An Application Software For Visualization and Control Configuration Selection of Interconnected Processes[☆]

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Abstract

This paper presents a new application software for control configuration selection of interconnected industrial processes, called ProMoVis. Moreover, ProMoVis is able to visualize process models and process layout at the physical level together with the control system dynamics. The software consists of a builder part where the visual representation of the interconnected process is created and an analyzer part where the process is analyzed using different control configuration selection tools.

The conceptual idea of the software is presented and the subsequent design and implementation of ProMoVis is discussed. The implemented analysis methods are briefly described including their usage and implementation aspects. The use of ProMoVis is demonstrated by an application study on the stock preparation process at SCA Obbola AB, Sweden. The results of this study are compared with the currently used control strategy.

The study indicates that ProMoVis introduces a systematic and comprehensive way to perform control configuration selection. ProMoVis has been released under the Apache Open Source license.

Keywords: Visualization, signal flow graphs, interaction measures, control structure, control configuration, multivariable control, process control, interconnected systems, pulp and paper industry

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1. Introduction

Continuity is an important aspect of industrial process plants. It means that the industrial plant has a certain level of availability for production and evolves with maintenance and optimization efforts. Nowadays, availability of production plants need to be very high and the production quality needs to be well aligned with customers' requirements, (El-Halwagi, 2006). In turn, the requirements on performance of processes, their control and maintenance are high, and any changes in hardware should lead to adaptations in the control systems more or less right away.

However, these industrial process plants are interconnected systems where hundreds or even thousands of variables are connected through dynamic systems, resulting in a so-called topological complexity, (Jiang et al., 2007). These connections can be physical connections between components, plant-wide access of information by the control system, or control actions by the control system on a plant-wide scale. Examples of physical interconnections are material flows and reflows, like discarded material which is returned to a previous process step and thus gives rise to large recycle loops.

A consequence of this topological complexity is that adding control loops to a process in an ad-hoc manner may result in a system with obscure causality and unforeseen dynamics. Understanding of such systems becomes a challenge which makes the control configuration task very difficult. Remember, control configuration selection (CCS) addresses the problem of finding a low complexity structure for a controller for an industrial process that has the potential to render a control system with desirable performance. It does not involve the parametrization of the controller.

The first methods date back more than four decades, initiated by the work published in (Bristol, 1966) and (Rijnsdorp, 1965) where small scale multivariable problems were addressed. Since then, the host of methods has

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increased largely and can now be used to determine feasible control configurations for problems of larger scale. This has also led to the introduction of the control structure selection problem which contains the I/O selection problem and the control configuration selection problem as sub-problems. A good overview of the topic and available methods is given in (van de Wal and de Jager, 2001), (Skogestad and Postlethwaite, 2005) and (Khaki-Sedigh and Moaveni, 2009). It is also important to mention that these methods are not viable on a plant-wide scale, where the total number of inputs and outputs exceeds a few dozen.

Despite the vast host of proposed methods for CCS, there are no up-to-date toolboxes available for industrial use of the methods. To the knowledge of the authors, the only toolbox reported in the literature is by Nistazakis and Karcanias (2004), but it does not seem to be widely available.

As indicated in (Rohrer, 2000), visualization is important both from a collaborative perspective as well as to provide a comprehensive understanding of processes. Within the areas of construction, manufacturing, or production management, visualization is recognized as an important tool, see (Bouchlaghem et al., 2005; Browning and Ramasesh, 2007), but when it comes to the design and maintenance of control systems in process industries, the use of visualization is still very limited. Available software that can be used for visualization focuses mainly on simulation of the process dynamics, such as ChemCAD, MATLAB/Simulink, LabView, Extend, or Dymola, the latter based on the generic modeling language Modelica. However, there is a lack of user-friendly toolboxes or software aiming at control configuration selection.

The aim of this paper is to propose a new application software, called ProMoVis, that combines a graphical representation of a process plant and control system with analysis of the dynamic interconnections for control configuration selection. The underlying mathematical framework is the directed graph which is a highly abstract way of representing topological complexity in various applications.

Based on this mathematical framework a set of selected control configuration methods is implemented and can be used to analyze interconnected processes. Thereby, even mathematically complex methods become available for industrial use. Obviously, analyses performed by ProMoVis have the same limitations as the implemented control configuration methods, which means that the user has to select at most a few dozen variables for an individual analysis. These variables do not need to belong to the same part of the process plant, may be selected on a plant-wide scale, and may include variables in the control system, like e.g. estimated variables. It should be noted that ProMoVis is not limited to the selected set of methods, and other analysis methods for interconnected systems can be added. The software is currently in use at several industry partners of the SCOPE consortium within ProcessIT Innovations, (ProcessIT Innovations, 2012), and is made available by the open-source project ProMoVis at Sourceforge, (OProVAT EF, 2012).

The paper is arranged as follows. First, the interface for modeling and visualization is discussed and some necessary notation is introduced. Thereafter, the implemented CCS methods are shortly summarized including their usage, properties, and limitations. Then the stock preparation process of SCA Obbola AB is introduced as a case study. It is shown how the stock preparation process can be represented in ProMoVis and how the CCS task is performed. Finally, the results from the CCS are compared with the currently implemented control strategy and are discussed. The paper is concluded with some final remarks.

2. Application software ProMoVis

Selection of a control configuration for processes with many interconnections is facilitated by a systematic approach, which is based on process knowledge in terms of dynamic models of the interconnected process. To the knowledge of the authors there is no software available which can visualize process variables including their dynamic interconnections and control configuration analysis results in a comprehensive way. For this end, we now propose the software ProMoVis, (**Pro**cess **Mo**deling and **Vis**ualization).

From a practical perspective, selection and assessment of a control strategy would require the following actions by a practitioner:

1. Derive a dynamic model for the process
2. Select a set of manipulated and controlled variables (I/O selection)
3. Determine a controller configuration
4. Design of the individual controllers according to the configuration
5. Implementation of the controllers
6. Assessment of the control performance

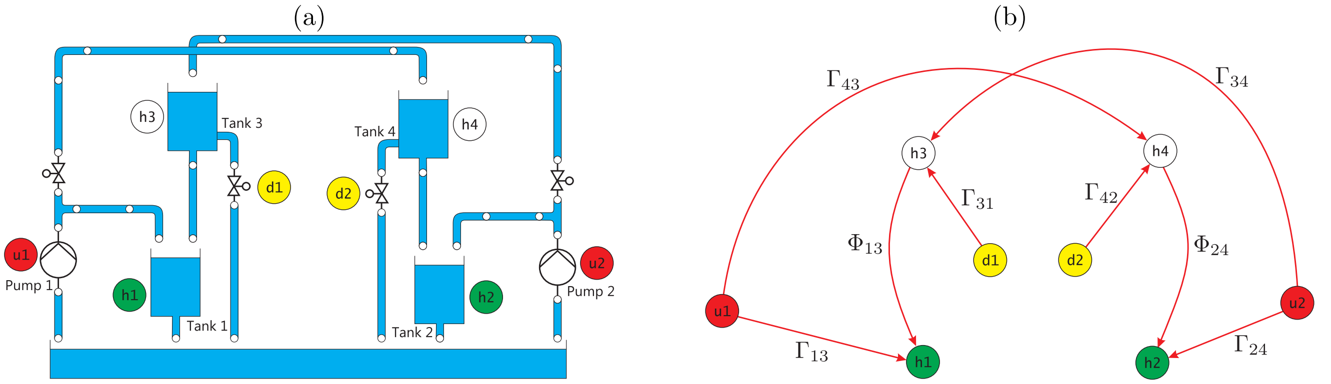


Figure 1: (a) Sketch of the quadruple tank process. (b) SFG for the quadruple tank process which contains informative labeling of the signals. Red edges indicate the model interconnections, red nodes indicate the actuators (pumps), yellow nodes represent the disturbances (leakage flows), white nodes represent the internal states (level in the upper tanks) and green nodes represent the measurement signals (levels in the lower tanks).

