CHAPTER II

LITERATURE REVIEW

2.1 Plantwide Control

A synthesis/analysis procedure for developing first flowsheets and base-case designs had been established by Douglas(1985). The procedure was described in terms of a hierarchy of decision levels , as follows:

1. Batch versus continuous
2. Input-output structure of the flowsheet
3. Recycle structure of the flowsheet
4. Separation system specification, including vapor and liquid recovery system
5. Heat exchanger network (HEN)

Douglas (1985) considered a continuous process for producing benzene by hydrodealkylation of toluene (HDA Process) to illustrate the procedure. The complete process was always considered at each decision level, but additional level terminates in an economic analysis. Experience indicated that less than one percent of the ideas for new designs were ever commercialized, and therefore it was highly desirable to discard poor projects quickly. Similarly, the later level decisions were guided by the economic analysis of the early level decisions.

Price,Lyman and Georgakis' (1994) presented a fundamental characteristic of a well-designed process plant regulatory control system was effective management of the rate of product manufacture and regulation of the inventories within the plant. They proposed guidelines for the development of production rate and inventory controls. The structures resulted satisfy the control objectives and maintained the plantwide characteristics of the problem. The applicability of these guidelines was illustrated using the complex test problem provided by the Tennessee Eastman Company.

Lyman and Georgakis (1995) focused on the development and performance of four plant-wide control structures for the Tennessee Eastman challenge problem. The control structures were developed in a tiered fashion and without the use of a quantitative steady state of dynamic model of the process. The throughput or production rate manipulator was selected first so that it was located on the major process path. The inventory controls were arranged in an outward direction from this throughput manipulator. The four structures were described and comments were given on their effective handling of the defined disturbances and setpoint changes.

Yi and Luyben (1995) presented a method that was aimed at helping to solve this problem by providing a preliminary screening of candidate plant-wide control structures in order to eliminate some poor structures. Only steady-state information was required. Equation-based algebraic equation solvers were used to find the steady-state changes that occur in all manipulated variables for a candidate control structure when load changes occur. Each control structure fixed certain variables: flows, compositions, temperatures, etc. The number of these fixed variables was equal to the number of degrees of freedom of the closed-loop system. If the candidate control structure required large changes in manipulated variables, the control structure was a poor one because valve saturation and/or equipment overloading will occur. The effectiveness of the remaining structures was demonstrated by dynamic simulation. Some control structures were found to have multiple steady states and produce closed-loop instability.

Luyben and Tyreus (1997) presented that generates an effective plantwide control structure for an entire complex process flowsheet and not simply individual units. The nine steps of the proposed procedured center around the fundamental principles of plantwide control: energy management; production rate; product quality; operational, environmental and safety constraints; liquid-level and gas-pressure inventories; makeup of reactants; component balances; and economic or process optimization. Application of the procedure was illustrated with three industrial examples: the vinyl acetate monomer process, the Eastman plantwide control process, and the HDA process.

McAvoy (1999) presented an approach to synthesizing plantwide control architectures that made use of steady-state models and optimization. The optimization problem solved was a mixed-integer linear programming (MILP) problem that aimed at minimizing the absolute value of valve movements when a disturbance occurs. Results were presented for its application to the Tennessee Eastman process.

Stephanopoulos and Christine Ng (2000) provided a comparative analysis of various approaches, with an emphasis on how well they address the inherent theoretical and practical issues associated with the design of such control systems. The principle of the Optimizing Feedback Control Structures was proposed as the formal medium for the identification of controlled variables. Furthermore, it was shown that the selection of the best sets of input (manipulated) and output (measured) variables for the formation of the controllers' structures was governed by classical control-theoretical aspects. Hierarchical viewing of a plant is proposed as an effective mechanism to contain the complexities of the problem by streamlining the (i) specification of control objectives at different time-scales, (ii) modeling needs and model uncertainties, (iii) selection of measured and manipulated variables, and (iv) formation of the control structures.

Wang and McAvoy (2001) discussed an optimization-based approach to synthesizing plantwide control architectures. The plantwide controller was synthesized in three stages involving fast and slow safety variables to be controlled, followed by product variables. In each stage a mixed integer linear program was solved to generate candidate architectures. The objective function involved a tradeoff between manipulated variable moves and transient response area. Controlling component balances and adding unit operation controls completed the plantwide control system design. The Tennessee Eastman process was used to illustrate the synthesis procedure.

Skogestad (2004) interested in control structure design deals with the structural decisions of the control system, including what to control and how to pair the variables to form control loops. He presented a systematic procedure for control structure design for complete chemical plants (plantwide control). It started with carefully defining the operational and economic objectives, and the degrees of freedom available to fulfill them. Other issues, discussed in the paper, include inventory and production rate control, decentralized versus multivariable control, loss in performance by bottom-up design, and a definition of a the ''complexity number'' for the control system.

