Here, three cells are connected where the first cell has to be emptied after a product changeover (Case B). The second cell adjusts the speed according to a product change but neither has it a heat exchanger nor is it emptied (Case A). The third case has a heat exchanger but does not have to be emptied between product changeovers (Case C). The plant parameters such as maximum flow rate and cell volume differ from Configuration I. This naturally affects the different operational routines.

Table 1. Alternative cell types

		Emptying during transition	
		No	Yes
Heat exchanger	No	Case A	Case B
	Yes	Case C	Case D

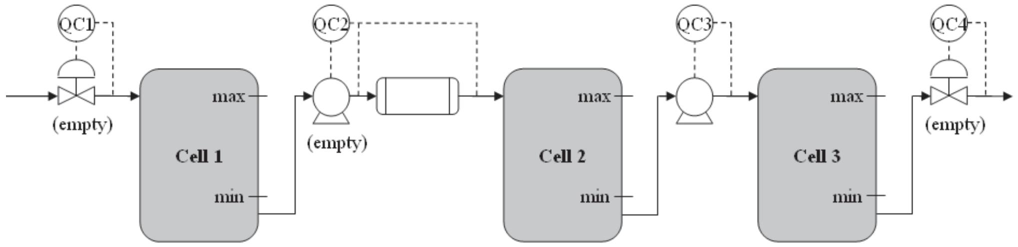

Fig. 2. Process schematic of Configuration II consisting of three cells.

2.3 Online process optimization

The described process is somewhat different to a standard continuous chemical process. Here, we deal with different products in operation with changing attributes. The controller has to deal with different states that alter with a product changeover: emptying, heating and normal operation. The aim of this study is to determine the flow rate set-points for a sequence of products under the given constraints, that is, limits of the constant flow rates and minimum and maximum cell levels. The objective is to maximize the outflow of the last cell. New setpoints are determined repeatedly, either:

a) Time based, that is, on a fixed time grid for example every ten seconds;
b) Event based, that is, if a defined event occurs, for example if a new product enters the process.

If an event occurs, the time grid is reset and restarted after the event. The high update frequency requires a fast result from the online optimization routine.

3. MODULAR MODELLING

The processes described in the previous section can be modelled as one single problem since the number of variables is limited. However, in order to re-use the optimization solution for both Configuration I and II and possibly other configurations, it is advantageous to model a basic building block and then configure and connect the blocks using the same description and connections. In the following, the basic building block is identified, the equations are identified, connections established and the objective function for the complete process is derived.

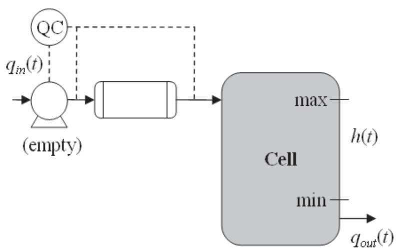

Fig. 3. Basic building block from which Configuration I and II can be constructed.

3.1 Identification of basic building block

By looking at Fig. 1 and Fig. 2 one can easily identify the repeating elements in the process such as the cell and inflow control. A basic building block that describes all cells and their inflow control is shown in Fig. 3. It consists of one cell and the adjustable flow rate of the inflow. The heat exchanger preceding the cell is included in the generic block and its parameters and equations will be set to zero if no heat exchanger is present. Variables are also introduced for emptying the cell. In case that the cell does not have to be emptied, these variables are also set to zero.

3.2 Building block equations

First, the decision variables to be optimized are introduced for each cell. These variables are noted with lower case letters and include the following. There are *p* products with p={1...P}.

$h(t)$	Cell level
$q_p^{in}(t)$	Inflow to cell
$q_p^{out}(t)$	Outflow of cell
τ_p	Time duration during which the product flows into the cell
τ_p^{empty}	Time duration during which the cell and the heat exchanger are emptied
τ_p^{warmup}	Time duration during which the product is warmed up in the heat exchanger

The flow rates are fixed for the duration while processing product *p*. If the flow rate is constant then the level is a linear function. The durations are auxiliary variables.

Parameters to be configured for each cell are as follows.