For all actions, besides action three, there exist software tools that support the control engineer. For modeling of processes and control design, toolboxes in MATLAB, (The Mathworks, Inc., 2012), or multivariate analysis and modeling tools from MKS Umetrics AB, Sweden (2012), are available. For the selection of I/O sets with manipulated and controlled variables the tools from MKS Umetrics AB, Sweden (2012) can be used from a multivariate perspective, whereas the methods proposed in (Skogestad, 2000), address the problem from a feedback control perspective. For the implementation of controllers in the control system there are tools proposed that support the automatic generation of control system code (Estévez et al., 2007) and (Vyatkin, 2012). Additionally, control systems provide standard blocks for certain types of controllers, like for example the PID. Further, many industrial control systems possess online tools to monitor the performance of control loops as part of the control system. The remaining gap is action three, where ProMoVis aims at providing support for CCS.

2.1. Software concept

In this section the required mathematical framework and notation is introduced and based on that the software concept is explained.

The signal flow graph (SFG) was proposed by Mason (1953) to represent interconnected dynamic linear systems, where the nodes represent the signals and the edges elementary linear dynamic systems, and will be used as the mathematical framework for the application software. Thus, the modeling task in ProMoVis reduces to the effort of collecting and combining information on the process plant and its control system. We will now state the algebraic form of the signal flow graph as given in (Johansson, 2010).

Let x_i, $i = 1, ..., p$ represent all exogenous signals, i.e. those variables that are not affected by any other variables in the interconnected system and let z_i, $i = 1, ..., n$ be all other variables of interest. The models are assumed to be formulated as

$$z_i = \Phi_{i1} z_1 + ... + \Phi_{in} z_n + \Gamma_{i1} x_1 + ... + \Gamma_{ip} x_p \tag{1}$$

for $i = 1, ..., n$ where Φ_{ij} and Γ_{ij} are linear dynamic systems that may represent process model interconnections as well as controllers. The set of exogenous signals may include e.g. external disturbances and manipulated variables but also set points. When a control loop is closed using a manipulated variable x_i and a variable z_j, then x_i will become an element in z and the associated set point variable will be introduced in x. Now, let us associate each signal x_i and z_i with a node, each $\Phi_{ij} \neq 0$ with an edge from z_j to z_i, and each $\Gamma_{ij} \neq 0$ with and edge from x_j to z_i. Then the SFG is obtained as a graphical representation of the model interconnections. Moreover, by collecting the signals x_i and z_i into vectors x and z and defining the multivariable, dynamic systems Φ and Γ whose i, jth element are Φ_{ij} and Γ_{ij} respectively, the signal flow graph representation may now be formulated as (Johansson, 2010)

$$z = \Phi z + \Gamma x \tag{2}$$

In the example in Fig. 1 a process sketch (a) and a signal flow graph (b) of a quadruple tank (Johansson, 2000b) are depicted. While the process sketch provides information on the construction and the variables in the process, the signal flow graph provides information on the dynamic interconnections. There, the exogenous inputs are the nodes d1, d2, u1, and u2 and constitute $x = [d1, d2, u1, u2]^T$, while the nodes h1 to h4 are the measurement signals and the internal states, which make up the vector $z = [h1, h2, h3, h4]^T$. Therefore, Φ_{13}, corresponding to the arrow from node h3 to h1, is a linear system modeling how the level in Tank 3 affects the level in Tank 1. Similarly, Γ_{43} is a model for how Pump 1 affects the level in Tank 4, and so on.

In the SFG framework variables are the interface between dynamic models, and some of them constitute the interface between process and control system. In ProMoVis, the process layout at the physical level is represented by interconnected entities referred to as components. These components do not contribute to the dynamics of the plant, but provide important information on the geographical location of the process variables and how they relate to the process physics.

In Fig. 2, this concept is captured and depicted for the quadruple tank example. Naturally, one could think of three layers: components, process models, and controllers. In each of these layers, the process variables are visible and represent the interface between the layers. This concept is very much in line with the industrial understanding of a plant where process variables and their properties are the central element. Performance requirements for processes and product qualities are always related to variables that are measured online, estimated, or derived from laboratory assessments. Therefore, components and process variables are the natural point to start modeling and visualizing a process, which is the component layer, similar to Fig. 1a. The process model layer then represents the dynamic interconnections in the process, which is the same SFG as already shown in Fig. 1b. The controller layer represents the dynamic interconnections in the control system, in this case an SFG of two SISO controllers for the quadruple tank with their associated set point variables r_h1 and r_h2.

A visualization can become very complex when all elements are visible at the same time, which might be of interest during composition or building, but unadvisable during analysis and decision making. In the latter case it is of interest to select certain information that should be visible, which can be achieved by the use of layers and their visibility. Such a complete representation of a plant in ProMoVis will be denoted a *scenario*.

2.2. Objects in ProMoVis

In ProMoVis a process plant including its control system is modeled using generic objects that are connected and arranged in different layers. There are four classes of objects: Variables, process models, controllers, and components. Process models, components, and controllers are collected in separated layers, which enable a differentiation of the view based on the class of the objects.

2.2.1. Variables

The variables represent the signals (nodes) in the SFG and can be divided into categories based on their character. For each category a color code is used in the interface in order to increase clarity for the user. Here, the default color setting is used but the user can reconfigure it.

Measured variables (green) represent the sensor input from the process into the control system.

User reference variables (blue) represent set points for controllers and can be interpreted as a manual setting by an operator. As such, they are the interface between the operator and the control system.

Manipulated variables (red) represent the interface from control system to process. Usually, actuator signals are manipulated variables.

Disturbance variables (yellow) represent exogenous disturbance signals, which may be induced by another process of the plant.

Estimated variables (orange) represent the result of a computation based on manipulated, controlled, or reference variables.

Internal or state variables (white) represent all variables which do not belong to any of the previous categories. These represent internal variables of the process or the control system, which are of importance for the control engineer.

Intermediate variables (white) are added automatically when two objects of the control system are connected with no interface variable. They are needed for the implementation of the SFG framework. They are considered as internal variables but have no user defined properties.

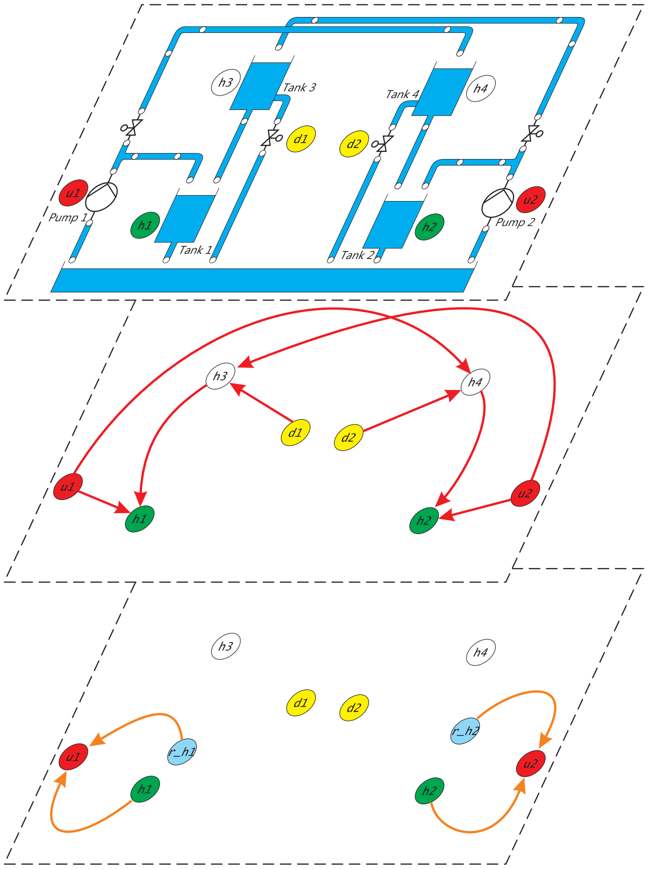


Figure 2: Different layers in the modeling and visualization concept. Components (top), Process models (middle), Controllers (bottom). Manipulated variables (red), Measured or controlled variables (green), Reference variables (blue).

