Application of the IFSH Methodology for Plantwide Control for an Evaporator Benchmark Process

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Abstract: Plantwide control (PWC) is an inherently complex task, which is why systematic guidelines and step-wise procedures are necessary to identify proper control pairings. Several different methodologies for the development of PWC structures have been proposed over the years, trying to balance the field between formal methods, practicality, and heuristics. The Integrated Framework of Simulation and Heuristics (IFSH) by Konda et al. (2005) utilizes simulators to support the heuristic decisions, thereby reducing the dependence of experience and prior understanding of the process behavior. In this article, the framework is successfully applied to the Forced Circulation Evaporator process by Newell and Lee (1989). A step-wise application of the methodology provides the basis for a discussion of how the methodology benefits from the utilization of simulations and how it differs from previously developed control structures for this evaporator process.

1. INTRODUCTION

The growth in the chemical industry has increased the competition and led companies to find ways of squeezing their profit margins and reduce production time. This is achieved by using material recycles to recover unreacted material, thereby improving yields, and through the implementation of energy integration of plants to minimize energy consumption. These factors are economically favorable, but have also led to an increase in interaction among the various unit operations, which makes smooth plant operation more challenging (Vasudevan et al. (2009a)). Therefore, Plantwide Control (PWC) is needed, to develop strategies for the control of entire chemical plants consisting of many interconnected unit operations. The plantwide control problem is very complex; it includes a large combinatorial number of choices, where many questions and decisions should be handled. Stephanopoulos (1983) described this complexity as follows:

"Which variables should be controlled and which should be measured in order to monitor the operation of a plant completely? Which inputs should be manipulated for effective control? How should the measurements be paired with the manipulations to form the control structure, and finally, what the control laws are?"

This clearly states that systematic guidelines for identification of control variables and effective selection of control pairings for SISO regulatory control are needed. From the 1990s, several researchers addressed the issue and developed different PWC methodologies, to ensure good control performance. These can be classified based on their main approach in the method and sorted into four categories; heuristics (process-oriented), mathematical (model-oriented), optimization (algorithmic), and mixed methods.

The heuristic or process-oriented approach contains guidelines, which are mainly based on experience when making control decisions. Therefore, the heuristic approach has some degree of subjectivity from the user applying the method. The main advantage of the heuristic based approach is the ease of understanding and implementation, where the most important thing is process knowledge, experience, and engineering judgment (Rangaiah and Kariwala (2012)). Luyben et al. (1997) made the first complete PWC methodology, which is a purely heuristic procedure. This procedure is probably the most popular heuristic based procedure and one of the most utilized. The pure reliance on heuristics is debated in the literature as it is difficult to apply to complex processes with unknown behavior. Other examples of heuristics methods are Price and Georgakis (1993); Konda et al. (2005).

The mathematical based methods, are a combination of steady-state and/or dynamic process simulations, where different controllability tools are utilized in screening and to support the control decisions. Normally, the utilized dynamic model of the plant is linearized and simplified, which results in omission bias in the analyses (Vasudevan et al. (2009a)). Examples of mathematical based methodologies are Dimian et al. (2001); Cao and Saha (2005)

In the optimization based methods, economically optimal control structures are developed by integrating optimization with control implementation and the use of numerical techniques such as mixed integer linear programming (MILP) or mixed integer non-linear programming (MILNP). The inherent complexities involved in large chemical plants make the applicability of these methods debatable (Vasudevan et al. (2009a)). Examples of this

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method are Zheng et al. (1999); Zhu et al. (2000).

The mixed approach is as the name indicates a mixture of the different approaches. In that way, some heuristic steps can be combined and supported by some controllability tools from the mathematical approach and/or with some of the optimization techniques, etc. (Rangaiah and Kariwala (2012)). Examples of mixed approach methods are Jørgensen and Jørgensen (2000); Skogestad (2004).

Plantwide Control has for a long time been a field with high reliance on experience, especially for the heuristic approaches. However, the methodology "An Integrated Framework of Simulation and Heuristics" (IFSH) by Konda et al. (2005) is a heuristic approach utilizing simulation to provide information about the process behavior. Thereby, reducing the heavy reliance on experience and supporting the heuristic based decisions with steady-state and dynamic simulations. The IFSH methodology has been utilized by Konda and co-workers to develop PWC structures for the HDA process (Konda et al. (2005)), the Styrene Monomer plant (Vasudevan et al. (2009b)), and Ammonia Synthesis process (Zhang et al. (2010)).

