Developing Operating Strategy for a Semi-Continuous Production Process

by

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Disclaimer

This thesis deals with the production process of a product not yet on the market. Due to confidentiality reasons, the product will be referred to as SAN (Substitute Any Name) throughout this thesis, and the company developing this product will be referred to as SANCO. In the interest of preserving this confidentiality without diminishing the value of this thesis some of the details of the production process have been abstracted from and some measurements have been modified or non-dimensionalized. As far as possible, the information contained within is complete and accurate.

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Abstract

A semi-continuous production process is used to produce a liquid product called SAN. A study was performed on the effect of various changeover strategies on the performance of the SAN production process, where the main objective was to develop an optimal operating strategy. This was achieved by developing a dynamic simulation of the system and using that simulation to learn about the system's performance over a variety of operating strategies. Performance optimization analysis was then used to determine the optimal operating strategy. Finally, possible modifications to the system hardware were investigated with the aim of identifying cost-effective options for further performance improvements.

The primary conclusion of this study is that a shutdown/startup changeover strategy should be used for the SANCO system. The shutdown/startup changeovers should be concurrent, whereby startup begins before the shutdown is completed. Furthermore, priming the feed preparation stage during startup should be done at four times the steady state flow rate, while the post-reaction refining stages should be shut down at four times the steady state flow rate. This strategy is projected to yield high production rate efficiencies (between 88.5% and 90%) and raw material efficiencies (between 90% and 92%). Production rate efficiency is similar to process reliability, while the raw material efficiency is a measure of how well input materials are utilized.

For the current SANCO system the above detailed strategy will yield the best results without hardware modifications. In designing and building a system for larger production, both the options of (a) implementing parallel stages where necessary and (b) using a continuous additive system should be investigated.

One obvious conclusion of this study is that the continuous changeover strategy is unfeasible for the SANCO system. The projected raw material efficiencies ranged between 40% and 65%, while the production rate efficiencies ranged between 45% and 75%. These are unacceptable results. Were a continuous changeover strategy to be used, the majority of the permitted co-mingling should be limited to the end of the run. Furthermore, the results revealed that increasing the permitted co-mingling of a production run did not significantly improve the system's performance.

Finally, if the demands on production are similar to those used to develop the proposed production schedule, the runs should closely follow the full test case scenario of 7 lots of mixed sizes discussed in chapter 3. The two larger final storage tanks should be dedicated to a single type of SAN each (to minimize co-mingling), and production lots should be made as large as possible to maximize efficiencies. If the demands on production become less focused on two main types of SAN, it would be worthwhile investigating converting the third final storage tank to the larger size.

Thesis Supervisor: Kamal Youcef-Toumi
Associate Professor of Mechanical Engineering

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I want to thank my family for all their support and love they've given me all my life. Corny as it may sound, I *do* realize how fortunate I am to have had such a close family.

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Table of Contents

1 Introduction

This chapter provides an overview of the main question and the underlying issues that were investigated in this thesis. Section 1.1 gives some of the background, briefly describing the current production system and the corresponding process that were examined. Section 1.2 details the specific objectives of the project, whereas section 1.3 describes the layout of the this report. This is all followed by a summary of this chapter.

1.1 The SAN Production Process

SANCO currently produces SAN using a semi-continuous process. This production process consists of raw material preparation operations feeding a Continuous Stirred Tank Reactor (CSTR) reaction train, followed by a series of refining and finishing stages. The processing is basically continuous with modest amounts of surge[1] during some of the feed preparation and refining unit operations.

The reaction itself is moderately slow and proceeds through four stages, creating significant problems for startup, shutdown and changeovers. Each stage is implemented with two CSTRs in series (for a total of 8 CSTRs). Operating conditions within each stage are different and can be independently controlled. Total residence time in all the CSTRs is 16-24 hours. The time to startup and line out the process to steady state center line conditions can take around 100 hours, while allowing all the residence in the system to run out when shutting down can take on the order of 90 hours.

Several types of SAN can be made on this single system, depending on the chemical used as the main reactant. Changeover from the production of some type A to type B is currently achieved by allowing the production of A to completely shut down (and run out),

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[1] Surge refers to the build up of materials in buffers.

cleaning out the system and then a new startup for the production of B. This will be referred to as a "dry" changeover.

Changeovers can also be achieved in a purely "continuous" fashion, whereby the type of raw material is simply changed while the process is otherwise uninterrupted. However, a purely continuous changeover will result in significant mixing of the two types of final product in the finished lot, which affects the quality of the final product. Generally speaking the term "co-mingling" is used to refer to mixing of two types of the final product, although specifically it is defined as a measure of the relative amount of mixing. For a final product lot to be worthwhile for sale it must comply with a maximum co-mingling limitation or tolerance. Figure 1.1 below shows how the co-mingling of the finished product flowing into the storage tanks typically varies during a continuous changeover.

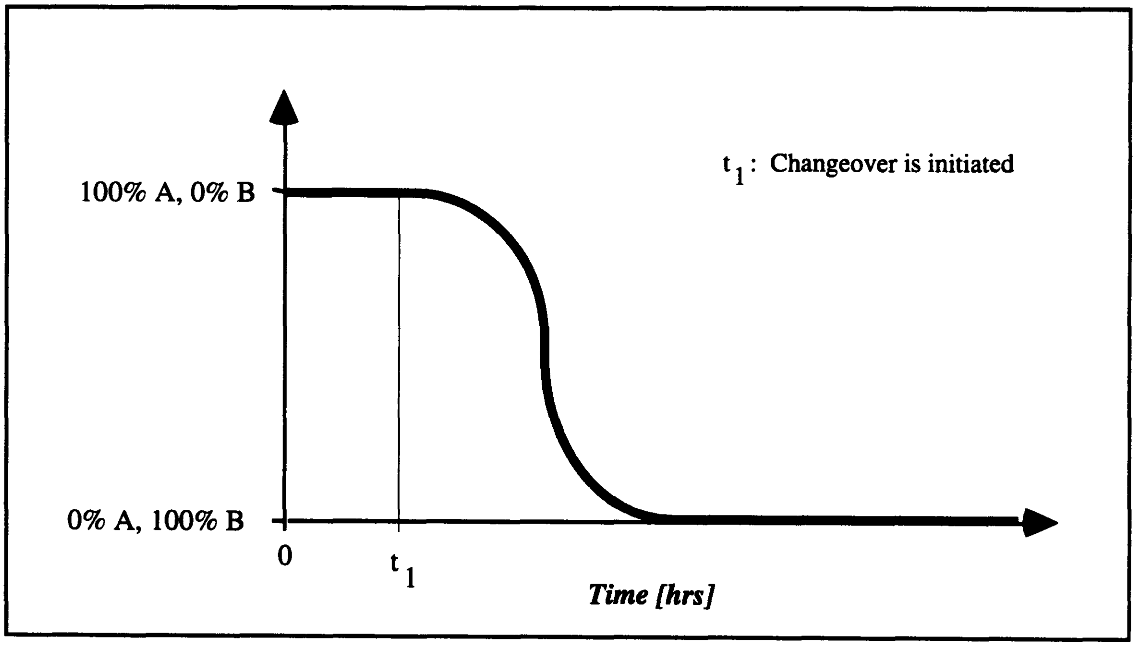

Figure 1.1: Typical co-mingling during a continuous changeover.

With either changeover method, complex and interrelated startup, shutdown, and changeover concerns exist in each unit operation. These include the amount of co-mingling that results, the amount of raw material and final product that must be scrapped, bottlenecks or limitations on the rate of production, and other such factors that will affect the success of this project, namely, the bottom line or profit margin for the company.

Other important issues that further complicate the process are feed stock and slurry management, equipment and personnel safety during transitions, refining and finishing operations, in-process and finished product tank management, and the relative tolerance for co-mingling between stocks.

1.2 Objectives

The general objective of this project was to develop a strategy for the startup, shutdown and changeover of the process from one type to another that yields optimum system performance. This statement begs the question of what is optimal performance? Defining optimal performance and how it applies to this process was clearly one of the necessary first steps of this study.

Of the three mentioned aspects of system operation, changeovers were of most interest. Although there is no question that both complete startups and shutdowns can significantly affect system performance depending on how they are carried out, one of the final goals of the SAN project is to be up and producing most of the time, thus necessitating relatively many more changeovers then simple startups and shutdowns. Furthermore, it would seem likely that changeovers, which would affect two production runs, would have a more significant impact on the final system performance.

Thus, after defining optimal system performance, the next step was the development of several different changeover strategies. These were compared with respect to several critical performance criteria. This was done by developing a dynamic model of and computationally simulating the SAN production process, and running test cases corresponding to these strategies. The results of these simulations were then used to optimize the strategies. Finally, once an optimal operating strategy for the current system was determined, cost-effective modifications to the system were investigated.

Thus the objectives of this thesis are to describe these steps that were undertaken in divising the optimal changeover strategy, present the actual results and discuss possible improvements.

1.3 Thesis Outline

Chapter 2 contains a detailed description of the system and the assumptions that were made in modeling it. It concludes with a description of the computer simulation. This is followed by a presentation of the test case standards and scenarios in chapter 3. This includes a definition of the critical performance criteria and how they were measured. The results are presented and discussed in chapter 4, and chapter 5 contains final conclusions and recommendations. Appendices containing test case data and software code are located at the end.

1.4 Summary

The main objective of this project was to develop operating strategy for the startup, shutdown and changeover from the production of one type of SAN to another for the current SAN production system. This was achieved by building a dynamic model of the system, computationally simulating the model, and consequently learning about the system's behavioral dynamics by varying operating strategies. Then performance optimization was used to determine optimal operating strategy. Finally, cost-effective modifications to the current production system were investigated.

2 System and Model Description

This chapter deals with the actual SAN production system and how it has been modeled. It begins with a short overview of the system, followed by a more detailed description of its components, and the assumptions that were made in modeling them. Section 2.3 contains a description of the computational model. This is followed by a short summary of the chapter.

2.1 System Overview

Figure 2.1 below shows a rough flow diagram of the SAN process. For the purposes of this thesis we will consider the process to consist of six stages. At the heart of this process is the reaction train stage. This is where the SAN is actually synthesized. Prior to this stage it is basically all raw material handling, whereas all the stages that follow it are refining and finishing processes of one type or another to transform the crude product into consumer quality product. This includes multiple separation processes. An important component of this process is the recycle flow, which returns the unreacted raw material that has made it to stage 5 to the feed preparation stage for re-use.

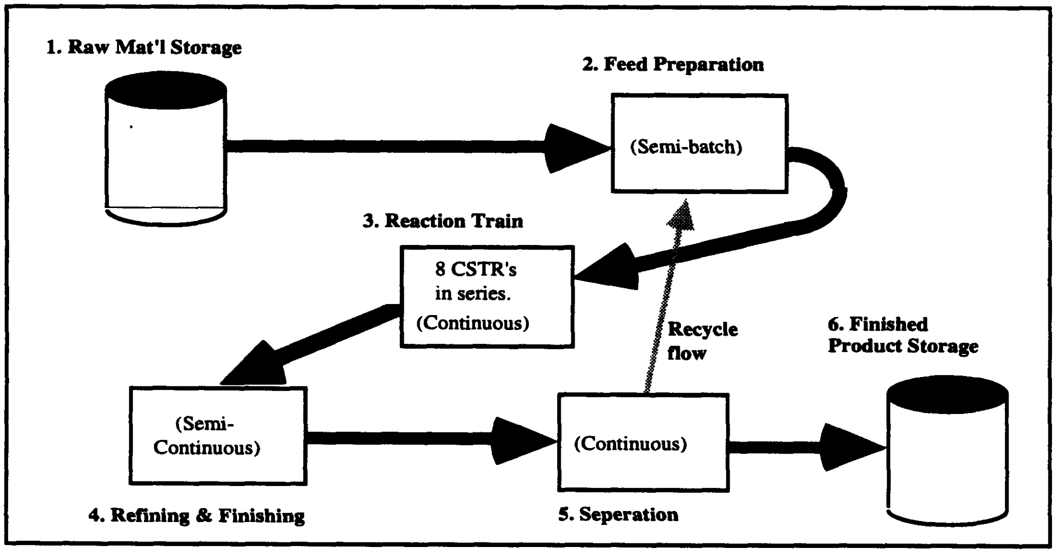

Figure 2.1: Rough process flow diagram

The process is overall continuous, although two of the stages are not. The second stage, feed preparation, could be called 'semi-batch', for it contains a mix tank to which an additive is added in batches, that feeds into another slurry tank that is continuously feeding (thus overall it appears to be continuous). On the other hand, the refining and finishing stage is to an extent only 'semi-continuous', for on a regular basis (approximately for one hour every 24 hours) outflow must be interrupted while some of its hardware is cleaned out. However, storage buffers before and after the flow interruption are used to keep the overall process continuous.

2.2 Process Stages

2.2.1 Stage 1: Raw Material Tank Farm

The raw material tank farm stores the main process raw material. For each of the five types of SAN there is a main raw material which is kept in a storage tank, which are directly filled from rail cars. Raw material flow from the tank farm is induced using a positive displacement pump.