Table 1: Applicability of variable properties depending on the variable category

Variable type / Property	Manipulated	Measured	Reference	Disturbance	Estimated	Internal	Intermediate
Range	X	X	X	X			
Limit	X	X		X	X	X	
Variance	X	X		X		X	
Sensor noise		X					
Operating point	X	X		X	X	X	
User set value			X				
Delay	X	X		X	X	X	

These categories are of importance as they determine how variables can be interconnected and how they interact with the information in the layers. It is important to note that controlled variables are either measured or estimated variables. In the sequel, the term controlled variables is used when the variables can be either estimated or measured.

Variables have different process related properties that can be set by the user, see Table 1. Some of these properties form part of all the dynamic models which connect a specific variable. These properties are:

- Limit (Saturation), which determines the allowed operating range of a variable.
- Delay, which allows the user to define input or output delays.

The value of the delay is integrated into the process models during the analysis. The remaining properties allow the user to specify process operating conditions which can be used for the scaling of the process variables during the analysis.

2.2.2. Process models

The process models correspond to the edges of the SFG and are the interconnections between variables representing the dynamic behavior of the plant. Generally, process models can be defined on a single-input-single-output basis, but multi-input-multi-output models are supported as well. In both cases, a process model can be defined as a transfer function or state space system in continuous or discrete time. When a process model is defined it is represented by a red edge, as shown in middle layer of Fig. 2.

In order to simplify adding process models, some model structures which are used within system identification of process models are pre-defined, like for example

$$\Gamma_{ij}(s) = \frac{K}{Ts+1}e^{-Ls} \quad or \quad \Phi_{ij}(s) = \frac{K}{Ts+1}e^{-Ls}$$

where the user only has to provide the parameters K, T and L in order to define the dynamics.

Currently, only linear time invariant models are supported. Clearly, a dependency on the operating points of the different variables arises, but most available CCS methods are only applicable on linear models.

It has to be noted that ProMoVis is an offline tool and does not derive the process models and their parameters. This has to be done in a previous step by the user.

2.2.3. Controllers

In most cases, controllers do not differ from process models in their implementation. Single-input single-output controllers can be represented by two edges, from reference and controlled variable to manipulated variable, see bottom layer in Fig. 2. Alternatively, Single-input single-output controllers can also be defined as blocks with two inputs (reference variable, controlled variable) and one output (manipulated variable). Either way, the resulting edges or blocks are then automatically generated. The reason is to simplify for users to create and connect controllers properly and thereby to avoid incorrect connections. Similar to process models, some controller types are pre-defined, such as PID controllers and filters. The user can choose between the block or edge representation. Multivariable controllers can be defined with multiple input and output ports.

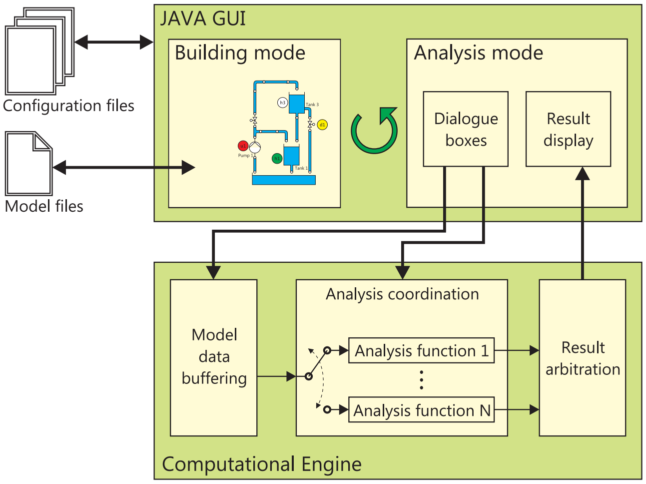


Figure 3: Software architecture of ProMoVis.

2.2.4. Components

The process layout of a plant at the physical level can usually be decomposed into smaller building blocks which are components. These components can have a graphical representation which can be used to create a visualization of the plant.

In ProMoVis, components have no functionality other than providing an understanding of the layout and construction of the plant with a rather coarse level of detail and realism. An effective representation of components can be created by using symbols according to industry standards (see for example SSG Standard Solutions Group AB, 2007a,b), or bitmap images of drawings or sketches.

For the design of symbols a simplistic script language is implemented that enables the user to create new sets of symbols and libraries. At the moment, there are sets of symbols available for the pulp and paper industry and mining industry. The script language is mainly composed of drawing commands for lines, polygons, ovals, coloring, and text. ProMoVis will interpret the commands and then draw the component symbols accordingly.

2.3. Software implementation

Building a representation of an interconnected process does not require any intense computations. Additionally, the focus is on interactivity and a graphical user interface which is versatile and easy to use on any computer platform. CCS methods depend on many mathematical operations that have to be performed on the SFG.

Therefore it was decided to implement the modeling and visualization in Java and the computational engine in MATLAB. A schematic of the software architecture is shown in Fig. 3. There, it can be seen that the Java GUI is configured using configuration files. The information flow between the Java GUI and the computational engine is limited to the transfer of the model data, the analysis commands and the reporting of the result data back to the Java GUI.

After startup, ProMoVis enters the building mode, where the user can create new scenarios or load existing scenarios from stored files. The user can then switch between building mode and analysis mode using menu commands. In the analysis mode, the user makes a selection of the analysis that should be performed and selects the parts of the scenario which should be considered. As soon as the analysis is called, the current model data is transferred to the computational engine where it is buffered until the user leaves the analysis mode. Additionally, the analysis coordination is executing the necessary analysis functions. Thereafter the result arbitration will combine the results from the analysis functions and report them back to the result display in the Java GUI.

The interface between the Java GUI and the computational engine is well defined and enables the porting of the MATLAB code onto other platforms without significant changes to the Java GUI. For industrial use, it is possible to combine the computational engine with the Java GUI into a stand-alone software.

Table 2: Available options for each method implemented in ProMoVis.

		RGA	DRGA	NI	PM	HIIA	Σ_2	SET	FETr	FETc	FDPTr	FDPTc
Consideration of time delays			X		X	X						
Frequency options			X								X	X
Scaling options	saturation, range				X	X	X	X	X	X	X	X
	input scaling				X	X	X		X		X	
	output scaling				X	X	X			X		X
Filter options					X	X	X					
Plot type			X									

3. Analysis methods for the selection of control configurations

The goal is to select a set of Interaction Measures (IMs) which is sufficient to solve the CCS problem for most of the cases. It is the belief of the authors that this includes traditional IMs like relative gains for the selection of input-output pairings, Niederlinski Index for testing the stabilizability of the resulting decentralized configurations, as well as more modern gramian-based IMs which are used for the design of sparse control configurations.