In this paper, the IFSH methodology is applied to the Forced Circulation Evaporator process by Newell and Lee (1989). The focus is on evaluating the applicability of the methodology, rather than an advanced PWC problem. The application is step-wise to point out where simulations helpfully overcome the reliance on experience and to see if there are some shortcomings in the methodology where improvements can be made. The rest of the paper is organized as follows: in the next section, the forced circulation evaporator is introduced. In section 3 the IFSH methodology is applied to the evaporator process. The developed IFSH control structure is discussed and evaluated in section 4. The conclusions are given in section 5.

2. THE FORCED CIRCULATION EVAPORATOR

The Forced Circulation Evaporator by Newell and Lee (1989) is a convenient example, which has been used for illustration and testing of process control technologies in numerous articles, e.g. Wang and Cameron (1994); Govatsmark and Skogestad (2001); Huusom and Jørgensen (2014); Dittmar (2015); Sadrieh and Bahri (2015). An evaporator system like this is often seen in sugar and paper mills as well as food and pharmaceutical industries. The evaporator system is typically part of a downstream process, where a product stream with low concentration requires removal of a solvent (often water) to concentrate the stream before drying or crystallization. The evaporator takes a liquid mixture, with minimum one non-volatile component, utilizing separation by evaporation. The evaporation chamber is similar to a heat exchanger, where a fraction of a circulating process stream is heated up and evaporated by latent heat from condensation of steam. After the evaporator, the stream consists of gas and liquid, which is led to a separator. The top product continues to a condenser where it is fully condensed with cooling water. A fraction of the bottom product is taken out as a product, whereas the rest is mixed with fresh feed and recycled to the evaporator. The process and process variables can be seen in Fig. 1.
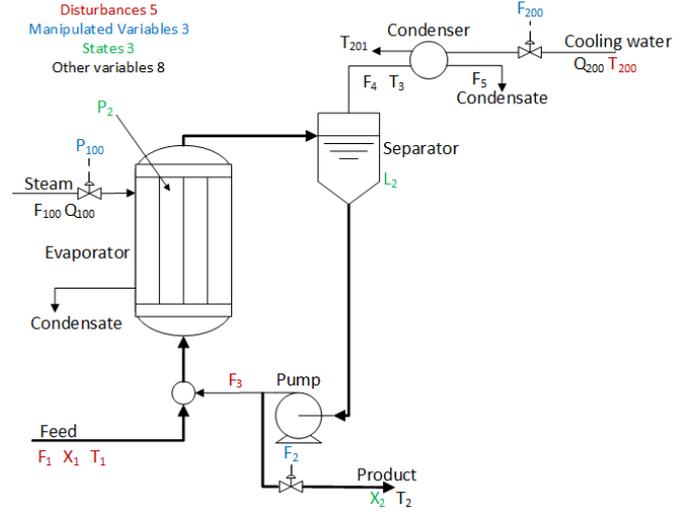
Fig. 1. The evaporator process, where disturbance, manipulated, state, and other variables are indicated with red, blue, green, and black color respectively.

2.1 Introduction to the evaporator model

Aside from the flowsheet and information described above, a simulation model of the evaporator system is also available. The equations for the simulation are presented in the following section, where F_i, X_i, and T_i denotes flow rates, compositions, and temperatures of stream i, respectively, and L_i, P_i, and Q_i are levels, pressures, and duties related to unit i. The model is divided into four sections evaporator, steam jacket, separator, and condenser, these are described below. Matlab/Simulink is used for simulations.

