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A tool to evaluate quality strategies for the KODAK dope production process

by

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Abstract

A physically-based model of the Kodak dope production process has been developed as part of a more general methodology of modeling quality for complex manufacturing systems. The model predicts with accuracy certain characteristics of the process that are directly tied to the assessment of quality and is a combination of various individual operations (i.e. mixers, delays, stream splitters) that are repeated throughout the process. The model has been used to examine production scenarios, to study the role of variation in materials and process steps, and to suggest improvements in plant design and control.

We describe the physical modeling of the individual operations and the integration of these components into a single model that calculates the concentrations of the chemicals in dope over time. Quality is defined as a function of the concentrations in dope and we use the model to predict the quality of dope at each step of the process. We illustrate the importance of the model in day-to-day production control by examining questions that challenge the Kodak dope production process. We identify that the most important source of poor quality is the feed of raw materials to the process and we propose an optimal feed-forward controller to improve the quality of the system.

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Dedicated to my beloved sister Eri who may no longer be among us but reigns in our hearts, driving our souls, inspiring our thoughts.

Acknowledgments

There are several people that deserve mention for their contribution, direct or indirect, to this work. First, I want to thank my advisors Duane Boning and Stan Gershwin for trusting me and giving me the opportunity to work in such an exciting area. They deserve recognition for their drive, enthusiasm and guidance throughout this project. I have learned a lot through them and with them and I am utterly thankful for their understanding during this period.

My solid collaboration with several Kodak employees made the outcome of this work possible. First and foremost, I want to thank Peter Castro for all his energy and enthusiasm throughout the process. Kurt Carlson, Bill Gamble, Dick Grant, Ron Swanson and David Bourne were always very helpful with data and operation issues and without them very little would have been accomplished. I also want to thank Glen Pearson and Jack Richards for their genuine interest in the project and their trust in me.

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Lastly, I want to thank my family for its love, support and care. My tenure in MIT was surely the most difficult of my life, not due to the complexity of the degree but instead because of the unexpected illness and death of my younger sister. My family stood united during this period and I definitely owe and dedicate this work to Ninos', Anni's, Iro's and Eri's strength, encouragement and inspiration.

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Chapter 1 - Introduction

1.1 Purpose

The performance of complex manufacturing operations has been dramatically improved in recent years due to the development of models to estimate quantity-related parameters of these systems [2] [4]. These models use data on machine availability and process flow to predict the throughput and inventory of a process, and subsequently provide a basis to develop optimal control and scheduling strategies, such as Kanban and CONWIP. However, there are no similarly widespread models that can predict quality-related parameters in a production line. Such models could eventually be used to determine optimal scrapping, process operation and maintenance policies that address combined quality and quantity issues. Although there are several approaches to quality management, there does not exist a common modeling methodology that reduces these approaches to shop floor terms and allows manufacturing personnel to simulate and evaluate different approaches for their day-to-day quality problems. This thesis provides a specific physically-based model that can be used to examine such quality "what-ifs". The development of this specific model provides insight and experience toward a more general framework and formulation that can be utilized in estimating a system's overall quality.

Specifically, this work develops a physical model of the Kodak dope production process and uses it in order to provide answers to certain production "what-if" questions. Simulink, the dynamic simulation tool of Matlab, was chosen as the software platform because it allows the user to reconfigure a process model in a short period of time. The model predicts with accuracy characteristics of the process that are directly tied to the assessment of quality. It is a combination of various individual operation models that appear repeatedly throughout the process. It addresses the trade-off between quality and quantity, and provides the basis for the evaluation of control strategies. The development of this tool is important to production control both in the short run and the long run. In the short run, production managers at Kodak can use the tool to train operators and examine various real-time scenarios on the computer. Moreover, they can increase their understanding of the process and identify good control policies. In the long run, the development of a methodology to model quality in complex multi-step manufacturing processes can serve as the foundation for systems-oriented quality management strategies that will help more production managers in controlling their processes.

1.2 Literature review

There is considerable literature analyzing different quality strategies. Crosby, Deming and Juran [9] have proposed quality management strategies that are tied to leadership and focus on transforming the culture of an organization and the use of statistical thinking to understand how systems function. However, their approaches do not provide a comprehensive analysis that can be used at each process step to determine good policies. Frey, Otto and Taketani [3] introduce a technique for modeling manufacturing systems using block diagrams where the blocks represent linear transformations of dimensionless noise vectors to normalized quality characteristic vectors. Kurtzberg and Levanoni [7] have introduced ABC, a generic methodology to improve the quality of manufacturing by providing local process control while globally optimizing the system. Their approach uses statistical modeling rather than physically-based modeling of quality. Here, we develop a physically-based methodology to model the quality of a manufacturing system. Graeser, Marcev, Ito, Waite and Bialkowski [5] have introduced a dynamic simulation model for a non-woven sheet manufacturing facility. The model is physically-based and used as a "life-cycle" design tool as well as a basis to train operators and develop control strategies. However, there is no attempt to use this model as a basis for a general quality modeling formulation. Our approach is to include a physical description of the process steps and develop a physically-based, rather than statistically-based, set of quality rules and strategies.

1.3 Thesis outline

In Chapter 2, we present the Kodak dope production process and the underlying unit operations. We explain the rules of operating the process and define quality in the production line. Chapter 3 discusses the physical modeling of the individual operations and the integration of these components into a single process. Chapter 4 describes the validation of the model and compares the model prediction with actual process data. In an effort to illustrate the use of the model, Chapter 5 introduces several actual production control studies that were examined for the Kodak dope production process following requests of the production managers. We discuss the applicability of the model in answering some of the day-to-day production questions that manufacturing production managers typically have. Chapter 6 discusses the studies we performed in order to gain insight into the actual production and understand which parameters of the process are the most crucial for quality. The discussion of such studies includes the dependence of quality on different configurations of the system, the identification of the most important sources of poor quality as well as economic considerations regarding buffer allocation in the process. Section 6.3 identifies the most important sources of variability, the feed of raw materials to the process, which is crucial in terms of controlling the overall quality of dope. Chapter 7 proposes an optimal feed-forward controller to control the quality at each step of the process. Finally, Chapter 8 concludes this thesis by summarizing the results and significance of the developed tool as well as laying the ground for future work that can be done in this area.

Chapter 2 - The dope production process

2.1 Background

Eastman Kodak, like all manufacturing companies, strives for excellence, a continuous effort to maintain and improve the quality of its products while at the same time increasing profit margins at no significant cost to the customer. The company is best known for its photographic film, which accounts for approximately 50% of its annual sales.

A roll of film can be manufactured in many ways; nevertheless, the basic framework is the same everywhere. The first two parts involve the manufacturing of a sheet that provides the base upon which emulsion and other coatings will be added. In the first part, a base mixture is produced or purchased from outside the company. In the second part, a sheet of this material is formed. The film products we see in the stores are different due to the various coatings that are added during the production of film and the different materials and processes used in the production of film base sheets. Kodak currently produces three film bases: *ESTAR (polyethylene teraphthalate), PEN (polyethylene naphthanate) and dope (cellulose triacetate).* The production of ESTAR is completed in two phases. The first part involves mixing of various polymers and the second part, where actually the sheet is formed, involves stretching of the mixture. PEN is purchased from outside the company. It then undergoes a thermal extrusion process to produce the sheet that will eventually serve as the base. Lastly, dope is a result of a process involving mixing and filtration. It then enters Roll Coating in order to produce the sheet that will serve as the base. Schematically, the overall process of film manufacturing is summarized in Figure 1.

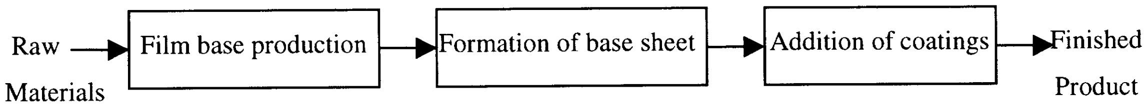

Figure 1. Film manufacturing

2.2 Overview of dope production

Dope production is essentially a mixing process. Different substances, including solid raw materials, liquid solvents, and dyes, enter a continuous maker where they are mixed together producing a very viscous liquid that resembles tapioca. The resulting mixture is stored in holding tanks where operators can add quantities of the raw materials if they determine that it is needed. The mixture then passes through filters that remove any foreign matter. Immediately after that, the mixture is stored in tanks. The mixture is then further mixed, and before entering the roll coating stage, portions of the solvents are vaporized in order to produce a more viscous material. Experienced operators monitor the dope production and intervene to change parameters of the process.

It is important that dope, the product that is being delivered to Roll Coating, is very uniform. Dope is composed of a set of chemicals that are present in the streams that enter the continuous maker in the first part of the process. The operators try to achieve targeted values for the weight fractions (or concentrations) of the chemicals in the finished dope product. Any variability in the weight fractions of the chemicals in the mixture can have a significant effect in the latter parts of film manufacturing. This can result in defects either in the form of broken sheets or unsatisfactory coatings due to variations in the thickness of the dope sheet that are in turn caused by the variability of the dope mixture. It is apparent then that the quality of the finished dope is inversely related to the variability of the fractions of the chemicals in the mixture. In other words, the more variable the weight fractions of the chemicals in the mixture, the lower quality the product has.

The variability of the finished dope is a result of the variability in the concentrations of the inputs to the process and the process conditions. The inputs can be divided in two categories, the solid materials and the liquid additives. The solid materials are *pulp* and *coarse pulp*, raw materials that are also used in paper manufacturing. In addition, a significant amount of defective dope sheet serves as an input known as RAS

(Recycled Acetate Support). The liquid inputs to the process are solvents and various dyes according to the specific dope that is being produced.

The variability in these input materials is high for two main reasons. The first reason is the variability of the raw materials that enter the process. Pulp and coarse pulp are materials in the form of wood chips that Kodak purchases from Eastman Chemicals. These materials arrive at the production site by railroad cars that can transport up to 200,000 pounds. Each campaign of delivering raw material to the dope production involves eight to nine such railroad cars. In other words, there are approximately 1,600,000 to 1,800,000 pounds of raw material delivered to the production during each campaign. Although, the raw material suppliers try to keep their shipments within the agreed specifications, there is often great variability observed between different campaigns. Hence, we can think of each campaign as a batch of raw material and claim that there is variability from one batch to another because wood chips is not a precision material. The second reason is the imprecise way of feeding material. In general, operators try to introduce a constant ratio of solid to liquid inputs to the first operation of the process. They feed the solid material from the railroad cars on weigh belts. These weigh belts operate at a constant speed in order to feed the process a constant amount of solid material over time. However, the rotational speed of the belt varies and as a result, the inflow of solids varies as well. At the same time, the liquid inflow can be measured with great precision and thus, the variability of the inflow of the solid results in variability of the concentrations of the material entering the process.

Another source of variability in the process is the formation of RAS, which is formed by cutting dope sheets that did not pass the specifications. A dope sheet can fail to meet the desired specifications due to a number of reasons. The sheet could break, for instance, due to a machine malfunctioning during roll coating. It is also possible that the sheet breaks due to thickness variations that are primarily caused by the variability of the dope mixture. Hence, by chopping and reintroducing a highly variable substance as an input to the process (RAS) one creates a loop, introducing the produced variability back in to the process that generated it.

The variations that are introduced in the process at its very first stage can propagate throughout the production. It is important that the process is operated in such a way that it will ensure a reduction of such variations.

2.3 Description of dope production

This section describes the mechanics of dope production and explains each unit operation. Since many of the operations are repeated several times throughout the process, we will omit such repetitions. We will include a representative diagram for a line of the process; this diagram represents the most general combination of unit operations that can take place during the process. There exist multiple such lines in the dope production factory that are able to interchange material with each other in emergency situations and can produce different forms of dope at the same time.

2.3.1 Unit operations

2.3.1.1 Continuous maker

The first component of the process is the continuous maker. As pointed out in the previous section, different solid and liquid substances enter the maker to be mixed with a small volume of mixture that is already present in the tank. The solid substances are either raw materials, i.e. pulp in the form of wood chips, or recycled dope from the roll coating process. The other inputs to the maker are all liquid substances such as various solvents and dyes. Depending on the type of film that is produced, different kinds of dope are used. The main difference among the various kinds of dope is the color and it is a result of the kinds of dyes that are used.

The continuous maker, pictured in Figure 2, mixes solids with liquids to produce a very viscous liquid. A large blade revolves at a high speed to mix the different substances. At the same time that the input substances enter the vessel, the output mixture exits the vessel leaving the relatively low level of mixture in the tank unchanged. Some of the mixture remains in the vessel instead of leaving because it sticks to the walls as a result of the high viscosity. However, because this portion of the mixture is very small compared to the mixture exiting at any time, it leaves the volume in the vessel essentially unaffected. No chemical reaction occurs during this mixing process because of the nature of the chemicals that are involved. In practice, although the mixing process is not ideal and solid parts still exist in the output mixture stream, the continuous maker is treated as a highly agitated vessel.

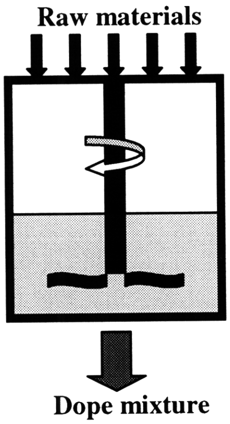

Figure 2. Continuous maker

2.3.1.2 Agitated crude tanks

After the mixture exits the continuous maker, it moves through pipelines to the next unit operation, the agitated crude tanks. The crude tanks are also highly agitated vessels where any incoming mixture gets mixed with the liquid in the tank by the means of two large propellers. As shown in Figure 3, in contrast with the continuous maker, the agitated crude tanks are horizontally oriented and the blades revolve at lower speeds than the continuous maker. However, the crude tank is a much larger tank and usually serves as a buffer for the process. At this point of the process, operators carefully monitor the concentrations of certain chemicals in the mixture that is produced in the crude tanks. Depending on the concentrations of the chemicals in the dope of the crude tanks, operators may add quantities of chemicals known as *batch doctors* in order to restore the mixture to a desired level of concentrations.