We define now the selected CCS methods and discuss their implementation. A typical procedure for CCS using IMs is described for the user of ProMoVis.

3.1. Implementation of the analysis tools

The implemented tools depend on the availability of accurate process models, which have to be derived prior to the analysis.

When the method to be used is selected, the user is required to choose an input/output set for which the analysis is performed. In general, the inputs are restricted to be manipulated variables, however future consideration of hierarchies will require including controller references in order to select higher level structures like the outer loops of cascades. Depending on the selected method, a different set of options is available, with predefined default values. These options are grouped in the following subsets:

- **Consideration of time delays**. For those methods which are sensitive to time delays, the user can decide if these are considered in the computation. If so, the order of the Padé approximation has to be given for the case of continuous-time systems.

- **Frequency options**. For those methods which result in an array of diagrams in the frequency domain, it is allowed to select the frequency unit, as well as the set of frequencies considered for analysis.

- **Scaling options**. Usual methods for scaling signals involve dividing each variable by its maximum expected or allowed change (Skogestad and Postlethwaite, 2005). For those methods which are sensitive to the scaling of the process variables, it is allowed to choose to scale the process variables by using the values entered in either the *Saturation* or the *Range* fields of the process variables. As an alternative, it is allowed to manually introduce input and/or output scaling matrices depending on the method.

- **Filter selection**. For the gramian-based IMs, it is possible to restrict the analysis to a range of frequencies of interest, *e.g.* around the crossover frequency, which is where most of the control action is usually present. This is done by filtering the input-output channels such that frequencies outside the selected range are attenuated (Birk and Medvedev, 2003). In ProMoVis, such filters can be declared in the calculation options.

- **Plot type**. This option is exclusive of the Dynamic Relative Gain Array (DRGA), which results in a complex array represented in the frequency domain. The user can choose to represent its magnitude, phase, real part or imaginary part.

The options which are available for each of the subsequently defined methods are summarized in Table 2.

For the analysis methods described here, the transfer function matrix $G(s)$ from the selected subset u of the exogenous inputs into the selected subset y of the process outputs is required and will be derived now from (2). Provided that (2) is well-posed (see (Johansson, 2010) for details) we may infer that the variables z are related to the exogenous inputs x as

$$z = (I - \Phi)^{-1}\Gamma x \tag{3}$$

Now, let B be a matrix selecting the variables u from x, i.e. $u = Bx$. Then ΓB^T will contain those columns from Γ that correspond to u. Similarly, let C be a matrix selecting the variables y from z, i.e. $y = Cz$. Then, for the continuous-time case transfer function matrix from u to y is

$$G(s) = C(I - \Phi(s))^{-1}\Gamma(s)B^T \tag{4}$$

In ProMoVis, the calculation $(I - \Phi(s))^{-1}\Gamma(s) = G_0(s)$ is done only once in order to reduce computational effort. Selecting different sets of inputs and outputs, i.e. multiplication by different C and B^T is then accomplished by picking out the appropriate rows and columns from $G_0(s)$.

After this computation, the selected method is applied to $G(s)$ and the result is appropriately displayed.

3.2. Analysis tools based on relative gains

The most popular tool based on relative gains is the RGA, introduced by Bristol (1966) to design decentralized control configurations based on steady-state gain information. Later, several authors addressed some of the limitations of the RGA, usually by introducing variants of this IM. This includes different extensions of the RGA to consider process dynamics, like evaluating the RGA at different frequencies by Witcher and McAvoy (1977), which was named Dynamic RGA (DRGA).

In the default set of CCS methods in ProMoVis, the RGA and DRGA methods have been implemented for the design of decentralized control configurations as well as the Niederlinski Index for discarding unstable configurations. Other advanced techniques based on relative gains are candidates for future versions of ProMoVis, like the Block RGA introduced by Manousiouthakis et al. (1986) for the design of block diagonal control structures and the partial relative gains introduced by Häggblom (1997) for the selection of sparse control configurations.

3.2.1. Relative Gain Array (RGA)

The RGA of a continuous process described by (2) and with input-output transfer function G as in (4) is:

$$RGA(G) = G(0) \otimes G(0)^{-T} \tag{5}$$

where $\otimes$ denotes element by element multiplication, and $G(0)^{-T}$ is the transpose of the inverse of the steady-state gain matrix. The normalization used in this calculation implies that the sum of all the elements in the same row or column of the RGA add up to 1.

Each of the values of the RGA is the steady-state gain of the corresponding input-output channel when all the other loops are open divided by the steady-state gain when the rest of the process is in closed loop under tight control. Based on this definition, the following rules have been formulated for the selection of a decentralized control configuration:

- The preferred pairings are those with RGA values close to 1 (Skogestad and Morari, 1992).
- The selection of positive values for the decentralized pairing is a necessary condition for closed-loop integrity, provided that all elementary subsystems are linear time invariant, finite dimensional, stable, and strictly proper (Campo and Morari, 1994). Integrity is a desirable property of the decentralized control system, which means that the closed-loop system should remain stable as each of the SISO controllers is brought in and out of service (Bristol, 1966). This is not applicable to time delayed systems due to their infinite dimensional aspect.
- Large values should not be selected since they are related to ill-conditioned behavior of the plant (Chen et al., 1994). Values exceeding 1 by more than a few tenths are very sensitive to model uncertainty and the nominal value can be easily perturbed to a large value, as indicated in the studies on 2×2 systems by Castaño and Birk (2008).

Note that these properties imply that the RGA might not indicate any appropriate decentralized control configuration, requiring other tools to design configurations. Moreover, the RGA is insensitive to input and output scaling and to time delays.

In addition, the RGA has certain limitations which need to be considered. Several of these limitations have been resolved by different authors, and some of these solutions have been implemented in ProMoVis, like the application to non-square plants with the use of the pseudo-inverse (Chang and Yu, 1990), or the computation of the RGA for systems with pure integrators (Arkun and Downs, 1990; McAvoy, 1998).

An important limitation is that the RGA is originally evaluated only at steady state, and therefore is not reflecting the dynamic properties of the process.

3.2.2. Dynamic RGA (DRGA)

The DRGA of a continuous process described by (2) and with input-output transfer function G as in (4) is:

$$DRGA(\omega) = G(\boldsymbol{j}\omega) \otimes G(\boldsymbol{j}\omega)^{-T} \tag{6}$$

The DRGA is an array of complex numbers and has a more obscure interpretation than that of the RGA. Usually, it is preferred to use its magnitude as indicator due to the gain interpretation, however only the sums of the rows or columns of the resulting complex array (or its real part) add up to 1. Moreover, by evaluating the magnitude alone, the sign of the DRGA is lost as an indicator, which is often used to rule out certain input-output pairings.

A shortcoming of the DRGA is that perfect control for all frequencies is assumed in its computation. This assumption is only valid for a very low frequency range. Other dynamic versions of the RGA have been defined to overcome this situation, like the Effective RGA (ERGA) introduced by Xiong et al. (2005). Nevertheless, the DRGA version implemented here has been selected for its simplicity and widespread use.

3.2.3. Niederlinski Index (NI)

For a system under decentralized control, and assuming that the process is described by (2) and with input-output transfer function G as in (4) which has been reordered so that the controller is a diagonal matrix, the Niederlinski Index (NI) can be computed as (Niederlinski, 1971):

$$NI = \det(G(0))/\prod_{i=1}^{n} G_{ii}(0) \tag{7}$$

This indicator is traditionally used to test the stabilizability and/or integrity of a decentralized configuration.

