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Investigation of the controllability of chemical systems with recycle

PhD Theses

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1. INTRODUCTION

The increase of the efficiency of the processes and the decrease of their costs have become one of the most important principles of the chemical industry. But in many cases these design purposes are not independent from each other, and the structure design has to take into consideration these two requirements. In the chemical industry the most frequently used technology is the component separation, which conventionally takes place in distillation columns. These distillation systems often contain mass-, or energy-recirculation, and some processes are not even carried out without recycle.

The conventional composition controls usually keep the output compositions at their prescribed values by interfering into the mass-, or energy balances. In case of recycle a symbolic positive feedback is added to the system, which has some harmful effects on the controllability of the system. In order to avoid these effects, modifications have to be carried out in the structure and in the settings of the control loops.

In case of more complex systems, a very important question is the decomposability of the task of the control structure design. If the control structure for the whole system can be carried out by designing the control structures for the individual blocks, then the task of the design of the global control structure is decomposable. But if the control structure for the whole system can be carried out only by simultaneous design for the individual blocks, then the control structure task design is not decomposable.

In the present work I investigated hypothetical and industrial systems from the point of the effects on the recycle and the decomposability, I worked out strategies to determine the control structure for the ethylbenzene-system in the time- and in the frequency-domains.

2. LITERATURE REVIEW

Most of the recycle-focused publications reflects to expectable difficulties of the control of recycle systems and expose the possible unstable behaviour. The recycle systems require special attention and their control structure design is more difficult. In the literature there are preliminary investigations on the correlation of the flow rate of the recirculated material streams and the unfavorable effects of the recycle. In many articles the subject of these investigations is the conventional reactordistillation column system. The recycle, as an integrated part of the system has become part of the process design/control design hierarchy, therefore it is necessary to investigate the effect of recycle in the earlier stages of the process design. In some cases without any control recycle causes permanent instability. In the recycle systems the responses for the disturbances, the gains and the time constants of the response functions, and the order of the transfer functions differ from that of the systems without recycle. There are known recycle-compensation methods, but these can neither be applied independently from the recycle systems nor applicable for all of the recycle cases.

The investigation of the recycle systems were carried out mainly based on mathematical models and rarely based on real, existing industrial systems. In particular theoretical works can be found on the investigation of the decomposability of the task of the control structure design and these works recommend the hierarchical consideration of the flowsheeting techniques. The Analytical Hierarchical Approach is a good summary of the recommendations for the decomposing methods. The main steps of the AHP:

- Estimation and selection of the possibilities of the process-decompositions (with the help of operational conditions)
- Setting up a systematic priority order by the design goals
- Priority also for the control goals
- Selecting from the competitive, favorable alternatives

This method suggests a multi-level approach for the control shcemes, and it can be applied successfully. Later the model was developed with a secvential extension.

At present time there cannot be found works in the literature which would apply the tools available in the frequency-domain for the analysis of the effects of the recycle and which would apply decomposability investigation for the control structure design for recycle systems. My work makes attempts to add new results to the state of the science in these two fields mainly, using several tools which are provided by process simulators and modern mathematical softwares.

In Proceedings:

4. Alajos Meszaros, Peter Mizsey, **Marcell Horvath**, Zsolt Fonyo **-** Dynamic analysis and control of recycle processes. V. (Proc. 31. Int. Conf. SSCHE), Tatranské Matliare (Slovakia), 116, **2004**.
5. Peter Burian, **Marcell Horvath**, Peter Mizsey, Alajos Mészáros in *33rd Int. Conference of SSCHE*, **2006**, pp. 38-42, Tatranske Matliare, Slovakia.