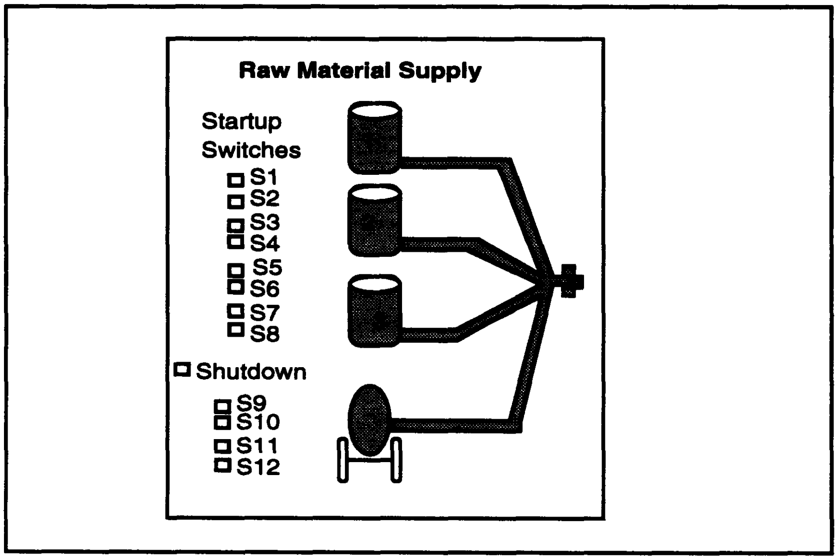

Figure 2.2.1: Basic model layout of stage 1.

Modeled as: Source of 5 types of raw materials. Raw materials amounts (lbs) do decrease with outflow, but can be instantly changed to any level. Outflow is chosen by setting an outflow schedule, whereby a given level of outflow (lbs/hr) is prescribed for a given time, as well as a corresponding type schedule, which sets the type of outflow at any time. It can be set so that the level and type of outflow can be changed if given digital input signals (from other components in the system) turn on and off. The outflow level is assumed to change instantaneously and exactly. Furthermore it is assumed that the raw material types do not co-mingle in the tank farm.

Key Assumptions:
1. Raw material outflow rate changes instantaneously and exactly.
2. There is no co-mingling of raw material in tank farm (outflow types change immediately).

Startup: At startup the raw material outflow is just enough to prime the feed preparation stage such that its slurry tanks fill to their steady state levels at the same time. As soon as they begin to feed into the first reactor the raw material outflow decreases slightly so that the outflows through the slurries are at their steady state levels. When the first reactor reaches its operating level there is a pause in flow as the reaction conditions are given time to equilibrate. Then as the various reactors begin feeding forward the outflow from the raw material source increases (using input

	signals) to include the raw material flow needed for the following reactors.
Steady State:	The raw material type changes according to changeover schedule. If raw materials from the separation stage begin recycling back to the feed preparation then the outflow level decreases accordingly (using an input signal).
Shutdown:	At the initial input signal that the system is shutting down the outflow decreases such that raw materials needed for the later stage reactors are flowing (but no flow to the feed preparation). As soon as the feed preparation runs out and the reactors cease to feed forward then the outflow completely stops.
Re-Startup:	It follows the same sequence of actions as with the initial startup; however, the outflow type depends on the type schedule.

2.2.2 Stage 2: Feed Preparation

The feed preparation stage consists of several subsystems which perform various raw material processes and then feed into the reaction train at the same time. These subsystems consist of multiple slurry tanks, which mix the main raw material with various additives. One of these additives is added in batch fashion to a slurry which uses a recycle loop to keep its output flow well mixed. As the additive is added in this fashion the residence level in the slurry is very high (20+ hours of steady state flow). Positive displacement pumps are used to propagate the flows.

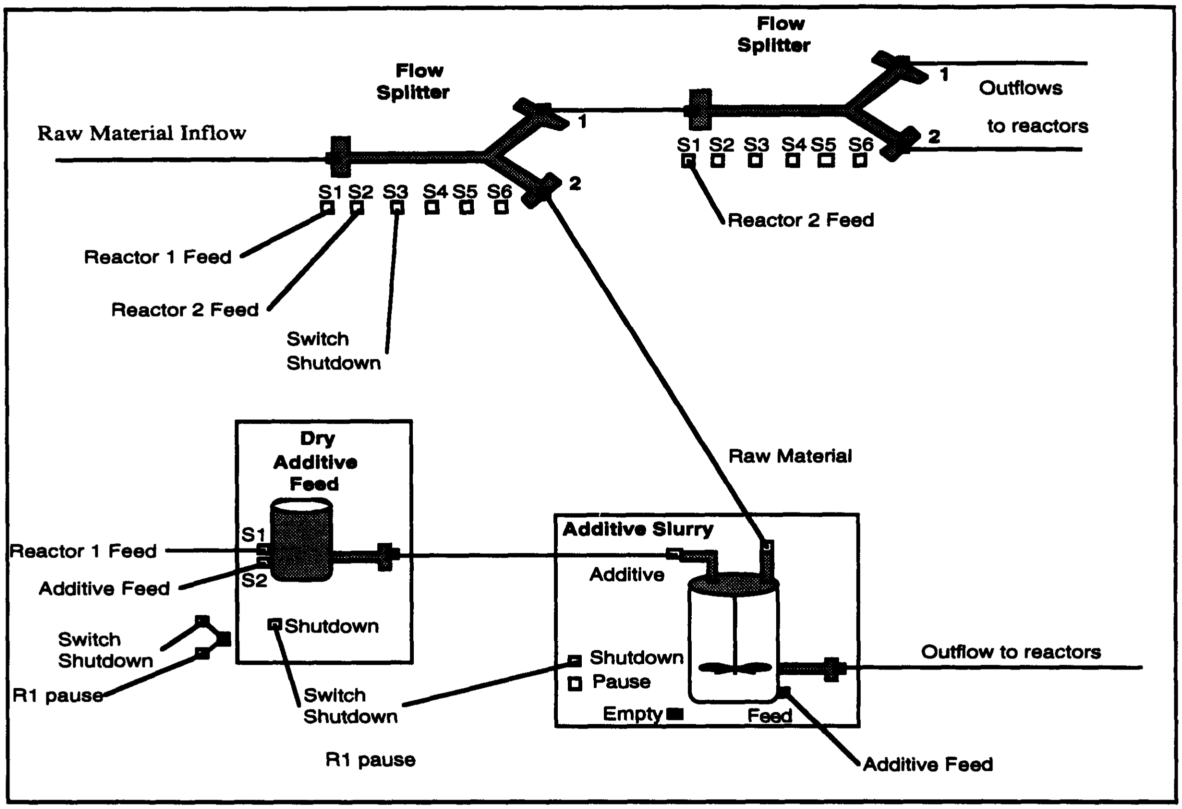

Figure 2.2.2: Basic model layout of one of stage 2's subsystems.

Modeled as:

Additive sources feeding into slurry mix tanks, along with raw material flows from the raw material tank farm. There is also inflow from the separation recirculation flow into the slurries. The slurries perfectly mix their contents, initially allowing the residence levels to build and then pass the flow continuously on keeping their levels constant (using proportional control). The additive sources can either be set to add a set amount to the flow, or a set percentage of the current flow.

Key Assumptions:

1. The slurry tanks perfectly and immediately mix their contents.

2. The batch addition of the additive can be modeled as continuous addition to the slurry's outflow.

Startup:

At startup additives are fed into the slurries, where they are perfectly mixed with the raw material flow. Once the operating residence levels are achieved then the flows are fed forward at the steady state outflow rates. One of these flows passes through another additive source, which adds the steady state flow rate of the additive whenever the through flow is non-zero. This flow feeds into another slurry, which fills up to its steady state operating level and then feeds forward using proportional control to keep its level constant. The raw material flows into the subsystems are coordinated such that the slurries will fill up to their operating levels at the same, so that they will begin flow into the reactor train at the same time. As the reactors fill up and begin feeding forward, one of the subsystems increases its outflow to include the flow needed by the following reactors (notified by an input signal).

Steady State:

No change.

Shutdown:

On shutdown the additive sources (which are notified using input signals) immediately cease their outflow. The slurry tanks (into which the raw material flows have also ceased) continue their outflow at steady state rates until they are empty.

Re-Startup: Same as initial startup.

2.2.3 Stage 3: Reaction train

The reaction train consists of 8 continuous stirred tank reactors. The reactors fill up to the various residence levels required for the reactions, and then feed forward into the next reactor (keeping their levels constant using proportional control). Some of the first reactors in the train are connected to a vacuum system that collects byproducts of the reaction. The last reactors' byproducts are also stripped by a vacuum system, but they are then processed and recirculated back into the reaction train.

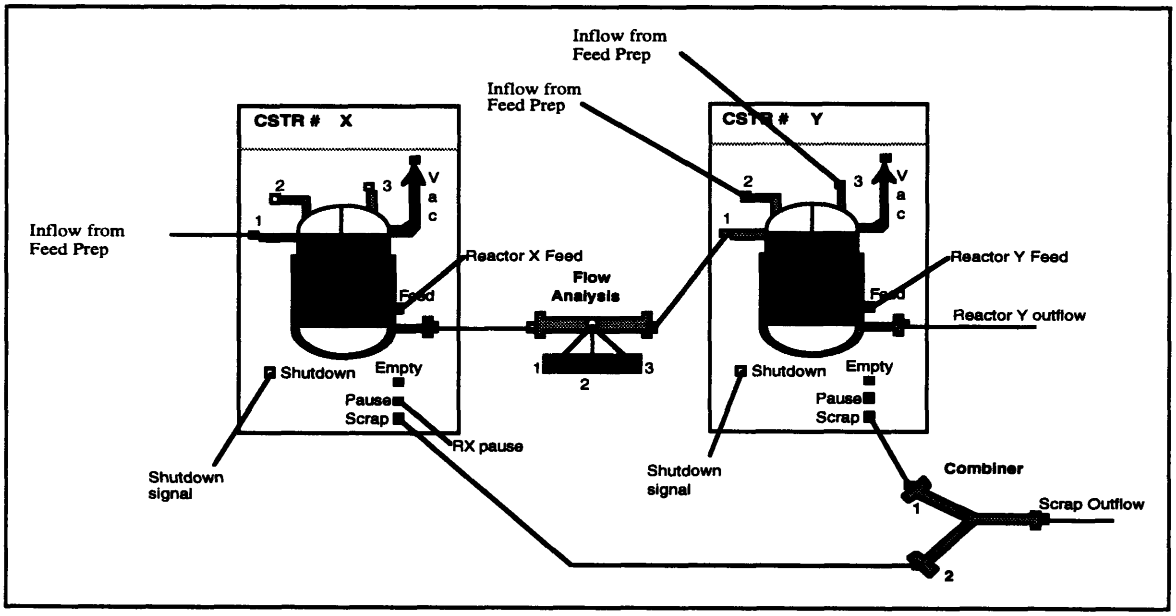

Figure 2.2.3: Basic model layout of part of reactor train.

Modeled as: A train of 8 reactors. External operating conditions such as temperature and pressure are ignored. The rate of byproduct production and the degree to which the reaction has progressed must be specified for each reactor. This information is used to determine the rate of SAN reaction / production. The byproducts are stripped off and scrapped for the first reactors. For the last reactors they are passed into a sub process, which recycles a specified amount and passes it back to the reaction train. The reactors feed forward such that their levels are held constant using proportional control.

Key Assumptions:

1. Some of the reactors require some time after their residence levels are up to operating levels for reaction conditions to equilibrate.
2. Reaction equilibrium for the other reactors is achieved as soon as their contents are up to their operating levels.
3. Reaction conditions are ideal.

Startup:

When flow into the first reactor begins (from the feed preparation and raw material tank farm) it fills up to its operating level and then flow pauses to allow reaction conditions to equilibrate. The reactor then begins feeding forward into the second reactor (using proportional control to keep the level constant). The following reactors act similarly, filling up to their specified operating levels and then feeding forward into the next reactor. As their contents feed forward they react in the proportions dictated by the SAN reaction and the specified reactor conditions.

Steady State:

No change.

Shutdown:	At system shutdown the first reactors immediately cease to feed forward as soon as inflow into them ceases. These last reactors continue to feed forward (with the same rate of reaction) as it was just prior to the shutdown, until they have drained empty. At this stage the recycled byproduct flow ceases. While the last reactors are draining out by feeding forward the first ones (that shut down immediately) are allowed to gravity drain to the sewer, scrapping their contents.
Re-Startup:	Same as initial startup.

2.2.4 Stage 4: Refining and Finishing

This stage consists of multiple subsystems in series, all which perform some type of refining or finishing process, most of which can be regarded as separation processes of one form or another. Many of these subsystems contain some type of mixing or feed tank, which fill up to specified residence levels and then feed forward such that the level remains constant (using proportional control). Treated water and other additives are added at different spots in the stage. Flow is driven forward by positive displacement pumps. One of the subsystems must be cleaned out every 24 hours, which causes an hour interruption. It is surrounded by two tanks which serve as buffers and keep the overall flow continuous. Some of the subsystems contain recycle loops. There is some scrap generated at the startup and shutdown of flow through some of the hardware.