Under the assumptions of stability of all the elementary subsystems represented by rational functions $G_{ij}(s)$, a value of $NI < 0$ is a sufficient condition for the instability of the closed loop system when all the SISO loops are under integral action. This condition is widely used for discarding unstable decentralized control structures prior to the design of the multi-loop controller.

Integrity can be verified by testing the stabilizability of the systems which result from opening each of the SISO loops. This is done by computing the value of NI for any of the principal sub-matrices $G^{ii}(0)$ resulting from removing the i^{th} row and column from $G(0)$. The system will not possess integrity if $NI < 0$ for any of the principal sub-matrices.

More restrictive conditions for stability and/or integrity exist like the tighter conditions derived by Chiu and Arkun (1991) for 2 × 2 plants. However, these tests are more complicated, and the reader can refer to the surveys in Chapter 10 by Skogestad and Postlethwaite (2005) or Chapter 2 by Khaki-Sedigh and Moaveni (2009).

3.3. Gramian-based IMs

For the design of control configurations other than decentralized, the modern gramian-based IMs can be used.

The gramian-based IMs are Index Arrays (IAs) in which a gramian-based operator is applied to each of the single-input single-output subsystems in order to quantify its significance. The use of different operators results in different IMs. The Hankel Interaction Index Array (HIIA) introduced by Wittenmark and Salgado (2002) uses the Hankel norm. The Participation Matrix (PM) introduced by Salgado and Conley (2004) uses the trace of the product of controllability and observability gramians, and the Σ_2 introduced by Birk and Medvedev (2003) uses the $\mathcal{H}_2$ norm.

For a continuous process described by (2) and with input-output transfer function G as in (4), the IAs are calculated as:

$$[IA]_{ij} = \frac{[G_{ij}(s)]_p}{\sum_{i,j=1}^{m,n} [G_{ij}(s)]_p} \tag{8}$$

where $[\cdot]_p$ denotes the corresponding operator of the used IA.

As a result of the normalization, all the elements of any of these IAs add up to one. The selection of the control configuration is made by selecting a subset of the most important input-output subsystems, which will form a reduced model on which control will be based. Choosing a configuration with a total contribution of the selected input-output channels larger than 0.7 is likely to result in satisfactory performance (Salgado and Conley, 2004).

An advantage of the gramian-based IMs over the RGA is their ability to be used for designing sparse control configurations. A disadvantage is that the quantification of the significance of the input-output subsystems depends on the scales used to represent the inputs and outputs.

At the moment there is no clear procedure for interpreting the gramian-based IMs in the presence of time delays. For the case of the operators used by the HIIA and the PM, the quantified significance of an input-output channel increases as the channel delay increases (Castaño and Birk, 2012). This might result in inadequate configurations, since channels exhibiting large time delays but low gain and bandwidth might end up forming part of the reduced model. This was revealed in Halvarsson (2008), where simulation work indicated that the presence of a time delay itself is not sufficient for saying that a particular input-output channel should be used in the controller. Due to this property of the PM and HIIA, it was decided that the user can select if the time delays will be neglected or not in the computation. No decision needs to be taken in the case of using Σ_2 due to its insensitivity to time delays.

3.4. Methods for structural analysis using weighted graphs

ProMoVis is able to visualize analysis results together with the process, *e.g.* as an overlayed weighted directed graph that shows the significance of the connections as the thickness of the edges. For this purpose, the analysis methods described by Castaño and Birk (2012) have been implemented: SET and FET.

These methods use the squared $\mathcal{H}_2$ norm as operator for quantifying the significance of the process interconnections in terms of signal energy transfer.

3.4.1. Structural graphs.

The method Structural Energy Transfer (SET) is applied to obtain a weighted structural graph describing the importance of the direct process interconnections.

Structural graphs have been extensively used for the design of control structures, and the work in Nistazakis and Karcanias (2004) describes its importance for deriving properties such as decomposability (Sezer and Šiljak, 1986) and structural controllability and observability (Lin, 1974).

The novelty of the method SET is adding weights to these structural graphs. This gives an enhanced visual understanding of the process and allows application of advanced methods for CCS which consider weighted graphs such as described by Johansson (2000a).

3.4.2. Functional graphs.

In Functional Energy Transfer (FET) a normalized weighted directed graph is derived for the input-output channels, which quantifies their significance. Two different normalizations are used such that either the weights of the edges entering an output node or the weights of the edges leaving an input node add up to 1. These normalizations are denoted as FET_r and FET_c, and for a process described by (2) and with input-output transfer function G as in (4) they are calculated as:

$$[FET_r]_{ij} = \frac{||G_{ij}||_2^2}{\sum_{l=1}^{n} ||G_{il}||_2^2} \quad ; \quad [FET_c]_{ij} = \frac{||G_{ij}||_2^2}{\sum_{k=1}^{m} ||G_{kj}||_2^2} \tag{9}$$

For each output, the relative effect of the selected process inputs is described by FET_r. For each input, the relative effect on the selected outputs is described by FET_c.

It should be noted that FET_r is insensitive to output scaling, and FET_c is insensitive to input scaling.

Several case studies indicated the usefulness of FET_r in CCS. A controlled variable should be associated with the minimum number of actuators which result in a value of the sum of their contributions (edge widths) larger than a designed threshold. Previous work indicates that a value larger than 0.7 should be achieved in order to expect a well behaving closed loop system (Castaño and Birk, 2012).

These measures can also be assessed in the frequency domain resulting in a function of frequency instead of a scalar number for each edge. This is done by normalizing the squared magnitude of each of the input-output interconnections so either all the edges entering a node add up to one or all edges leaving a node add up to one. These operations result in the methods named $FDPT_r$ and $FDPT_c$. For a process described by (2) and with input-output transfer function G as in (4), $FDPT$ is calculated as:

$$[FDPT_r(\omega)]_{ij} = \frac{|G(\mathbf{j}\omega)_{ij}|^2}{\sum_{l=1}^{n} |G(\mathbf{j}\omega)_{il}|^2} \quad ; \quad [FDPT_c(\omega)]_{ij} = \frac{|G(\mathbf{j}\omega)_{ij}|^2}{\sum_{k=1}^{m} |G(\mathbf{j}\omega)_{kj}|^2} \tag{10}$$

3.5. Tools for the reconfiguration of control structures

A control deficiency could be the consequence of a tuning deficiency or of a structural deficiency in the controller. In the latter case, a redesign of the control structure should be done, preferably by adding or removing a minimal amount of controller interconnections.

The development of tools which identify if there is a structural deficiency in the controller and suggest a redesigning of the controller configuration has only recently received attention. A method was proposed by Birk (2007), that makes use of the factorization of the closed loop sensitivity function matrix and has been implemented in ProMoVis. This method quantifies the performance loss due to neglected interconnections in the process and considers the currently used controller. The method was further analyzed and assessed in a comparative study in (Birk and Dudarenko, 2012).

An appropriate output scaling is required for the application of the method, which is limited to control systems with decentralized or block diagonal control structures.

In ProMoVis, this method can be used if a 1-DOF controller is used and the parameters of the controller are declared.

3.6. Typical procedure for CCS using IMs

The following procedure can be used for selecting control configurations based on the IMs.

Step 1. Seek a decentralized control structure using methods based on relative gains. If a decentralized structure is indicated by the use of the RGA as described below, then the DRGA will help to determine if the structure is still feasible at other frequencies different to steady-state. The value of the DRGA at the crossover frequency is of special interest, since it is usually the range of frequencies at which control is more active.