Lectures:

6. **Marcell Horvath**, Alois Meszaros, Agnes Szanyi, Peter Mizsey – Investigation of the controllability of systems with recycle **-** *Hungarian Chemical Engineering Conference in Veszprém,* **2004** p. 253-257.
7. **Marcell Horvath**, Peter Mizsey – Investigation and controllability problems of systems with recycle **-** *Hungarian Chemical Engineering Conference in Veszprém,* **2005** p. 198-201.
8. **Marcell Horvath**, Peter Mizsey **-** Modelling, controlling and dynamics of systems with recycle **-** *Hungarian Chemical Engineering Conference in Veszprém,* **2006**, p. 284-288.
9. **Marcell Horvath**, Peter Mizsey **-** Investigation of controllability of systems with recycle, **2006**, *CHISA*, Prague
10. **Marcell Horvath**, Peter Mizsey – Control investigations for recycle systems, **2007**, *Richter Centenáriumi Alapítvány ülése,* Budapest.
11. **Marcell Horvath**, Peter Mizsey **-** Investigation of controllability and dynamics of systems with recycle in (35th Int. Conference of SSCHE), Tatranské Matliare, Slovakia, page. 260-, **2008**.
12. **Horváth Marcell** – Control tasks for recycle systems **-** MTA Vegyipari Műveleti Munkabizottsági Ülés, **2009**, Veszprém.
13. **Marcell Horvath**, Peter Mizsey **-** Decomposability Studies of Control Structure Design for Systems with Recycle In (36th Int. Conference of SSCHE), Tatranske Matliare, Slovakia, **2009**.

5.) I proved that values of the different controllability indices show correlation with the flow rates and the number of material streams in the recycle loop. The increase of the recirculated material flows generates more unfavorable controllability indices while the quality of the controls decreases. Therefore, if more design opportunities are applicable, the one alternative has to be chosen which operates with no or less recycle streams or operates with the smaller flow rate of the recirculated stream.

6. APPLICATION OPPORTUNITIES

The results can help the design of control structures for industrial systems making the structure design simpler and faster and the consistency of the results can be expected in the steady-state, in the time- and in the frequency-domains. The results of the hypothetic systems can be generalised for 2×2 MIMO-systems, if their transfer function matrices are similar to the investigated ones. The measuring methods in the steady-state-, in the time- and in the frequency-domains and the new, own modified controllability indices in the frequency-domain provide good description and model for the investigated structures. The decomposability which can be used during the control structure design for the industrial system makes the design of the global structure simpler and more efficient.

7. PUBLICATIONS

In scientific journals:

1. **Marcell Horvath**, Zsolt Szitkai, Peter Mizsey - Investigation of controllability of systems with recycle - A case study. Periodica Polytechnica **2007**, 51/2, pp. 37-44.
2. **Marcell Horvath**, Peter Mizsey - Decomposability of the Control Structure Design Problem of Recycle Systems - Ind. Eng. Chem. Res., **2009**, 48 (13), pp 6339–6345 [IF: 1.895]
3. **Marcell Horvath**, Peter Mizsey - Decomposability Investigations for Control Structure Design of Recycle Systems in the Frequency-domain – Revista de Chimie **2010**

3. CALCULATION METHODS

The quantitative description of recycle effects is an essential part of my work which can highlight the importance of the recycle analysis.
I investigated the effects of the applied recycles in case of hypothetical and industrial systems in the steady-state-, in the time- and in the frequency-domains. In the first two cases the recycle effects were quantified by analyzing the response functions and by evaluating different controllability indices while in the frequency-domain with the help of the state-space representation I calculated different frequency-dependent controllability indices and this way I carried out comprehensive investigation for different systems. After constructing the composition control loops, I investigated the decomposability investigation of the task of the control structure for the whole systems, firstly based on the results of the load-rejection analysis (IAE-values). In the frequency-domain the decomposability investigations were based on the different frequency-dependent controllability indices (CN, MRI, RGA).

The results which represent the whole investigated structure are presented as two-variable functions, where the indipendent variables were the different control structures of the individual units of the system. The results proved the decomposability conceptions, and having the results, I recommended a strategy for a simpler, faster, more efficient control sructure design possibility for the ethylbenzene-producing industrial system. The function which represents the whole system gives a global control structure and proves that there is no other pairing of the different controls for the individual units which could result in a better control performance. So this way it is the best global control structure for the system.

4. RESULTS

A plenty of preliminary investigations prove that in case of simple systems the increase of the transfer gain of the recycle path causes harmful effets on the whole system with and without control, too. (**Fig. 1**).