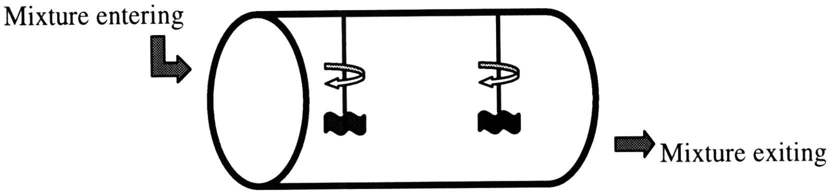

Figure 3. Crude tank

2.3.1.3 Filters

The mixture is subsequently transported to the filters. The filters separate the mixture from any foreign matter, such as dirt specks, fibers or plastic. A cylindrical steel tube is located at the center of the filter, as shown in Figure 4. Along the tank's diameter, stainless steel plates are connected at both sides of the tube. In addition, a filter-aid solution fills up the tube in order to make the filter process more effective. The dope mixture enters the tank from the bottom and is elevated through the tube to the top of the tank. Subsequently, it spreads in opposite directions and travels through the plates of the filter in an orderly fashion. Any foreign matter is trapped in the plates and the dope mixture is transported to the next unit operation. The operators disrupt the operation of the filters at regular intervals in order to clean the plates and remove the foreign matter that has accumulated over time.

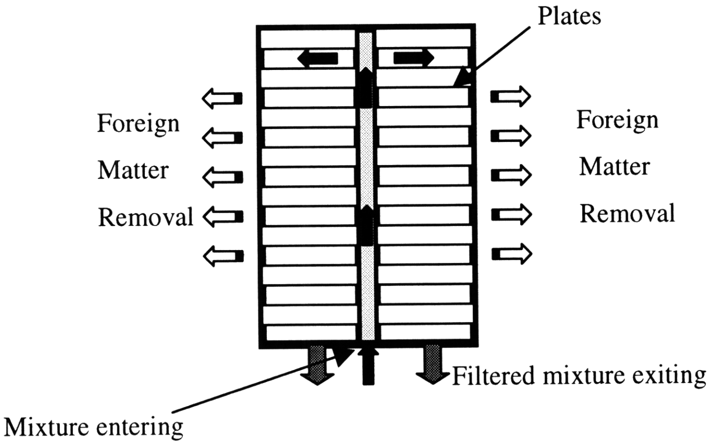

Figure 4. Filter Operation

2.3.1.4 Finished tanks

The remaining dope mixture is then pumped into very large tanks, the finished dope tanks. These tanks serve as the backbone of the dope production since they ensure that there is always dope available upon demand. The operators try to keep the level of dope in these tanks at a constant level in order to account for shortages when something unexpected occurs. The finished dope tank is a highly agitated tank where the mixture exiting the filter gets mixed with the dope in the tank. It is essentially the same unit operation as the agitated crude tank. The material exiting the tank can be considered fairly uniform. However, there is a difference in the two unit operations in the way the mixing occurs. As shown in Figure 5, mixing in the finished tanks takes place by means of a large thresher that is placed horizontally.

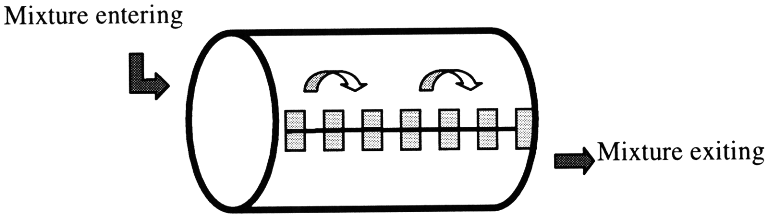

Figure 5. Finished tank

2.3.1.5 Storage tanks

The storage tanks are used in the late stages of the dope production to store the produced dope mixture. They are large holding tanks where the dope enters from the top and exits from the bottom. The storage tank is considered as a highly unagitated tank, where layers of dope are formed on top of each other in the tank because of the high viscosity of the material. It can be essentially considered as a silo where material accumulates on top of the existing material in the silo. In Figure 6, one can see how the layers of dope accumulate on top of each other. If we assume that each rectangle is a layer of dope mixture, then the entering layer will be placed on top of the preceding layer of dope without any mixing of the two layers occurring.

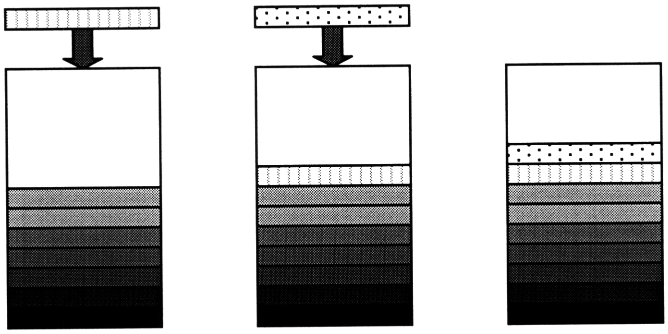

Figure 6. Operation of storage tanks

2.3.1.6 Stream splitter

The stream splitter is a distillation column, where the evaporation of certain solvents takes place. Although the vast majority of solvents are evaporated and subsequently recovered during the roll coating process, evaporation also occurs during the latter stage of dope production. As summarized in Figure 7, a certain fraction of the liquid mixture that enters the stream splitter is vaporized in such a way that the evolved vapor is in equilibrium with the residual liquid, separating the liquid from the vapor and condensing the vapor. The distillation works in the following way: dope passes through a heat exchanger and the result, a mixture of liquid and vapor, enters a vapor separator. In the separator, vapor leaves through the top and the liquid through the bottom and is transported through pipelines to the next unit operation.

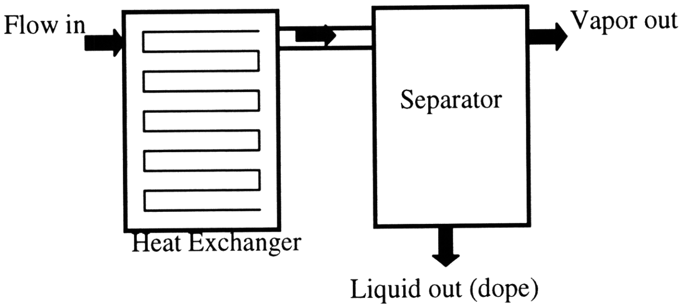

Figure 7. Stream splitter

2.3.1.7 Mixers

During the last stages of the process, dope undergoes further mixing in mixers. The mixers are large tanks that operate in the same fashion as the finished tanks. The only difference in these tanks is their geometry, as shown in Figure 8. Two symmetrical semi-cylindrical cavities are formed in the bottom surface of the tank. A thresher is placed inside each of these two cavities and blends the mixture in the vessel with any incoming material.

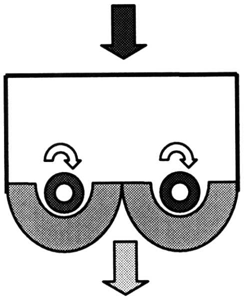

Figure 8. Mixer

These are the basic unit operations that are present during the dope production. The actual process is a combination of these unit operations in various configurations. With these unit operations now in mind, we can proceed in describing the overall dope production process.

2.3.2 Overall process

This section describes the dope production process and how the various unit operations are linked. The overall dope production process can be divided in two parts where the flow of information travels in different directions; the front end and the back end of the process.[1]

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[1] For the sake of simplicity, we will describe each of these parts separately.

2.3.2.1 Front end of the process

The following is a generic diagram of the front end of the process.

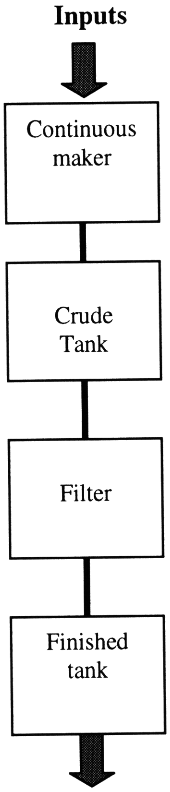


Figure 9. Generic process flow in front end

We will follow the propagation of dope through the various tanks to understand what happens in the front end of the process. The process represented and discussed in this section is the simplest one seen in the actual production. Variations of this generic line include more tanks in parallel with each other. For instance, a line could have two crude tanks in parallel after the continuous maker and the flow would be split into two flows instead of directly feeding one crude tank. In a similar fashion, a line could have two filters or finished tanks in parallel. However, for the sake of simplicity we will describe the process for this generic line and the same procedure can then be extended without any loss of generality for much more complex lines.

Initially, raw materials, solvents and dyes are poured into the continuous maker where they undergo mixing. The description of the flow rate information for the front end is summarized in Figure 10. Assuming that the flow into the continuous maker is *F* pounds of material per hour, the continuous maker is operated in such a way that the inflow is always equal to the outflow. Essentially, at the exit of the continuous maker, the mixture is pumped into the crude tanks at the same rate it enters the continuous maker, F, and the result is that the continuous maker's volume level does not change over time. The rate, F, at which material enters the continuous maker, and subsequently the crude tanks, is dependent on the volume level of the crude tanks. We will describe this operation in Section 2.3.1.

The mixture that is produced in the continuous maker is transported through pipelines to the crude tanks. We previously mentioned that inflow to the crude tank is F pounds of material per hour. However, the outflow from the crude tank is in general different than the inflow, thus resulting in fluctuations in the volume. The outflow is determined by a set of operator conditions that we will describe in Section 2.3.2. Assuming that this outflow is *A* pounds of material per hour, A pounds of material per hour enters the filters.

Any foreign matter present in the mixture entering the filter will be removed from the mixture and accumulate in the plates of the filter. However, on average this quantity is very small in comparison to the actual inflow of material into the filter. Hence, we can assume that the outflow from the filters will be equal to the inflow to the filters, A pounds of material per hour. Upon exiting the filters, dope is directed via pipelines at an inflow rate A pounds per hour to the next unit operation, the finished tanks.

So far we have witnessed two different sources of transport rates in the system. The first rate (F) is the inflow rate to the continuous maker and is determined by certain operator rules that are described in the following section. The second rate (A) is the outflow rate from the crude tanks which is in turn determined by operator rules that are also discussed in the following section. The information of these flow rates is traveling in a forward fashion from the continuous maker to the finished tanks. As we will see in the following section, these rates are also dependent on certain states of the tanks that follow them and hence we can think of their determination as a simple feedback control loop. In the figure that follows one can see how the flow of information travels in the front end of the process, including the feedback accomplished by operators on the line.

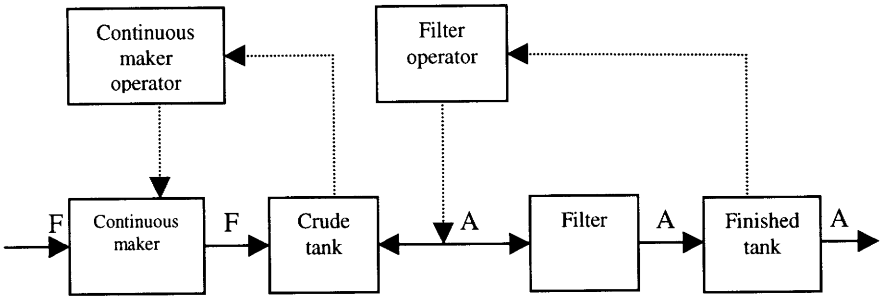


Figure 10. Flow of information in front end

2.3.2.2 Operator rules in the front end of the process

Human operators are an integral and essential part of every manufacturing process. They are the people who operate a process and whose role, through experience or feeling, is very important for the final outcome. Hence, in order to model the process in the most effective way, we must consider the actions of the operators during production. These actions are susceptible to changes to reduce the variation of the final product.

The operators run the process according to established rules. We will state these rules and how we model them. The rules are associated with the operation of specific machines based on performance measures of other machines. Although the machines that are directly affected by these rules are the continuous maker and the filter, all the machines in the process are influenced by these operators' actions.

2.3.2.2.1 Continuous maker

The continuous maker runs in batch mode, depending on the volume level of the crude tanks that immediately follow it, in an effort to keep the volume level of the crude tanks within specified levels. Let us assume that the highest level of the crude tank is *UB* pounds of material and that the lowest level is *LB* pounds of material. The continuous maker mixes material until the volume level of the crude tank reaches UB pounds, as illustrated in Figure 11. Then the maker shuts off until the level of the crude tank drops to LB pounds. At that instant, the maker turns back on and mixes material until the level of the crude tank reaches UB pounds. Then, the maker is shut off and this cycle repeats.

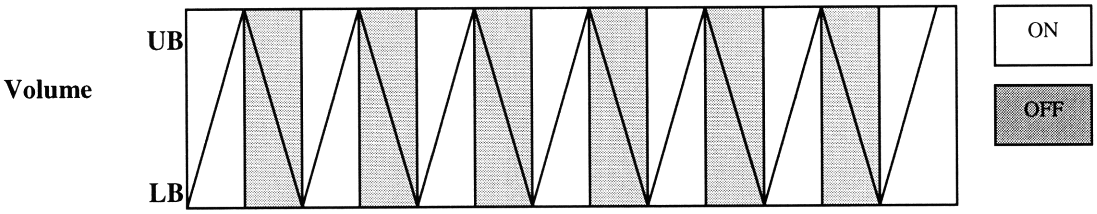


Figure 11. Continuous maker operation

By running the continuous maker in such a way, the operators generally manage to keep the levels of the crude tanks within specified limits. Nevertheless, there is always the chance of human error or delay in the implementation of the changes. In other words, the volume of the crude tank may exceed the UB pound threshold at time instant t, but the operator may not realize this condition has been reached and therefore not shut off the continuous maker until a later time t+dt.