V_p	Volume of product p
V^C	Volume of cell C
V^{HE}	Volume of the heat exchanger
$Q_p^{\min}$, $Q_p^{\max}$	Minimum and maximum flow rate

$H^{\min}$, $H^{\max}$ Minimum and maximum cell level

If no heat exchanger is located ahead of the cell (Case A and B) then volume V^{HE} is set to zero.

The duration during which the product flows into the cell is defined as the volume of product p minus the volume of the heat exchanger divided by the flow rate of product p. When the next product enters the cell the flow rate changes to q_{p+1}^{in}.

$$\tau_p = \frac{V_p - V^{HE}}{q_p^{in}} \tag{1}$$

This equation is nonlinear and thus can cause difficulties for most solvers. It is therefore necessary to reformulate this equation as well as the following into a bilinear form by multiplication ($\tau \cdot q_p^{in} = V_p - V^{HE}$).

When emptying the cell, the valve or pump is closed off and the inflow rate is hence set to zero. The duration during which the tank is emptied is determined by the outflow rate. The volume to be emptied is the volume in the cell plus the volume in the heat exchanger.

$$\tau_p^{empty} = \frac{V^C + V^{HE}}{q^{out}} \tag{2}$$

The duration during which the product is warmed up is defined by the volume of the heat exchanger divided by the inflow rate. It is independent from the outflow rate as one might initially expect.

$$\tau_p^{warmup} = \frac{V^{HE}}{q_p^{in}} \tag{3}$$

The level is proportional to the difference between the in- and outflow rate. The proportional coefficient depends on the area of the cell.

$$h(t) \sim q^{in}(t) - q^{out}(t) \tag{4}$$

Eq. (1)–(4) describe the dynamics of the cell. Inflow, outflow and level have to be defined for each time point for which a switch occurs, that is, when a new product reaches a measuring point. There are two measuring points in case of the presence of a heat exchanger, one before and one after. At these switching points, the level reaches its minimum or maximum value as the function increases and decreases only linearly. If the cell level does not violate the constraints at two consecutive switching points, it will not violate the constraints at any time between those switching points. The reformulation of the inflow, outflow and level for these switching points is rather cumbersome in notation but straight forward otherwise. It will therefore not be detailed in this article.

In addition to the equations describing the process dynamics there are also constraints that determine the operation of the cells. These constraints are considered for the inflow rate q^{in} and for the cell level h.

$$Q_p^{\min} \le q_p^{in}(t) \le Q_p^{\max} \tag{5}$$

Table 2. Parameter adaptation for cell types

		Emptying during transition	
		No	Yes
Heat exchanger	No	$V^{HE} = 0$; $\tau_p^{empty} = 0$	$V^{HE} = 0$
	Yes	$\tau_p^{empty} = 0$	none

$$H^{\min} \le h(t) \le H^{\max} \tag{6}$$

The constraints on the outflow rate do not have to be considered as they are defined in the successive cell.

3.3 Connection of building blocks

The cells are connected by the flow through the process. The connection is formulated by equating the outflow rate of cell C with the inflow rate of the subsequent cell C+1.

$$q^{out,C}(t) = q^{in,C+1}(t) \tag{7}$$

3.4 Objective function

The objective of the optimization problem is to maximize the throughput of the process. As the throughput is determined by the outflow rate of the last cell, this is the quantity to be maximized.

$$\max \int q^{out,C=C_{last}}(t)dt \tag{8}$$

Alternatively, it is possible to minimize the sum of all durations defined in Eq. (1)–(3). In some cases, a better solution is obtained by maximizing the flow rate in all cells and not only the one of the last. This is particularly valid for very short product sequences as the first cells may not process with the highest rate as the finishing of the product sequence in the last cell does not depend on it. As a result, the objective function is set to Eq. (8) plus an additional term including the flow rates in the other cells multiplied by a weighting factor smaller than one.

3.5 Configuration

The basic building block can be packaged into a stand alone function with input and output variables as shown in Fig. 4.

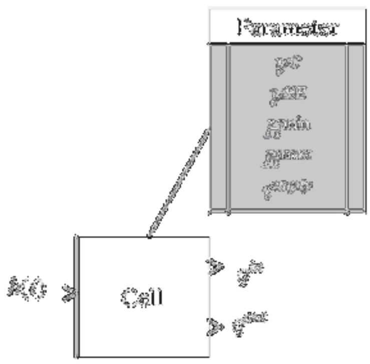

Fig. 4. Configuration block for implementation.

