

Operational Issues Towards Optimised Processes

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Abstract

In chemical process optimisation, a number of controllability and operability issues are required to be considered in parallel with the optimisation techniques and objectives of the processes. A comprehensive optimisation framework is proposed that spot the trade-offs between the various goals in the process design and/or synthesis stages and is demonstrated through an industrial case study.

Keywords: Process optimisation, Heat integration, Controllability and Operability

1. Introduction

In these days of increasing concern towards energy conservation and environmental protection, process systems engineers are required to integrate their processes to achieve economic, environmental and social objectives, while at the same time keeping their plants readily operable. In general, process integration techniques originate a dilemma between control and operation on one hand and process design on the other. Thus forcing the process engineers to consider the operational issues, i.e. plant-wide controllability, operability and dynamic performance, of the optimised processes in the early stages.

This paper presents an integrated framework for multi-objective optimisation problems to identify the trade-offs arising between various goals in flowsheet design, synthesis and operation. Life Cycle Assessment (LCA) is used to quantify and qualify the environmental consequences of any selected flowsheet in the proposed framework. Heat integration and Heat Exchanger Network (HEN) designs are integrated within the framework as process improvement options. Process and plant-wide control is carried out to perform the controllability assessment of the integrated flowsheets.

On the other hand, process integration leads to tight the designs and force process designers to consider potential control problems and assess the process controllability and operability in the early stages. In general, the success of an integrated design is measured based on its agreement with its ability to be controlled. Therefore, a systematic procedure is required to evaluate the operability and/or controllability issues of the integrated processes. This paper extends the work of Alhammadi et al. (2002a) and Alhammadi and Romagnoli (2003) as to include HEN designs and controllability and operability analyses within the multi-objective optimisation environment.

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Moreover, a plant-wide control approach is proposed to design the control strategies for both integrated and non-integrated processes. Additionally, process modelling and simulation are included in the proposed framework as a mean of validating and testing the steady state and dynamic performance of the designed plant and its control structure. To illustrate the effectiveness of the proposed approach, a case study on the production of vinyl chloride monomer (VCM) process is used.

2. Integrated Framework for Operable Design

Chemical process design problems are multi-objective in nature; hence several objectives are required to be satisfied, maximised or minimised, simultaneously within a specified range of constraints. The main objective of this study is to optimise the formulated objectives as much as possible within the specified constraint region. However, the multi-objective optimisation problem lies in the conflict between the objectives and goals. The decision maker wants to attain more than one objective in selecting the course of action within the specified constraints. In multi-objective optimisation problems, it is very rare to get a single solution that simultaneously optimises all objectives. Though, a Pareto curve is produced to visualise the trade-offs between the objectives through a set of design alternatives and it is defined as a set of 'non-inferior' solutions defining a boundary beyond which none of the objectives can be improved without sacrificing at least one of the other objectives (Miettinen, 1999).

A HEN controllability assessment framework is developed where it extends and incorporates the work of Glemmestad and Gundersen (1998) and Westphalen et al. (2002). This sub-framework is integrated within the overall framework targeting for an optimal design and operation conditions. The aim of this sub-framework is to develop a systematic procedure that helps the design and process engineers in the evaluation and assessment process to select the best controllable and operable designed HEN among a number of different alternatives.

The degree of freedom methodology proposed by Glemmestad and Gundersen (1998) is adapted in this study as the first step of the controllability assessment procedure of the designed HEN. The number of degree of freedom (N_{DOF}) is expressed as follow:

$$N_{DOF} = R + N_U - N_T \quad (1)$$

Where R is the rank of the inner HEN, N_U is the number of utility streams and N_T is the number of targets. No further clarifications will be provided due to the space limitation.

Figure 1 shows a schematic structure of the proposed step-wise procedure to accomplish the performance analysis of a designed HEN and then of the optimised process. The approach starts by developing the HEN designs where the required data to develop a HEN is obtained from the process model and the pinch analysis provides the utility targets of the HEN.

Then the designed HEN is required to be analysed in term of sub-network and loops identifications where each sub-network goes through the degree of freedom analysis where a zero degree of freedom is the minimum requirement of a controllable HEN. Then the process gain matrix of the HEN that passed the degree of freedom analysis is calculated. Square matrices from the overall gain matrix are developed where the available manipulated variables and the required variables to be controlled are grouped in different combinations.