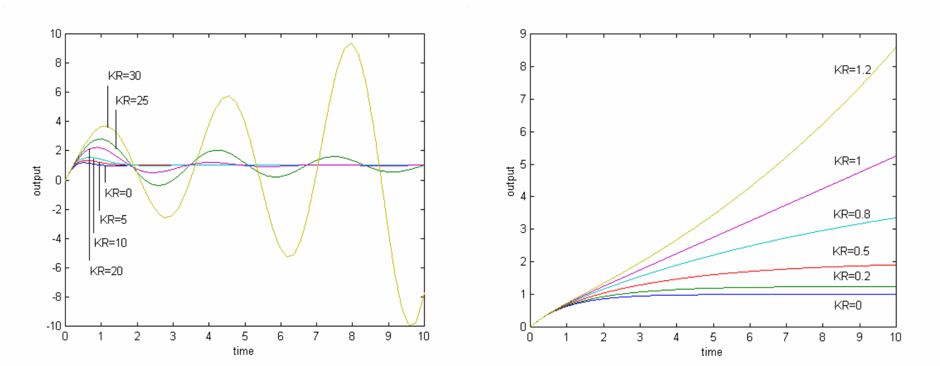

Fig. 1: The effects of recycle in case of a simple system

The investigated ethylbenzene producing complex industrial structure can be seen on **Fig. 2.** I investigated this system in the steady-state, in the time- and in the frequency-domains, I showed and quantified the effects of the applied recycles in this three domains. I determined the control structures for the system.

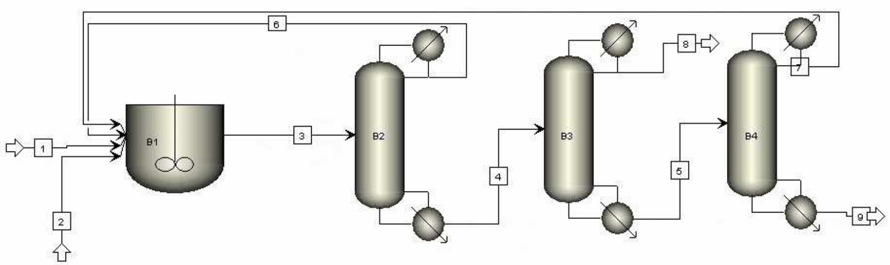

Fig. 2: Industrial system for ethylbenzene, 1: benzene, 2: ethylene, 8: ethylbenzene, 7: diethyl-benzene, 9: triethyl-benzene

In the steady-state domain I applied step-disturbances, registered the output compositins and obtained the steady-state controllability indices: NI (Niederlinski-index), CN (condition number), MRI (Morari resiliency index), RGA (reltive gain array), and based on the conventional criteria for these indices I determined the control structures for the recycle and no-

5. THESES

1.) I proved that the relative gain array (RGA), as a steady-state controllability index, changes in case of recycle. This proves that in presence of recycle the controllability properties change since the recycle modifies the controllability of the given system.

2.) I developed new controllability indices and applied them for the characterization of recycle systems. The new indices are the averaged and the integrated values of the conventional indices in the frequency-domain. These are the averaged condition number and the integrated MRI values. With the help of these new indices, constants can be presented instead of functions where these constants indicate the dynamic behavior and offer a more representative and sipmler way to characterize the investigated systems in the whole frequency-domain.

3.) I proved that the task of the control structure design for the control structure is decomposable: the most favorable control structure for the recycle system is equivalent to the application of the different individual units in the recycle loop with their most favorable control structures. The investigation of the individual units can only be carried out in presence of the recycle. This way the control structure design becomes a simpler and more efficient task. The qualification and the order of the different control structures were based on quantitative analysis of the controllability indices and their frequency-functions in the investigated domains. I examined the decomposability possibilities for the hypothetical systems and for the industrial system, too. In most chemical processes the dynamic behavior can be approached with the model of a first order lag with dead-time, the statement above can be generalised for a wide range of the recycle systems.