2.2 HDA Process

Cao and Rossiter (1997) introduced a new technique for selecting manipulated variables from a range of possible control inputs . The new technique, Single-Input Effectiveness (SIE), provided a screening criterion for eliminating certain options when deciding which inputs to the process should be used in a control scheme. These inputs were selected so as to have the largest effect on the selected outputs. The new tool could be used for pre-screening inputs and avoided the combinatorial difficulty which usually occurs when performing control structure selection.

Cao, Rossiter and Edwards (1998) In this work, the HDA case study was revisited but the nonlinear model had been revised to include modified models for the distillation columns and other unit operations. The modeling issues associated with the development of this more rigorous HDA model were discussed in the context of use for control structure selection.

Luyben (2000) studied the process had the exothermic, irreversible, gas-phase reaction A + B f C occurring in an adiabatic tubular reactor. A gas recycle returns unconverted reactants from the separation section. Four alternative plantwide control structures for achieving reactor exit temperature control were explored. The reactor exit temperature controller changed different manipulated variables in three of the four control schemes: (1) CS1, the set point of the reactor inlet temperature controller was changed; (2) CS2, the recycle flow rate was changed; and (3) CS3, the flow rate of one of the reactant fresh feeds was changed. The fourth control scheme, CS4, uses an "on-demand" structure. Looking at the dynamics of the reactor in isolation would lead one to select CS2 because CS1 had a very large deadtime (due to the dynamics of the reactor) and CS3 had a very small gain. Dynamic simulations demonstrated that in the plantwide environment, with the reactor and separation operating together, the

CS3 structure gave effective control and offered an attractive alternative in those cases where manipulation of recycle flow rate was undesirable because of compressor limitations. The on-demand CS4 structure was the best for handling feed composition disturbances.

Luyben (2000) explored the impact of activation energy and reactant concentration on both the steady-state economics and the dynamic controllability of a process in which an exothermic, irreversible, gas-phase reaction $A + B \rightarrow C$ occured in an adiabatic tubular reactor. A gas recycle returned unconverted reactants from the separation section. Two control structures were explored, one with the limiting reactant concentration controlled by fresh feed and the other with this fresh feed fixed. The first structure was only effective with low activation energies. The second handled large activation energies, but only when reactant concentrations are not high.

Kookos and Perkins (2001) presented an optimization-based method for selecting manipulated variables for regulatory control schemes. The objective of this mathematical programming technique was the minimization of the overall interaction and sensitivity of the closed-loop system to disturbances. In addition, a general methodology for incorporating qualitative knowledge as linear constraints to the problem was demonstrated. The main advantage of the method was that the plantwide nature of the problem was preserved, because decisions related to different levels of the base regulatory control scheme were made simultaneously. The usefulness of the method was demonstrated using a double-effect evaporator case study, the HDA case study, and the Tennessee Eastman challenge problem.

Kietawarin (2002) presented a comparison among 4 control structures designed for withstanding disturbances that cause production rate change of HDA process. The changes had been introduced to the amount of toluene and feed temperature before entering the reactor. Compared with the reference control structure using a level control to control toluene quantity in the system, the first control scheme measured toluene flow rate in the process and adjusted the fresh toluene feed rate. This structure resulted in faster dynamic response than the reference structure. The second control scheme was modified from the first scheme by adding a cooling unit to control the outlet temperature from the reactor , instead of using internal process flow.

The result was to reduce material and separation ratio fluctuations within the process. The product purity was also quite steadily. In the third control scheme, a ratio control was introduced to the secon control scheme for controlling the ratio of hydrogen and toluene within the process. This scheme showed that it could withstand large disturbances. Dynamic study showed that the control structure had significant effect on process behavior. A good system control should quickly respond to disturbances and adjust itself to steady state while minimizing the deviation of the product quality

Qiu, Rangaiah and Krishnaswamy (2003) In this study, a rigorous model for the hydrodealkylation of toluene (HDA) process was developed using the commercial software, HYSYS.PLANT. After reviewing the reported methods for plant-wide control, a systematic method, namely, Control Configuration Design (CCD) method, was selected for application to the HDA process. The resulting control structures from the application of this method were evaluated and compared through rigorous dynamic simulation. The results show that the CCD method successfully yields workable base-level regulatory control structures for the HDA process.

Herrmann, Spurgeon and Edwards (2003) presented a sliding mode control methodology using output information was demonstrated in application to the HDA-plant, a plant for production of benzene. This process is a highly integrated, non-linear large scale process with non-minimum phase and relative degree zero characteristics. The non-linear control law was designed on the basis of a linear observer-based control system. The non-linear control law used the states of the linear observer. The performance in the sliding mode was determined by a linear stable submanifold of the linear closed loop control system chosen via a robust pole selection scheme

2.3 Process Controllability Analysis

Grosdldler and Morarl (1985) explored closed-loop properties of open-loop stable multivariable systems when the controllers include integral action. The studied properties comprised closed-loop stability, sensor and actuator failure tolerance, feasibility of decentralized control structures, and robustness with respect to modeling errors. All the results were based on steady-state gain information only. They elucidated the relationship between the new theorems and the Relative Gain Array (RGA).