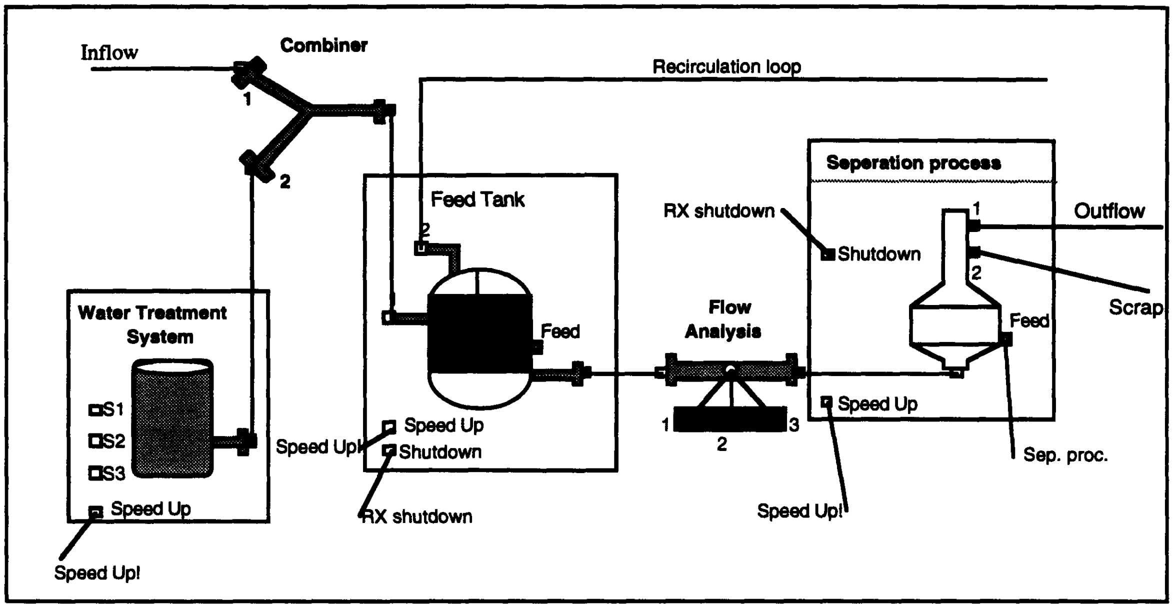

Figure 2.2.4: Basic model layout of one of stage 4's subsystems.

Modeled as: A series of subsystems performing various separation processes. The separation hardware fill up and then divides the through flow in two, sending specified percentages of each component of the flow to be either disposed of or continue in the process. There are several feed tanks which fill up to specified levels and then feed forward such that their levels are kept constant using proportional control. A water treatment system adds both chelant and treated water to the refining flow. Other additive sources add other reactants to the flow.

Key Assumptions:

1. Outflow rate changes instantaneously and exactly.
2. Feed and mix tanks mix their contents perfectly and immediately.

3. Some separation processes immediately split flow correctly as soon as they fill up. Others require some amount of scrapping.

4. Flow is assumed to be continuous throughout.

Startup: The subsystems start up in succession, the next one in the series only commencing once the previous one is at steady state. The feed tanks fill up to their specified level and then feed forward. The water treatment system and additive sources, which all feed into mix tanks, are configured to begin outflow coinciding with the startup of their subsystems. The separation hardware fill up and then begin splitting the individual components of the through flow as specified.

Steady State: No change.

Shutdown: The subsystems also shutdown in consecutive order, whereby the next one only begins to shutdown when the previous one is complete. At shutdown the feed tanks continue to outflow at the same rate as just prior to shutdown until they are empty. At that time the water treatment systems and additive sources cease their outflow. The separation hardware also empties out with the same outflow as prior to the shutdown. Some of the subsystems retain significant amounts of material at shutdown, which consequently must be scrapped.

Re-Startup: Same as initial startup.

2.2.5 Stage 5: Separation

This stage consists of two subsystems, both which perform separation operations. The first contains a feed tank, which is fed by the outflow of the refining and finishing stage. The feed tank fills up to a specified residence level and then outflows into the separation hardware. This hardware separates the remaining unreacted raw material and recycles it back to the preparation feed stage to be re-used. The forward flow into the next subsystem is driven by a centrifugal pump. At this stage a water treatment system adds water to the flow, which then passes through another separation process. This completes the final refinements and passes the finished product SAN flow to the final storage tanks.

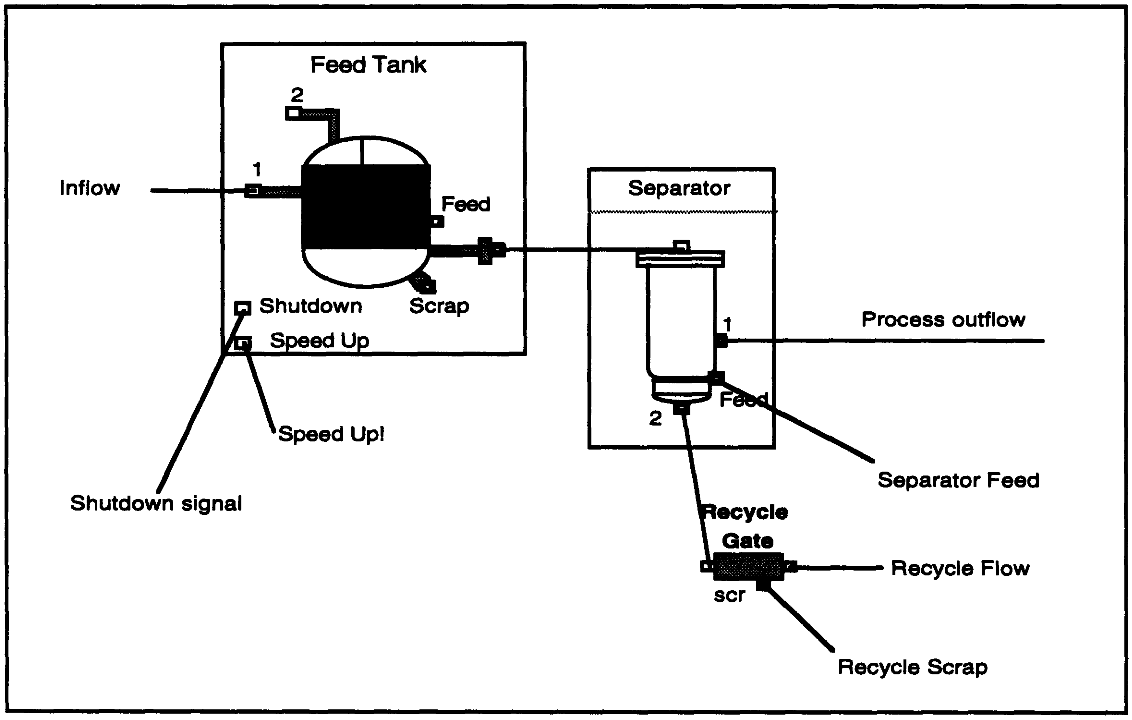

Figure 2.2.5: Basic model layout of part of stage 5.

Modeled as: A feed tank which fills up to a specified level and then feeds forward such that the level is kept constant using proportional control. The separator divides the flow in two, sending specified percentages of each component of the flow to be either recycled to the feed preparation or continue in the process. The next separation hardware again divides the flow in two, scrapping the last contaminants to a vacuum system and feeding the remaining SAN forward.

Key Assumptions:

1. Flow rate changes instantaneously and exactly.
2. Feed tank immediately and perfectly mixes its contents.
3. Separation requires no time, and the flow is split perfectly as soon as it passes through the hardware.
4. A certain amount of flow through the stage is scrapped on startup.

Startup:

The feed tank fills up from the reactor outflow to a specified level and then feeds forward into the separator hardware. The separator then begins two outflows, dividing the individual components of its contents and incoming flow as specified for steady state flow. One of the outflows is recycled while the other continues on in the process. As soon as flow passes into the next subsystem it immediately splits the individual components as specified, scrapping any contaminants remaining in the flow. A certain amount of flow through the stage is scrapped on startup.

Steady State:

No change.

Shutdown:	At shutdown the feed tank continues to outflow at the same rate as just prior to shutdown until it is empty.
Re-Startup:	Same as initial startup.

2.2.12 Stage 6: Finished Product Storage

The flow feeds into one of the three final product storage tanks, which can be emptied into either rail cars or trucks. Two of the tanks are the same size, each approximately one and a half times as large as the third.

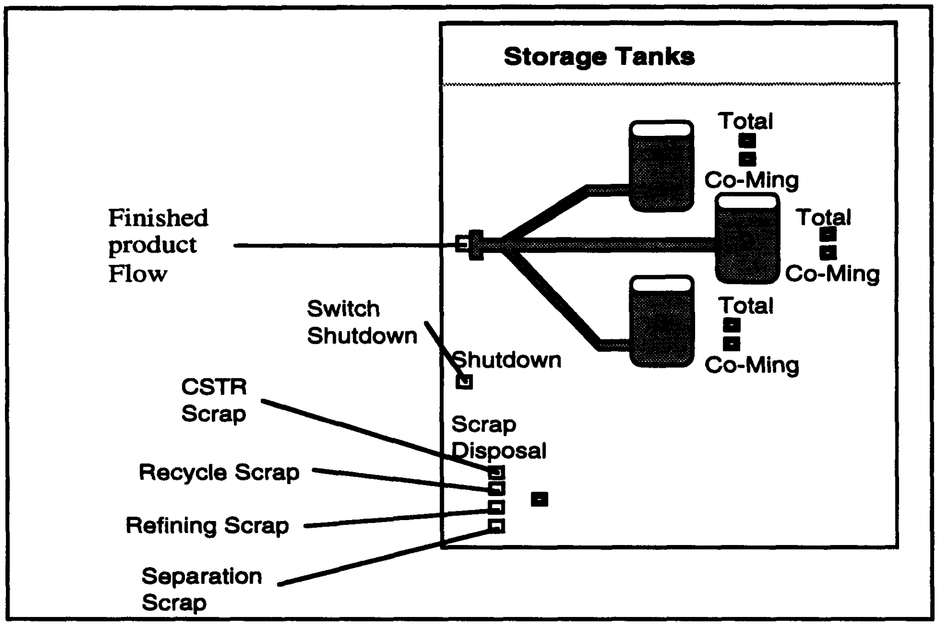

Figure 2.2.6: Basic model layout of stage 6.

Modeled as:	Three storage tanks with a schedule specifying which tank should be storing the inflow at what time.
Key Assumptions:	1. There is no co-mingling of materials in the pipes to the tanks.

Startup: Finished product is stored in the tank as specified by the tank schedule.

Steady State: Tanks fill up until they are full (exceed lot size) or are 75% full and exceed the specified co-mingling limit, at which time inflow is scrapped. Tanks are emptied as specified in an emptying schedule.

Shutdown: No change.

Re-Startup: No change.

2.3 Computational Model

The computational simulation was built using a non-linear dynamic software package called Extend. The Extend simulation closely matches the actual process. Each of the main hardware components has a corresponding block in the simulation, and many of the operating decisions that would be made prior to an actual production run need to be made for the simulation. The code corresponding to the components in the model is contained in the appendices.

The simulation is divided into seven stages, the last six corresponding to the stages in the process. Stage 0 is a general data entry area, where information about a simulation test case should be entered.

Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6

Figure 2.3.1: General Model Layout

Prior to running a test case one has to input the operational instructions for the simulation. This can be done in three ways. The easiest is to instruct the simulation to load a test case file, which has all the information already in it. Another option is to enter the required information into the simulation notebook. The last (most tedious) option is to simply go through the entire model and input the information for each stage manually.

Determining the operational instructions is basically done in the same fashion as would be done for a run of the real system. One needs to decide how much of the five types should be produced, the general order in which they should be produced, how long of a production run this would need, when changeovers should occur, etc.

Output from the simulation comes in several forms. At any time during the simulation run the user can inspect the contents of most of the hardware or the composition of its input/output flow by clicking on the corresponding block or that of the flow analysis block either preceding or following it and looking at their dialogs. There are also several I/O Plotter blocks in the model which record certain data for the total run (and graph it). This data can be inspected any time during or after a run. Finally, the simulation generates an output text file that basically keeps a chronological record of the run and the important data. The user will be prompted for a name for this file at the end of each run.

3 Test Case Standards and Scenarios

This chapter defines the simulation framework that was used in examining the system's behavior. Specifically it will discuss the type of testing that was performed and what behavioral characteristics were sought. As was mentioned in the introduction, one of the necessary first steps was to define what optimal performance for the SAN system is. This is done in section 3.1 in general terms. Section 3.2 also addresses this question, but in a more specific fashion relative to this study. In that section the main performance parameters that were used in this study are defined. Section 3.3 presents the proposed general test case scenarios that were used, and the chapter is summarized in section 3.4.

3.1 Optimal System Performance

The goal of this study was to develop operating strategy for the SAN system which would yield optimum system performance. Optimum performance for this industrial project (as practically for all) is defined as yielding maximum differential between revenue and total cost - in other words, profit. The revenue from the sale of SAN can be assumed to depend on both the market price of the final product and the amount produced. The price customers will be willing to pay depends on the quality of the final good, which for the purposes of this project, is inversely related to the degree of co-mingling. An in-depth market study would needed to determine the exact form of the relationship between the resulting revenue and the co-mingling (or quality). However, given the exclusivity and appeal of this product, it is practically certain that all the SAN that is produced will be sold.

The main components of total cost in producing SAN are the material costs, the equipment costs, the installation costs and the operating costs (including labor). Only the amount of SAN that must be scrapped is relevant with respect to this project, for the amount of material needed per pound of final product will not change. Similarly, it is only the costs of any *extra* equipment that would have to be purchased and installed that are pertinent to this project, for the equipment that has already been purchased are sunk costs and need not be considered. Finally, operating costs would be affected only if more labor would be needed to keep system producing.

In summary, for the scope of this study optimum performance of the SANCO system entailed the most production, the least co-mingling, the least scrap and the least additional equipment and operating requirements. Clearly some of these objectives were at odds with each other, and a compromise was needed in order to achieve the best overall solution.