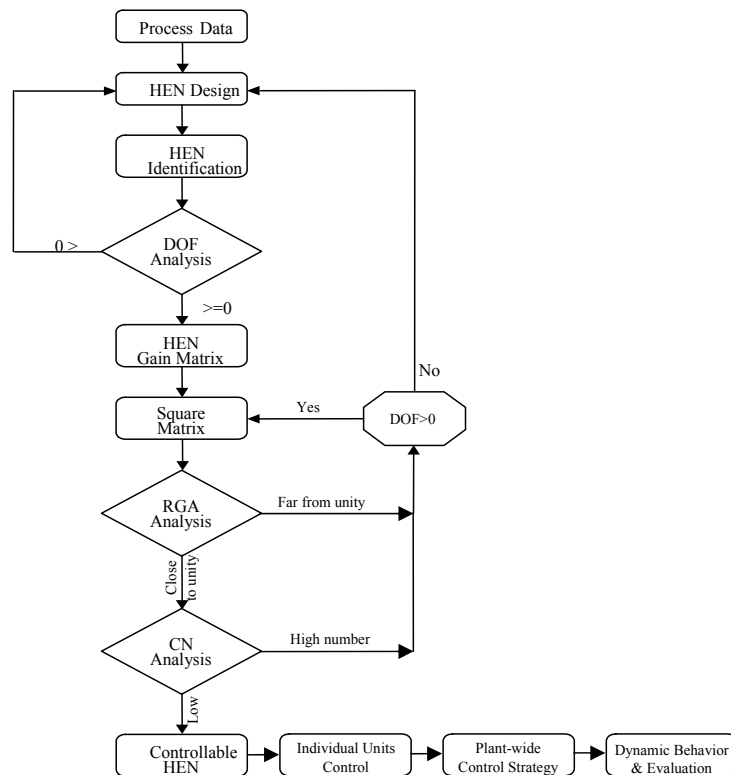


Figure 1. Integrated approach for operability/controlability assessment of integrated processes

The relative gain array (RGA) analysis is used as a guide in the pairing process between the variables as it measures the interactions within each square matrix. This is followed by the condition number (CN) analysis to measure the ease of controlling the system. In this paper, further details of these issues will not be given due to the space limitation and the reader is referred to Alhammadi and Romagnoli (2003) for further detail.

Advanced control strategies have received wide acceptance in the process industry in the recent years as an effective means of implementing multivariable constrained control on real processes. For complex units, such as distillation column, a number of integrating variables are required to be controlled where it forms a challenging task for control engineers. The aim of the proposed individual units control sub-framework is to develop and evaluate satisfactory control structures of each individual unit of the entire plant. Each considered unit is modelled in a dynamic mode using a simulation package, e.g. *HYSYS*, where the available manipulated variables and the controlled variables are identified. *HYSYS* is linked with Excel which is used as a recorder of each individual process output response for a step change of each process input. These responses are used to identify the relationships between the process inputs and outputs through process identification tools. The transfer function matrix of each evaluated unit is

developed and existing analysis tools (RGA, conditions number, etc.) are used to pair the most suitable controlled and manipulated variables so that the minimum interacting loops can be achieved.

The proposed hierarchical procedure for plant-wide control developed by Luyben and co-workers (1998) is utilized, as stepwise guidelines to perform the plant-wide process control strategy. In the proposed framework, the development of the plant-wide control system is performed into two stages. First, the plant-wide control system is developed for the base design where no heat integration is utilised. This stage is performed and evaluated, according to its dynamic performance, as a first step to make sure that the basic designed process is controllable. Then the selected designed HEN, based on the decision maker's preferences, is integrated within the entire plant and the plant-wide control structure is adjusted accordingly.

Process simulation packages provide a great cut down in the required time for process development. Moreover, they provide the opportunity of comparing process alternatives on a consistent basis where a number of different ideas can be analysed in a short time. In term of plant-wide control considerations, process simulation of highly integrated processes within a plant directs the process design/control engineers to the available interactions between the processes.

In the proposed framework, *HYSYS.PLANT* simulation package is used to validate both the steady state and dynamic models even though the switchability from steady state to dynamic mode is not a trivial procedure.

3. Case Study: Vinyl Chloride Monomer (VCM) Plant

The proposed framework has been demonstrated through a developed case study for the production of vinyl chloride monomer (VCM). This typical integrated process produces VCM from ethylene, chlorine, oxygen and a portion of the by-product hydrogen chloride (HCl). The details of the VCM production processes can be reviewed in Alhamadi et al. (2002b). The selected process design variable for the multi-objective optimisation search engine is the portion of HCl recycled to the oxychlorination unit. For the ease of demonstration, a single variable was considered; however, it would be a straightforward extension to the framework to include multiple design variables. In this case study, the most sensitive environmental potential, i.e. global warming potential (GWP), was selected as an exemplar as the entire environmental potentials trend in the same direction.

The ϵ -constraint method was used to solve the multi-objective optimisation problem and obtain the Pareto curve. Here, the economic objective was optimised while the environmental objective was converted into a constraint with a specified upper bound. Each objective function was normalised (over the specified range of the selected process variable) and scaled between 0 and 1 where 0 represents the best value and 1 represents the worst value of the objective. This scaling is required in multi-objective optimisation problems to ease the comparison between the formulated objectives and avoid the computational confusion that is due to different scaling and different path of optimisation (maximisation or minimisation).