The Evaporator is modeled by five equations, where two of them are differential equations. The differential equations determines the product composition and the operating pressure, in equation (1) and (2), respectively.

$$M\frac{\mathrm{d}X_2}{\mathrm{d}t} = F_1 X_1 - F_2 X_2 \qquad (1)$$

M is a $20\,\mathrm{kg}$ constant liquid hold up in the evaporator.

$$C\frac{\mathrm{d}P_2}{\mathrm{d}t} = F_4 - F_5 \qquad (2)$$

$C = 4^{kg/kPa}$ is the conversion of vapor mass into pressure in the vessel. The other three equations for the evaporator determines the exit temperatures T_2 and T_3 and the flow rate of the evaporated solvent, F_4.

$$T_2 = 0.5616P_2 + 0.3126X_2 + 48.43 \qquad (3)$$

$$T_3 = 0.507P_2 + 55.0 \qquad (4)$$

$$F_4 = \frac{Q_{100} - F_1 C_p(T_2 - T_1)}{\lambda} \qquad (5)$$

C_p is the heat capacity and λ is the latent heat of evaporation of the process liquid, which are assumed constant at $0.07^{kW/(K(kg/min))}$ and $38.5^{kW/(kg/min)}$ respectively.

The Steam Jacket is simulated by three algebraic equations, due to the assumption of very fast dynamics, i.e. in pseudo-steady-state. The three equations determine temperature, duty, and flow rate, which are denoted T_{100}, Q_{100}, and F_{100}, respectively.

$$T_{100} = 0.1538P_{100} + 90.0 \qquad (6)$$

$$Q_{100} = 0.16(F_1 + F_3)(T_{100} - T_2) \qquad (7)$$

$$F_{100} = \frac{Q_{100}}{\lambda_s} \qquad (8)$$

where $\lambda_s = 36.6 kW/(kg/min)$ is the latent heat for steam.

The Separator is modeled by a total mass balance over the separator and evaporator having the feed flow as input and outputs being the product flow, F_2, and evaporated solvent outflow, F_4. The total mass balance gives the following differential equation for the separator level, L_2.

$$\rho A \frac{dL_2}{dt} = F_1 - F_4 - F_2 \qquad (9)$$

Where ρA is the liquid density and cross sectional area of the separator, with an assumed value of $20 kg/m$.

The Condenser is modeled as three algebraic equations assuming pseudo-steady-state. The three equations calculate the duty, Q_{200}, temperature, T_{200}, and the flow rate, F_5. $UA2 = 6.84 kW/K$ is the overall heat transfer coefficient times the area.

$$Q_{200} = \frac{UA2(T_3 - T_{200})}{1 + UA2/(2C_P F_{200})} \qquad (10)$$

$$T_{201} = T_{200} + \frac{Q_{200}}{F_{200}C_p} \qquad (11)$$

$$F_5 = \frac{Q_{200}}{\lambda} \qquad (12)$$

All the equations listed counts a total of 12 equations and 20 variables. This gives a degree of freedom of eight variables. These eight variables are F_1, X_1, T_1, F_2, F_3, P_{100}, F_{200}, and T_{200}. The three feed variables F_1, X_1, T_1, the cooling water temperature, T_{200}, and the recycle flow, F_3, are classified as disturbances, under the assumption that it is a continuous process. The last three variables, F_2, P_{100}, and F_{200}, are classified as actuators, which can be regulated, to control the system. This is also indicated in the flowsheet in Fig. 1. The product specification, safety, and design constraints for the evaporator system are shown in Table 1. The constraints on P_2, L_2, P_{100}, F_{200}, and F_3 are safety constraints and must be respected at all times, i.e. these are hard constraints. The constraint on the product purity X_2 must be respected on average, meaning that small violations in dynamic simulations of the constraint are acceptable for a short time. Nominal steady-state process conditions for the evaporator system are given in Table 2, which are used later in the simulations.

Table 1. The product specification, safety, and design constraints for the evaporator system (Newell and Lee (1989); Govatsmark and Skogestad (2001)).

$X_2 \geq 25\%$	$P_2 \in [40; 80]$ [kPa]	$L_2 \in [0.3 - 2.0]$ [m]
$P_{100} \leq 400$ [kPa]	$F_{200} \leq 400$ [kg/min]	$F_3 \leq 100$ [kg/min]

3. APPLICATION OF THE IFSH METHODOLOGY

In the next section, the IFSH methodology is applied to develop a control structure for the evaporator process.

Step 1: Define plantwide control objectives
The first step is to define plantwide control objectives and determine control degrees of freedom. The control objectives for this PWC structure, are to achieve a fast

Table 2. Steady-state process condition for the evaporator system (Newell and Lee (1989)).

