Using the Seven-Step Method to Reduce Defects in a Polymer Sheet Making Process

by

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B.S. Chemical Engineering—Yale University (1988)

Submitted to the Sloan School of Management
and the Department of Chemical Engineering
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Management
and
Master of Science in Chemical Engineering

in conjunction with the
Leaders for Manufacturing Program
at the
Massachusetts Institute of Technology
June 1994

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Abstract

The Eastman Kodak Company has been making polyethylene terephthalate (PET or polyester) film base under the trademark "ESTAR" for almost 35 years. The product goes into photographic applications such as x-ray films, microfilm, and graphic arts support. This work examined the issue of particulate, known as inclusions, in the film. The company has divided them into the categories of small (10-40μm) and large (>40μm).

Recently the inclusions, which have always been in the product, have become a focus for the company because of the more refined applications for which the customer is using the product. At the same time, the issue is viewed as a long-term strategic one since customers do not currently cancel orders because of inclusions but may do so in the future with increasingly stringent, new applications. In addition, the organization does not scrap much product because of inclusions, which are acceptable to most customers within a certain set of specifications that the process can meet repeatably for most products. The task was to find out the most important causes of inclusions across the multidivisional process flow.

The task developed into using the Seven Step Method to identify the primary causes of inclusions in the product. This methodology has been used at other companies such as Teradyne and Analog Devices with success. The course of the work takes the problem through the first three steps and into the fourth. The primary activity was following the methodology to reduce the problem to a manageable one, collecting process and product data related to the hypothesized causes of inclusions, and analyzing the data using partial least squares techniques to determine the factors that track most strongly with inclusions.

The analysis suggested that the most significant contributors to inclusions consisted of machine cleaning, catalyst component concentration variability, degradation reaction products, and the presence of molecular oxygen trapped interstitially in the incoming polymer. Further work and specific improvement activities are suggested.

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The author would like to acknowledge gratefully the support and resources made available through the Leaders for Manufacturing Program, a partnership between the Massachusetts Institute of Technology and major U.S. manufacturing companies.

Acknowledgments

First of all, I would like to thank those directly involved with the project. The enthusiastic support of Kodak employees Tony Spatorico, Ed Hoffman, John Border; those in Kodak's Roll Coating Division; in the Polymer Manufacturing Division; and in the Chemometrics Group stands out as particularly noteworthy. There is certainly a risk of having to listen to what you might not want to hear when supporting an LFM internship project. Nevertheless, I appreciate the fact that Kodak employees were much more open to me than I ever thought they would be to an outsider. In addition, I am grateful to my MIT advisors, Steve Graves and George Stephanopoulos, for their time, insight, and guidance.

I would also like to acknowledge my parents and siblings for their support and for keeping my address in pencil the past few years. Finally, a special thanks goes to my grandparents, living and deceased, the most educationally fortunate of whom got to finish a couple years of high school; and the least, the fourth grade. I don't think my three university degrees will ever top their intelligence, cleverness, and hard work.

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Overview of Thesis Work

The work for this thesis centered around a quality improvement effort at one of the Eastman Kodak Company's film substrate-making facilities. Specifically, the project focused on finding the primary causes of particulates, known as inclusions, that can be found imbedded in the substrate, which henceforth will be referred to as web. Although the inclusions are small enough and in low enough concentration for most applications, Kodak desires to position the product to enable its use in newer applications with tighter specifications. This goal means decreasing inclusion levels. To set the framework for this document, the content of the different chapters is described below.

- **Chapter 1**

  This section provides an overview of the product and the manufacturing process. It also details the chemistry behind the polymer production and degradation.
- **Chapter 2**

  This section describes the inclusion issue, provides information about its magnitude, and summarizes the extent of knowledge about inclusions before this particular study commenced.
- **Chapter 3**

  This section describes the approach taken to determine the primary causes of inclusions.
- **Chapter 4**

  This section describes the data collection procedure.
- **Chapter 5**

  This section describes the methodology used to analyze the data and details the data and data transformations used in analysis. It also describes the results of the data analysis and some verification of the conclusions.
- **Chapter 6**

  This section gives actions for reducing the problem by using the results of the data analysis.
- **Chapter 7**

  This section provides a more general discussion of some significant lessons taken from the study.
- **Appendix**

  This section contains the normalized data.

Chapter 1: Introduction to Product and Process

This chapter introduces the product under study, as well as the manufacturing process and chemistry used to make it.

ESTAR® Product

Kodak has made a biaxially oriented polyester (polyethylene terephthalate or PET) web under the trademark "ESTAR" since the early 1960s for a variety of photographic and non-photographic applications. The largest single company application for this material is x-ray films, which are photographically active. Producing transparent films for the printing and publishing industry consumes the second largest amount of web internally. Recently, Kodak has also begun selling its polyester film to a few outside customers.