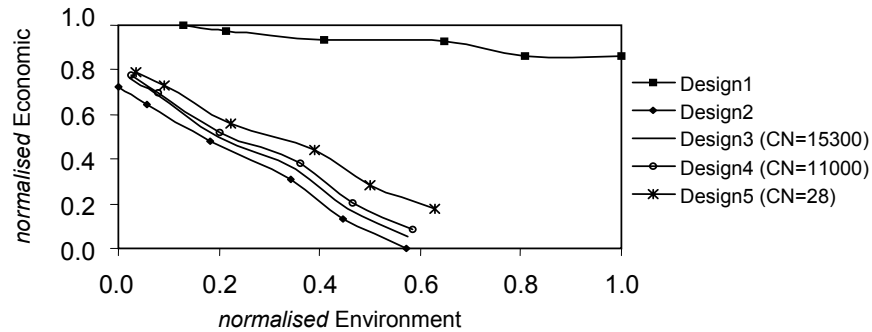


Figure 2. Pareto curves for different designs

The pinch analysis is performed based on the utility streams of the VCM process. This analysis draws the guidelines for the HEN designs. The multi-objective optimisation problem was performed for different developed HEN designs that include no heat integration option (Design 1) where the utilities are at their maximum load. In the second case (Design 2), the process was examined for optimal heat integration with the minimum (target) heating and cooling requirements being determined by the pinch analysis technique. In three different cases (Designs 3, 4 & 5), different developed HEN designs for the process were examined.

4. Results and Discussions

Figure 2 represents the optimisation results to the decision makers in a transparent way through the Pareto curves for the entire designs over the whole range of the selected process variable. The curves for designs 1 and 2 provide the lower and upper bounds for all possible levels of heat integration at all operating points. The practical HEN designs shift the Pareto curve of no heat integration condition towards the optimal heat integration curve. The 'optimal heat integration' curve (Design 2) shows the maximum possible reduction achievable for the objectives.

In term of controllability and operability point of view, moving from the 'no heat integration' level towards the 'optimal heat integration' level results in more process interactions through the HEN that leads to difficult operation and control. Therefore, plant controllability is required to be formulated as one of the trade-offs to be considered in addition to the economic and environmental objectives. The degree of freedom analysis is performed for each independent sub-network of the examined HEN. This step is performed to check the feasibility of the HEN design. The details of the degree of freedom analysis will not be shown here because of the space limitation. After that, the pairing analysis between the controlled variables and the possible manipulated variables is performed through the relative gain array (RGA) analysis of the process gain matrix of the examined HEN design. Finally, the condition number analysis of the process gain matrix is used as a dimensionless measure of the interactions between the control loops paired by the RGA analysis. The condition number analysis provides an

excellent measure of controllability for the designed HENs. For the tested HEN designs, the smallest condition number leads to a better controllable process, while regarding the RGA analysis the closer to identity matrix, the less interaction between the control loops leading to better controllability. For the designed HEN, designs 3 and 4 shows the best improvement toward the optimal design based on the pinch analysis. However, the condition numbers for designs 3 and 4 are 15300 and 11000 respectively, which are very big and indicate a poor controllability. Design 5 is produced from design 4 where small exchangers are removed or combined and more sub-networks are introduced causing the condition number to be improved reaching a value of 28. This improvement in the controllability is at the price of a reduction in the other objectives.

Plant-wide process control forms the final stage of the process synthesis, design and operation assessments. The proposed plant-wide control procedure for the VCM case study shows the importance of employing the engineering judgments and experiences together with the available systematic analyses. Moreover, a rigorous dynamic model was used to implement and validate the developed plant-wide control structure and to test the overall dynamic performances of the plant. The proposed stepwise plant-wide control procedure and the dynamic validation using non-linear plant model for the optimised plant – design 5 - are not provided here due to the space limitation.

5. Conclusions

In this paper, a methodology has been proposed that incorporates economical, environmental, heat integration and operational considerations within a multi-objective optimisation framework. The methodology as it stands enables the design engineers to draw 'boundary' Pareto curves corresponding to the maximum and minimum levels of heat integration for all operating points achievable by the process. It is also possible to use the proposed approach to draw the Pareto curve for any designed HEN between the calculated limits, and thus to quantify the trade-offs between economic and environmental objectives. Improving energy efficiency generally increases plant complexity and which leads to significant impacts on plant operability and/or controllability. The controllability of the designed HEN is analysed explicitly through the RGA and condition number techniques. Plant-wide control and dynamic evaluation are integrated within the framework as a means of including control and operational considerations in the early stages of design.

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