2.3.2.2.2 Filter

The filter is greatly affected by the operators' actions. The inflow rate for the filter and hence the outflow rate for the previous machine, the crude tank, are dependent on a set of operator rules. The filter runs also in batch mode since it shuts off for a period of time to allow for operators to remove foreign matter from the filter plates. The operation rules for the filter are summarized in Figure 12.

Initially, the inflow rate to the filter is *CR* (Catch–up Rate) pounds per hour. This rate is dependent on the level of the finished tanks that immediately follow the filter. The operators try to ensure that the volume of dope in the finished tanks is constant. The reason for that is the extremely important storage role of the finished tanks: in case of an emergency, the finished tanks will provide the necessary amount of dope in order to meet the demand from Roll Coating. Initially, the level is *LL* (Low Level) pounds and the inflow rate to the filter ensures that the finished tanks get filled. Let us assume that the prescribed volume level for the finished tanks is *SL* (Steady Level) pounds. As soon as the level reaches SL, the inflow to the filter changes to such a value (*SR* pounds per hour– Steady Rate) that ensures that the outflow of the filter, and hence inflow to the finished tank, is equal to the outflow demand from the finished tank. In such a way, the inflow to the finished dope tank is equal to the outflow from the tank and hence the level of the tank remains constant.

This operation mode continues until the throughput of the filter reaches a specified value, *TT* pounds of material. At that point the filter shuts off until a specified time interval, *CT* hours, elapses. During this time interval, operators clean the foreign matter from the filter. As soon as the interval has elapsed the inflow is once again set to CR pounds/hour and the same cycle starts again.

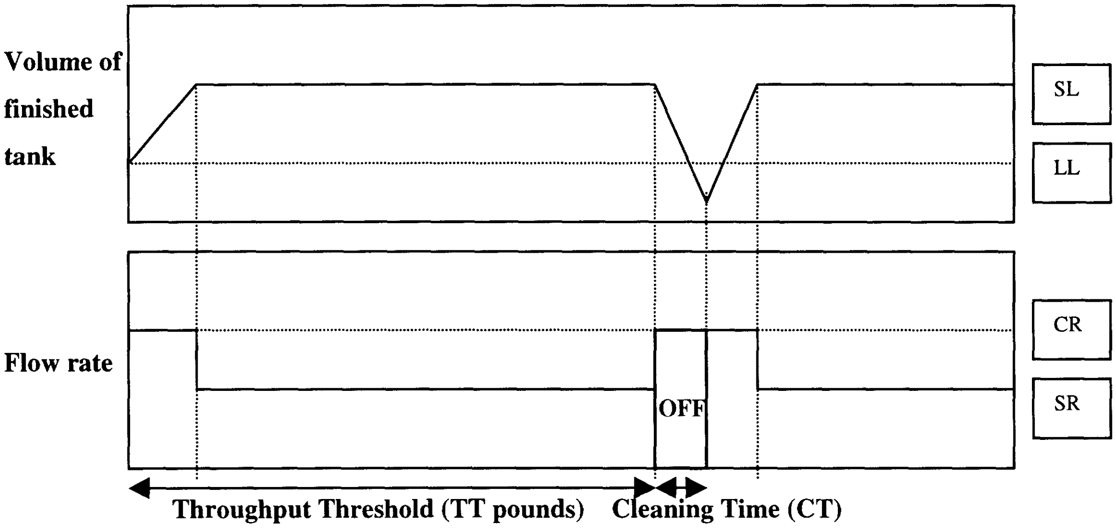


Figure 12. Filter operation

As pointed out, the operators try to regulate the inflow of dope to the filter in order to keep the volume of the finished tanks at a constant level. Nevertheless, the volume of the finished tanks fluctuates greatly, either overshooting or undershooting the level SL. The reason behind this is that when the operators realize that the volume is less than SL, they immediately increase the inflow rate to the filter. However, then the volume increases and exceeds the level SL resulting in the operators decreasing the inflow rate. Hence, the operators engage in a constant regulation of the inflow in a cyclical manner and as a result the volume of the finished tank varies as well.

2.3.2.3 Back end of the process

We have described what happens at the front end of the process, until the point of inflow of material into the finished tanks. The back end of the process starts with the outflow rate from the finished tanks and includes all the following stages until the finished dope is delivered to Roll Coating. The flow of information in this part of the process travels in an opposite direction than in the front end of the process: the inflow and outflow rates to and from the tanks of the back end are regulated according to the demand for dope from Roll Coating. In most cases, simple controllers regulate these flows as to ensure that the levels in the tanks are constant. The following is a generic diagram of the back end of the process.

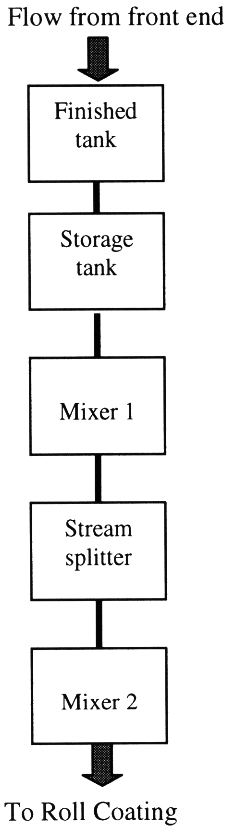


Figure 13. Generic process flow in back end

The generic flow shown in Figure 13 represents the simplest configuration seen in actual production. Many variations of this configuration exist in the actual production but they are simply extensions of this generic diagram; the same principles can be applied to these complex configurations without any loss of generality.

The first machine in the back end is the finished tank, which was also the last machine in the front end of the process. However, in this case we will commence our discussion from the last machine of the back end since the information is propagated backwards based on demand from one unit step to the next, as illustrated in Figure 14. The last machine of this process is mixer 2. This is the last point before the dope is fed into the Roll Coating machines and provides additional mixing in order to smooth out any variability and deliver a more uniform product. The flow rate at which mixer 2 delivers the dope is determined by Roll Coating as part of a longer supply chain model that originates with customer demand of film. Let us assume that Roll Coating demands *D* pounds of dope delivered to it every hour. Therefore, the outflow rate from mixer 2 is D pounds per hour. A PI (Proportional and Integral controller) determines the inflow rate to the mixer. The controller ensures that the volume level of dope in mixer 2 is at a specified threshold value and regulates the flow accordingly. In steady state, the inflow to mixer 2 will be equal to the outflow from it, namely D pounds per hour.

Dope is delivered to mixer 2 via pipeline from the previous unit operation, a stream splitter. In steady state, the outflow rate from the stream splitter is D pounds per hour, which is what mixer 2 requires as an inflow. A PI controller, which ensures that the level of dope inside the tank is constant, regulates the stream splitter's inflow. In steady state, the inflow to the stream splitter is *E* pounds per hour which is a larger rate than D, because some of the solvents get vaporized during this unit operation.

Subsequently, the stream splitter requires E pounds of dope to be pumped into it by the previous unit operation, mixer 1. This mixer operates exactly in the same way as mixer 2 and a PI Controller again regulates the inflow rate to it. We can therefore deduce that in steady state the inflow rate to mixer 1 is E pounds per hour. Hence, the outflow rate from the previous unit operation, a storage tank, is also E pounds per hour. The storage tank serves as a buffer where dope is stored before passing through the last mixing stages. Although there is no mixing taking place during this unit operation, the same kind of PI controller again regulates the incoming flow to the storage tank. The controller ensures that the level in the storage tank is held at a constant level and, therefore, in steady state the inflow rate to the storage tank is E pounds per hour.

We know now what the outflow rate from the finished tank is; E pounds of dope per hour. It is apparent therefore, that the inflow and outflow rates from the finished tank are in general different and operators intervene and try to equate them in order to keep the level of dope in the finished tank constant over time. Under the action of automatic control loops and operator intervention, the flow of information is from Roll Coating backward to the finished tank as summarized in Figure 14.

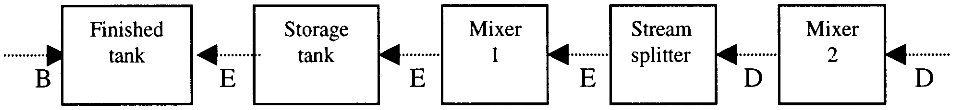


Figure 14. Flow of information in back end

Chapter 3 - Modeling of the process

In this chapter, the physical modeling of the actual unit operations is described. The models are classified into three types of tanks – well-stirred tanks, plug flow vessels and stream splitters. Each unit operation is described either by one of these component models or by a combination of them. To describe the above models we will use the following notation:

$F^{I}_{j}(t)$	Total flow into tank j at time t (lbs./hr)
$F^{Ik}_{j}(t)$	Total flow into tank j at time t in stream k (lbs./hr)
$F^{Ik}_{ij}(t)$	Flow of chemical i into tank j at time t in stream k (lbs./hr)
$F^{I}_{ij}(t)$	Flow of chemical i into tank j at time t (lbs./hr)
$c^{I}_{ij}(t)$	Concentration of chemical i entering tank j at time t
$c^{Ik}_{ij}(t)$	Concentration of chemical i entering tank j in stream k at time t
$c_{ij}(t)$	Concentration of chemical i in tank j at time t
$c^{o}_{ij}(t)$	Concentration of chemical i leaving tank j at time t
$c^{ok}_{ij}(t)$	Concentration of chemical i leaving tank j in stream k at time t
$F^{o}_{j}(t)$	Total flow out of tank j at time t (lbs./hr)
$F^{ok}_{j}(t)$	Total flow out of tank j at time t in stream k (lbs./hr)
$F^{ok}_{ij}(t)$	Flow of chemical i out of tank j at time t in stream k (lbs./hr)
$F^{o}_{ij}(t)$	Flow of chemical i out of tank j at time t (lbs./hr)
m^{I}_{j}	Number of input streams into tank j
m^{o}_{j}	Number of output streams from tank j
$V_{j}(t)$	Volume in tank j at time t (lbs.)

Material can enter a tank in one or more streams and also leave a tank in one or more streams depending on the tank. The following general relations hold:

$$\mathrm{F}_{\mathrm{j}}^{\mathrm{I}}(\mathrm{t}) = \sum_{k}^{m_j^I} \mathrm{F}_{\mathrm{j}}^{\mathrm{Ik}}(\mathrm{t}) \qquad (1)$$

and

$$\mathrm{F}_{\mathrm{ij}}^{\mathrm{I}}(\mathrm{t}) = \sum_{k}^{m_j^I} \mathrm{c}_{\mathrm{ij}}^{\mathrm{Ik}} \mathrm{F}_{\mathrm{j}}^{\mathrm{Ik}}(\mathrm{t}) \qquad (2)$$

Equation (1) states that the total volumetric flow into the tank at time t is equal to the sum of the volumetric flows of all the streams that enter the tank. Equation (2) states that the volumetric flow of chemical i in the tank at time t is equal to the sum of the volumetric flows of chemical i in each stream. The volumetric flow of chemical i in a particular stream is merely the weight fraction (concentration) of the chemical in the stream multiplied by the volumetric flow of the stream.

The outflow equations are similar:

$$\mathrm{F}_{\mathrm{j}}^{\mathrm{o}}(\mathrm{t}) = \sum_{k}^{m_j^o} \mathrm{F}_{\mathrm{j}}^{\mathrm{ok}}(\mathrm{t}) \qquad (3)$$

and

$$\mathrm{F}_{\mathrm{ij}}^{\mathrm{o}}(\mathrm{t}) = \sum_{k}^{m_j^o} \mathrm{c}_{\mathrm{ij}}^{\mathrm{ok}} \mathrm{F}_{\mathrm{j}}^{\mathrm{ok}}(\mathrm{t}) \qquad (4)$$

We now describe the model underlying each of the three components we previously mentioned.

3.1 Well-stirred tanks

The continuous maker has been modeled as a CSTR (Continuous Stirred Tank Reactor) [8]. It is a highly idealized model, assuming ideal mixing conditions. The three main assumptions of the model are: conservation of mass, well-stirred tank, and well-mixed tank. By conservation of mass, we assume that no mass is added or destroyed by any means during the operation. Under the well-stirred tank assumption the whole mixture is characterized by uniform concentration of chemicals. Finally, the well-mixed assumption implies that the outflow is also characterized at each time instant by a uniform concentration of chemicals, which is the same as the mixture concentrations.

Suppose tank j is a CSTR. At time t there are $V_j(t)$ pounds of material in the tank. If we assume that the concentration of chemical i in the mixture is $c_{ij}(t)$ at time t, then there are $c_{ij}(t) \cdot V_j(t)$ pounds of chemical i in tank j at time t. Then, based on the conservation of mass and the well-stirred tank assumption the following relations hold:

$$\frac{d(c_{ij}(t)\,V_j(t))}{dt} = F_{ij}^{I}(t) - c_{ij}(t) \cdot F_j^{o}(t) \qquad (5)$$

and

$$\frac{dV_j(t)}{dt} = F_j^{I}(t) - F_j^{o}(t) \qquad (6)$$

Then, by expanding the left side of equation (5) and substituting (6) we get the following equation for the concentration of chemical i in tank j at time t:

$$\boxed{\frac{dc_{ij}(t)}{dt} = -\frac{F_j^{I}(t)}{V_j(t)} \cdot c_{ij}(t) + \frac{F_{ij}^{I}(t)}{V_j(t)} \qquad (7)}$$

In addition to the continuous maker, the crude tanks, finished tanks and mixers are also modeled as well stirred tanks. The underlying operation behind all of these tanks is the same; the entering mixture is mixed with the remaining volume in the tank by means of impellers, or threshers. Although the geometry of each tank is different, the mixtures in all of the tanks are very agitated. This observation allows one to infer that the CSTR model is suitable for all these operation units.