4.) I stated that based on the results of the dynamic investigations in the time-domain, the same control structures are the most favorable in the frequency-domain, as well. On the grounds of this result, the control structure design of the processes can also be carried out in the frequency-domain, and this way the control structure design becomes significantly simpler. This statement is based on the investigation of the industrial technology.

IAE-values in the time-domain and the averaged CN- and the integrated MRI-values in the frequency-domain. The 3D surfaces of these functions can be seen in **Fig. 4-5-6.**

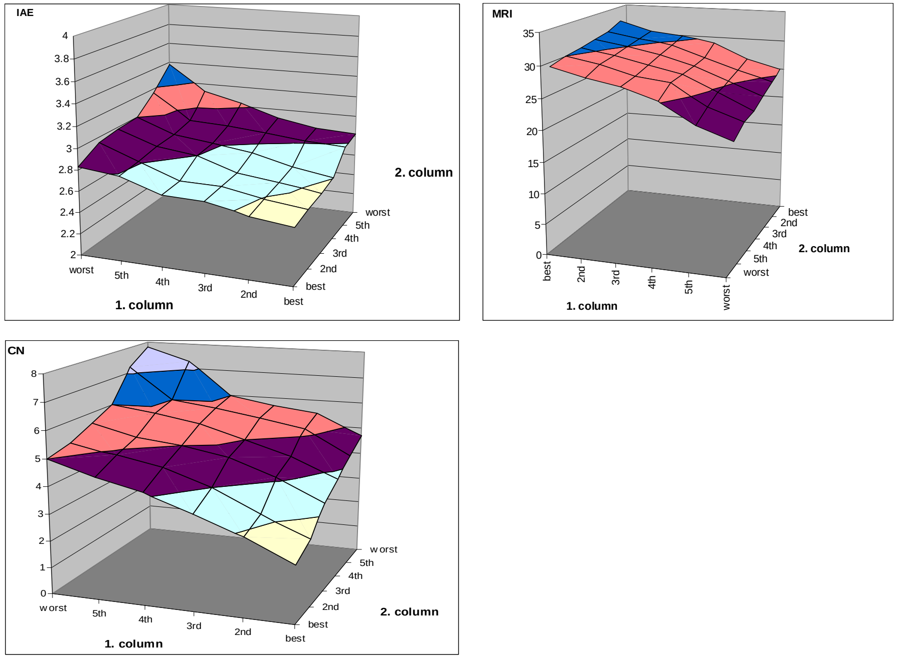

Fig 4, 5 and 6: Investigations for the global system in the time- and in the freuqncy-domain

The surfaces which were obtained by the simulation in the time- and in the frequency-domains show that the distance of each point from the optimum is monotonously increasing in case of IAE and CN and decreasing in case of MRI. It proves that there is no other pairing which could issue in a better structure like the one which is built from the local best contol structures. These decomposability results can easily be followed by these 3D surfaces.

recycle cases, too. The obtained control structures in the stady-state domain can be seen in **Table 1.**

	Column 1	Column 2	Column 3
Without recycle	L-Q	R-Q	L-B
With recycle	L-Q	R-B	L-B

Table 1: Control structures in the steady-state-domain (L: reflux rate, Q: reboiler duty, R: reflux ratio, B: bottoms rate)

The results of the steady-state investigations did not represent the dynamic behavior of the system, therefore in order to investigate the system in the time-domain, the steady-state investigations were extended to the time-domain. In the time-domain I used different step-disturbances, registered the responses and obtained the gains and the time constans which provided information for the tuning of the composition control loops. I constructed the control loops for the systems with and without recycle, the obtained control structures can be seen in **Table 2.**

	Column 1	Column 2	Column 3
Without recycle	L-Q	R-Q	R-Q
With recycle	L-Q	R-B	R-Q

Table 2: Control structures in the time-domain

The first column operated with the highest material flow rate and the second column separated the main product, the ethylbenzene, therefore the first and the second columns were the most important distillation columns of the investigated industrial structure. In the steady-state domain and in the time-domain the same control structures were forund to be best for the first and the second column and it can be interpreted as a verification of the applied methods.