3.2 Optimal Performance Parameters

Process efficiency measures were needed to provide a clearer means of distinguishing the performances of different operating strategies. As mentioned in the previous chapter, the main objective of a performance measure is to gauge how the project's bottom line is affected. As far as SAN production is concerned, there are two critical aspects:

- Time efficiency, that is, lbs produced / time period
- Input efficiency, that is, lbs produced / raw material used

To be true efficiency measures, "ideal" or 100% efficiency datum's were needed to compare against . For the first one, the steady state production rate was used as the standard. However, for the second one it was difficult to determine exactly what the ideal amount of raw materials per pounds of produced SAN is. A more logical approach was to consider the $ value of the scrap, for that was easier to keep track of. Thus, for these reasons, two performance efficiencies measures, the production rate efficiency (μ_r) and the raw material efficiency (μ_m), were defined as follows:

$$\mu_r = \frac{\text{production rate from beginning to end of run}}{\text{steady state production rate}} \times 100\ \%$$

$$\mu_m = \frac{\text{\$ value of SAN produced}}{\text{\$ SAN + \$ scrapped raw material}} \times 100\ \%$$

Production rate efficiency is very similar to process reliability as defined by SANCO; the only difference is that it does not consider unscheduled downtime. These two measures, which will provide a means of performance comparison, were automatically calculated by the computational model and incorporated into each test case simulation report.

A measure of the quality of produced SAN was also important. As mentioned previously, co-mingling served as the quality measure for the purposes of this project. Finally, capital costs would not have varied significantly unless the developed strategy called for radical changes to the system. These were considered on a case by case basis.

3.3 Proposed Test Case Scenarios

There exists a proposed production schedule for the SAN system. It is based on the production of five types of SAN: A, B, C, D and E. 40% of the production cycle is dedicated to type A, 30% to type B and 10% each to types C, D and E. For the computational model it was logical for the test cases to be very similar to the proposed production schedule.

The SAN system has 3 final storage tanks, 2 that can hold 315K lbs of SAN and 1 that can hold 210K[1] lbs. So as to include somewhat of a safety margin, production lot targets were either 300K lbs or 200K lbs.

To minimize co-mingling it was logical to dedicate the two larger tanks to two of the SAN types. Thus, each of those two tanks were dedicated to one of the two larger components of the production cycle, types A and B. Furthermore, as it did not make sense to produce fractions of maximum lot sizes, types A and B were assumed to require equal amounts of production, approximately 35% of the total cycle. The other three types should make up approximately 10% each. This was satisfied with the following test case scenario shown in Table 3.1.

Lot #	Final Tank #	SAN Type	Lot Size [lbs]
1	1	A	300,000
2	3	C	200,000
3	2	B	300,000
4	3	D	200,000
5	1	A	300,000
6	3	E	200,000
7	2	B	300,000

Table 3.1: Production run cycle based on proposed schedule.

The total cycle entails 1,800K lbs of production. In total, 600K lbs of both A and B will be produced, which is 34% of the total production for each. 200K lbs of C, D and E will be produced, which is 11% of the

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[1] K refers to kilo as in 1000.

total production for each. The production of the larger lots are alternated so as to allow sufficient time to empty the larger tanks.

It should be noted that simulation of a run of this size takes a significant amount of real time - over an hour. Furthermore, often slight adjustments must be made and the simulation re-run depending on the setup. Consequently, it is very time consuming to run even one full test case as proposed above. Therefore, the initial test cases, which were repetitively used to determine general system behavior, were abbreviated versions of 5 lots of either 200K lbs or 300K lbs (one lot for each of the 5 types of SAN). However, sample full version test cases were used throughout to verify results.

3.4 Summary

The goal of this study was to determine operating strategy for the SANCO system which would yield optimum system performance, where optimum is defined as maximum profit. In the context of this project optimum performance of the SAN system entailed the most production, the least co-mingling, the least scrap and the least additional equipment and operating requirements.

Process efficiency measures were used to provide a clearer means of distinguishing between the performances of different operating strategies. Accordingly, two performance efficiencies measures were defined. The production rate efficiency (μ_r) gauges how time efficient production has been, while the raw material efficiency (μ_m) gauges how efficient production has been with respect to input raw materials. A measure of the quality of produced SAN was also important; co-mingling served as this measure for the purposes of this project. Finally, capital costs, which would not have varied significantly unless the developed strategy called for radical changes to the system, were considered on a case by case basis.

A production run test case scenario was developed based on an existing proposed production schedule for the SANCO system. It entailed producing 7 lots of both 200K and 300K lbs, whereby 600K lbs of two types are produced and 200K lbs of each of the remaining three types are produced. It is very time consuming to simulate full test cases as proposed above. Therefore, initial test cases, abbreviated versions of 5 lots of either 200K lbs or 300K lbs (one lot for each of the 5 types of SAN), were repetitively used to determine general characteristics of the system behavior. However, sample full version test cases were used throughout.

4 Results and Discussion

The first section of this chapter details the execution of the two types of changeovers, that is, both the dry[1] shutdown/startup and continuous changeovers. Sections 4.2 and 4.3 present and discuss the initial set of test cases that were simulated and the corresponding results. Section 4.4 and 4.5 then go on to present and discuss the optimized test cases (which are based on the learning's of the initial test cases) and their respective results. Section 4.6 contains a final analysis of all the results, and 4.7 summarizes the chapter.

4.1 Plain Changeovers

This section presents the details of the plain dry startup and shutdown as well as the plain continuous changeovers, focusing on the amount of time spent in each of the stages. Basically it presents in chronological order the stages that the process will go through during a startup and changeover for both types of changeovers.

4.1.1 Dry Startup & Shutdown

This is a typical run of 200K lbs lots using a dry startup and shutdown changeover.

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[1] A dry changeover is the simplest version of that type of changeover.

```
Lot size                     =    200,000 lbs
Co-mingling limit            =    1 %
Recycling                    =    On

Runtime Statistics:
                                  Time:          Total time for stage:

Raw Mat'l Flow begins             0                  0
Feed Prep begins                  0                  43
Reaction Train begins             43                 19
Refining begins                   62                 20
Separation begins                 82                 18
Final Storage begins              100
-------------
Steady State Production           100                154
-------------
Shutdown begins                   165
Feed Prep flow ends               210                45
Reaction Train flow ends          218                8
Refining flow ends                238                20
Separation flow ends              253                15
Final storage flow ends           254                1
--------------
Next lot begins                   254
==============
Total time for startup            =     100
Total time for shutdown           =     89
Total production time             =     154
Total lbs SAN produced            =     200000
```

Figure 4.1: A 200K lbs lot with a plain startup/shutdown changeover.

4.1.2 Continuous Changeover

The following Figure 4.2 details the execution of the startup and purely continuous changeover from one type SAN to another for lots of 200K lbs. Again the focus is on the amount of time spent in each stage.

```
Lot size                    =    200,000 lbs
Co-mingling limit           =    1 %
Recycling                   =    Off


Runtime Statistics:
                                 Time:          Total time for stage:
Initial   Startup:

Raw Mat'l Flow begins            0                   0
Feed Prep begins                 0                   43
Reaction Train begins            43                  19
Refining begins                  62                  20
Separation begins                82                  18
Final Storage begins             100
------------
Steady State Production          100                 154
------------
Changeover begins                207
(Raw mat'l changes)
1st Lot complete at              254
(scrapping begins)
Scrapping ends                   262

2nd Lot storage begins           262
===========

Time for initial startup         =      100
Total changeover time            =      255
Total production time            =      154
Total lbs 1st Lot                =      200000
Co-mingling of 1st lot           =      0.68 %
Total lbs scrapping              =      344000
```

Figure 4.2: A plain continuous changeover 200K lbs lot.

A strategy that was adopted for the continuous changeovers was to keep most of the permitted co-mingling to the end of each lot. The simulation test cases were planned so as to allow only up to 10% of the permitted co-mingling at the beginning of a lot. This was to ensure that if for some reason the system had to be shutdown unexpectedly, then unless less than 10 % of the lot had been produced, the product already in the storage tanks did not need to be scrapped (otherwise the co-mingling of the stored finished product might have been above the limit).

4.2 Base Test Cases

4.2.1 Shutdown/Startup Changeovers

For a shutdown/startup changeover strategy the most obvious test case is the one detailed in 4.1.1, that is, a plain dry shutdown and then startup (see Figure 4.3a below). The constraining factor on the flow rate is the reaction train, for the flow rate must allow the necessary residence times in each of the CSTRs to ensure the reaction goes to completion. However, largely due to the initial overdesign of the system, there is nothing restricting the flow rate (within the capacities of the pumps) subsequent to the reaction train. Thus, this leads to an improved shutdown/startup changeover: as soon as the reaction train has run out during shutdown, the following refining stages should be sped up, consequently decreasing the total time needed for both shutdowns and changeovers. Examination of the existing equipment specifications suggests a factor of X4 speedup. Utilizing this strategy, which will be referred to as post-reaction speedup, yields the production profile shown in Figure 4.3b.

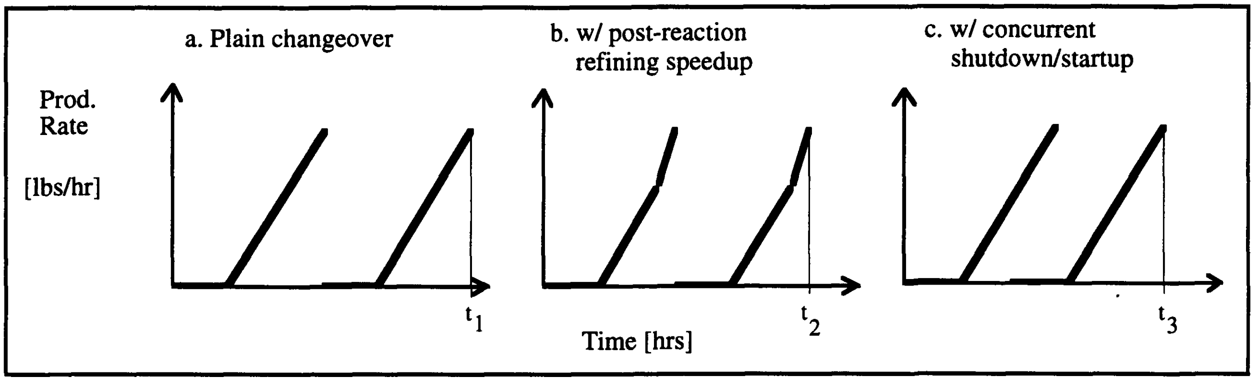

Figure 4.3: Base case startup / shutdown changeovers.

Figure 4.3a clearly illustrates the inefficiency of beginning the startup of the next lot only once the previous one has completely shutdown, for then each changeover entails a long period of non-production while the startup occurs. Overlapping the startup with the shutdown would clearly be beneficial. Now, the feed preparation priming could not be started until it has completely run out and raw material is not needed for the reaction train. Thus startup would have to wait until at least the third CSTR has run out, which requires around 46 hours. Allowing some margin for error, one could begin startup about 50 hours after shutdown is initiated. This option, which will be referred to as the concurrent shutdown/startup changeover, is illustrated in figure 4.3c.

Thus, the dry shutdown/startup along with the various combinations of post-reaction refining and concurrent shutdown/startup constitute the base cases for this type of changeover. As can be seen from Table 4.4, there are four test case combinations with 5 (different type) lots of 200,000 lbs. Then there are the same four combinations with 5 (different type) lots of 300,000 lbs. Finally, there is a test case using both concurrent shutdown/startup and post-reaction refining with the run of 7 lots of both 200,000 and 300,000 lbs as specified in section 3.3.[2] Thus, these nine cases are the base cases for the shutdown/startup changeover type.

Case #	# Lots	Lot Sizes [lbs]	Post-refining	Concurrent Shdn / Stup	Co-mingling [%]
1	5	200K	No	No	1
2	5	200K	Yes	No	1
3	5	200K	No	Yes	1
4	5	200K	Yes	Yes	1
5	5	300K	No	No	1
6	5	300K	Yes	No	1
7	5	300K	No	Yes	1
8	5	300K	Yes	Yes	1
9	7	200K, 300K	Yes	Yes	1

Table 4.4: Shutdown/Startup Changeover Base Cases

---

[2] Only the best combination was used with this run, for simulating it took an inordinate amount of time.

4.2.2 Continuous Changeovers

For the continuous changeovers there are fewer options to vary. It is inherent to this type of changeover that it occurs during steady state operation. The main parameter that can be varied is the permitted co-mingling. The current SANCO co-mingling standard is 1%. However, it is of interest to SANCO whether increasing the co-mingling might significantly ease changeovers.[3] Thus, as can be seen in Table 4.5, there are five test cases utilizing continuous changeovers with 1, 2, 4, 5, and 8% permitted co-mingling, for 5 (different type) lots of 200,000 lbs. Similarly, there are five test cases utilizing continuous changeovers with these co-mingling limits for 5 (different type) lots of 300,000 lbs, and five test cases for the seven lot runs with mixed 200,000 and 300,000 lbs lots.

Case #	# Lots	Lot Sizes [lbs]	Co-mingling [%]
1	5	200K	1
2	5	200K	2
3	5	200K	4
4	5	200K	5
5	5	200K	8
6	5	300K	1
7	5	300K	2
8	5	300K	4
9	5	300K	5
10	5	300K	8
11	7	200K, 300K	1
12	7	200K, 300K	2
13	7	200K, 300K	4
14	7	200K, 300K	5
15	7	200K, 300K	8

Table 4.5: Continuous Changeover Base Cases

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[3] If so, this might serve as motivation to initiate a detailed study on the effects of co-mingling on the final product quality.

4.3 Base Case Results

This section presents and discusses the results of the base test cases. For the purpose of analysis, most of the data is graphically presented; the numerical data can be found in appendix 1 (section 6.1).