3.2 Plug flow vessel

In order to describe accurately the effects of unagitated tanks and pipeline delays throughout the process, we use the plug flow reactor model [8]. In general, plug flow means that a material which enters a tank at a time interval $(t,t+\Delta t)$ will travel through the tank without having any interaction with any material that entered before time t or any material that will enter after time $t+\Delta t$. Nevertheless, mixing and chemical reactions could occur in the material that enters during the time interval $(t,t+\Delta t)$.

However, in this case, we are not concerned with any mixing or chemical reaction taking place, mainly due to the nature of the mixture. Hence, we can assume that the material entering the vessel during the interval $(t,t+\Delta t)$ has uniform properties throughout its volume. Furthermore, these properties do not change while the volume is still inside the tank since there is no interaction within the material or with any material preceding or following the material of interest.

The plug flow vessel is a silo. Layers of different materials (or a single type of material with varying characteristics) form on top of each other, travelling through the vessel at a rate determined by the inflow and outflow rates as well as the volume of material in the tank. Let us assume that there is a certain amount of material in the silo and that the inflow rate of material, F, is the same as the outflow rate. Then, the volume level in the tank will be constant at all times. Material A is present inside at the silo at time t and at time $t+\Delta t$, material B will enter the silo. In Figure 15, every rectangle represents $F\cdot\Delta t$ pounds of material. Hence, in the time interval $(t,t+\Delta t)$, $F\cdot\Delta t$ pounds of material B enters the tank and $F\cdot\Delta t$ pounds of material A leaves the tank. Then, the material, B, that entered during this time interval accumulates on top of the remaining volume of material A in the tank without mixing with it. Since the inflow is equal to the outflow for the simple model we are describing, the volume of material in the tank remains unaffected at all times. In the next time interval, $(t+\Delta t,t+2\Delta t)$, material C enters the tank and material A exits. The amount of material C that enters the tank accumulates on top of material A and material B. Figure 15 provides a schematic representation of the plug flow vessel model for three time intervals.

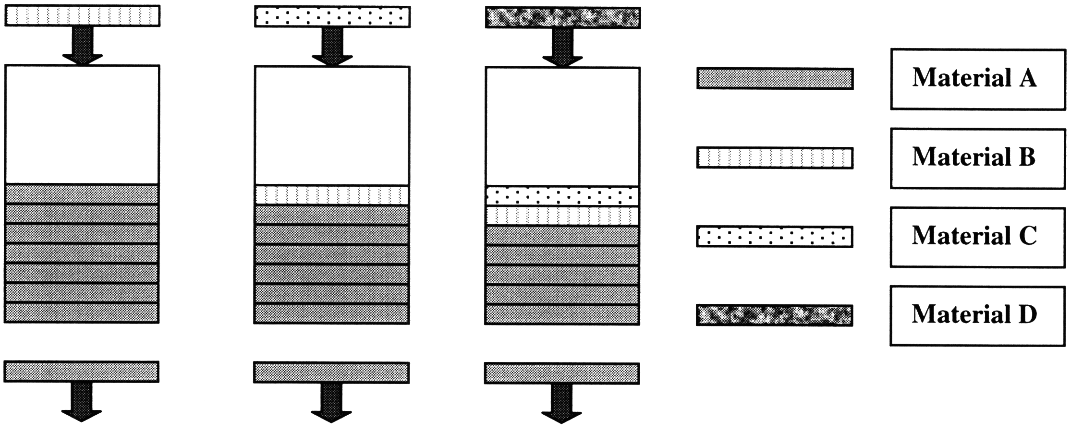


Figure 15. Plug flow operation

Because of the batch characteristic of the process and also because of the slow flows that characterize the movement of material throughout the process, we devise a discrete time approximation for the plug flow. According to this approximation, matrices of volume and concentrations characterize the mixture inside the vessel because of the effects of no agitation. Each rectangle, representing the amount of material entering or exiting during a fixed time interval, can be thought of as a row of a matrix. Thus, each row represents the concentrations that characterize the mixture entering the vessel during the represented time interval. In conjunction with this *concentration matrix*, a *volume matrix* with the same number of rows is formed where each row corresponds with the analogous row of the concentration matrix and represents the volume of material present. We will describe our model in a general way, considering the concentration of a chemical i in the mixture. However, it can extend in the same way for all possible numbers of chemicals in the mixture.

We first assume that $V_j(t)$ lbs. of material i are initially in the vessel with concentration of $c^{I}_{ij}(t)$ in the mixture. So, the first row of the volume matrix will be $V_j(t)$ and the first row of the concentration matrix will be:

$$[c^{I}_{1j}(t)\ c^{I}_{2j}(t) \ldots\ c^{I}_{ij}(t) \ldots . c^{I}_{Nj}(t)]$$

During (t,t+Δt), $F^{I}_{j}(t+\Delta t)\cdot\ \Delta t$ pounds of material enter the vessel and $F^{o}_{j}(t+\Delta t)\cdot\ \Delta t$ pounds of material exit the vessel. We assume that the concentrations of the material entering the vessel are:

$$[c^{I}_{1j}(t+\Delta t)\ c^{I}_{2j}(t+\Delta t) \ldots\ c^{I}_{ij}(t+\Delta t) \ldots . c^{I}_{Nj}(t+\Delta t)]$$

Then, the updated matrices for the volume and concentrations respectively are:

$$\begin{bmatrix} c^{I}_{1j}\ (t) & c^{I}_{2j}\ (t) \ldots & c^{I}_{ij}\ (t) \ldots & c^{I}_{Nj}\ (t) \\ c^{I}_{1j}\ (t+\Delta t) & c^{I}_{2j}\ (t+\Delta t) \ldots & c^{I}_{ij}\ (t+\Delta t) \ldots & c^{I}_{Nj}\ (t+\Delta t) \end{bmatrix}$$

$$\begin{bmatrix} V_{j}(t) \\ F^{I}_{j}(t+\Delta t)\cdot\Delta t \end{bmatrix}$$

However, during the interval (t,t+Δt), there is an outflow of $F^{o}_{ij}(t+\Delta t)\cdot\ \Delta t$ pounds from the vessel. In our model, this outflow is first compared to the total volume in the tank in order to ensure that there is enough volume to perform the task. Assuming that the total volume in the tank is larger than the outflow during the interval (t,t+Δt), the outflow is then compared with the first entry of the volume matrix. If the first entry of the matrix V is larger than the outflow, then the volume and concentrations matrices as well as the exit concentrations are computed as follows:

$$\begin{bmatrix} c^{I}_{1j}\ (t) & c^{I}_{2j}(t) & \ldots c^{I}_{ij}\ (t) & \ldots c^{I}_{Nj}\ (t) \\ c^{I}_{1j}(t+\Delta t) & c^{I}_{2j}(t+t\Delta) & \ldots c^{I}_{ij}(t+\Delta t) & \ldots c^{I}_{Nj}(t+\Delta t) \end{bmatrix}$$

$$\begin{bmatrix} V_{j}(t) - F^{o}_{ij}(t+\Delta t)\cdot\Delta t \\ F^{I}_{ij}(t+\Delta t)\cdot\Delta t \end{bmatrix}$$

$$\boxed{c^{o}_{ij}(t+\Delta t) = \frac{1}{F^{o}_{j}(t+\Delta t)\cdot\Delta t}\cdot c^{I}_{ij}(t)\cdot V_{j}(t) \qquad (8)}$$

If the volume of the first row is smaller than the outflow during the time interval (t,t+Δt), then some of the volume of the second row will leave the vessel during this interval. Then, the exit concentrations are:

$$\boxed{c_{ij}^{o}(t+\Delta t)=\frac{1}{F_j^{o}(t+\Delta t)\cdot\Delta t}\cdot[c_{ij}(t)\cdot V_j(t)+c_{ij}(t+\Delta t)\cdot(F_j^{o}(t+\Delta t)\cdot\Delta t-V_j(t))] \qquad (9)}$$

Since the whole volume and concentrations of the first row have exited the vessel, the first row from both the volume and concentration matrices will be deleted. Hence, the matrices are now:

$$\left[c_{1j}^{I}(t+\Delta t)\ \ c_{2j}^{I}(t+\Delta t)\ldots c_{ij}^{I}(t+\Delta t)\ldots c_{Nj}^{I}(t+\Delta t)\right]$$

$$\left[F_j^{I}(t+\Delta t)\cdot\Delta t-(F_j^{o}(t+\Delta t)\cdot\Delta t-V_j(t))\right]$$

During the interval (t+Δt,t+2Δt), new volume and concentrations enter the vessel. The same procedure continues during each time interval. In cases where the outflow is larger than the corresponding volume of the same time interval, i.e. the outflow is larger than the entry of the volume matrix corresponding to the interval, a different formula should be used. Let us assume that the outflow is larger than the sum of n rows of the volume matrix, rows r to r+n. Then these n rows will be deleted and the exit concentration will be computed as follows:

$$\boxed{c_{ij}^{o}(t)=\frac{1}{F_j^{o}(r+n+1)\cdot\Delta t}\cdot\{\sum_{k=j}^{r+n}[c_{ij}(k)\cdot V_j(k)]+[F_j^{o}(r+n+1)\cdot\Delta t-\sum_{k=j}^{r+n}V_j(k)]\cdot c_{ij}(r+n+1)\} \qquad (10)}$$

We use the plug flow model to model pipeline delays throughout the process, storage tanks and filters. The dope mixture is transferred from one unit operation to the next one through very long pipelines. It is apparent that the mixture spends quite some time in these pipelines before being introduced to the next unit operation. Hence, there is a time delay between the unit operations and it can be effectively represented by the plug flow model. The storage tanks are silos and the analogy between the model and the storage tank operation is evident. The last unit operation that is modeled as a plug flow is the filter. Although the filter is not a silo, it can be thought of as a pipeline. Dope is travelling through the filter plates at a constant speed and the foreign matter volume that is collected in the filtration process is minimal compared to the remaining mixture at each time instant. Hence, we can also use the plug flow model to represent the filter and capture the delay that it also introduces in the process.

3.3 Stream splitter model

The stream splitter operation is probably the most complex unit operation in the process. In order to model it, we assume a distillation column model that is commonly used to model certain industrial chemical operations [8]. We divide the chemicals in the mixture in two general classes, the volatile (V) and the non-volatile (NV) chemicals. Specifically, the volatile chemicals get partially vaporized during this process, whereas the non-volatile chemicals are unaffected throughout this unit operation. The model we describe here is based on simple energy and mass balances for the materials.

Let us assume that the concentration of chemical i (which is volatile) in the entering mixture is $c_{ij}^{I}(t)$. If the molecular weight of this chemical is MW_i, then we can calculate the mole fraction of this chemical in the set of the volatile components as follows:

$$M_i = \frac{\dfrac{c_{ij}^{I}(t)}{MW_i}}{\displaystyle\sum_{i\varepsilon V} \frac{c_{ij}^{I}(t)}{MW_i}}$$

By using the Antoine's curve (Vapor Pressure) for chemical i we can calculate its vapor pressure [8]. Since the temperature inside the stream splitter is not known, we can approximate it as the average of the temperatures at the entering and exiting parts of the splitter. Let A_i and B_i be the Antoine's curve slope and intercept, respectively. Then, the partial vapor pressure for component i is:

$$Pv_i = M_i \cdot [A_i \cdot \frac{(T_{in} + T_{out})}{2} - B_i]$$

The mole fraction of chemical i in the vapor can be then calculated as:

$$Mv_i = \frac{Pv_i}{\sum_{i \varepsilon V} Pv_i}$$

Using the molecular weight, we can now calculate the weight fraction of the chemical in the vapor:

$$Wv_i = \frac{Mv_i \cdot MW_i}{\sum_{i \varepsilon V} Mv_i \cdot MW_i}$$

Let us assume that the heat of vaporization for the volatile component i is g_i. Then the heat of vaporization can be calculated:

$$Gv = \sum_{i \varepsilon V} Wv_i \cdot g_i$$

The weight fractions of the volatile components in the vapor as well as the heat of vaporization have been calculated so far. We will now consider all the components in the mixture in order to perform the energy and mass balance calculations. Assuming that $F^I_j(t)$ is the inflow of material in the stream splitter, $F^v_j(t)$ is the outflow of vapor and $F^{fd}_j(t)$ is the distilled outflow, the following mass balance holds:

$$F^{fd}_j(t) = F^I_j(t) - F^v_j(t)$$

Let us further assume that the specific heat capacity of chemical i (either volatile or non volatile) is q_i. Then, the average heat capacity of the entering mixture is:

$$S_{in} = \sum_{i \varepsilon V,NV} c_{ij}^{I}(t) \cdot q_i$$

Similarly, if $c_{ij}^{fd}(t)$ is the concentration of chemical i in the distilled flow, the average heat capacity of the distilled flow is:

$$S_{fd} = \sum_{i \varepsilon V,NV} c_{ij}^{fd}(t) \cdot q_i$$

Then, the following energy balance holds:

Rate of Heat in = Rate of Heat out + Rate of Heat of Vaporization

$$F_j^{I}(t) \cdot S_{in} \cdot T_{in} = F_j^{fd}(t) \cdot S_{fd} \cdot T_{out} + F_j^{v}(t) \cdot G_v$$

The non-volatile components are unaffected by the operation of the stream splitter and hence the following mass balance holds:

$$F_j^{I}(t) \cdot c_{ij}^{I}(t) = F_j^{fd}(t) \cdot c_{ij}^{fd}(t) \qquad \text{(i is non-volatile)}$$

For the volatile components, after taking into account the amount that vaporizes a similar mass balance equation holds:

$$F_j^{I}(t) \cdot c_{ij}^{I}(t) = F_j^{fd}(t) \cdot c_{ij}^{fd}(t) + F_j^{v}(t) \cdot c_{ij}^{v}(t) \qquad \text{(i is volatile)}$$

The above relations constitute a non-linear system of five equations with five unknowns - S_{fd}, $F^{fd}_j(t)$, $F^{v}_j(t)$, $c^{fd}_{ij}(t)$ (volatile), $c^{fd}_{ij}(t)$ (non-volatile) – which can be solved iteratively or with any other known method.