Variable	Description	Value	Unit
F_1	Feed flowrate	10.0	$[kg/min]$
X_1	Feed composition	5.0	%
T_1	Feed temp.	40.0	[°C]
F_2	Product flowrate	2.0	$[kg/min]$
X_2	Product composition	25.0	%
T_2	Product temp.	84.6	[°C]
F_4	Vapor flowrate	8.0	$[kg/min]$
T_3	Vapor temp.	80.6	[°C]
L_2	Separator level	1.0	$[m]$
P_2	Operating pressure	50.5	$[kPa]$
F_3	Circulating flowrate	50.0	$[kg/min]$
F_5	Condensate flowrate	8.0	$[kg/min]$
F_{100}	Steam flowrate	9.3	$[kg/min]$
P_{100}	Steam pressure	194.7	$[kPa]$
Q_{100}	Heater duty	339.0	$[kW]$
F_{200}	Cooling water flowrate	208.0	$[kg/min]$
T_{200}	Cooling water inlet temp.	25.0	[°C]
T_{201}	Cooling water outlet temp.	46.1	[°C]
Q_{200}	Condenser duty	307.9	$[kW]$

and robust control structure, which ensures the product specification, safety, and design constraints presented in Table 1. Furthermore, a cost optimization to minimize the operational cost, related to utilities, could be a steady-state economic objective. However, this is not done in this paper. The control degrees of freedom is determined by counting the control valves in the flowsheet, thereby giving three control degrees of freedom, corresponding to the system definition in section 2.1.

Step 2.1: Identify and analyze disturbances
The second step is to: "identify and analyze plantwide disturbances and set performance and tuning criteria". From the flowsheet in Fig. 1, the disturbances are given as feed flow, composition, temperature, recycle flow, and the cooling water temperature, F_1, X_1, T_1, F_3, and T_{200}, respectively. To analyze how the disturbances propagate throughout the system, dynamic simulations with a 3% decrease to the different disturbances, made as step changes, are shown in Fig. 2. The disturbance analysis of the system shows that the separator level, L_2, is unstable and will not find steady-state after any of the five disturbances are introduced. The 3% step change in the feed flow, F_1, has a significant effect on the separator level and within 50 minutes the system will be out of safety constraints, meaning that simulations after this point is not feasible. The feed flow, F_1, recycle flow, F_3, and cooling water, T_{200}, are found to have the most severe influence on the separator level, L_2. The feed composition, X_1, influence the product composition, X_2, whereas changes to the other disturbances do not affect this variable. The disturbances have a less severe effect on the evaporator pressure, P_2, where the recycle flow, F_3, has the most significant influence. This indicates that the pressure is self-regulating, finding a new steady-state after the disturbance.

Step 2.2: Performance and tuning criteria
Settling time is chosen as the performance criterion for the system. Especially for the level and pressure control, where an offset is not very important, quick settling is preferred, whereas for composition loops zero offset is favored (Konda et al. (2005)). For liquid levels, it is favored
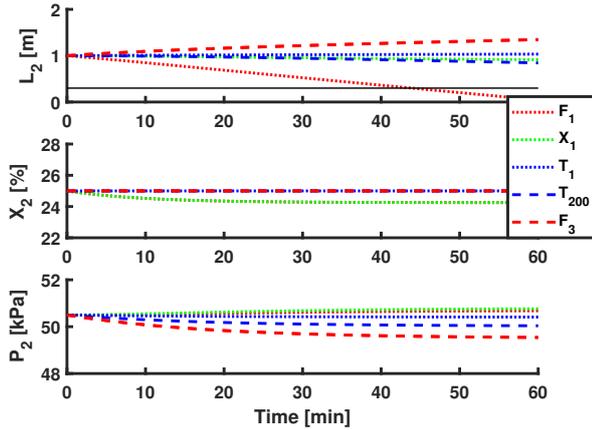
Fig. 2. Disturbance analysis. F_1, X_1, T_1, F_3, and T_{200} are decreased by 3%, one at a time. The lower safety bound for L_2 is indicated by a black line.

to use a P-controller, whereas for control loops like product composition a PI-controller is preferred.