Investigations in the frequency-domain

The base of the investigations in the frequency-domain was the state-space representation of the system:

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du + v$$

where A, B, C, D are the state matrices and they were determined by CDI (Control Design Interface) and Matlab software. From these matrices I calculated the frequency-dependent controllability indices (RGAno, CN, MRI) and from these functions I determined the control structures for the system with and without recycle. The results can be seen in **Table 3.**

	Column 1	Column 2	Column 3
No recycle	L-Q	R-Q	R-B (R-Q)
DEB recycle	L-Q	R-B	R-Q
B recycle	R-Q	R-Q	R-Q
Both of recycles	L-Q	R-B	R-Q

Table 3: Control structures in the frequency-domain

With the frequency-domain results the investigations of the recycle-effects for the industrial system have been completed. The steady-state results show consistency with the results from the time- and the frequency-domain, the dynamic- and the state-space model of the system is correct.

Decomposability studies

In the second part of the present work I investigated the decomposability possibilities of the task of the control structure design for the hypothetical and for the industrial system, too.The investigated hypothetical system can be seen in **Fig. 3.** This contains two 2×2 MIMO systems and one recycle stream. For the modelling of the blocks, I used hypothetical transfer function matrices which can be seen in **Table 4.**

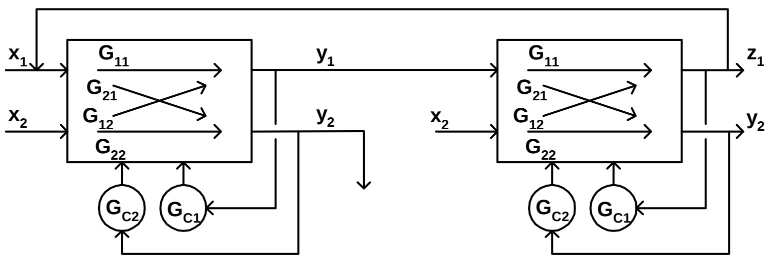

Fig. 3: 2×2 hypothetic MIMO-system with recycle

$G_1 = \begin{bmatrix} \frac{10}{10s+1} & \frac{1}{1s+1} \\ \frac{1}{1s+1} & \frac{10}{10s+1} \end{bmatrix} e^{-0.1s}$	$G_2 = \begin{bmatrix} \frac{10}{1s+1} & \frac{1}{100s+1} \\ \frac{1}{100s+1} & \frac{10}{1s+1} \end{bmatrix} e^{-0.1s}$	$G_3 = \begin{bmatrix} \frac{10}{0.1s+1} e^{-1s} & \frac{1}{10s+1} e^{-0.1s} \\ \frac{1}{10s+1} e^{-0.1s} & \frac{10}{0.1s+1} e^{-1s} \end{bmatrix}$

Table 4: Transfer function matrices for the hypothetic system

Two constructions are possible for the control loops. Applying DP (direct pairing) the first controlled variable is controlled by the second manipulated variable whereas the second controlled variable is by the first manipulated variable. In case of CP the first controlled variable is controlled by the first manipulated variable, and the second controlled variable is by the second manipulated variable. After the tuning of the control loops, I applied disturbances and measured the IAE (integral absolute error) values for the control loops and qualified the different control structures with their IAE-values. The individual blocks and the connected system were investigated too and the results which can be seen in the dissertation prove that the design task for the control structure of the whole system is decomposable.

Similar, but more extended investigations were carried out for the industrial system, based on load-rejection analysis using different frequency-dependent controllability indices. The results showed similar results as previously in the steady-state- and in the time-domains. The load-rejection analysis was carried out by applying disturbances and the IAE-values for the output compositions were registered, while in the frequency-domain new, modified controllability indices were used (average CN-values and integrated MRI-values). I executed these measurements for the individual units and for the whole system too. The results of the investigations showed that the most favorable control structure for the global system can be built from the best control structures of the different individual units and no other pairing of the individual control structures can result in a preferred control structure for the global system.

This fact proves the decomposablity of the task of the control structure design for the industrial technology and offers a simpler way to construct the global control structure. The results were introduced as two-variable functions where the independent variables were the applied control structures of the first and the second columns, and the values were the