The vapor flow is then being condensed and transformed into liquid form. A fraction R of this liquid rejoins the distilled flow at the exit of the stream splitter. This fraction has been estimated by the operators of the dope production as 0.5%. The exit flow is then:

$$F^{o}_j(t) = F^{fd}_j(t) + R \cdot F^{v}_j(t)$$

The exit concentration for chemical i in the mixture leaving the stream splitter is:

$$c^{o}_{ij} = \frac{F^{I}_j\, c^{I}_{ij}}{F^{o}_j}, \qquad \text{for non volatile components} \qquad (11)$$

$$c^{o}_{ij} = \frac{F^{fd}_j\, c^{fd}_{ij}}{F^{o}_j} + \frac{R\, F^{v}_j\, c^{v}_{ij}}{F^{o}_j}, \qquad \text{for volatile components} \qquad (12)$$

Chapter 4 - Validation of the model

This chapter describes the validation of the model, which entails the comparison of the model with the actual dope production process. One must clearly define what the goal of a model is. In the case of the Kodak dope production model, the purpose is the prediction of the variations in the concentrations of dope. Specifically, the model must predict the larger variations that occur over time rather than small short term variations that are not significant for the quality of the product.

In order to determine if the developed model is successful, we utilize existing sensors in the process. The measurements of the first available sensor in the process (at the finished tank) are used as inputs to the model's following unit operation (the first mixer). Then, the measurements of the remaining sensors in the process are compared to the predictions of the model at the same points in the process. A representation of such a procedure can be seen in Figure 16.

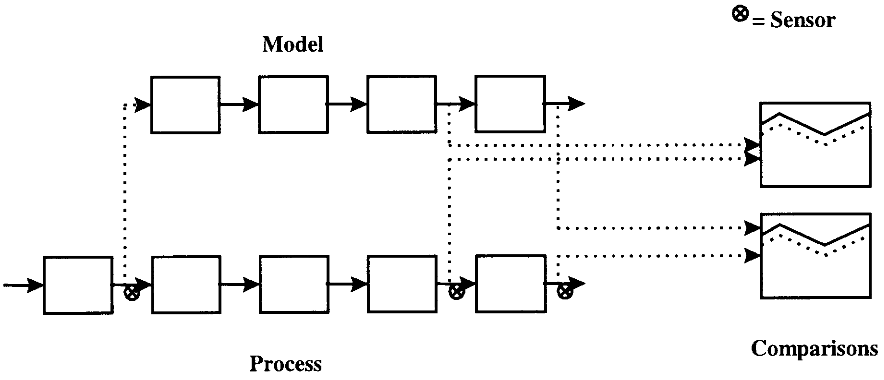


Figure 16. Procedure of validating the model

The caveat to such a validation procedure is the fact that sensors are not installed at every single point of the process. However, since many of the operations in the actual process are repeated, one can be confident that the behavior of such operations will not change from one place to another. The validation procedure is performed many times in order to ensure that the model will predict the results with a desired accuracy. Modeling is an iterative process of testing and updating and hence it was expected that in the beginning the model would not be accurate. However, with several rounds of revision and updating of the components, the model has been found to be successful in predicting accurately the concentrations of the chemicals in dope.

In Figure 17, we compare the prediction of the model with the actual production data as measured by the sensors at the last mixer before Roll Coating. Quantitatively, the model predicts with accuracy the concentrations of the chemicals in the dope. It captures the large long-term variations in the concentrations, and produces a smoother signal than the data measured by the sensors. Naturally, some of the small fluctuations are a result of noise in the measurements. In addition, there is a small constant bias between the predicted value and the actual measurement. There are two explanations for the existence of the bias. First, the sensor could have been calibrated with an offset from the actual value. Second, it could still be the case that the bias is due to insufficient modeling of certain parts of the process.

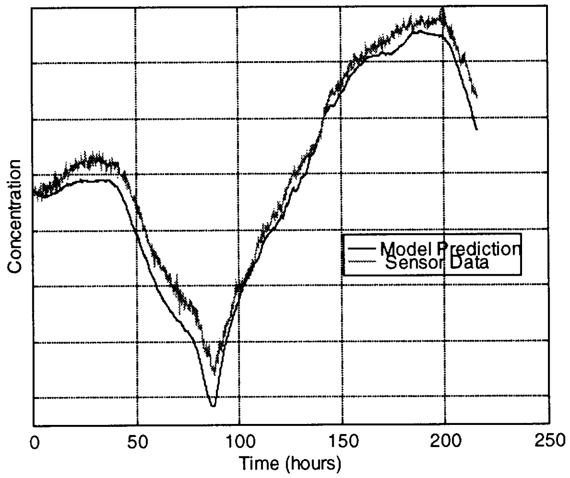
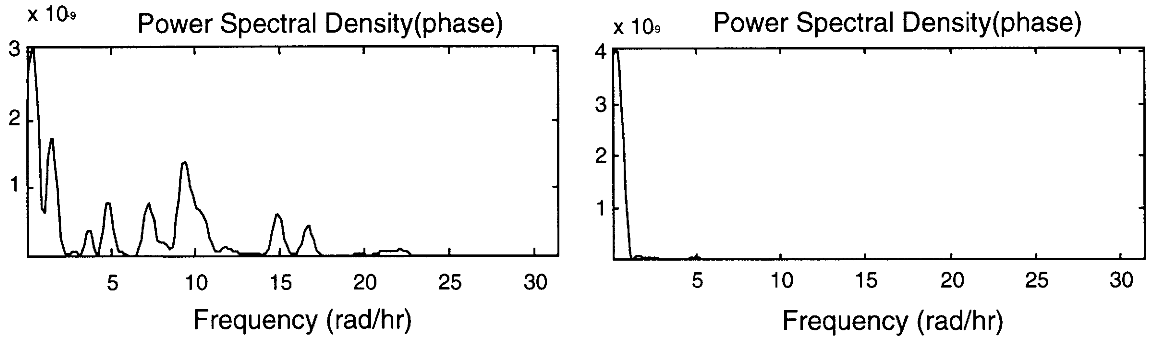


Figure 17. Comparison of model prediction and sensor data (mixer)

An auto-correlation test for the residuals qualitatively assessed the performance of the model. The residual is defined as the difference of the predicted output and the measurement of the sensor. By performing such a test, we deduced the extent of the dynamics of the process. The auto-correlation of the residuals drops after 5 lags to 0.2, hence the model explains many of the dynamics of the process (each lag corresponds to 0.2 hours). Optimally, if the residual were a pure white noise signal, the auto-correlation would have dropped to zero at the first lag. This would have indicated that the model was a perfect representation of the process and no further improvements could be done.

Figure 18 compares the power spectral density of the data and the prediction. At the low frequencies, the densities for both the prediction and the real data are very similar, implying that the model predicts successfully the large low frequency variations. At higher frequencies, the model does not capture all the dynamics of the process. These low frequency discrepancies can arise from parts of the process that were not modeled, such as pumps and the propellers of the mixers.


Power Spectral Density(phase)

Power Spectral Density(phase)

DATA

PREDICTION

Figure 18. Power spectral density of model prediction and sensor data

However, no model is perfect and the extent of its success shall be determined separately each time. For the dope production process, the Kodak team decided that the model was capturing all the necessary information that was needed.

Chapter 5 - Applications of the model to production control

This chapter discusses the applications of the model in the actual production. Section 5.1 describes the use of the model in the planning of raw materials, both in terms of quantity and time. Section 5.2 describes the calculation via the model of upper and lower bounds in the concentrations of the inputs. Finally, Section 5.3 discusses the evaluation of a new pattern of actions that could be very risky to implement in real-time.

This is where the true usefulness of the model becomes apparent. By trying in the computer different studies, specific or general, simple or extreme, one can understand the impact that certain actions have on the quality of the finished product. Moreover, since the studies are made on a computer model, there is no disruption of production and hence, no downtime caused. The ability to view in the computer the impact of risky actions that would never otherwise be studied in the process in fear of a catastrophe, opens the possibility of discovering revolutionary changes. We need to remind the reader that the purpose of these studies is to examine the impact certain actions have on quality while at the same time meeting the demand from Roll Coating. Hence, we want to see in each of these cases the tradeoff between quantity and quality. On the whole, these studies demonstrate the direct applicability of the model to production control.

5.1 Time organization of additions

This section discusses the importance of the model in planning additions of raw materials. A major concern for the managers in dope production is the efficient organization of the additions of certain chemicals to the process. It is very usual that upon inspection of the quality of dope at certain points in the process, a further amount of a certain chemical is needed in order to achieve the desired level of concentrations in the mixture. These additional quantities of chemicals are added at different time intervals in order to ensure that the system is not largely disturbed and therefore, large fluctuations of the concentrations of the finished product take place. The addition of chemicals should take place only after the previous addition has propagated throughout the process and its disturbing effect has vanished. Hence, in order to add extra quantities of a certain chemical, the production manager has to ensure that the system has reached a steady state after the introduction of a previous upset. There is great significance in knowing the time it takes the system to reach this steady state. If one underpredicts this period of time, then the next addition of chemicals will take place when the system has not yet reached steady state and hence, it will introduce even more variability to an already volatile system. That in turn will cause great variability in the concentrations of the chemicals and therefore, poor quality. On the other hand, if one overpredicts the time interval, then a significant amount of time that could be utilized in order to restore the quality of the product at its desired level would be lost and that also can have a significant economic effect.

The tool we have developed can act as an estimator of the time that the system needs in order to reach steady state after an upset is introduced. The model can predict the elapsed time interval before the product at any particular stage in the process reaches steady state. Hence, the production manager can organize accordingly the timing of the additions. As an example of such a case, we will now discuss a real-time example of this application, as it was studied at the dope production process of Eastman Kodak.

The specific question asked by the dope manufacturing coordinator, David Bourne, was to calculate the intervals at which he could sequentially add certain portions of chemicals in order to restore the concentrations of the dope at a certain point in the process to the desired level. Moreover, Mr. Bourne wished to know for this specific case, the quantities of certain chemicals he should add each time in order to reach the desired quality in the product. These were questions that, given the complexity of the process as a structure, one would find very difficult to answer.[2]

The importance of the study lies mainly in the way an upset, which in this case is an addition, propagates and eventually gets buffered throughout the process. Since we are dealing with a dynamic system characterized by large delays that are mainly due to the pipelines transporting the mixture, such timing issues are of great importance. In Figure 19, we plot the concentration of a certain chemical at three points in the process versus time. It is assumed that the concentration is constant before more of the same

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[2] A set of initial conditions was specified for the model, which are not discussed here.

chemical is introduced in the process. The addition of the chemical, which can be realized as step change in the concentration entering the continuous maker, can be seen relatively quickly in the continuous maker output where because of the small volume of the tank any changes propagate quickly. However, it takes a significant amount of time until this change has reached steady state at two later points in the process, the finished tank and the mixer before Roll Coating. As soon as steady state has been reached at these points, a new amount of chemical can be added to the first stage of the process resulting again to a change in the concentration of the chemical in the mixture. As discussed before, this upset takes different times to propagate and eventually leads to a steady state at various points in the process.

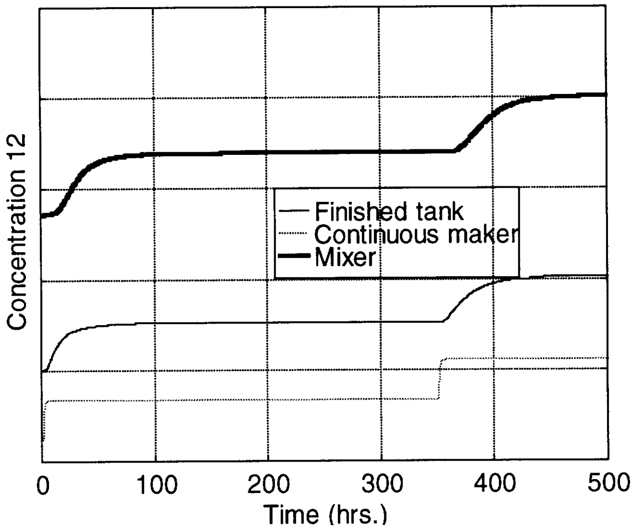

Figure 19. Effect of organizing raw material additions

This study shows the importance of the model in organizing the planning of raw materials. The model calculates the amount of chemical needed to bring dope to a desired level, and the time that it takes for each change to reach a steady state.

5.2 Design experiment – Identifying the magnitude effect of a change

In this section we describe a design experiment that the Kodak team used in order to quantitatively evaluate upper and lower bounds in the concentrations of the finished dope as a result of similar bounds in the incoming raw materials [1]. It is often the case that an upset is introduced deliberately in the process in order to correct for certain deviations from a target value. However, it is usually very difficult to predict the impact of certain upsets on the concentrations of the finished product, especially when many stages are involved in between. Often, the production people know the maximum changes they can introduce in the front part of the process without realizing the exact impact on the magnitude of the product at the last part of the process. Our model can be very useful in such a case since it can predict well the impact of such changes either if the production people know only the sustainable back end margins or if they only know the allowable front end changes.

The Kodak team designed an experiment to determine the effect of multiple variations in the concentrations of the incoming material on the finished dope. We assume that there are five chemicals[3] and for each of these chemicals there is a normal population with a mean and standard deviation. The nominal value of each concentration is the calculated mean and the maximum a concentration can change is three times its standard deviation. By formulating such a max-min problem, we help the production people identify the magnitude effects that an upset, or multiple upsets, in the beginning of the process will have on the finished dope product. In Table 1, we describe the structure of the design experiment. We assume that only four of the five concentrations can vary independently and therefore the experiment consists of sixteen runs. We have identified the maximum value of a concentration by 1 (corresponding to the mean plus three standard deviations) and the minimum value by –1 (corresponding to the mean minus three standard deviations).