Step 2. Check the stabilizability of candidate decentralized configurations. Decentralized structures with negative values of NI must be discarded for being unstable under integral action in all the SISO loops. Several other tests for stability and/or integrity of the decentralized control structure using NI and the RGA can be used. The reader can refer to Chapters 10 and 2 respectively in the books by Skogestad and Postlethwaite (2005) and Khaki-Sedigh and Moaveni (2009) for surveys on these tests.

Step 3. Design a sparse control configuration if needed. It is recommended to contrast the indications obtained using relative gains with other CCS methods. One reason is that the RGA might indicate severe loop interaction if a decentralized structure is to be used. Another reason is that there might be severe loop interaction which is not captured by the RGA, i.e. in triangular plants. These cases present severe difficulties for decentralized configurations, and the gramian-based IMs can then be used to design a sparse control configuration. As an alternative to the gramian-based IMs, the method FET_r can be used, which provides a visual and intuitive analysis as well as being insensitive to the scaling of controlled variables.

4. Case study: A stock preparation process.

The stock preparation process in SCA Obbola AB, Sweden is described below and will be used as illustrative example for the typical work flow with ProMoVis. At the moment of the described work, the plant was operating with a decentralized controller under stable conditions but exhibiting significant perturbations in the controlled variables. The case study will therefore be considered a success if an analysis with ProMoVis indicates the same decentralized configuration as feasible, and gives insight in potential modifications on the control structure relating to the deficiencies.

Prior to the use of ProMoVis, process information has to be acquired in the form of mathematical models and/or process flow charts. First the process model is implemented in ProMoVis by creating a visual representation of the flow charts and declaring the mathematical process models. Then the control structure can be selected using the implemented methods.

4.1. Description of the stock preparation process.

The stock preparation process is present in many paper plants for the refining of pulp and chemical treatment. In conventional refining, the pulp is pumped through the gap between two grooved discs. A moving disc can be rotated and displaced in the axial direction, and the friction of the fibres with the discs and with each other creates the refining effects. Refining creates major changes in pulp properties as described by Annergren and Hagen (2004). Its goal is to improve web strength, but also results in decreasing the dewatering capacity of the paper web and thus needs to be tightly controlled for optimum results.

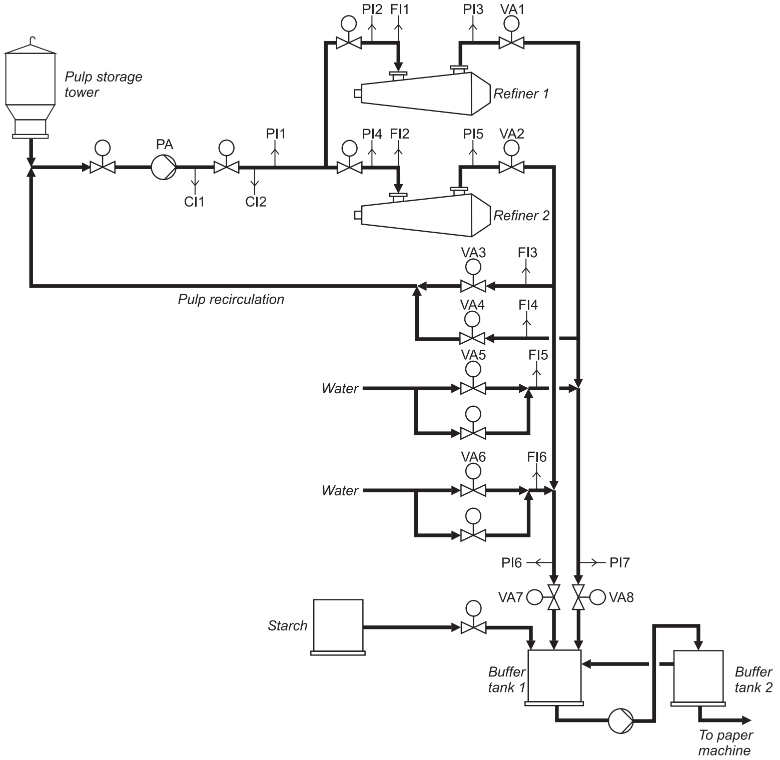


Figure 4: Schematics of the stock preparation process at SCA Obbola. Pipes with indicated flow directions are wide solid lines, descriptions or component names are in italics and variables are in capital letters. Symbols are in accordance with the SSG standard.

A schematic of the process is depicted in Fig. 4. First the pulp is pumped from a storage tank and the flow bifurcates towards two parallel refiners. Note that a fraction of the pulp is recirculated again for balancing the mechanical load in the refiners. The pulp is then diluted to the required concentration for the chemical treatment, being finally discharged to a storage tank, in which starch is added, and from where the pulp is pumped to subsequent tanks to continue with the chemical treatment. The structural complexity of the process requires a deep analysis of the process interconnections in order to design a control configuration. The set of considered sensors and actuators is summarized in Table 3.

The refiners have internal controllers to track a set point for the specific energy that is used to affect the pulp. Safety, quality, and production depend on well-maintained set points for the considered flows and the pressure at the entrance of the refiners. In the current control of the process, four independent single-input single-output PID controllers are used to maintain the flows at the desired operating points. The centrifugal pump is then used as actuator in another control loop to keep the pressure before the refiners at the operating point. The dilution water is delivered to each of the branches with the use of cascade structures, which have as outer loops the desired concentration for the pulp, and as inner loops the needed flow of pulp to achieve such concentration. In both branches, the pressure at which the pulp is discharged to the storage tank is controlled by a valve with a PID controller.

4.2. Implementation of the stock preparation process model in ProMoVis

The visual representation resulting from implementing the stock preparation process in ProMoVis is depicted in Fig. 5. First, a visualization of the process layout at the physical level was created by connecting components representing elements such as pipes, valves, pumps, and refiners. Secondly, the corresponding process variables were declared.

In order to collect significant process data for the modeling task, the process was excited during normal operation by perturbing the actuators with additive white noise. In a first modeling step, a model structure was created by selecting a subset of controlled variables and actuators to be considered for control, and identifying which actuators generate an observable impact on certain controlled variables. System identification techniques were used to model the input-output channels reflected by the identified model structure, and the resulting transfer functions of the

Table 3: Considered sensors and actuators in the refining section.

Actuators

Tag	Name	Description
PA	Pump Actuator	Pumps the flow through the refiners
VA1	Valve Actuator 1	Valve after refiner 1
VA2	Valve Actuator 2	Valve after refiner 2
VA3	Valve Actuator 3	Valve at the recirculation from refiner 2
VA4	Valve Actuator 4	Valve at the recirculation from refiner 1
VA5	Valve Actuator 5	Valve at the dilution for the pulp form refiner 1
VA6	Valve Actuator 6	Valve at the dilution for the pulp form refiner 2
VA7	Valve Actuator 7	Valve before discharge to the storage tank (branch from refiner 1)
VA8	Valve Actuator 8	Valve before discharge to the storage tank (branch from refiner 2)

Sensors

Tag	Name	Description
PI1	Pressure Indicator 1	Pressure before the flow bifurcation
PI2	Pressure Indicator 2	Pressure at the entrance of refiner 1
PI3	Pressure Indicator 3	Pressure at the output of refiner 1
PI4	Pressure Indicator 4	Pressure at the entrance of refiner 2
PI5	Pressure Indicator 5	Pressure at the output of refiner 2
PI6	Pressure Indicator 6	Discharge pressure before the storage tank (branch from refiner 1)
PI7	Pressure Indicator 7	Discharge pressure before the storage tank (branch from refiner 2)
FI1	Flow Indicator 1	Pulp flow through refiner 1
FI2	Flow Indicator 2	Pulp flow through refiner 2
FI3	Flow Indicator 3	Pulp flow recirculated from refiner 2
FI4	Flow Indicator 4	Pulp flow recirculated from refiner 1
FI5	Flow Indicator 5	Dilution water for pulp from refiner 1
FI6	Flow Indicator 6	Dilution water for pulp from refiner 2
CI1	Concentration Indicator 1	Concentration before the flow bifurcation
CI2	Concentration Indicator 2	Concentration before the flow bifurcation