Step 3.1: Production rate manipulator

In the third step, the primary process path and throughput manipulator should be identified. The primary process path is the most direct way from the feed to the final product. The primary path goes from the feed through the evaporator to the bottom flow of the separator and then out through the product stream, as indicated by a bold line for the relevant streams in the flowsheet shown in Fig. 1. The evaporator system is said to be part of a downstream process, where the feed flow, temperature, and composition are disturbances. This means that the feed rate is already specified as the throughput, due to the specification of the evaporator process.

Step 3.2: Product quality manipulator

The manipulator for the product quality can be found close to the unit associated with the product stream, thereby making it a local decision. The evaporator system consists of three unit operations (evaporator, separator, and condenser) due to the circulation flow, F_3, both the separator and the evaporator can be seen as local units for the product composition, X_2. This gives two possible manipulated variables: the steam pressure, P_{100}, and the product flow, F_2. To find the manipulated variable that affects the product composition most, simulations with a 10% decrease to each of the manipulated variables (one at a time) is shown in Fig. 3. The simulation indicates that only F_2 affects X_2 (for the open-loop system).
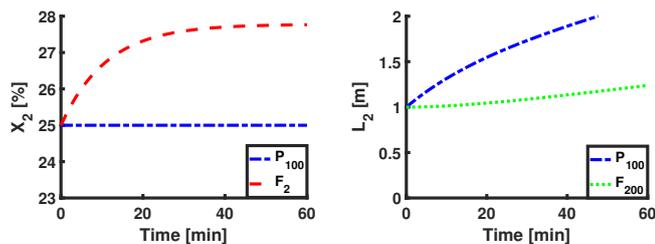
Fig. 3. Gain analyses, to see how a 10% decrease in the MV influences the CV. In the right plot a PI-controller controls $X_2 \leftrightarrow F_2$.

Step 4.1: Selection of MV for severe CV

In step four selection of manipulators for severe control variables like equipment and operating constraints, safety concerns, and process stability issues should be dealt with. From the disturbance analysis above, it is known that the separator level is unstable, and therefore needs to be controlled. Control of liquid levels should be handled differently depending on whether the levels are placed in the primary process path or not. The separator is, as shown in Fig. 1, part of the primary process path, meaning that the liquid level should be controlled while ensuring that it is self-consistent. Therefore, depending on the throughput manipulator, the control should be either in or opposite the direction of the flow (Konda et al. (2005)). As mentioned above, the throughput manipulator is the feed rate, which means that the control of the liquid level should be in the direction of the flow. This indicates that the product flow, F_2, should be the manipulated variable for the level control. F_2 is already selected for product quality control, therefore, one of the other two manipulated variables should be used. To check whether P_{100} or F_{200} is the best choice for the separator control loop, simulations of the two manipulated variables influence on the level are shown in Fig. 3. The simulation is performed with the already selected product control loop, X_2 controlled by F_2 with a PI-controller tuned by autotune in Simulink. Both P_{100} and F_{200} have an effect on the separator level, where P_{100} is the most significant. Therefore, the steam pressure, P_{100}, is chosen to control the separator level, L_2.

Step 4.2: Selection of MV for less severe CV

Here the control loops for levels and pressures are handled. The separator level is already handled above do to process stability concerns. The IFSH method state that the pressure needs to be controlled, even if it is self-regulating. In that case, it will be adequate to control the pressure at one place in the process. F_{200} is selected to control P_2, provided that it will give safe control. A validation and evaluation of the control structure are given later, see Fig. 4. Pairing $L_2 \leftrightarrow F_{200}$ and $P_2 \leftrightarrow P_{100}$ are in accordance with the pair-close rule, therefore, it was also considered. However, the result clearly showed that F_{200} is not able to control L_2 within the safety bounds for a 15% increase in F_1, therefore, the simulation crashed, see Fig. 5.

Step 5: Control of unit operations

At this point the manipulated variables have been assigned to a control loop, therefore this step is not considered in this work.