The parameters have to be set for each block. The differentiation between the cell types as given in Table 1. leads to a parameter configuration that is summarized in Table 2. The final step is the connection between the in- and outflows of the consecutive cells as given in Eq. (7) to derive the complete plant setups of Fig. 1 and Fig. 2.

4. OPTIMIZATION RESULTS

The same model is applied for both Configuration I and II with only changes to the parameters and the number of cells. The optimization problem was implemented in GAMS and as a nonlinear program solved with CONOPT. CONOPT is based on the generalized reduced gradient method which transforms inequality constraints into equality constraints by introducing slack variables. The solver then searches along the steepest slope of the super-basic variables.

In some instances, nonlinear models can easily lead to infeasibility. However, as the initialization of the optimization routine is already close to the optimum results can be found reliably. Upper constraints of flow rate and level are used as initial values. The solution is also not necessarily the global optimum. This decision is left to the writer of the GAMS code and the model developer.

Fig. 5 shows the results of Configuration I of Fig. 1. Here, two cells were connected with a heat exchanger between the cells. The first cell had to be emptied/flushed in preparation for a product change. The outflow of the process was also interrupted to allow the product to be filled into tanks. The tanks have to be removed and the process outflow closed off during that period. The process operation can be best seen in the flow rates. The left hand side of Fig. 5 shows the three flow rates, q_1-q_3 for three products. The first flow rate is the process inflow and is interrupted each time a new product enters the cell. The maximum flow rate into the first cell is large for both products, however, the set point is set to a lower level to not exceed the level in the cell as the outflow of the first cell is limited by significantly lower constraints. Flow rate $q_2(t)$ is at its maximum constraint as it poses, together with $q_3(t)$ the bottle neck in the process. While the first part of a product is processed in the second cell, a reduced flow rate is applied. The flow rate $q_3(t)$ is at a higher value than $q_2(t)$ but a stop time interrupts the flow during the product changeover.

The cell levels shown in the right hand side of Fig. 2 indicate that the cell level of the first cell is in the region of its upper limit, i.e., the cell is filled during most time of the operation. The second cell, on the other hand, hits on some occasions the lower constraints.

The results of the optimization routine of Configuration II are shown in Fig. 6. Here, four flows and three cell levels are shown for three products. The first cell is emptied with every product changeover, as can be seen in $q_1(t)$. A heat exchanger is placed ahead of the second cell which affects the flow rate $q_2(t)$. The flow rate $q_3(t)$ changes only with the different products while the last flow rate includes stops during which a new tank is replaced. The stop times for the tanks are constant.

The last cell level is somehow cyclic as the cell is emptied for the new product and then filled up again. The cycle would be repeated if the optimization would have been carried out for more products. The level $h_1(t)$ shows similar features while $h_2(t)$ decreases and then stays at its minimum level for the last product as the in- and outflow rates are identical.

Because of the modular approach, the same model could be re-used for both configurations. The model changes are only changes to the input parameters but not the model equations. In both cases, the outflow rate was optimized which ensures that the flow rates are at their maximum for the bottleneck cells.