Skogestadt and Morari (1987) introduced that large elements in the RGA implied a plant which was fundamentally difficult to control. (1) The plant was very sensitive to uncorrelated uncertainty in the transfer matrix elements. (2) The closed-loop system with an inverse-based controller was very sensitive to diagonal input uncertainty. With adiagonal controller, the system was not sensitive to diagonal input uncertainty, but the controller did not correct for the strong directionality of the plant and may therefore give poor performance even without uncertainty.

Skogestadt and Morari (1987) presented that the effectiveness of disturbance suppression in a multivariable control system could depend strongly on the direction of the disturbance. The "disturbance condition number" was introduced to quantify the effect of disturbance direction on closed-loop performance. As an example a two-point composition control system for a distillation column was analyzed for various disturbance and setpoint changes.

Fisher, Doherty and Douglas (1988) described a systematic procedure for assessing process controllability at the preliminary stages of a process design At the preliminary stage of a process design, the optimum steady-state designs of various process alternatives were often uncontrollable; i.e., there were not enough manipulative variables in order to satisfy the process constraints and to optimize all of the operating variables. Controllability could be restored by (1) modifying the flow sheet to add more manipuiative variables, (2) overdesigning certain pieces of equipment so that the process constraints never become active for the complete range of the process disturbances, or (3) ignoring the optimization of the least important operating variables. The goal of a controllability analysis is to determine which of these alternatives has the smallest cost penalty

Arkun and Downs (1990) proposed a general method based on singular value decomposition and state-apace models was presented to calculate a set of gains between inputs and outputs of processes with integrators. The practical importance of these gains for determining input-output sensitivities and asymptotic properties was illustrated along with the calculation of the relative gain array for integrating systems. The results were particularly applicable to large chemical processes and could be easily incorporated into flowsheet simulators.

Hovd and Skogestadt (1992) presented results on frequency-dependent tools for analysis, structure selection and design of control systems. This included relationships between the relative gain array (RGA) and right half plane zeros, and the use of the RGA as a sensitivity measure with respect to individual element uncertainty and diagonal input uncertainty. It was also shown how frequency-dependent plots of the closely related performance relative gains (PRGA) and a new proposed disturbance measure, the closed-loop disturbance gains (CLDG), can be used to evaluate the achievable performance (controllability) of a plant under decentralized control.

Dimian, Groenendijk and Iedema (1992) presented an application of systems analysis in handling impurities in a complex plant for operation diagnosis or for revamping. Tracing impurities necessitates careful calibration of the plant material balance and the study of the recycle loops dynamics. Thus may be predicted operation difficulties originating mainly from interactions, to evaluate plantwide control properties of flow sheet alternatives and to suggest design improvements. Then, dynamic simulation on a reduced flowsheet may be used to asses robust flowsheet alternatives. A case study of a VCM plant illustrates the methodology.

Skogestad and Havre (1995) interested in the relative gain array (RGA) and condition number which were commonly used tools in controllability analysis. So they presented new results that link these measures to control performance, measured in terms of the output sensitivity function with input and output uncertainty.

Semino and Giuhani (1997) proposed control structures for chemical processes with recycle streams were often affected by the so-called "snowball effect", which consists in very large variations of the manipulated variables required to reject relatively small disturbances. This occurrence was related to a wrong choice of the control structure, which may be relatively easy to detect for simple systems, but was difficult to discover for complex ones. A systematic steady state analysis had been developed for systems with recycle, which was able to classify all possible control configurations which were and which were not affected by snowballing.

Zhong-Xiang Zhu (1996) presented that the relative interaction array (RIA) in terms of its features, properties, and relationship to the relative gain array (RGA). It was demonstrated that the RIA offered a better measure of individual interactions than the RGA. Moreover, it was shown that the RIA also contains direct information about closed stability, integrity, and robustness. The RIA was further extended to propose a new overall interaction measure which was able to avoid ambiguities associated with the RGA pairing criteria and to overcome problems associated with other overall interaction measures

Dimian, Groenendijk and Iedema (1997) presented a simulation based methodology for evaluating the effect of recycle interactions on dynamics and plantwide control of complex plants. Steady-state and dynamic simulations were combined with controllability of two flowsheet alternatives was evaluated. The steady-state analysis was confirmed at low frequencies. Possible difficulties may occur at higher frequencies, where the period of disturbances and the time constants of the distillation columns were of the same order of magnitude. The relative direction of disturbances played a significant role. Closed loop simulation validates the main trends of the controllability analysis, showing in the same time the difficulty in managing a perfect multivariable control of the material balance.