Estimated Variables

Tag	Name	Description
CE1	Concentration Estimation 1	Average of two redundant concentration sensors before flow bifurcation.
CE2	Concentration Estimation 2	Concentration of pulp to be diluted after refiner 1
CE3	Concentration Estimation 3	Concentration of pulp to be diluted after refiner 2
FE1	Flow Estimation 1	Flow of pulp from refiner 1 which is not recirculated
FE2	Flow Estimation 2	Flow of pulp from refiner 2 which is not recirculated

interconnections in the model of the stock preparation prcess are summarized in Table 4. Each of the obtained transfer functions was declared in ProMoVis, resulting in red interactive edges represented in Fig. 5, which can be used to access and edit the parameters of the associated process model.

Finally, the controllers representing the current control of the process were defined in order to visualize and maintain the information on the control system.

Notice that controlled variables can be either measured or estimated. The distinction is used in order to make the user aware of the fact that estimated variables are the result of a calculation in the control system, represented by observers. Therefore, measured variables may only be connected to other process variables, while estimated variables may be connected to variables in the control system as well.

CE1 is the average of two redundant concentration sensors. FE1 and FE2 are the flows of pulp before adding the dilution water, and they are computed as the difference between the flow through the refiners and the recirculation flow. CE2 and CE3 are the concentrations of pulp before the dilution; they are the controlled variables of the outer loops in the cascades to control the addition of dilution water, and they are estimated as being the concentration of pulp before the refiners with a transport delay which depends on the flow of pulp before adding the dilution water.

Note that reference variables can be part of a control loop referring to an operating point for a controlled variable, or the manual setting of an actuator. As an example, in the pressure control loops actuating VA7 and VA8 in Fig. 5, the user can switch from manual to automatic mode. The position of the switches determine different operational modes for the analysis.

4.3. Analysis of the stock preparation process with ProMoVis

A control configuration for the stock preparation process will now be selected using ProMoVis.

The existing controllers of the process for the pressures PI6 and PI7 were causing large oscillations during the experiment. For this reason, the valves VA7 and VA8 were manually placed at a certain opening during most of the experiments, which means that the collected data was not informative enough to create models which include these variables. Therefore further experiments need to be conducted in order to include those variables in the CCS problem.

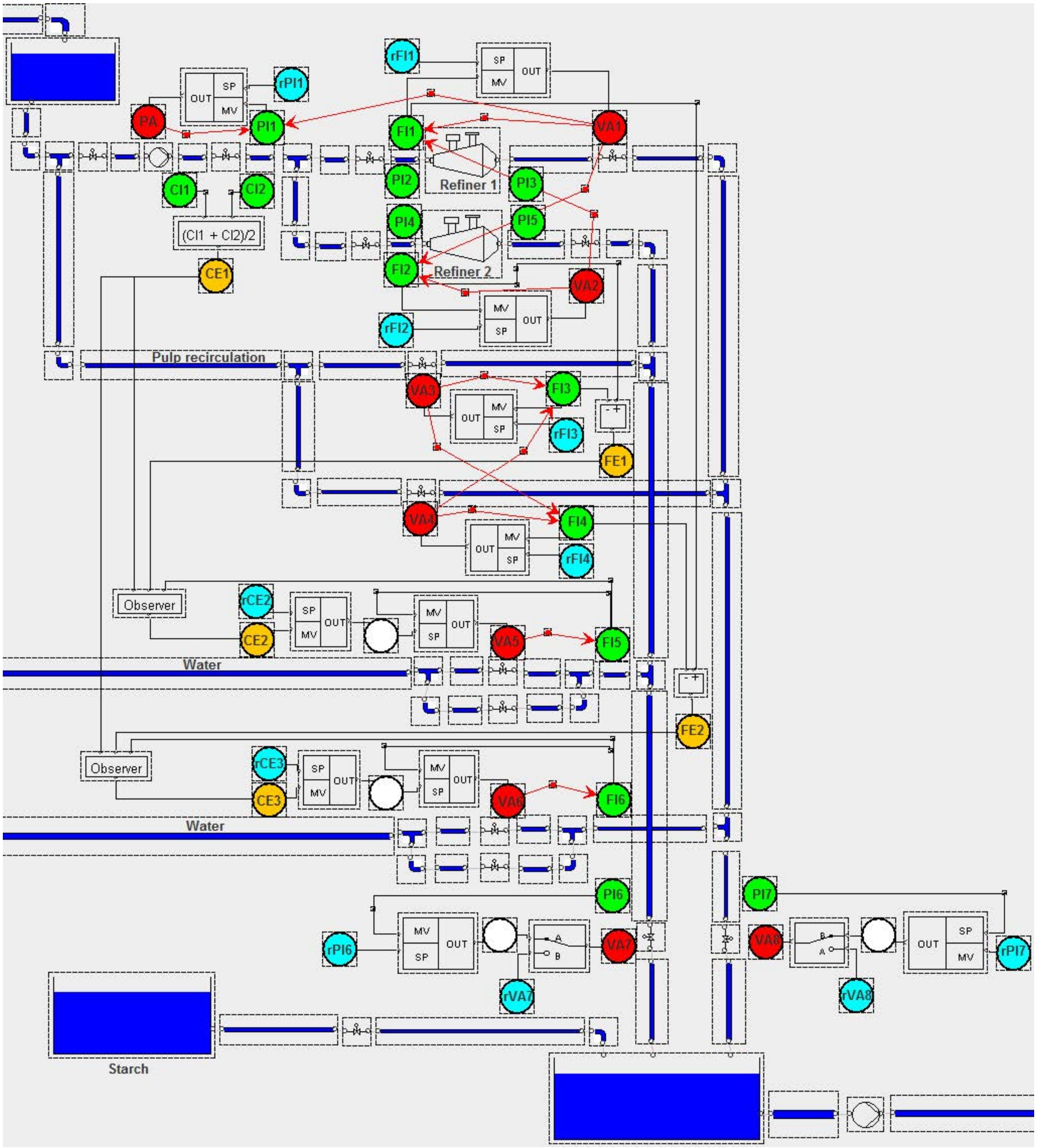


Figure 5: ProMoVis screenshot. Refining section of the stock preparation process at SCA Obbola.

Table 4: Transfer functions of the interconnections in the model for the stock preparation process.

Input-Output	Transfer function
PA - PI1	$2.8961/(5.8279s^2 + 2.965s + 1)$
VA1 - PI1	$-0.54313/(2.9712s + 1)$
VA2 - PI1	$-0.87994/(0.92472s + 1)$
VA1 - FI1	$1.5359/(42.331s + 1)$
VA2 - FI1	$0.40553/(20.046s + 1)$
VA1 - FI2	$0.35223/(18.8525s + 1)$
VA2 - FI2	$1.8979/(29.6601s + 1)$
VA3 - FI3	$0.24843/(4.5058s + 1)$
VA4 - FI3	$-0.019761/(2.1097s + 1)$
VA3 - FI4	$-0.042479/(4.7492s + 1)$
VA4 - FI4	$-0.20199/(2.018s + 1)$
VA5 - FI5	$4.3294/(2.9661s + 1)$
VA6 - FI6	$0.35864/(15.9248s + 1)$

As for the dilution water, it is trivial from the structure of the determined model, that the pairings VA5-FI5 and VA6-FI6 have to be selected.