4.3.1 Shutdown/Startup Changeovers

Figure 4.6 below displays the results of the nine shutdown/startup changeover base cases. The raw material efficiency is overall very high, ranging between 90 and 92 %. The test cases with the 300K lbs lots (#'s 5-8) have higher raw material efficiencies than the 200K lbs lot cases, for although more SAN is produced the amount of scrap is basically the same (thus the value of the scrap is less significant relative to the value of the SAN produced). This is because (a) scrapping only occurs at each changeover or shutdown, and (b) is basically a constant amount no matter what size the lot is. Therefore, as these test cases all have five lots the amount of scrap is the same.

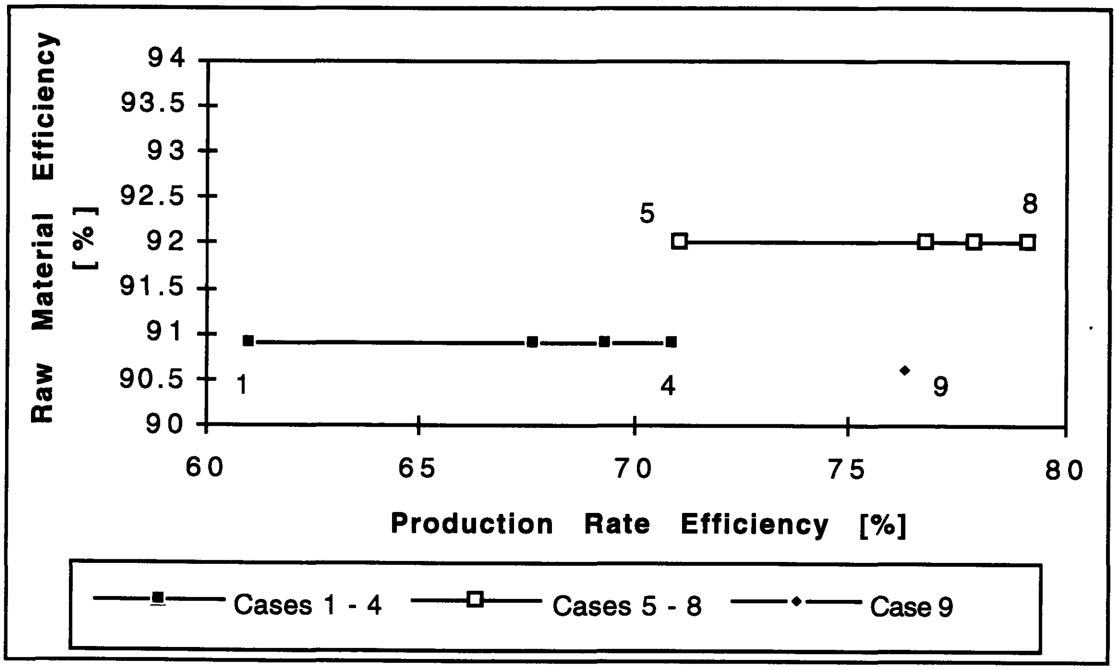

Figure 4.6: Shutdown/Startup Base Test Case Results

Case #9 achieves a slightly lower raw material efficiency. This is because there are seven changeovers/ shutdowns. Thus even though more SAN is produced, the value of the scrap is higher relative to the amount of produced SAN.

The production rate efficiencies for cases 1 through 4 vary significantly from case to case. Adding the post-reaction refining speedup increases production rate efficiency by about 6.5%, for although the same amount of SAN has been produced, the run took 125 hr's less due to faster changeovers. Similarly, making the changeovers concurrent increased the production rate efficiency by about 8.5%, for the run took 154 hr's less. When both of these changeover options are used, production rate efficiency only increases by about 10% (instead of a combined 15%). This is because the concurrent option dominates the two, and the post-reaction refining speedup is only significant for the last shutdown. This is illustrated in Figure 4.7 below.

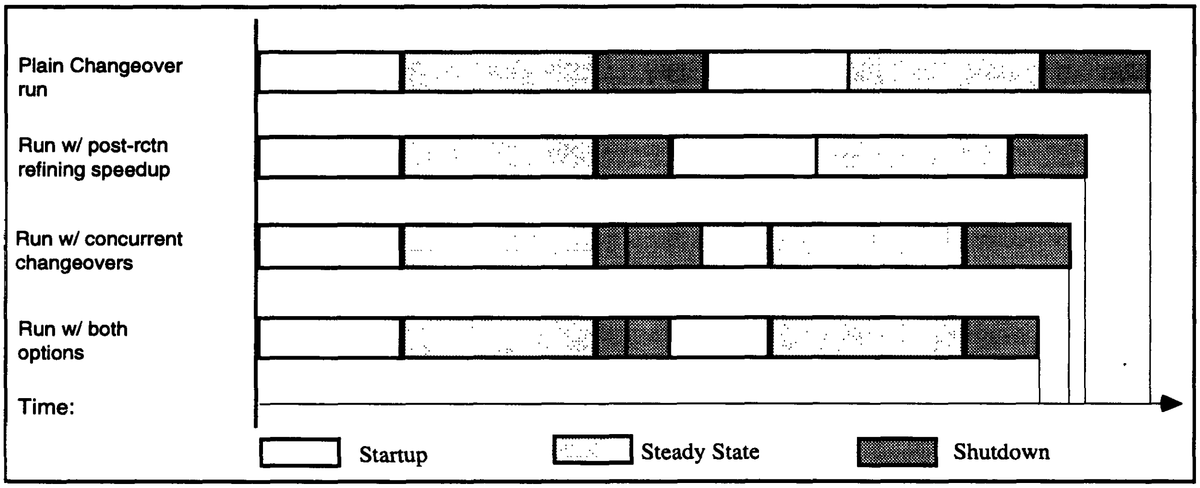

Figure 4.7: A breakdown of the components of the different shutdown/startup changeovers.

As can be seen in the figure above, the top run utilizing a normal shutdown/startup changeover took the longest. Adding the post-reaction speedup decreased the shutdown times, thus affecting the overall run time at both the changeover and at the last shutdown. Although using a concurrent shutdown/startup strategy only shortened the changeover time, it was significant enough to make the total run time less than that of post-reaction speedup run. Now, the last run which combines both options is only slightly better than that of the concurrent shutdown/startup run, for even though every shutdown is shorter due to the post-reaction speedup, individual changeover times are not affected because the startup begins the same amount of time after the beginning of the previous shutdown. Thus, it is only on the last shutdown that post-reaction speedup yields any gains.

Considering cases 5 - 8, one can see that the 300K lbs lot runs behaved very similarly to the 200K lbs lot runs, with basically the same production rate performance improvements resulting from the different options. By increasing the lots from 200K to 300K lbs the production rate efficiencies increased overall (that is, cases 5 - 8 compared to 1 - 4) by approximately 9.5%. This is because with the bigger lots the downtime due to changeovers is less significant relative to the total amount of steady state production, for the steady state production time increases while downtime stays the same.

Finally, case 9 has a production rate efficiency of 76%, about 3% less than that of case 8. This is because some of its lots are 200K lbs; therefore, the negative impact of its changeovers on the efficiency is more significant than that of the run with only 300K lbs lots.

4.3.2 Continuous Changeovers

Figure 4.8 below contains the results of the 15 continuous changeover base cases (the numerical data can be found in Appendix 2, section 6.2).

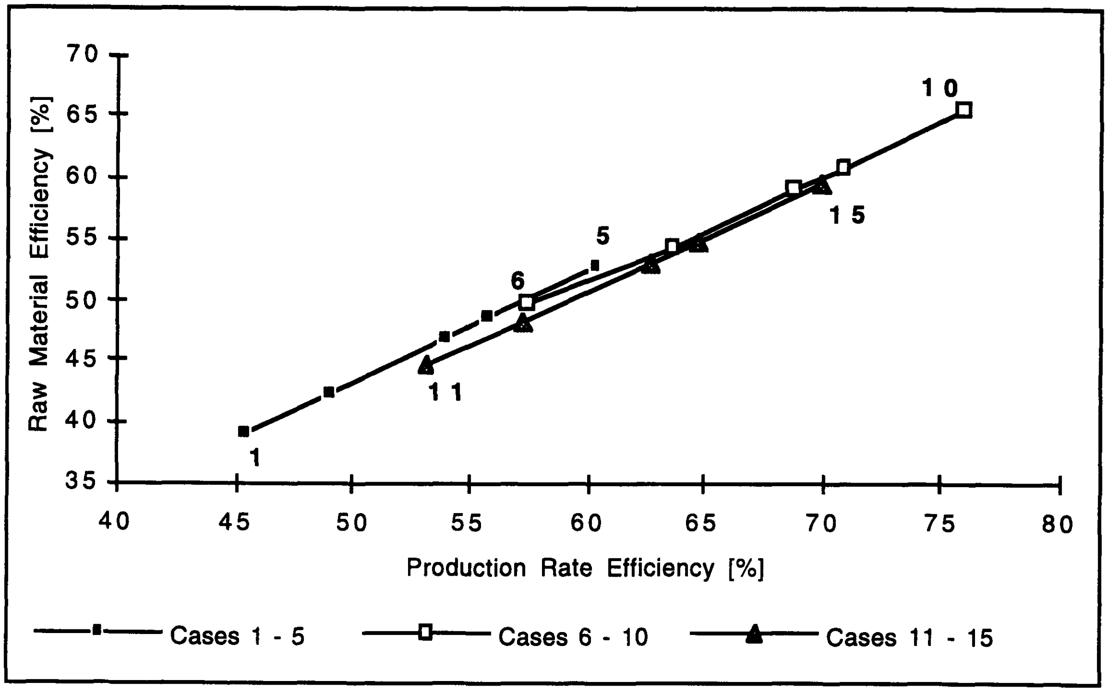

Figure 4.8: Continuous Changeover Base Test Cases.

Raw material efficiencies range between 40% and 65%, while production rate efficiencies range from 45% to about 75%. All three test case series clearly exhibit a linear relationship, with very similar slopes. One conclusion that can be made is that both raw material and production rate efficiencies follow the same type of function of co-mingling (thus the linearity as co-mingling is varied). To determine more about the actual function the two efficiencies were graphed against co-mingling, as is shown in the following Figures 4.9 and 4.10.

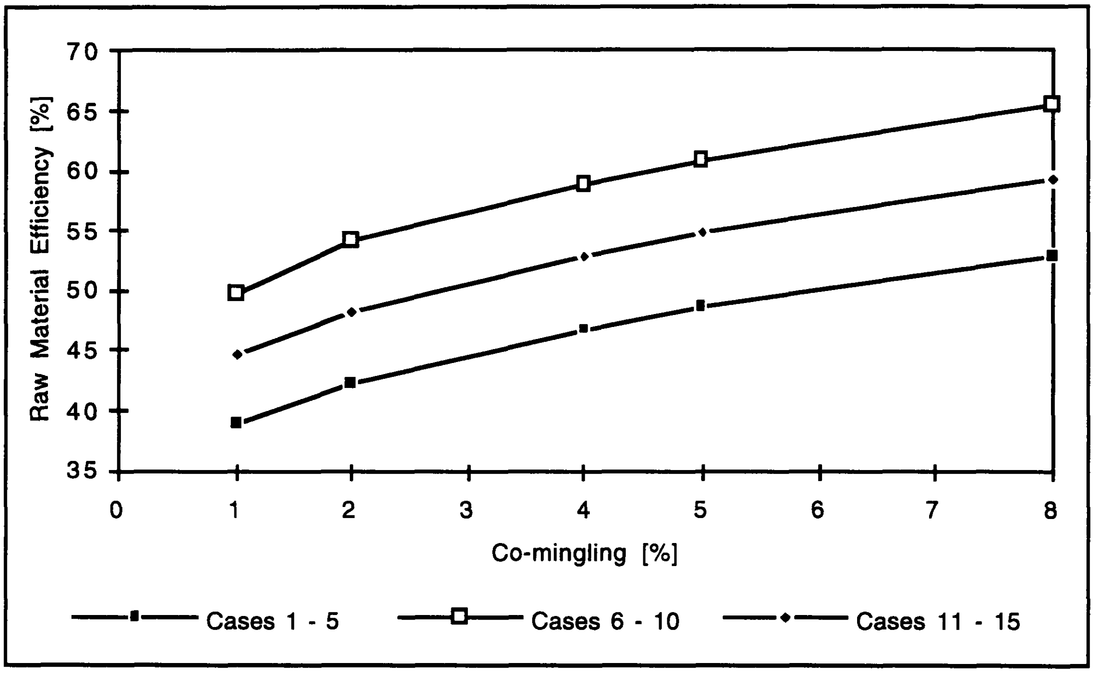

Figure 4.9: Raw material efficiencies for continuous base test cases.

The above figure clearly indicates that all three test case series exhibit the same relationship of raw material efficiency with co-mingling. This relationship exhibits diminishing returns, and unfortunately is already quite flat at co-mingling limits of greater than 1% (at 1%, raw material efficiencies range between 40 and 50%, yet only increase another 14% for a 8% co-mingling). This would tend to discourage any proposal that there is a great need to revise the 1% SANCO co-mingling limit as it currently stands.

The raw material efficiencies of the 300K lbs lots test cases (6 - 10) are around 12% higher than those of the 200K lbs lots (1 - 5). This is because the former set of test cases spend a relatively higher proportion of their run times at steady state production than the latter cases, thus the scrapping during changeovers is more significant for the latter. The raw material efficiencies for test cases 11 - 15 lie centrally in between those of the other two series, which is logical for they contain lots of both 200K and 300K lbs.