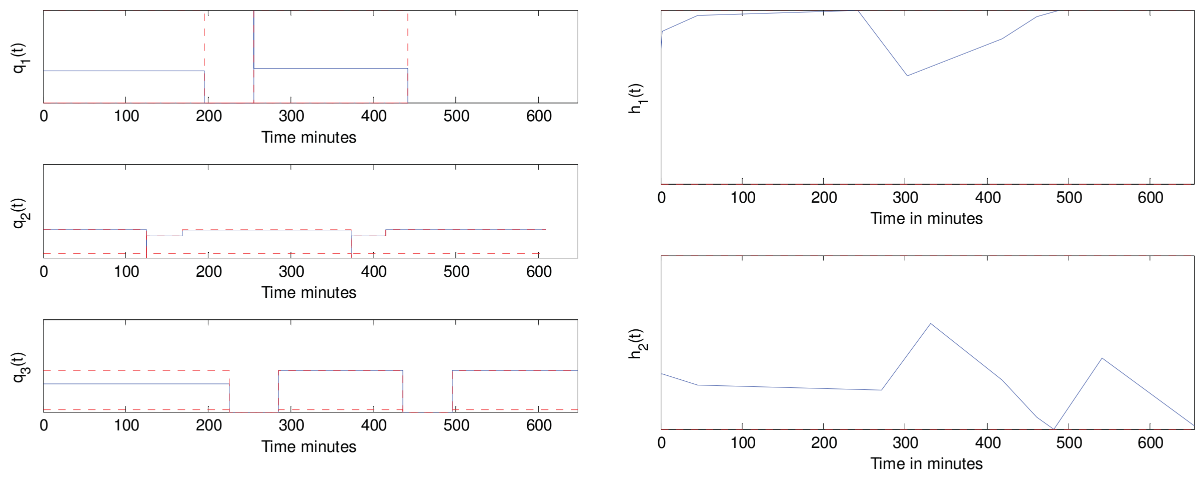

Fig. 5. Results for process Configuration I: cell inflow rates $q(t)$ and levels $h(t)$. Dashed lines indicate the upper and lower constraints.

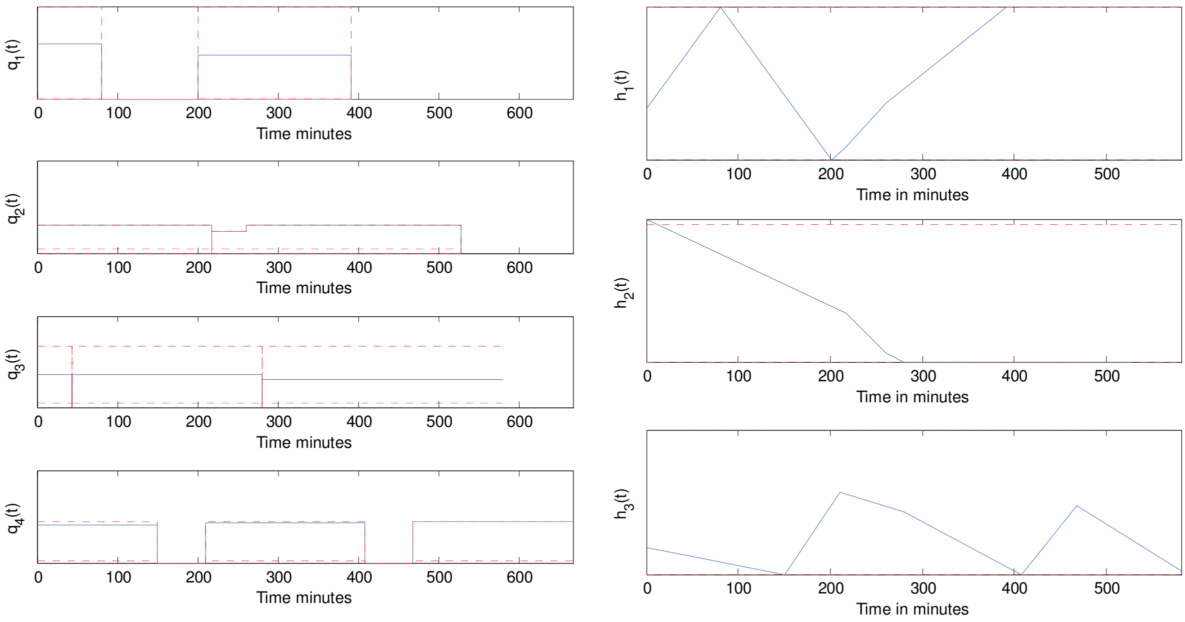

Fig. 6. Results for process Configuration II: cell inflow rates $q(t)$ and levels $h(t)$. Dashed lines indicate the upper and lower constraints.

5. CONCLUSIONS

To achieve a viable business model of advanced control and optimization solutions the modelling, implementation and maintenance effort has to be as small as possible. Re-usable solutions do not only decrease the modelling effort but also make it easier to maintain the solution as the development and commissioning engineers have to be familiar with one solution type. It is therefore attractive to build a modular solution that can be applied to different process setups. In this article a modular solution for a process with different configurations has been derived. The model has been applied to industrial processes and is currently in the process of deployment.

The key steps followed were as follows. A basic building block was identified and the equations introduced, including the connection between the blocks. Optimization results were discussed. Deriving this kind of modular approach is key when developing solutions that can be easily adapted and therefore have the potential to become a business success.

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