Our problem is now reduced to find a control configuration for the sensor/actuator set in Table 5.

Table 5: Input-output set to be considered for analysis.

Actuators	PA VA1 VA2 VA3 VA4
Sensors	PI1 FI1 FI2 FI3 FI4

Applying the RGA to the selected input-output set yields the numbers in Table 6. According to the pairing rules, the diagonal pairing of inputs and outputs is preferred for decentralized control.

Table 6: Result of the RGA analysis of the stock preparation process.

Input Output	PA	VA1	VA2	VA3	VA4
PI1	1	0	0	0	0
FI1	0	1.05	-0.05	0	0
FI2	0	-0.05	1.05	0	0
FI3	0	0	0	1.02	-0.02
FI4	0	0	0	-0.02	1.02

Using ProMoVis, the value of NI for the selected pairing was calculated to be $NI = 0.935$.

This steady state analysis of the process indicates that a decentralized control structure is likely to lead to acceptable performance.

To complement this information, one or several of the gramian-based IMs could be used. The result of applying the PM to the stock preparation process is given in Table 7.

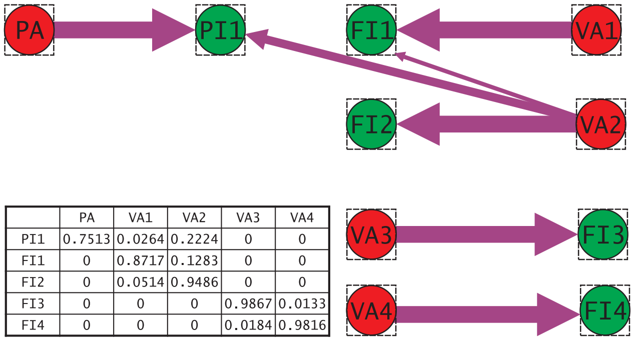
There, the sum of the diagonal elements in the PM is 0.950, which means that a decentralized configuration will consider 95% of the system dynamics. However, the user should at this stage be aware of the fact that the gramian-based IMs are sensitive to input-output scaling. The manipulated variables are expressed in % of actuator opening. However, the measured variables are represented in different scales, since there are both pressure and flow measurements, and also the recirculation flows (FI3 and FI4) are only a fraction of the primary flows (FI1 and FI2). This is probably the reason why the input-output channels related to the pressure measurement have a rather high significance, whilst the ones associated with the recirculated flows have a rather low one. A possible remedy is to scale the process variables using their observed range of variation.

Another possible approach is to use the recently introduced method FET_r, which is independent of output scaling. The result of applying FET_r is depicted in Fig. 6. The most significant edges entering a measured variable identify the actuators which can deliver the highest energy contribution on the measured variable. An optional threshold of 0.1 on the significance of the edges determines their visibility and thereby the graphical representation is simplified.

By inspecting Fig. 6, and pairing each of the measured variables with the actuator connected with the most significant edge, it is clear that the best decentralized control structure suggested by FET_r, is the same as the one

Table 7: Result of the analysis using the Participation Matrix of the stock preparation process.

Input / Output	PA	VA1	VA2	VA3	VA5
PI1	0.724	0.011	0.029	0	0
FI1	0	0.088	0.006	0	0
FI2	0	0.005	0.134	0	0
FI3	0	0	0	0.002	$1.5 \cdot 10^{-5}$
FI4	0	0	0	$6.7 \cdot 10^{-5}$	0.002



	PA	VA1	VA2	VA3	VA4
PI1	0.7513	0.0264	0.2224	0	0
FI1	0	0.8717	0.1283	0	0
FI2	0	0.0514	0.9486	0	0
FI3	0	0	0	0.9867	0.0133
FI4	0	0	0	0.0184	0.9816

Figure 6: Combined ProMoVis result displays. Analysis of the stock preparation process with the method FET_r. Either a graph, or the connectivity matrix related to the graph can be chosen as displayed result. The layers including the components, the process models, and the controllers with their corresponding references are selected as not displayed.

suggested by the RGA, and coincides with the one currently used in the process. Nevertheless, it is suspected that there exist a potential for improving the control performance by considering the dynamic connection from VA2 to PI1 in the control system, since this will increase the sum of contributions on PI1 from 0.7153 to 0.9737.

To obtain a deeper insight in the effects on PI1, the tool $FDPT_r$ is applied using ProMoVis, and the result is depicted in Fig. 7. This tool results in a frequency domain description of the relative power contribution of the actuators on a given measured variable. At each frequency, the sums of all the contributions on a measured variable add up to one. It can be observed that the contribution from VA2 has a significant impact at frequencies around the maximum crossover frequency of the considered channels, causing interaction between the control loops which may result in oscillations. This conclusion is supported by the following facts: (i) the centrifugal pump has rotor dynamics which are slower than the dynamics of the valve; (ii) by the observations of the plant operators and engineers, which confirm the existence of the mentioned oscillations.

A potential of improving the existing control configuration has therefore been identified. The suggestion is to consider the actuator-sensor connection from VA2 to PI1 in the control configuration, *e.g.* by adding a decoupling pre-compensator which compensates for the affect of VA2 on PI1.

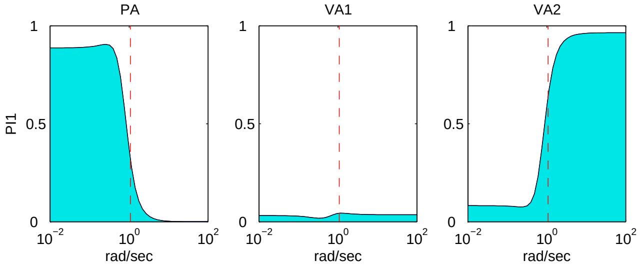


Figure 7: ProMoVis result display of $FDPT_r$. The tool $FDPT_r$ describes the contributions on PI1 from the actuators in the frequency domain. The largest crossover frequency of all the considered actuator-sensor channels is marked by a dashed line.

5. Conclusions

In this paper we have presented a new application software for control configuration selection in interconnected systems. The software is designed to support control engineers in the selection of a control configuration for a process. At the same time, information on the process and the control system can be maintained together which simplifies the effort to keep process control systems updated with the processes. This is achieved by combining (i) a graphical representation of the process layout at the physical level, (ii) a directed graph that represents the process dynamics and controllers and, (iii) control configuration analysis tools, into one and the same user interface. Additionally, analysis results can be depicted in the same view as the visualization of the process and control system.

The software concept has been described and many implementation aspects of the visualization and the CCS tools are discussed. The architecture of ProMoVis has been chosen to facilitate the implementation of additional analysis methods. ProMoVis features traditional tools for CCS as well as methodologies for the selection of sparse control structures and the visualization of them.

Moreover, a case study is presented where the refining stage in a stock preparation process is visualized and the CCS task is performed using ProMoVis. It is demonstrated that ProMoVis confirms the control configuration currently in use, which achieves a sufficient level of performance and that it indicates modifications that could lead to further improvement of the process performance.

It can be concluded that ProMoVis is useful in industry in its current version and can be further enhanced by implementing new research results, which makes these new results quickly available for industrial evaluation.

Finally, it should be mentioned that ProMoVis is now available under the Apache Open Source license to keep the software updated with additional and new CCS tools.

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