Haggblom (1997) developed analytical relationships useful for frequency-dependent relative gain analysis of distillation control structures. An expression that related the RGA for an arbitrary control structure to the transfer functions for the so-called LV-structure was derived. Relationships that directly related the relative gains for different control structures to one another were also derived. The usefulness of the relationships was illustrated by calculation of frequency dependent relative gains for nine different control structures for a distillation column.

Cao, Rossiter and Edwards (1997) proposed two new input screening techniques that consider the disturbance rejection capability of a process in the presence of manipulated variable constraints. These were used to overcome the difficulties associated with the combinatorial problem that naturally arises in control structure selection. The measures used to provide screening criteria are the Worst Case Input-Disturbance Gain (WCIDG) and the Input-Disturbance Gain Deviation (IDGD). These criteria were used to determine the best choice of manipulated variables to provide a control structure with the best disturbance-rejection capability.

McAvoy and Miller (1999) presented an approach to using steady-state simulators to obtain approximately the same gain matrix . Once this matrix was calculated, it can be used to assess the operability of plantwide control schemes. The methodology was developed using a distillation tower system, and then it was applied to analyze the "snowball effect" in a three reactor/three distillation tower plant. The methodology was also applied to the Tennessee Eastman process.

Groenendijk, Dimian and Iedema (2000) presented a simulation-based methodology for evaluating these phenomena and finding the best flowsheet structure was reported from a controllability point of view. Steady state and dynamic simulations were combined with controllability analysis tools, both steady state and in the frequency domain, which extracts more value from simulation than the usual sensitivity studies. The case of a vinyl chloride monomer (VCM) plant with impurities handling as a main issue demonstrates the power of the approach.

Dimian, Groenendijk and Iedema (2001) proposed a methodology for evaluation the dynamic inventory of impurities that consists of a combination of steady-state and dynamic flowsheeting with controllability analysis. This approach was used to assess the best design alternative and/or to propose subsequent modifications. A VCM process with four recycle alternatives illustrated the approach. Taking advantage of the effect of interactions enabled three impurities to be kept under control with only two controllers. The approach was generic and could be used to improve the environmental performances of chemical processes.

Robinson et al. (2001) presented an approach to designing decentralized plantwide control system architectures. The approach was based on splitting the optimal controller gain matrix that results from solving an output optimal control problem into feedback and feedforward parts. These two parts were then used to design and evaluate decentralized control systems. For this system, the optimal control based approach suggested feedback pairings that are significantly different than those suggested by the steady state RGA. They presented comparison of the results produced by the best decentralized plantwide system and a model predictive control system .

Chen and Seborg (2002) interested in the influence of process model uncertainty on RGA analysis. Analytical expressions for RGA uncertainty bounds were derived for 2 x 2 control problems and for general, n x n control problems. The RGA uncertainty bounds provided useful information concerning model accuracy requirements and the robustness of decentralized control system.

Chodavarapu and Zheng (2002) showed that ensuring process flexibility did not guarantee steady-state robust feasibility. They illustrated the distinction between these two concepts using simple mathematical examples, the HDA process, and a simple RSR system. They proposed a definition for steady-state plantwide controllability that ensures steady-state robust feasibility.

Schmidt and Jacobsen (2003) focused on performance, and considered in particular the problem of selecting control structures that enable a desired performance to be achieved through independent tuning of the subsystems. They showed that, for this task, the common assumption of perfect control within the bandwidths of the subsystems was a poor one. Based on this, a new measure of interactions, the decentralized relative gain (dRG), was proposed. Finally, it was stressed that the effect of interactions on the magnitude as well as on the phase lag of the subsystems should be considered when selecting control configurations for performance.

McAvoy and Braatz (2003) considered processes with a large maximum singular value. It was shown that the closed-loop control of such processes can result in poor transient performance as a result of valve accuracy considerations, *even if the condition number is small and the minimum singular value is large*, which would indicate no performance limitations according to existing controllability criteria.

Further, processes with large singular values could be prone to sensor saturation. This indicated that the magnitude of all of the singular values should be considered when assessing the controllability of a process. A new interaction tool based on output correlation was introduced to help select measurements and manipulated variables that had a good range of singular values for practical application. The approach proposed was illustrated on two simple examples and on the Tennessee Eastman process.

Kariwala, Forbes and Meadows (2003) presented some new algebraic properties of BRG and establish its relation with closed-loop stability, controllability, block diagonal dominance, and interactions. Block relative gain (BRG) was a useful method for finding suitable pairings for block decentralized control. They showed that strongly interacting systems could have BRG that is nearly the identity matrix. Our results provided simple rules for pairing of variables. We also extended the known method for calculating relative gain array for interacting systems to BRG.