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[3] Chemicals 1, 4, 10, 11, 12.

Run	C1	C4	C11	C12
1	1	1	1	1
2	1	1	1	-1
3	1	1	-1	1
4	1	1	-1	-1
5	1	-1	1	1
6	1	-1	1	-1
7	1	-1	-1	1
8	1	-1	-1	-1
9	-1	1	1	1
10	-1	1	1	-1
11	-1	1	-1	1
12	-1	1	-1	-1
13	-1	-1	1	1
14	-1	-1	1	-1
15	-1	-1	-1	1
16	-1	-1	-1	-1

Table 1. Design experiment structure

In the way the experiment is structured, one can examine the impact of multivariate changes on the concentration levels at various points in the process. As an example, we show in Figure 20 the results for concentration 11 during run 9. The concentration of chemical 11 in the mixture is plotted with time at three points of the process; the continuous maker, the finished tank and the mixer. One can see that a change in the concentration at the beginning of the process is realized after some long period of time in the later stages of the process. Moreover, depending on the ratio of the different concentrations in the mixture, the change that is realized, especially in the later stages, differs from time to time. It changes because of the interaction of the chemicals as well as the sensitivity of the chemicals to certain changes. For example, a large portion of chemical 10 is evaporated during the operation of the stream splitter. It could be the case that if the concentration of chemical 1 is decreased and the concentration of chemical 10 increased at the feed to the continuous maker, the effect at the last stage of the process would be an increase in the concentration of chemical 1. Such a scenario could not be readily analyzed without the use of a tool because of the complexity that arises in the calculations.

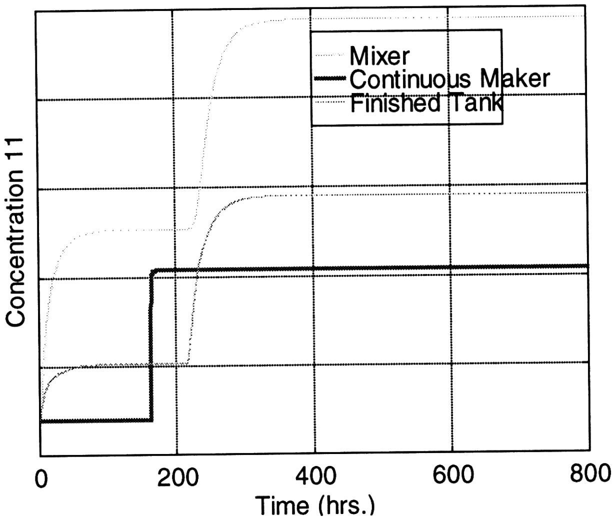


Figure 20. Design experiment results

The examined design experiment represents an important application of the model to the day-to-day production control. It predicts the upper and lower bounds in the finished dope concentrations as a result of certain changes in the incoming materials. A simpler version of this experiment examines the effect of the independent variation of each concentration. In such a way one can examine the independent effect that a change in a single concentration (as opposed to five concentrations) will have on the finished product.

5.3 Examining if a system will run out of material

This section discusses the evaluation of a new pattern of actions for the Kodak dope production process. There are always scenarios that production managers want to implement in order to improve the quality of their product or increase the throughput of a process. Nevertheless, because such scenarios are often very risky in their nature, production managers never implement them. The utilization of the model as a prediction tool for such scenarios can be a decision-making factor in implementing changes.

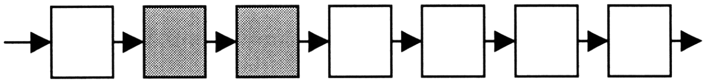
The Kodak team examined a new pattern of shutting down the first part of the process in order to clean the filters. According to this pattern, the filters were to be cleaned at more frequent intervals for shorter times. The production managers were interested to find out whether the system will run out of dope under the different demand conditions from Roll Coating. The model was able to predict the times at which the system will run out of material and to explain on physical terms why it was happening.

Chapter 6 - System insights developed by using the model

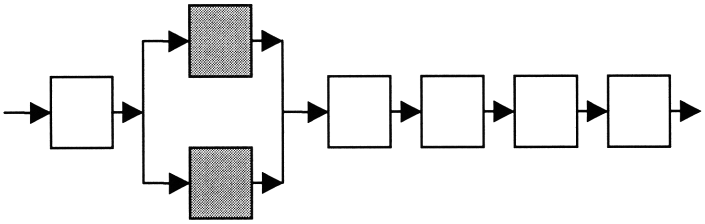
This chapter discusses the studies that we performed in order to develop system insights. There is an inherent difference between the studies of the previous chapter and the studies of this chapter; the former are used to answer short term production questions while the latter can have a significant impact on the long term goals of the production managers. We will examine the impact of difference configurations on controlling quality (Section 6.1) as well as the importance of optimal allocation of buffer space (Section 6.2). Lastly in the third section of this chapter, we will describe the effect of the various sources of variability on quality and the importance of controlling the most important source.

6.1 Tank usage studies

This section discusses the effect of different tank configurations on the quality of finished dope. We specifically examine series and parallel configurations for the crude tank in the beginning of the process and evaluate their effects on quality. The dope production is a flexible process in the sense that there is always the opportunity to change the configurations of specific systems in order to achieve certain goals. We want to investigate whether different machine configurations can have a significant effect on the variability of the finished product. For instance, we can try two different configurations, a configuration with two crude tanks in series after the continuous maker and a configuration with two such tanks in parallel (with the flow splitting in two parts). By trying different configurations, thus allocating buffer space in different ways, we want to view the impact on the variability of the finished product and determine the effect of buffer and machine allocation on the quality of the finished product. Figure 21 represents a schematic for the two different configurations.



Series Configuration



Parallel Configuration

Figure 21. Series and parallel configurations

The simulation of the two different systems, subject to the same input and initial conditions, showed no substantial difference in the quality of the dope produced from the two configurations. Figure 22 plots the results for the concentration of chemical 4 against time. We introduced various disturbances to the concentration of the specific chemical, and we can see that in both the series and parallel systems, the magnitude of the response to these disturbances does not differ substantially (the series configuration appears to be only slightly less extreme). However, there is a difference in the time that each of the two systems starts to respond to the disturbance. For the series configuration, the response to the disturbance is realized two hours later than the response of the parallel system. In effect, although both systems lead to the same steady-state results, the system with the series configuration has a slower response time than the system with the parallel configuration because the response is first realized at the first series tank and subsequently at the second series tank. This result can be particularly important for a quality strategy; the fact that the series configuration system will respond slower but also have approximately the same rise time as the parallel configuration system leads to an earlier detection of an upset when implementing the parallel configuration.

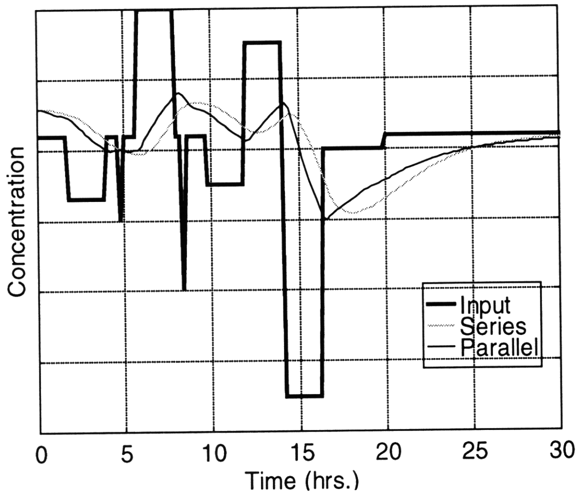


Figure 22. Series and parallel configuration results

6.2 Economical allocation of buffer space

Most quantity-based manufacturing strategies are designed to allocate optimally buffer space in a production line while maximizing the throughput. A common realization in manufacturing is that inventory has a cost, thus it should be kept at a minimum, yet throughput-maximizing, level. However, in quality strategies, increased buffer level does not necessarily remove value in the sense of increased cost, but can very effectively add value by greatly improving the quality of the product. This section examines the effects of different buffer levels on the quality of dope. We shall note that in the dope production process, buffer level corresponds to the volume of dope in a tank and hence a tank represents both a machine and a buffer at the same time.

In Figures 23 and 24, we compare two systems that were operated under identical conditions. The only difference in the two systems is the buffer level of the crude tank; in one of the systems the buffer level is twice the buffer level of the other system. Figure 23 plots the concentration after the crude tank and Figure 24 plots the concentration at the end of the process. The increased buffer level has an effect on the concentration after the crude tank. The concentration signal is smoother and the peaks are smaller compared to the small buffer system. Nevertheless, the large fluctuations in the concentrations still exist and the improvement in quality is not that great to justify the increased cost of doubling the level of the buffer.

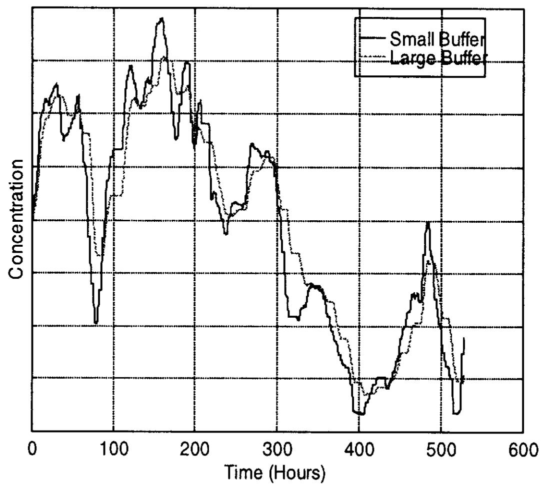


Figure 23. Effect of increased buffer level on concentration (crude tank)

The same argument is more justified by the results of Figure 24, which represent the steady-state concentration of dope at the end of the process, at the exit of the mixer. One can witness a difference in the dynamics between the two systems, mainly due to the different rise times that are caused by the difference in the buffer levels. However, in terms of improving the system's overall quality, the results are not favorable to an increase in the buffer level. The long term, large variations in the final concentration of dope are existent in both the large and small buffer systems and in terms of metrics, the standard deviation of the concentration in the two systems is almost the same. Hence, the effect of doubling the buffer level in the crude tank does not improve the quality of dope at the end of the process.

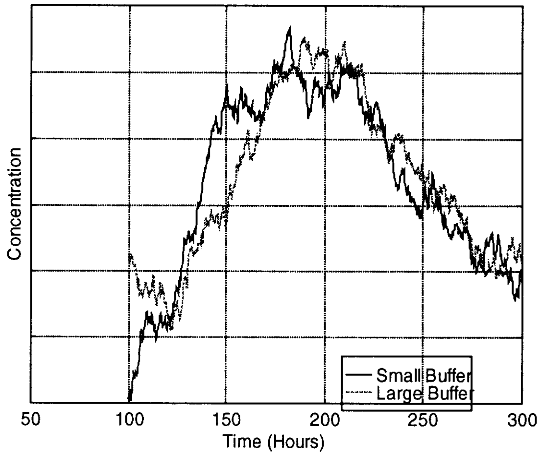


Figure 24. Effect of increased buffer level on concentration (mixer)

An alternative consideration that could possibly yield much more favorable results is to increase the buffer level of the last tank in the process, the mixer. In such a way, one could possibly succeed in both improving the quality of the finished product and also providing hedging in case machines fail and there is danger of running out of material. Figure 25 demonstrates the effect of increasing the buffer level of the mixer on the overall dope quality. Although there is a difference in the dynamics of the two responses and the large buffer response lags the small buffer response, the large variations in concentrations still exist. The short-term, small variations are smoother in the large buffer system but that does not improve the overall quality of the system since that is largely determined by the larger variations in the concentrations. The standard deviations for the two systems are comparable which leads us to conclude that the improvement in quality is very small and does not justify the large costs of excess inventory.

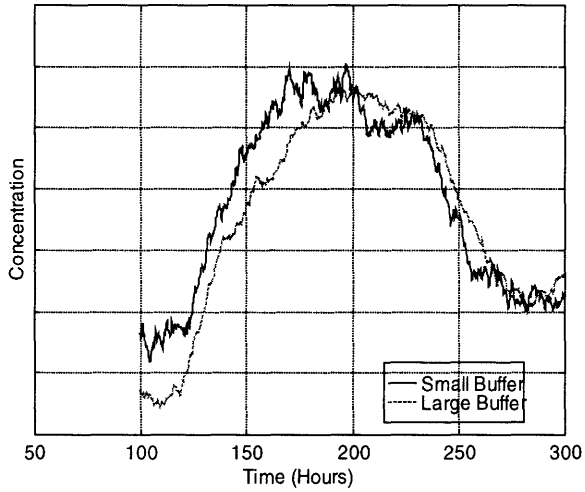


Figure 25. Effect of increased buffer level on concentration (mixer)

6.3 Identification of major sources of variability

This section describes an intriguing aspect of using the model, the identification of the major sources of variability. The biggest problem in the quality of dope is the variability in the concentrations of the chemicals that are in turn caused by variations in inputs or characteristics of the process. Hence, in order to improve the quality of dope, one should focus on eliminating the variations of the sources of variability in the process. In a perfect world, one could monitor all of these possible sources of variation and accordingly control them in order to achieve the desired quality. Nevertheless, we do live in a real world and the costs of measuring and controlling all of the parameters in a process are extremely high. Therefore, one should control only the parameters that contribute the most to the variations in the concentrations of the chemicals. Our aim is the identification of a small fraction of the sources that contribute the most variability to the process, and the focus on their control in order to improve the quality of the finished product.