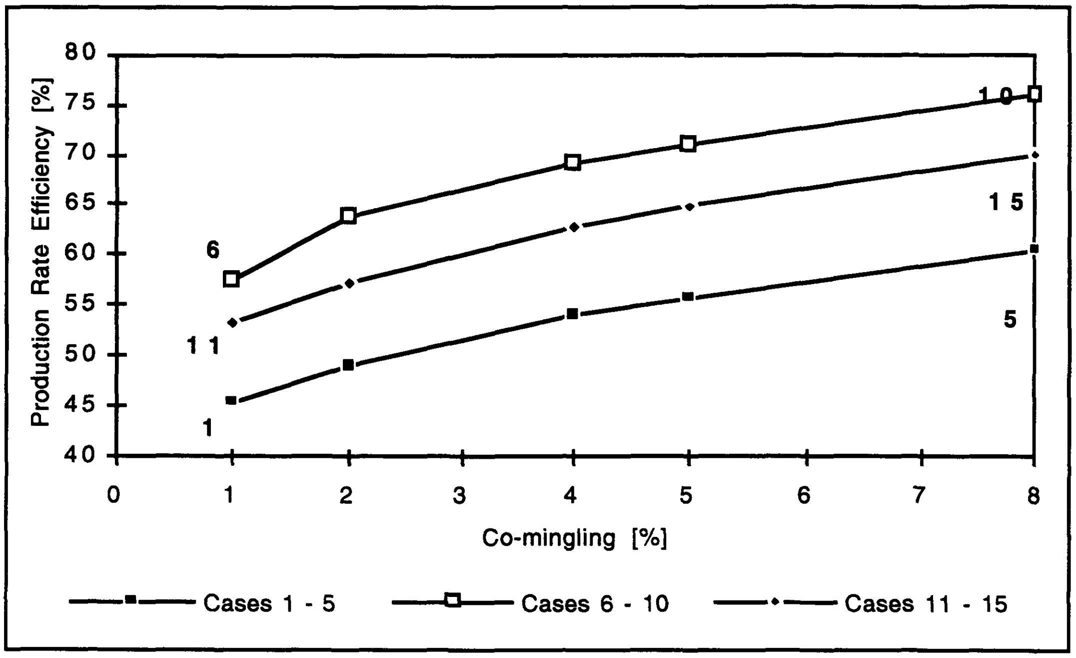

Figure 4.10: Production rate efficiencies for continuous base test cases.

From the above figure it can be seen that all three series of test cases exhibit a very similar relationship of production rate efficiencies with co-mingling limits. As was the case with raw material efficiencies, this relationship also exhibits diminishing returns. At 1% co-mingling, the production rate efficiencies range between 45 and 57%. Increasing co-mingling to 8% increase these efficiencies by about 17%. Once again, as compared to 8-fold increase in co-mingling the relative increase in efficiency is low, and thus would tend to discourage the need to revise the 1% co-mingling limit as it currently stands.

The production rate efficiencies of the 300K lbs lots test cases (6 - 10) are around 14% higher than those of the 200K lbs lots (1 - 5). This is because the former set of test cases spend a relatively higher proportion of their run times at steady state production than the latter cases, for the time needed for changeovers is less significant for the former. The production rate efficiencies for test cases 11 - 15 again lie in between those of the other two series, which is logical for they contain lots of both 200K and 300K lbs.

4.4 Optimized Test Cases

To really put the results in perspective, it is useful to step back and look at all the data together on the full 0 - 100% scale axes. From Figure 4.11 below, it is obvious that the shutdown/startup changeover strategy significantly outperforms the continuous changeover strategy. None of the continuous test cases even reach 70% raw material efficiency, while the shutdown/startup cases are all above 90% raw material efficiency. Similarly, the best production rate efficiency of any of the continuous test cases is 76% - and that is case 10, which, with 8% co-mingling, is not a realistic production option. However, the shutdown/startup case 9, which is most similar to the proposed production schedule, achieves more than 76% production rate efficiency.

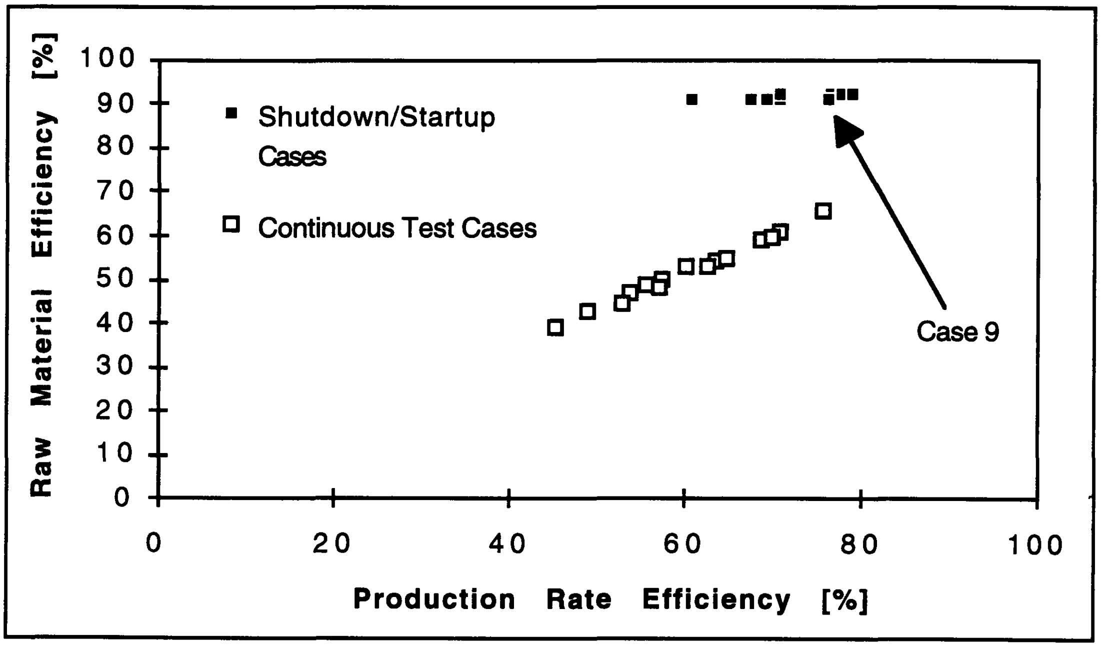

Figure 4.11: Results from all base test cases.

In fact, one does not need to compare the continuous test case results with those of the shutdown/startup strategy to basically rule out the continuous strategy, for they are unacceptable on their own. A *best case* production rate efficiency of around 70% and a *best case* raw material efficiency of 60% are not high enough to justify production (current SANCO process reliability standard is a minimum of 85%). Unless the strategy and or possibly the production process can be modified to radically improve both these efficiencies, the continuous changeover strategy does not seem to be viable.

The shutdown/startup changeover strategy is a completely different story. The projected raw material efficiencies are extremely high, perhaps even unrealistically so. In any case, from a raw material efficiency standpoint, this strategy is very good for the current system. The production rate efficiencies of these test cases very closely approach 80%, with case 9 (the most realistic test case) achieving 76%, as previously mentioned. Although this is much better than the continuous test cases, there is still clearly a need for improvement if the production process is to satisfy the SANCO 85% process standard. Thus, improving this aspect of the strategy is the next priority.

4.4.1 Shutdown/Startup Changeovers

The first step to optimizing this strategy was a careful analysis of the shutdown/startup strategy and what was limiting its performance. This involved breaking down a changeover into all its respective steps, as is shown in figure 4.12.

Due to the significant amount of time spent in shutting down and starting up the feed preparation stage (the longest of any of the stages/subsystems by far), it can be seen from Figure 4.12 that this stage is the bottleneck to shorter changeovers. This is because it is preventing the startup from overlapping the shutdown even further, for this would require shutting down and starting up the feed prep simultaneously (consider shifting the startup blocks to the left in Figure 4.12).

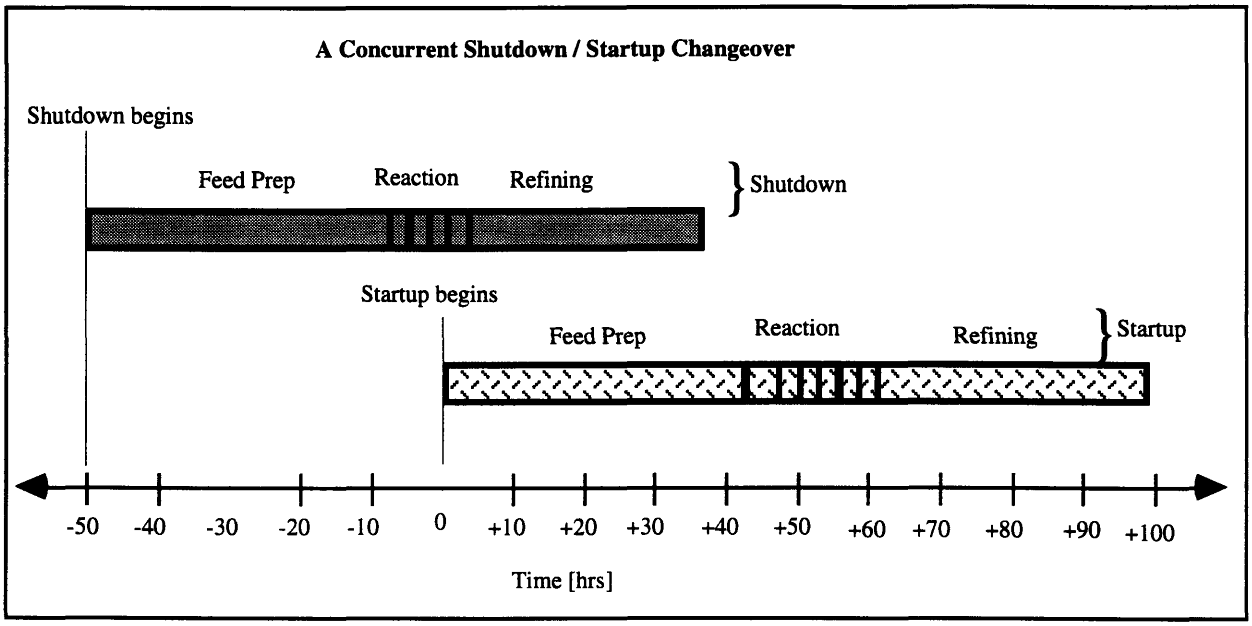

Figure 4.12: Analysis of a concurrent shutdown/startup changeover.

Thus there is a need to decrease the time needed for the feed preparation stage. One possible solution is to add a slurry tank subsystem to the system. This would basically yield two parallel feed preparation stages, so that one could be primed as the other was being drained. This would allow a complete overlap of the startup and shutdown of this stage, and it would be next largest stage (which is on the order of 10 hours) that would limit how much after the shutdown the startup would begin. However, this solution would require a significant capital investment and would need to be more carefully investigated to be justified.

Another approach is to question why does feed preparation stage require so much time? Because of the high residence time needed in one of the slurries to sufficiently mix the additive which is added in batch form. Thus, another solution might be to modify the reactant addition method. Perhaps a continuous feed (for example, using a LIW / screw feeder system) could replace the existing system. Therefore the residence time of the slurry could be much smaller, significantly reducing the time needed for the feed preparation stage.

Again, however, this would require a significant capital investment and would need to more carefully investigated to be justified.

The question that remains is what can be done if the residence level in the slurry is not changed? The flow rate into that slurry is limited by the flowrate into the reaction train (which is specified so as to ensure full reaction completion). However, a very interesting point is that there is no flow into the reaction train until that level has been reached and the feed preparation stage has been completely primed. Therefore, during startup, *the slurry could be filled at much faster flowrate* - as constrained by the existing hardware, and not the reaction! Feed preparation shutdown would still take as long, but this really does not matter; the system is producing SAN during the whole shutdown. It is only during startup that it is not producing.

This seems to be a very good solution. It would not require any serious capital investment, and yet would significantly decrease the amount of time during which SAN would not be produced during each changeover. In fact, it would also speed up the initial startup at the beginning of every run. Investigation of the existing hardware specifications show that the flow rate could be quadrupled (large amounts of over-design were included when the system was built). This speedup would decrease the total feed preparation priming time to about 10 hours, a reduction of 34 hours per startup!

This modified concurrent shutdown/startup strategy seems to have merit and should be tested. Consequently five more startup / shutdown test cases were prepared. As can be seen from the following Table 4.13, they are analogous to cases 5 - 9 (the only difference being the new startup strategy).

Case #	# Lots	Lot Sizes [lbs]	Feed Prep Speedup	Post-refining Speedup	Concurrent Shdn / Stup	Co-mingling [%]
10	5	300K	Yes	No	No	1
11	5	300K	Yes	Yes	No	1
12	5	300K	Yes	No	Yes	1
13	5	300K	Yes	Yes	Yes	1
14	7	200K, 300K	Yes	Yes	Yes	1

Table 4.13: Optimized Shutdown/Startup Changeover Test Cases

4.4.2 Continuous Changeovers

The main problem is the amount of type A in the system when the flow of type B begins. At steady state there is on the order of 120,000 lbs of materials being processed in the system. Thus a very large amount of type B must be passed through the system before satisfactory co-mingling levels are reached; this causes a large amount of scrap, and requires a significant amount of time. Basically, due to the large amount of material required to keep the system at steady state production a continuous changeover strategy is inherently inefficient.

A possible solution to consider would be to lower the residence levels in all the tanks to minimum values (as constrained by the hardware). However, even in this case, there would still be a lot of type A in the system. This would cause significant scrap and off-quality SAN. To be truly efficient it would be necessary to lower the levels all the way down till the tanks are nearly empty - which is in essence the shutdown/startup strategy. Everything considered, the continuous changeover strategy seems to be a losing proposition. Possible performance improvements seem limited, and will probably not be close to the performance of the shutdown/startup changeover.