Step 6: Check component material balances

In the evaporator process, there are two balances to check, a total and a solute. The total mass balance over the system is to ensure what comes in also leave the system:

$$F_1 = F_2 + F_5 \tag{13}$$

The evaporated solvent is exiting the process with stream F_5 after the condenser, where it is fully condensed. The rest of the solvent and the product is leaving the process through the product stream, F_2. In the feed stream F_1, there is also a product composition, X_1, which should be concentrated from 5 to 25% and leave with the product stream F_2. This gives the following balance for the solute:

$$X_1 F_1 = X_2 F_2 \tag{14}$$

For the control structure developed above, the product composition X_2 is controlled by F_2 and the separator level L_2 is controlled by P_{100}, thereby ensuring that the two balances are maintained.

Step 7: Effects due to integration
In this step, the effect of integration, like a recycle, should be investigated and the risk of snowballing evaluated. For the forced circulation evaporator, it is defined that the recycle flow, F_3, is a disturbance and not a manipulated variable to control. Therefore, due to the system specification, this step will not be further investigated.

Step 8: Improve dynamic controllability, if possible
In this step, the possibility and necessity of implementing a more advanced control structure to enhance performance are evaluated. Other control structures for the evaporator system have been developed, Govatsmark and Skogestad (2001) made an economic optimal "self-optimizing control" structure, Huusom and Jørgensen (2014) developed a Model Predictive Control (MPC) structure, and Dittmar (2015) developed an Active Disturbance Rejection Control (ADRC) structure. It is possible to develop more advanced control structures for the evaporator process. This is out of the control objectives for this paper, which is to develop a fast and robust control structure while maintaining the product specification, safety, and design constraints.

4. DISCUSSION AND IMPROVEMENTS

From the application of Konda et al. (2005) methodology in section 3 a control structure for the evaporator process has been successfully developed. Steady-state and dynamic simulations are utilized in several of the steps, to analyze both disturbances and influence of different manipulated variables. The simulations have provided the necessary information about the process behavior to make control decisions and develop the following control structure:

$$X_2 \leftrightarrow F_2 \, , \, L_2 \leftrightarrow P_{100} \, , \, P_2 \leftrightarrow F_{200}$$

The decisions for the control pairings are supported by dynamic simulations and selected to achieve fast and stable control. The developed control structure is evaluated for changes in F_1 and X_1, which in the disturbance analysis were found to be the most severe. Fig. 4 shows that the system is within safety bounds for the given disturbances.

Control pairings are often supported by a RGA analysis. In this case, an integrating RGA (Arkun (1990)) or Dynamic Relative Gain Array (DRGA) (Kadhim et al. (2016)) could be considered. It was chosen no to include the integrating RGA, as the focus is on the combination of heuristic and simulations. However, the result gave the same pairings as the pair-close rule, C_1 in Fig. 5. For C_2 in Fig. 5, P_2 is left self-regulating, the rest is similar to the chosen control structure. C_2 shows good control of the system, where P_2 is stabilizing with time, thereby leaving F_{200} free and enabling the possibility of using it from optimization purposes. Further analysis is needed to see if P_2 can be self-regulating for all possible disturbances. Nevertheless, it is interesting why the pressure needs to be controlled.