We designed an experiment in order to identify the major sources of variability. However, we deviated from the traditional form of a design experiment in the sense that instead of using the actual process for the experiment we used the model, a close representation of the process. By looking at the available data and by talking to the people who actually operate the process, we were able to identify the possible sources of variability. For some of these sources, detailed measurements were available and we constructed probability distributions in order to represent them. Nevertheless, for some sources, data was not available and could not be obtained. For such sources, we assumed certain normal distributions that seemed rational to the most experienced people running the process.

As soon as the sources of variability had been identified and fitted with probability distributions, we were able to run the experiment in order to determine which of the sources of variability would contribute the most to the variability of the finished product. We tackle this issue in two different ways. First, we run a max-min experiment in which the maximum value of a variable comes from a normal population with the normal standard deviation of this variable and the minimum value comes from a normal population the reduced standard deviation. With such an experiment, we can see the multivariate effects of reducing the standard deviation of the sources, hence, of controlling the sources of variability. Second, by keeping all variables at their nominal levels of variation, we can increase the standard deviation of each variable independently and examine the individual effect on the quality of the finished product. In such a way, we can examine the impact of the variability at each source on the overall quality as well as the effect of controlling each source on improving the quality.

The standard deviation of the concentrations in the mixture is used as a metric for quality. We discuss in this section the results for one of the chemicals in the mixture as an effort to illustrate the importance of this study. We identify five major sources of variability, four of the five concentrations[4] as well as the temperature of the stream splitter. In order to reduce the number of runs, we observe that the chemicals are introduced at a constant ratio of solids to liquids. Hence, we can assume that the liquids will vary together at the same time and the solids will also vary together. In such a way, we can combine the parameters C1 and C4 into parameter C14 and likewise parameters C11 and C12 into C1112. By reducing the variables of the experiment to three we are able to reduce the number of runs from 32 to 8 which saves a great amount of computer time.

Table 2 describes the structure of the experiment. We have assigned 1 to a variable when its standard deviation is at its nominal level (i.e. the level that is usually observed in the process) and a -1 when the nominal standard deviation has been reduced to half. For instance, a -1 assignment for T2 could signify among other things that a more sophisticated controller was installed in the process and hence, the level of temperature variation reduced greatly.

Run	C14	C1112	T2
1	1	1	1
2	1	1	-1
3	1	-1	1
4	1	-1	-1
5	-1	1	1
6	-1	1	-1
7	-1	-1	1
8	-1	-1	-1

Table 2. Structure of design experiment

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[4] Concentrations 1, 4, 11 and 12. We will refer to them in the text as C1, C4, C11 and C12.

Each run represents a simulation of ten runs where each time point is sampled from a distribution.

We will now discuss the results of this experiment for chemical 1. Figure 26 plots the standard deviation in the concentration of chemical 1 for each run[5]. For the first four runs, there is no significant change at the variation levels for this concentration. If we refer back to Table 2, we observe that the variation of concentration is at the nominal level and the reductions in the variations of the liquids and the temperature do not reduce the standard deviation of concentration 1 in the continuous maker. The temperature is introduced much later in the process and hence, it does not have any effect on the concentrations at the continuous maker. Furthermore, the liquid concentrations C11 and C12 are much smaller than C1 and hence a reduction will not alter significantly the behavior of chemical 1. In the last four runs, the variability of chemicals 1 and 4 is at a reduced level (corresponding to –1 in Table 2) and as a result the standard deviation reduces during these runs.

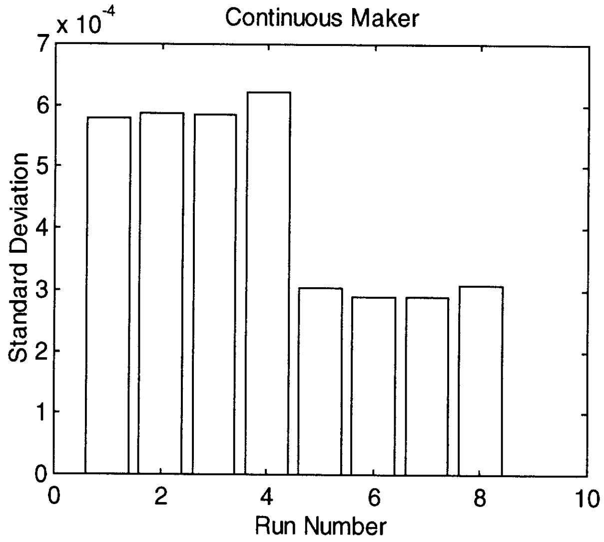

Figure 26. Variability in the continuous maker

Figure 27 plots the standard deviation of the concentration at each run for the crude tank. The variability in the concentration is reduced because of the larger buffer level of the crude tank. Nevertheless, the pattern of behavior is still the same with the

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[5] The standard deviations in Figures 26 through 31 are scaled numbers and do not represent any absolute measure but rather illustrate the relative effect of the different sources on quality.

corresponding runs at the continuous maker since the temperature variation has not yet been introduced in this part of the process and the crude tank operation is very similar to the operation of the continuous maker.

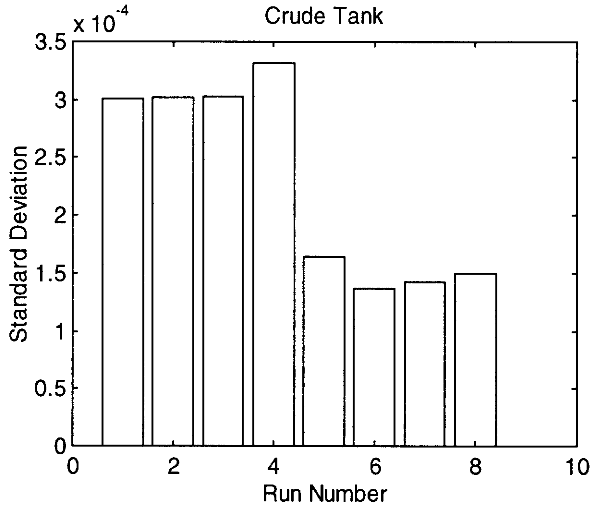

Figure 27. Variability in the crude tank

Similarly, we observe the same behavior in the finished tank where the variability is further reduced due to the additional buffering in the intermediary tanks. However, since no additional variability is introduced and because of the fact that all the tanks in the first part of the process are either mixers or pipelines, the reductions are of the same nature with the reductions observed in the continuous maker and crude tank. In Figure 28, the standard deviation for C1 in the finished tank can be seen for each run.

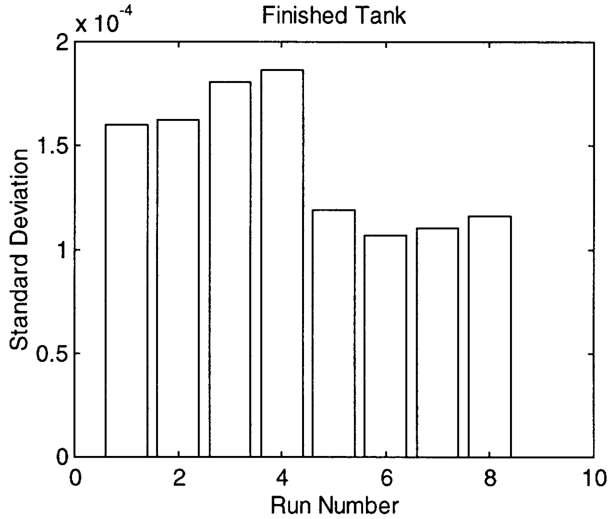

Figure 28. Variability in the finished tank

The pattern that we have been describing so far changes with the introduction of additional variability at the stream splitter. Until now, the variability had been introduced as variations in the feed of the raw materials at the entry of the continuous maker. After that point and as the mixture passes through various tanks the variability decreases as a result of buffering. However, at the stream splitter, temperature is an input and the temperature fluctuations introduce more variability in the process. In Figure 29, the standard deviation of concentration 1 in the stream splitter is higher than it was at the finished tank because of the introduction of additional variability. Moreover, for the runs where the variability of temperature is at reduced levels (even numbered runs), the standard deviation reduces as well almost by a factor of two compared to the other runs, implying a one to one relationship between temperature variation and output variation at the stream splitter.

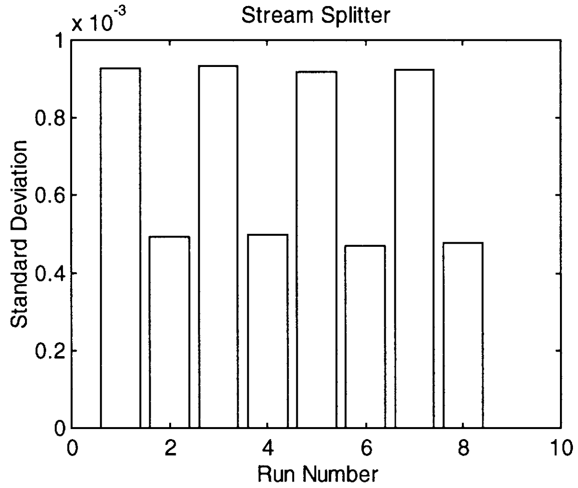

Figure 29. Variability in the stream splitter

Figure 30 plots the results at the last machine of the process, the mixer before Roll Coating. The variability in the last four runs is lower than the variability in the first four runs. Moreover, the variability when the temperature variation is at a reduced level (even numbered runs) is lower than the variability during runs with nominal temperature variation. However, the relative increase in quality that is caused by a decrease in the variation of temperature is smaller than the realized improvement caused by the control of the variations in the raw materials concentrations, even though temperature is introduced at the last part of the process.

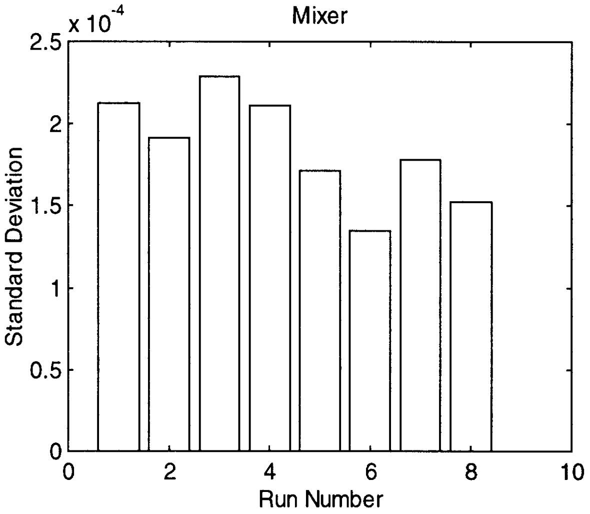

Figure 30. Variability in the mixer before Roll Coating

The importance of controlling the input feeds versus controlling the temperature at the stream splitter is also apparent from the examination of the independent contribution of each source to the overall system variability. In this experiment, all the sources of variability are kept constant except from one that is allowed to vary at its nominal level. Hence, one can observe the independent effects of each source at various points in the process. Six different runs were examined and each run corresponded to the variation of a single source. The first five runs represent the individual variations in the concentrations of the chemicals 1, 4, 11, 12 and 10 respectively, whereas the last run corresponds to the variation in the temperature of the stream splitter.

Figure 31 plots the variation in concentration 1 at the mixer before Roll Coating for each run. The largest contributor of variation is the variability in concentration 1 at the feeding to the continuous maker (run 1). The next two biggest sources of variability are concentration 10 (run 5) and the temperature at the stream splitter (run 6). The temperature variability is introduced very late into the process and hence it is expected to be part of the overall variance of the system. The variability of concentration 10 is caused by the feed to the continuous maker. However, since chemical 10 is by far the most volatile component in the dope mixture, its variability has a significant effect to the other components of the mixture, especially during the stream splitter operation where this component gets evaporated.

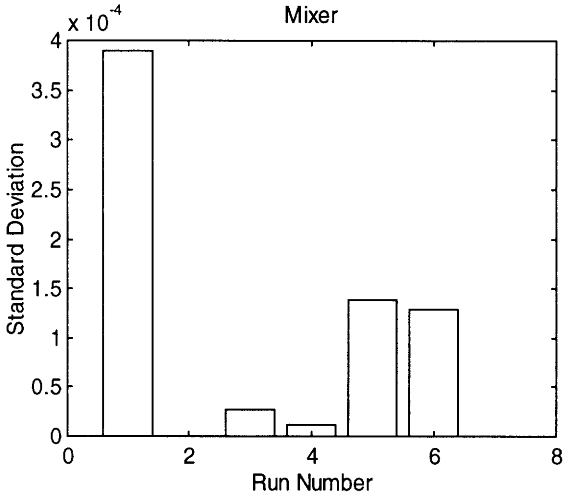

Figure 31. Individual effects in the mixer

The major source of variability is the feed to the process. The same conclusion is true for all the other four components in the dope mixture and hence, we can propose that the absence of precise control of the material entering the process is the major obstacle to improved quality.

Chapter 7 – A control strategy

This chapter proposes a control strategy to improve the quality of dope at each step of the process. The important aspect of this strategy is the interaction of the control action with the state of dope at different machines of the production line. In particular, by monitoring the state of the mixture at one machine, we can determine via an optimal feed-forward controller the actions that will improve the quality of the product at the later stages of the process. In Section 7.1, we discuss possible strategies to correct the quality of dope. Section 7.2 describes the proposed control strategy, and Section 7.3 displays the results of the controller actions.

7.1 Possible strategies to correct the quality of dope

The problem in the quality of the dope is the large fluctuation in the concentrations of its chemicals. In Section 6.3, we identified that the major source of variability in the process is the variation in the feeds of the raw materials to the first machine of the process, the continuous maker. We demonstrated that by reducing the variability in the feeds to the continuous maker we achieve a significant improvement in the quality of dope. Hence, a control strategy that is very effective is the control of the feeds of raw materials. Such a strategy is mostly a design issue since it involves the control of certain parameters of the feeding machines in order to feed the continuous maker with less variable material. We will not discuss these issues here, and we will conclude our discussion by stressing the importance of controlling these machines.