One obvious optimization to the current continuous changeover strategy is to add raw material recycle when the system is not in changeover. The recycle can be begun as soon as system has scrapped enough to begin storage in a new tank, and turned off as soon as next type changeover flow begins. This was done for five cases analogous to cases 11 - 15, as can be seen in the following Table 4.14.

Case #	# Lots	Lot Sizes [lbs]	Ester Recycle [On / Off]	Co-mingling [%]
16	7	200K, 300K	On	1
17	7	200K, 300K	On	2
18	7	200K, 300K	On	4
19	7	200K, 300K	On	5
20	7	200K, 300K	On	8

Table 4.14: Continuous Changeover Base Cases

4.5 Optimized Test Cases' Results

4.5.1 Shutdown/Startup Changeovers

The results of the optimized shutdown/startup changeover test cases are shown below in Figure 4.15. Speeding up the filling of the feed preparation slurry increased the production rate efficiencies by more than 10%, while keeping the raw material efficiencies essentially constant (the speedup should not affect the amount of scrap). These are very promising results; case 14, which is most similar to proposed future production schedule, yielded a production rate efficiency of 88.5% and a raw material efficiency of 91%. If they are truly achievable such efficiencies would be very good for the startup of the SANCO system.

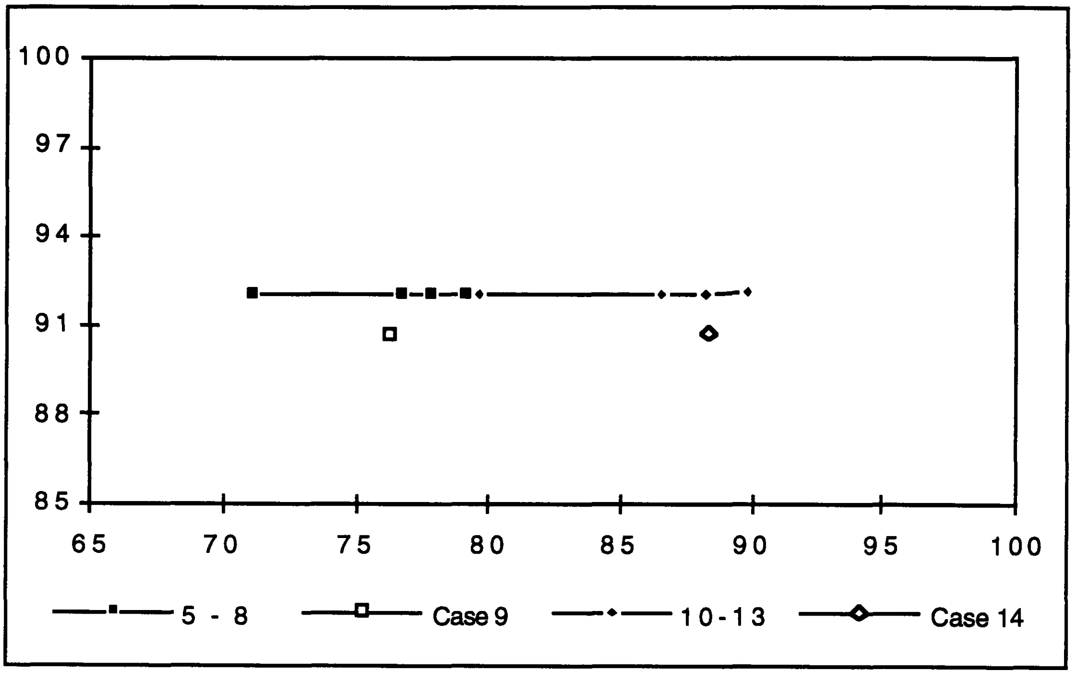

Figure 4.15: Results of optimized shutdown/startup test cases.

4.5.2 Continuous Changeovers

As can be seen below in Figure 4.16, adding raw material recycle to the continuous changeover test cases only affected the achieved raw material efficiencies. This is as expected, for it should not change the amount of SAN produced nor the time needed. However, it does definitely decrease the amount of scrap, and thus consequently increases the raw material efficiencies by about 5.5%. Although this is a decent improvement, both efficiencies are still far from any satisfactory level.

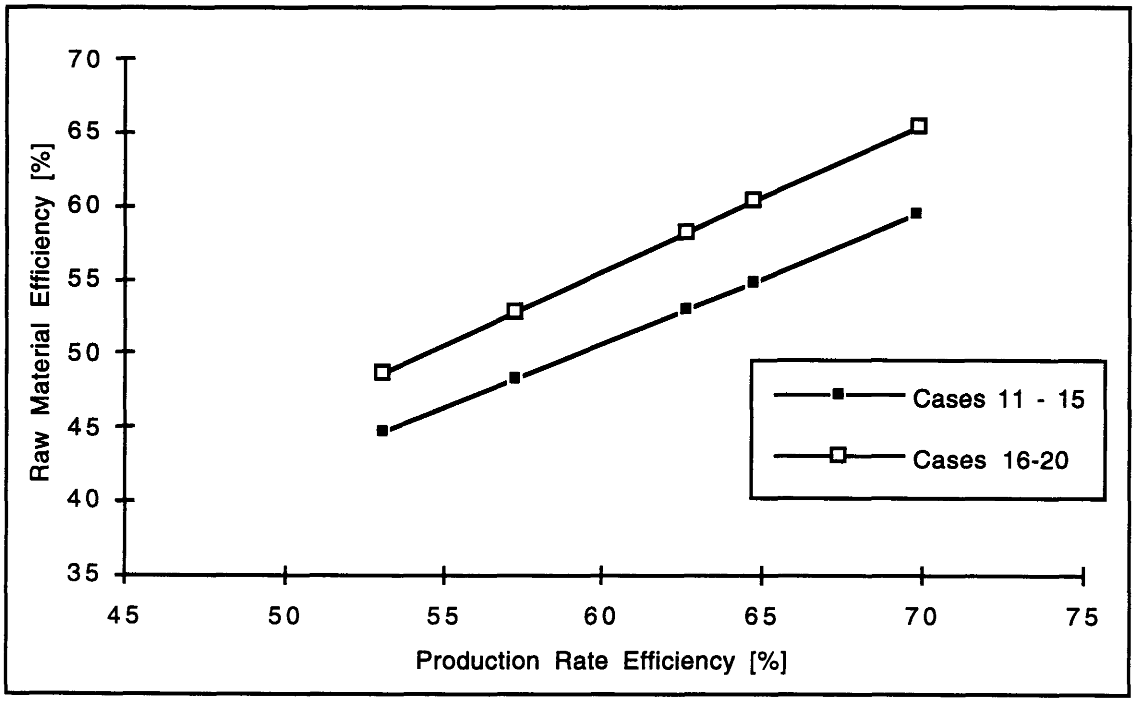

Figure 4.16: Results of optimized continuous changeover test cases.

4.6 Analysis

This section contains an analysis of the optimized concurrent shutdown/startup strategy with the current system, with the goal of determining what future improvements might be possible.

4.6.1 Raw Material Efficiency

The raw material efficiencies seem quite high (90+ %). However, perhaps this can be improved with a more careful examination of the scrap and where it is generated. The scrap generated during a run using the concurrent shutdown / startup changeovers can be categorized into four main stages.

- **Separation Scrap:** During each startup the first hour of flow through the separation stage is scrapped.

- **CSTR Scrap:** At shutdown the first two reactors in the reaction train stop at steady state, and their contents are scrapped.
- **Refining Scrap:** At shutdown approximately 750 lbs of material remains in the refining hardware and must be scrapped.
- **Recycle Scrap:** Once shutdown has commenced the recycle flow from the separation to the feed preparation stage is scrapped, which lasts until the separation stage has shutdown.

The relative value (in an ideal run) of these scrap sources is the recycle scrap, the CSTR scrap, the separation scrap and the refining scrap in decreasing order, whereby the recycle scrap is worth about 75% of the total scrap. Assuming that all these scraps are necessary for producing a lot using the current system, a best case raw material efficiency can be calculated (for the mixed 200K/300K 7 lot run):

$$\mu_{m,\max} = \frac{\$SAN}{\$SAN + \$SCRAP_{\min}} \approx 90.8\%$$

Thus this would confirm that the achieved 90.6% is very close to best possible. However, this assumes that the scrap is at a minimum. The refining and separation scraps are definitely minimum for they are inherent to the using the hardware (the refining will retain that scrap at shutdown and the separation requires that much flow prior to proper operation). Similarly, the CSTR scrap is probably at a minimum for the reaction dictates that the first two reactors cannot sustain continued synthesis below the steady state operating levels. Hence, this material must be scrapped at shutdown. Thus only the recycle scrap has potential for improvement; fortunately, as it has the greatest magnitude of the four it also yields the greatest opportunity for improvement.

The recycle scrap is currently produced the whole time from the beginning of shutdown until the separation stage shuts down, which is a period of over eighty hours. This is because the recycle flow returns to the feed preparation stage, which is the first stage to begin shutdown (and thus would not want any inflow). If the recycle flow could be moved forward in the process (for example, into the reaction train) then it would not have to be scrapped while the feed preparation stage was being shutdown, which would cut that scrap by about half - a significant saving. The effect on the best case raw material efficiency of such a change can be calculated.

$$\mu_{m,\max} = \frac{\$SAN}{\$SAN + \$SCRAP_{\min} - \$SCRAP_{saving}} \approx 93.9\%$$

Thus, by redirecting the recycle flow forward in the process increases the best case raw material by 3.1%. Further savings would occur if all the recycle flow could be saved. This might be accomplished by redirecting the flow into a storage tank during shutdown, and then blending it back into the process the next time that type of SAN is being produced. The best case raw material efficiency would again improve.

$$\mu_{m,\max} = \frac{\$SAN}{\$SAN + \$SCRAP_{\min} - \$SCRAP_{recycle}} \approx 97.9\%$$

This change would increase the best case raw material efficiency by a further 4% or a total of 7.1% relative to the currently achieved efficiencies.

SANCO research and development experts believe that both of the above mentioned process improvements are possible. It is unlikely that the recycle scrap will be completely eliminated in any case, but reducing it should yield significant benefits. The graph in Figure 4.17 illustrates exactly how much the raw material efficiency is depending on the number of hours the recycle flow is scrapped.

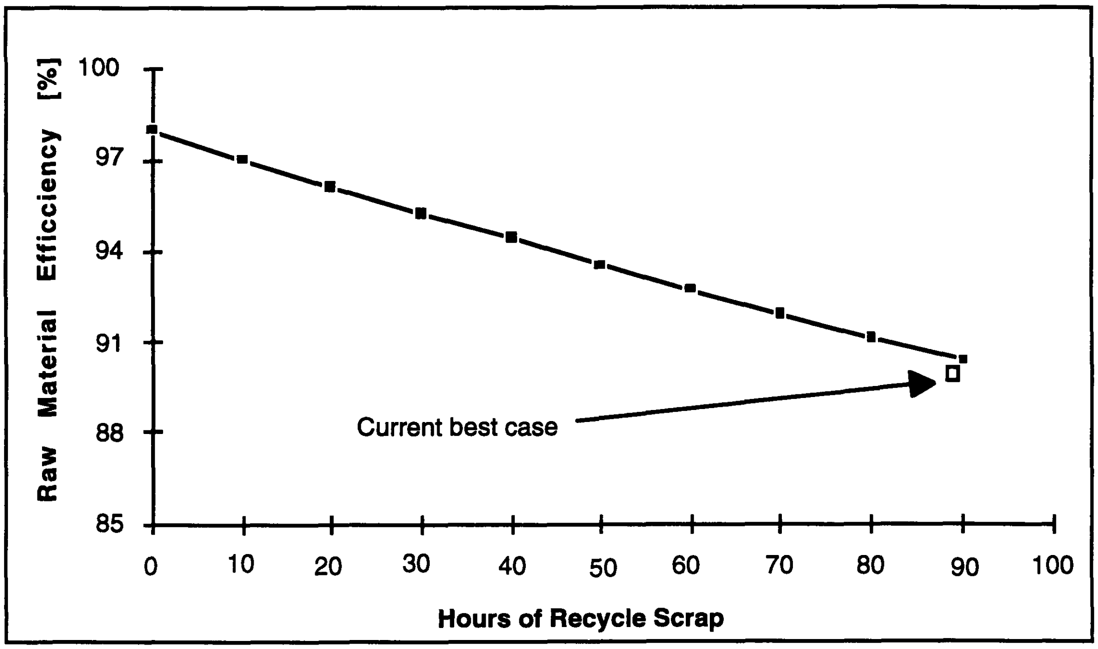

Figure 4.17: Effect of hours of recycle scrap on raw material efficiency.

From the above graph the recycle scrap - raw material efficiency relationship looks nearly linear. However, the nonlinearity would become more apparent if the hours of recycle scrap were increased even more than 90 hours. For the 0 - 90 hour range it is clear that significant raw material efficiency improvements are to be had by decreasing the hours of recycle scrap. The other point that should be noted is that the predicted simulation best case efficiency is very near the 'ideal'. Thus, for the given system without any of the discussed changes this efficiency is near optimal.

4.6.2 Production Rate Efficiency

Figure 4.18 below illustrates the sequence of events that make up the concurrent changeover.