The disturbance analysis of the system, in Fig. 2, shows that the separator level is an integrating state and makes the system unstable. Especially, the feed flow, F_1, shows a significant effect on the separator level. Normally, levels
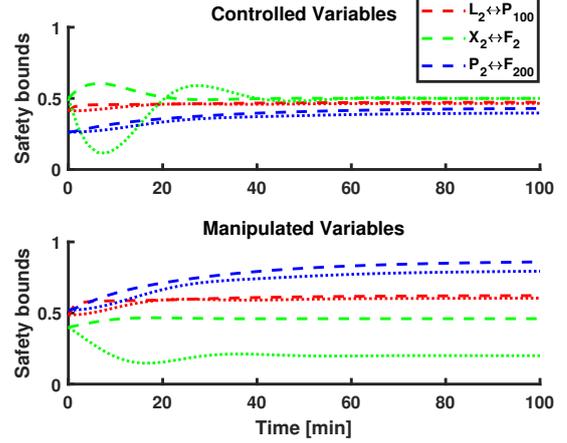
Fig. 4. Evaluation plot. F_1 is increased 15% and X_1 is decreased 50%, dashed and dotted lines respectively. The y-axes are scaled for upper and lower safety bounds, indicated by one and zero.
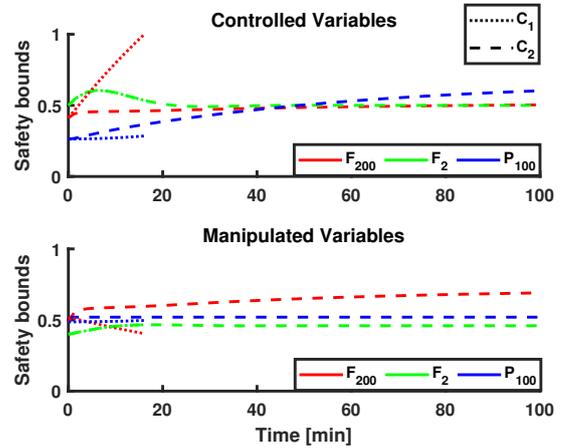
Fig. 5. Evaluation of the alternative control structures C_1 (dotted) is $L_2 \leftrightarrow F_{200}$, $X_2 \leftrightarrow F_2$, $P_2 \leftrightarrow P_{100}$ and C_2 (dashed) is $L_2 \leftrightarrow P_{100}$, $X_2 \leftrightarrow F_2$, P_2 self-regulating.

in the primary process path is controlled in the direction of the flow to obtain a self-consistent control structure (Konda et al. (2005)). Thereby, L_2 should be controlled by the product flow, F_2. This is not possible as the product flow is already selected to control the product composition, X_2, which is given higher priority by Konda et al. (2005). In contradiction to this priority, the three other papers mentioned in step 8, all choose to control the separator level with the product flow, F_2, as they want to stabilize the system before performing a RGA analysis or implement more advanced control strategies. The selection of F_2 to control L_2 corresponds with the principles for self-consistent inventory control, which were presented by Buckley (1964) and further developed by Price and Georgakis (1993). Therefore, this priority leads to a control structure, which is against basic control principles for robust and stable control. In this case, the process is stable but for other cases where the control structure conflicts with self-consistent control, stability analyses are essential.

In the book by Newell and Lee (1989), they develop different control structures and perform a quantitative analysis

of the control performance in Table 15.1. Here they have five control structures: full Generic Model Control (GMC), GMC with no feedforward, GMC with no sensible heat, PI Inventory Control, and Predictive Control. From the integral of the absolute error multiplied by time (ITAE) analysis, it is found that the full GMC is the best control structure. The GMC structure suggests the same control pairing as the one found by applying Konda et al. (2005) methodology above, but with interaction decoupling from F_2 on P_{100} and from both F_2 and P_{100} on F_{200}. The PI Inventory Control structure is $F_2 \leftrightarrow L_2$, $P_2 \leftrightarrow F_{200}$, and $X_2 \leftrightarrow P_{100}$, this structure performs significantly worse than the other control structure for control of X_2 and L_2.

The benefits of this methodology are limited by the availability of a reliable simulation model of the process, as this is the main key to achieve an understanding of the process behavior. This is one drawback of the methodology as this is not always the case in the industry (Bähner et al. (2019)). More and more companies are trying to develop simulation models of each process unit and full process plants, which will help process control in many ways and also enable better utilization of methodologies, such as the IFSH by Konda et al. (2005). Therefore, this methodology and the combination of heuristics and simulation for the development of better control structures will likely receive increased interest in the years to come, as more full process plants will be modeled and simulated.

5. CONCLUSION

The Integrated Framework of Simulation and Heuristics by Konda et al. (2005) is successfully applied to develop a control structure for the Forced Circulation Evaporator process by Newell and Lee (1989). The combination of a systematic heuristic procedure, which is easy to understand and follow, and the use of simulation to provide information of process behavior, have shown to be effective and lowers the necessity for a prior process understanding. In the methodology, product control is given the highest priority, which for this case means the developed control structure refrains from the basic principle of self-consistent inventory control. This priority adds a risk of developing a control structure, which is not stable for all disturbance scenarios, therefore, stability tests should be carefully studied. The evaluation of the developed control structure indicates fast and robust control of the process with feasible changes to the manipulated variables.

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