In Section 2.3.1.2, we mentioned that operators of the process add batch doctors in certain tanks in order to restore the quality of the product. We will use the addition of such substances as a basis for an optimal control strategy. If we perceive that the quality of dope is low at a tank, then by means of an optimal controller we can calculate the optimal quantity of the batch doctor that is needed in order to improve the quality of dope at the following tank. This is a feed-forward control strategy between two adjacent tanks, and if implemented for all tanks in the process, it can maximize the quality of dope subject to some constraints of the process and physical limitations. In the next section, we discuss the operation of such controller.

7.2 The control strategy

We will describe the control strategy for the general case of N chemicals in the dope mixture and the discussion can be extended to any number of chemicals without loss of generality. A key assumption behind the strategy is that there is a specified optimal concentration for each of the chemicals in the dope mixture at each stage of the process. Hence, we claim that there is an optimal "recipe" for dope that is different at each machine and eventually culminates in an optimal product.

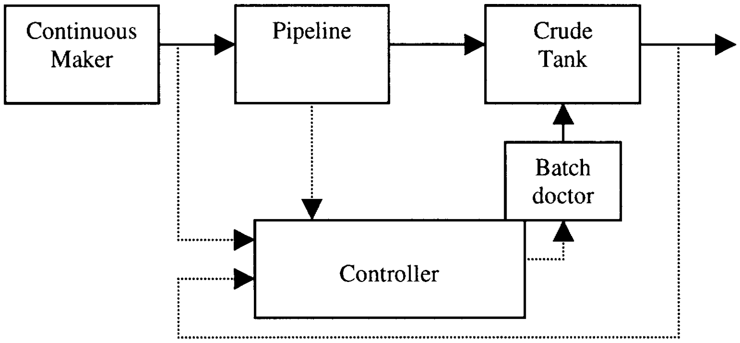

Figure 32. Control strategy schematic

Figure 32 describes the control strategy for the first two machines of the process. At each time instant, the state of the mixture at the continuous maker, the crude tank and the pipeline is fed to the controller. The controller then calculates the optimal amount of batch doctor that should be added to the crude tank in order to produce dope of optimal quality at the crude tank. Let us assume that the optimal target concentrations at the crude tank are $c_1^T,\ldots, c_j^T, \ldots, c_N^T$ and the actual concentrations are $c_1^a(t),\ldots, c_j^a(t), \ldots, c_N^a(t)$. We define the following objective function:

$$f(t, c_1^a(t),\ldots, c_j^a(t), \ldots, c_N^a(t)) = (c_1^a(t)-c_1^T)^2+(c_j^a(t)-c_j^T)^2+\ldots(c_N^a(t)-c_N^T)^2 \qquad (13)$$

The above function is defined for the time instant t. Over a time interval, we can define the cumulative objective function F as:

$$\boxed{F(t,t+T)=\sum_{t=t}^{t=t+T} f(t,c_1^{\,a}(t),\ldots,c_j^{\,a}(t),\ldots,c_N^{\,a}(t)) \qquad (14)}$$

The constraint to the minimization of the cumulative objective function is the flow of the batch doctor. We will assume that the batch doctor can be fed up to a rate of F_{BD} pounds per hour and can take only positive values. The controller runs several simulations of duration T at each time instant in order to determine what batch doctor rate at time t will minimize the cumulative objective function F for the time interval (t,t+T). We assume that during this interval the batch doctor flow is constant, thus, we calculate at each time instant the constant flow that we would input during this interval in order to minimize the objective function F. This calculation also assumes that the inputs to the crude tank from the previous stages are kept constant during the interval (t,t+T) and assume the values they had at time instant t. Hence, in such a way the controller utilizes the latest information that is available in order to predict the performance of the system subject to different batch doctor flows. By calculating the delay d at the pipeline, the controller introduces the calculated flow at time instant t+d.

We run internal simulations of a certain interval at each time instant in order to control more effectively the accidental upsets that can take place. If, for instance, we perceive an upset at the continuous maker at time t and calculate a flow based on the minimization of the objective function f (instead of F), then we would introduce the flow at time t+d and correct this upset. However, if we miscalculate the actual delay at the pipeline as d_1 and we introduce the corrective action at time t+d_1, then the corrective action could very well upset the system instead of improve it. Hence, by introducing a cumulative objective function, we succeed in a more robust and effective controller. The duration of the "internal" simulations that the controller runs, T, is dependent upon the flow rates and volume of the specific machine at the time instant of the calculation. It should be long enough in order to let the system reach a steady state and short enough to keep the computer time of the calculation small compared to real-time.

At the next time instant, the algorithm continues in the exact same way. The controller runs new internal simulations and calculates a new optimal flow for the batch doctor. Hence, the flow is actually updated at each time instant instead of being kept constant. The same control strategy can be implemented for every tank in the process provided that there are known optimal concentration targets and sufficient metrology.

7.3 Results of controller actions

In this section we discuss a simple study to illustrate the effectiveness of the controller for the dope production process. We assume again the schematic of Figure 32 and five concentrations for the dope mixture. For simplicity, the target concentrations for the crude tank are all 0.2 and the input to the continuous maker has initially all concentrations at the 0.2 level. We allow the input concentrations to vary greatly after the first hour and we examine the responses. Figure 33 plots the controlled and uncontrolled responses of the concentration of chemical 1 at the crude tank. The uncontrolled response is very variable and fluctuates between 0.21 and 0.175. The controlled responses greatly reduce this variation and the signals have a lower bound of 0.197 and an upper bound of 0.1996.

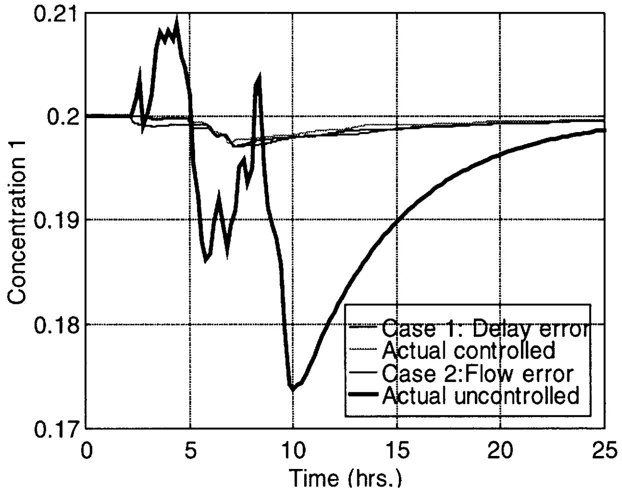

Figure 33. Comparison of controlled and uncontrolled responses at the crude tank

Figure 34 plots the effort of the controller. That represents the flow of the batch doctor, which was constrained between zero and 1000 pounds per hour. The flow varies a lot during the first five hours and it gradually diminishes as the concentration approaches the optimal target.

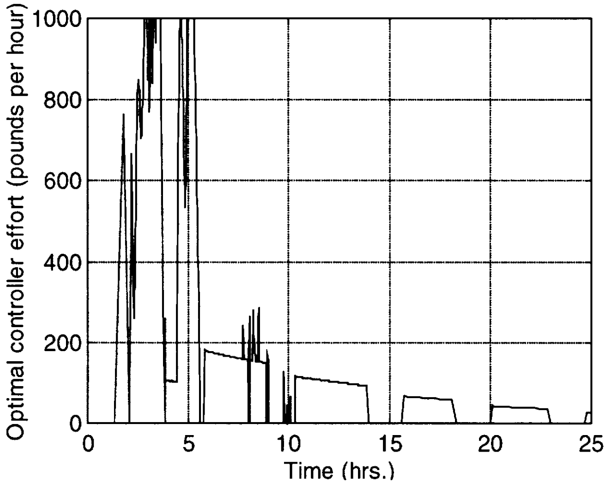

Figure 34. Plot of the controller action

There are three cases of the controlled response plotted in order to illustrate the low sensitivity of the controller to miscalculations of certain parameters of the system. For all three cases, the response follows a similar path; almost identical compared to the uncontrolled response of the system. All controlled responses result in a more stable concentration, implying a dope of higher quality (less variable) than during the uncontrolled case.

Figure 35 plots the three different controller cases on a larger scale. The three cases differ in the assumption of certain parameters of the system. Sensors or models often are not perfect measures of the parameters of a system, and it is a good idea to check the sensitivity of the controller to such errors. The first case examines the controller action if the controller had known the actual value of these parameters while the other two cases involve errors in the actual value of a parameter. In the second case, the delay of the pipeline is 10 percent higher than the actual value and in the third case, the flow to the crude tank is 10 percent higher than the actual flow. The controller is not very sensitive to such errors, and the differences in the responses are not great, implying that the controller is also very robust.

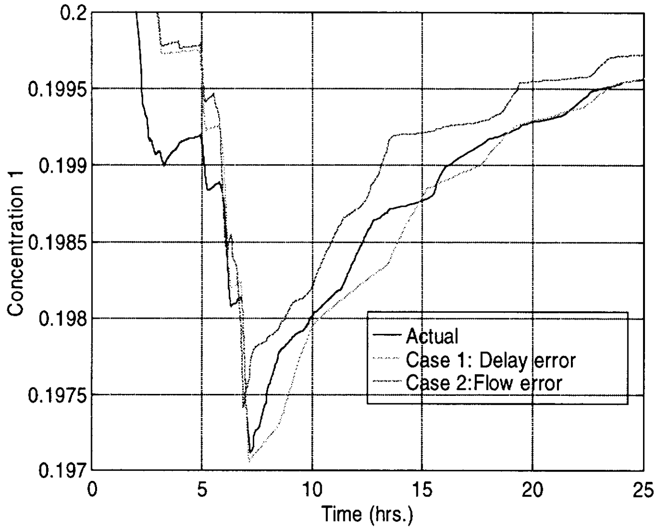

Figure 35. Comparison of the controlled responses at the crude tank

The above study assumes a batch doctor solution consisting of equal proportions of two out of the five chemicals. An extension to the proposed control strategy stems from the availability of more batch doctor solutions that can be used to control the concentrations of dope. At each time instant, the controller could decide not only what the flow is but also which one of the solutions is optimal. However, there is an additional constraint to this optimization problem since the batch doctor solution can not change faster than the minimum time required to change the setup of the inflow.

Chapter 8 – Conclusions

8.1 Summary

This thesis has presented a tool to evaluate quality strategies for the Kodak dope production process. It provides a specific example of a physically-based model of quality for complex manufacturing processes and serves several short-term and long-term goals. In the short run, it serves as a computer model used by the Kodak dope production managers to train operators and improve their understanding of the process based on physical explanation rather than empirical feeling. For the long run, it points to a more general direction of formulating quality strategies for a general class of manufacturing processes and letting this methodology be used by managers of such operations. In developing this model, we defined quality as a function of certain states of the system, namely the concentrations of the chemicals, and we physically modeled the operations of the process in order to predict these states and subsequently the quality of the system.

We introduced a model that can predict the quality at each step of the process and that is flexible enough to achieve different configurations in order to evaluate quality strategies. The model was validated by comparing the predicted output with actual process data subjected to the same inputs. We demonstrated the usefulness of the tool in examining day-to-day production scenarios and in developing system insights. Finally, we illustrated the effectiveness of the model in designing strategies to control the quality of the product.

8.2 Further work

There is certainly plenty of room for future work on this topic in two separate arenas, the industrial and the academic. On the industrial side, there is further work to be done at Kodak to take advantage of the capabilities of the developed tool. We propose that additional testing of some components be done in order to gain more confidence for operations of the process that could not be tested due to lack of metrology. After gaining more confidence, we propose that Kodak uses the improved model as an estimator of the process. Figure 36 describes the proposed real-time utilization of the improved model. At each time instant, process data is fed into the model that simulates the process faster than real-time and subsequently serves as a decision-making tool. The decisions can be made either by the operators who monitor the process or by installed optimal controllers such as the one that we described in Section 7.2.

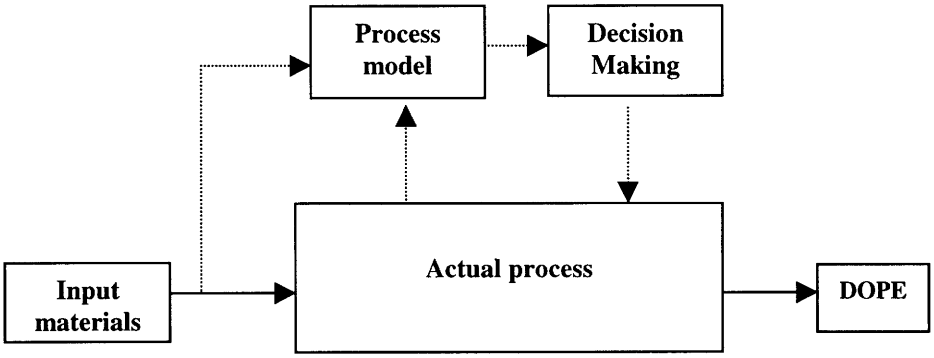

Figure 36. Real-time utilization of the model in the Kodak dope production

On the academic side, the examination of other examples of mixing manufacturing operations can extend the model. Such examples can be found in the Industrial Coatings division of Polaroid or the paint production process of General Motors, to name a few. We propose that modeling of new processes includes the unreliability of machines (our model did not address that issue) and reactions among the chemicals of the mixtures. A more formal incorporation of quality as a state should be considered when examining such new operation examples. The integration of quality and quantity decision making using such models is of high interest in jointly optimizing these two needs. A good deal of work remains to be done. However, even at this early stage of development, the importance of this research both in the short run and especially in the long run is readily apparent.

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