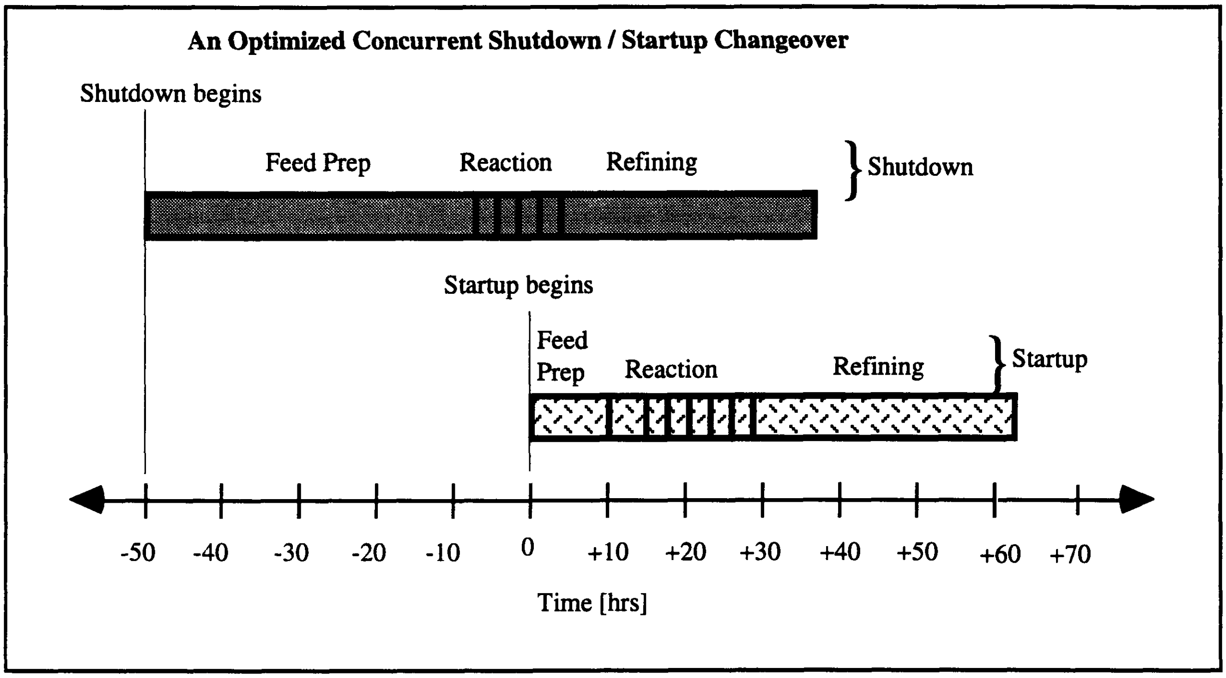

Figure 4.18: Analysis of optimized concurrent shutdown/startup changeovers.

Even with the optimized strategy there is about 24 hours of non-production between the ends of the shutdown and startup. It is still the feed preparation stage that is limiting how early the startup can begin. One suggestion to overcome this was to add a parallel feed preparation system to the existing system, thus basically allowing the free system to be primed while the one in use was being drained. This would involve high capital investment, for a completely new slurry subsystem would have to be added along with all the additional hardware used by this stage.

'Parallelizing' the feed preparation stage would seem to save the ten hours needed above to prime this stage. However, if one looks further down the process this would not be the case. One of the separation feed tanks in stage 5 currently requires a residence level of around 20 hours. Therefore, startup cannot end less than 20 hours after the previous shutdown has ended. In fact, as the refining subsystems prior to the separation stage also would need some time gap between shutdown ending and startup ending, *the 24 hours of* *non-production that exist currently are probably very close to a minimum.*

One could investigate modifications to the separation stage (either to the hardware or to the operating levels). The high residence level is needed so that flow through the system is continuous while the flow is interrupted in the previous stage. The excess hours serve as a safety margin. Thus modifying that would be difficult. Now the other option would be to add a parallel separation stage. However, this would require adding a significant amounts of hardware that would cost a large amount and require many changes to the production facility. The added capital investment and complexity of operation would be extremely difficult to justify.

Another suggestion to speed up the feed preparation stage was to convert the additive addition to some type of continuous system. This would also require some capital investment, though probably less than adding a parallel feed preparation subsystem tank. However, the performance improvements due to this modification would also be limited by the separation stage. And again, modifying the evaporation stage to improve on the 24 hours of non-production would be difficult to justify.

4.7 Summary

To summarize it is again useful to step back and step back and look at the results on the full 0 - 100% scale axes. It is clear from Figure 4.18 below that the shutdown/startup changeover strategy is the one to use. The continuous changeover strategy test cases achieve unacceptable efficiencies, with the *best case* yielding a 76% production rate efficiency and a 65% raw material efficiency. Utilizing the shutdown/startup strategy on the other hand, case 14 which most closely resembles the proposed future production schedule achieves 88.5% production rate efficiency and a 91% raw material efficiency. These are very promising efficiencies.

The analysis of this strategy on the current system revealed that without very high capital investments to completely rebuild a 'parallel' system, the current performance is near optimal. Thus, the current results are definitely very good indications of the basic strategy that should be employed

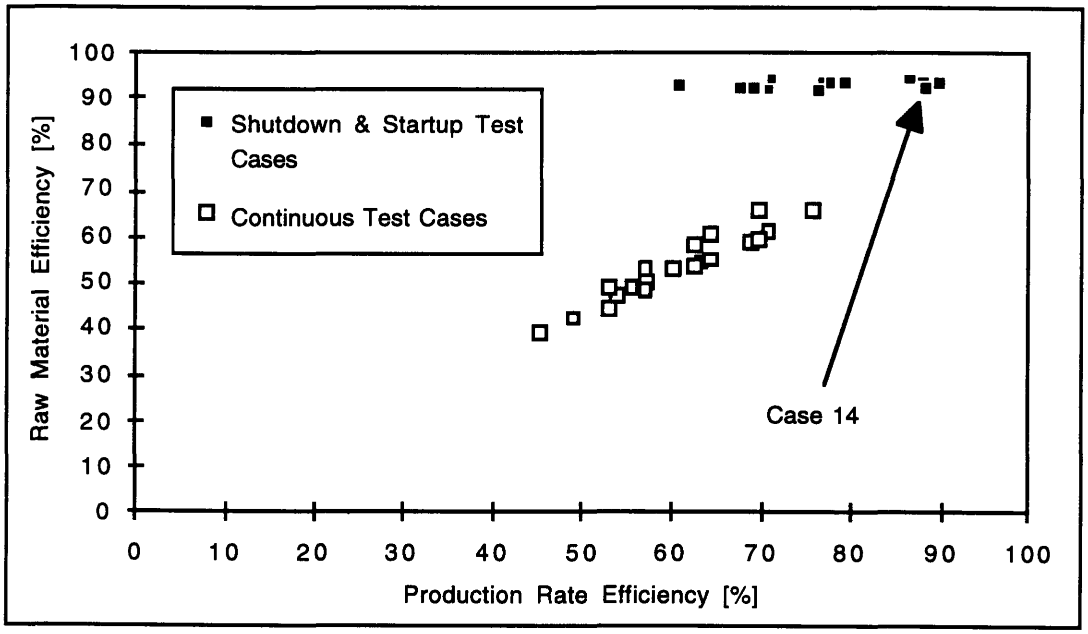

Figure 4.18: Results of all test cases.

One should remember this model makes assumptions and that these are really best case results. Thus, although these results will serve well as a foundation on which to begin test market production, as in any manufacturing process, there is a need for a continual state of ongoing improvement.

5 Conclusions and Recommendations

The primary conclusion of this study is that a shutdown/startup changeover strategy should be used for the SANCO system. The shutdown/startup changeovers should be concurrent, whereby startup begins before the shutdown is complete. Furthermore, priming the feed preparation stage during startup should be done at four times the steady state flow rate, while the post-reaction refining stages should be shut down at four times the steady state flow rate. This strategy is projected to yield very high raw material efficiencies (between 90% and 92%), as well as high production rate efficiencies (between 88.5% and 90%).

It was shown that the concurrent shutdown/startup actually eclipses the effect of the post-reaction refining stages speedup (that is, the speedup would have no effect of the system performance except for the last shutdown of the run). However, it is recommended that the speedup strategy should be employed for every changeover throughout the run. This is to ensure that even if a shutdown run down is proceeding slower than it should, the following startup will not "catch up" to the shutdown in the post-reaction stages. Basically, it buffers the shutdown from the startup, which serves as a safety margin.

With the current SANCO system the feed preparation stage is the cause of the 24 hours of non-production during every changeover. The time of non-production could be decreased by adding a parallel feed preparation stage (or at least the main components). However, to achieve an significant decrease other stages of the system (most notably the separation stage) would also have to be made parallel. Considering all the changes that would have to be made, the capital investment that would be required makes this option economically unfeasible. As far as the SANCO system is concerned, the above detailed strategy will yield the best results. In designing and building a system for scaled up production, both the options of (a) implementing parallel stages where necessary and (b) using a different additive addition system should be investigated.

One obvious conclusion of this study is that the continuous changeover strategy is unfeasible for the SANCO system. The projected raw material efficiencies ranged between 40% and 65%, while the production rate efficiencies ranged between 45% and 75%. These are unacceptable results.

With the continuous changeover strategy both performance efficiencies clearly exhibited a similar relationship with co-mingling, thus yielding a linear relationship between the two efficiencies as co-mingling was varied. Unfortunately, the efficiencies yielded diminishing improvements as co-mingling was increased; increasing the co-mingling standard to higher than 1% does not yield significant performance benefits. Thus there is no immediate need to investigate the effect of co-mingling on the final quality of the produced SAN.

Were a continuous changeover to be used, most of the permitted co-mingling should be kept for the changeover at the end of the run. This ensures that in the event of an unexpected early shutdown, the SAN that had already been produced does not need to be scrapped unless it occurs very early on. The rule used in this study was to allow maximum 10% of the total co-mingling at the beginning; therefore, if an unexpected shutdown occurred the SAN could be kept as long as it occurred after 10% of the run had been completed.

Finally, if the demands on production are close to those used to develop the proposed production schedule, the runs should closely follow the full test case scenario (7 lots with both 200K lbs and 300K lbs lots - see section 3.3). The 315K final storage tanks should be dedicated to a single type of SAN (to minimize co-mingling), and lots should be made as large as possible to maximize efficiencies. If the demands on production become less focused on two main types of SAN, it would be worthwhile investigating converting the 210K lbs final storage tank to 310K lbs.

6 Appendices

6.1 Appendix 1: Summary of data

		Shutdown & Startup Changeovers				
Case No.	Lot Types & Sizes	Recycle (On/Off)	Ref. Speedup (Yes/No)	Co-Ming. (%)	Prod Rate Effic (%)	Raw Mat. Effic (%)
1	A, B, C, D & E (1x 200)	On	No	1	60.99	90.9
2	A, B, C, D & E (1x 200)	On	Yes (X4)	1	67.63	90.9
3	A, B, C, D & E (1x 200)	On & Con	No	1	69.32	90.9
4	A, B, C, D & E (1x 200)	On & Con	Yes (X4)	1	70.86	90.9
5	A, B, C, D & E (1x 300)	On	No	1	71.07	92.01
6	A, B, C, D & E (1x 200)	On	Yes (X4)	1	76.8	92.01
7	A, B, C, D & E (1x 200)	On & Con	No	1	77.92	92.01
8	A, B, C, D & E (1x 200)	On & Con	Yes (X4)	1	79.17	92.01
9	A & B (2x 300), C,D & E (1x 200)	On & Con	Yes (X4)	1	76.29	90.62
10	A, B, C, D & E (1x 300)	On	No	1	79.65	92.04
11	A, B, C, D & E (1x 300)	On	Yes (X4)	1	86.6	92.03
12	A, B, C, D & E (1x 300)	On & Con	No	1	88.25	92.04
13	A, B, C, D & E (1x 300)	On & Con	Yes (X4)	1	89.85	92.09
14	A & B (2x 300), C,D & E (1x 200)	On & Con	Yes (X4)	1	88.4	90.7
		* Con = Concurrent shutdown / startup				
		Continuous Changeovers				
Case No.						
1	A, B, C, D & E (1x 200)	Off	No	1	45.36	38.96
2	A, B, C, D & E (1x 200)	Off	No	2	49.04	42.32
3	A, B, C, D & E (1x 200)	Off	No	4	53.96	46.89
4	A, B, C, D & E (1x 200)	Off	No	5	55.68	48.67
5	A, B, C, D & E (1x 200)	Off	No	8	60.35	52.9
6	A, B, C, D & E (1x 300)	Off	No	1	57.44	49.76
7	A, B, C, D & E (1x 300)	Off	No	2	63.6	54.21
8	A, B, C, D & E (1x 300)	Off	No	4	68.82	58.93
9	A, B, C, D & E (1x 300)	Off	No	5	70.88	60.79
10	A, B, C, D & E (1x 300)	Off	No	8	75.93	65.41
11	A & B (2x 300), C,D & E (1x 200)	Off	No	1	53.1	44.59
12	A & B (2x 300), C,D & E (1x 200)	Off	No	2	57.25	48.21
13	A & B (2x 300), C,D & E (1x 200)	Off	No	4	62.65	52.96
14	A & B (2x 300), C,D & E (1x 200)	Off	No	5	64.74	54.81
15	A & B (2x 300), C,D & E (1x 200)	Off	No	8	69.87	59.38
16	A & B (2x 300), C,D & E (1x 200)	On (1)	No	1	53.11	48.65
17	A & B (2x 300), C,D & E (1x 200)	On (1)	No	2	57.26	52.79
18	A & B (2x 300), C,D & E (1x 200)	On (1)	No	4	62.65	58.17
19	A & B (2x 300), C,D & E (1x 200)	On (1)	No	5	64.75	60.25
20	A & B (2x 300), C,D & E (1x 200)	On (1)	No	8	69.88	65.38