ESTAR Facilities

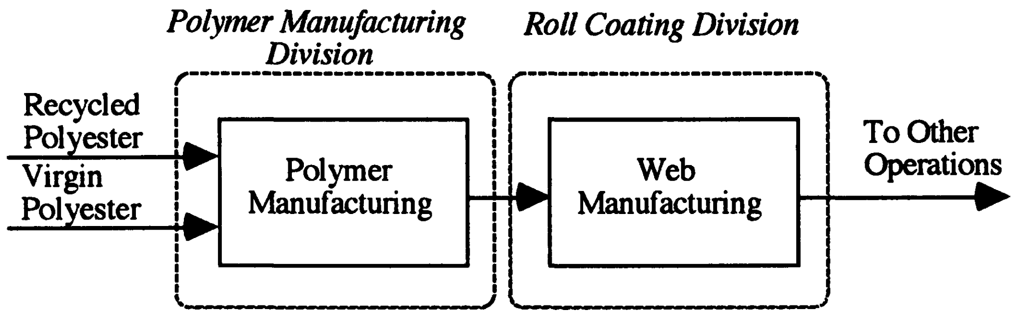
The company has four manufacturing sites spread across the world for the PET web. Each of these facilities supplies plants that further convert the product to other forms. The work for this study was done at the main plant in Rochester, New York, U.S.A. This facility remains unique for the following reasons:

- It has its own raw material production facility on site
- It has the most machines
- It has the largest product mix

ESTAR Process Overview

On site, other organizational units produce raw materials that are supplied to the web-making plant. The polyester originates from both recycled material and virgin material. The raw materials for the polymer are reacted on site to make material which can be fed into the web-making process. The block diagram in Figure 1.1 shows the simplified process along with the organizational unit to which each operation belongs. Later discussion gives further details on each block.

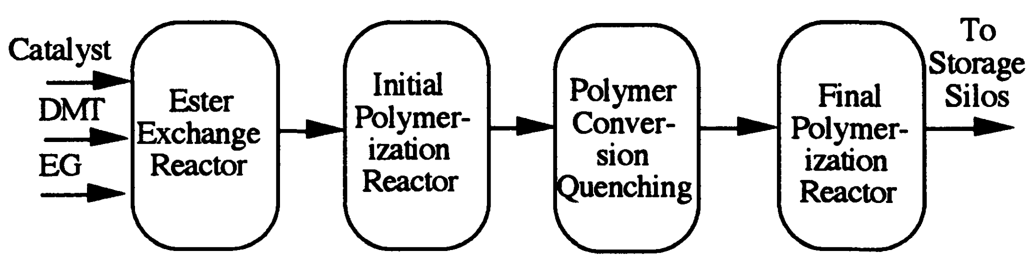
Figure 1.1: Conceptual Process Flow with Organizational Units



Polyester Recycling and Manufacturing

Kodak operates one of the few polyester recycling operations in the world. The inputs into the process are recycled materials such as x-ray film and other PET material. The mix of recycled material can and does change from day to day or week to week. The company also conducts processes to produce virgin polyester from raw materials. In this process, parts are run in batches, while other ones run continuously. Figure 1.2 provides a conceptual process diagram of the polyester manufacturing operation.

Figure 1.2: Polyester Manufacturing Conceptual Process



The reaction itself occurs in two steps. The first one, ester exchange or transesterification, substitutes ethylene glycol groups for the terminal methanol groups. The resulting product represents the monomer for the condensation reaction that follows. The condensation reaction is actually carried out in two stages of the process. Both the ester exchange and the condensation reactions are summarized in Figures 1.3 and 1.4 . The reverse reactions also occur, but the kinetics and equilibrium are not discussed in detail here. Although both reactions involve catalysts, details of the catalytic cycles are also not discussed here.

Figure 1.3: Ester Exchange Reaction

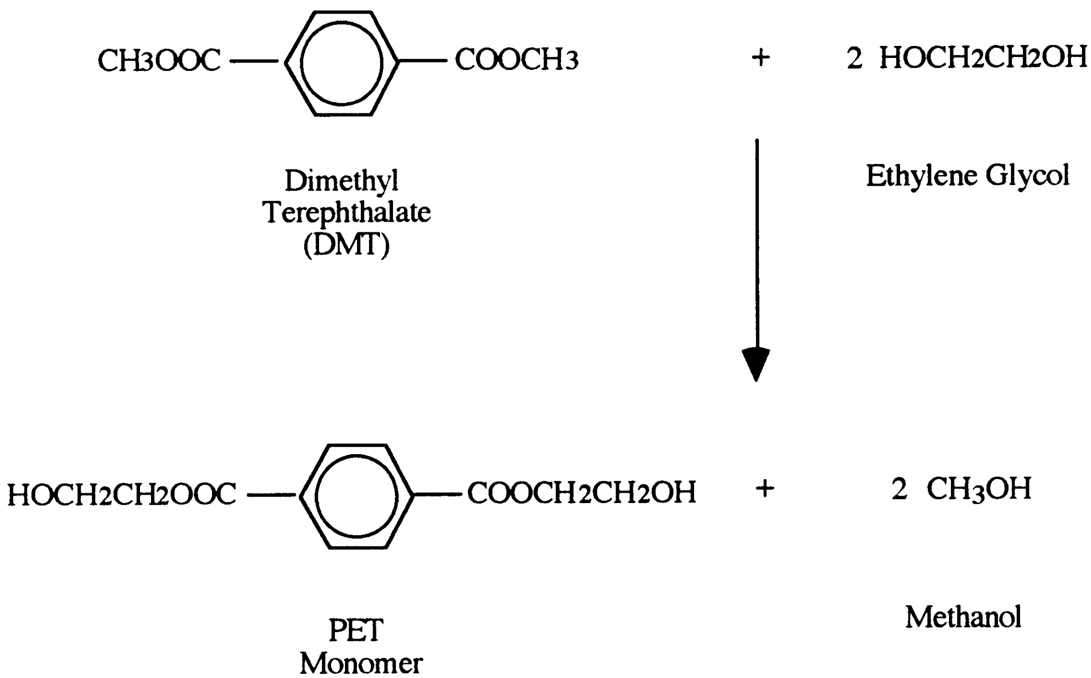
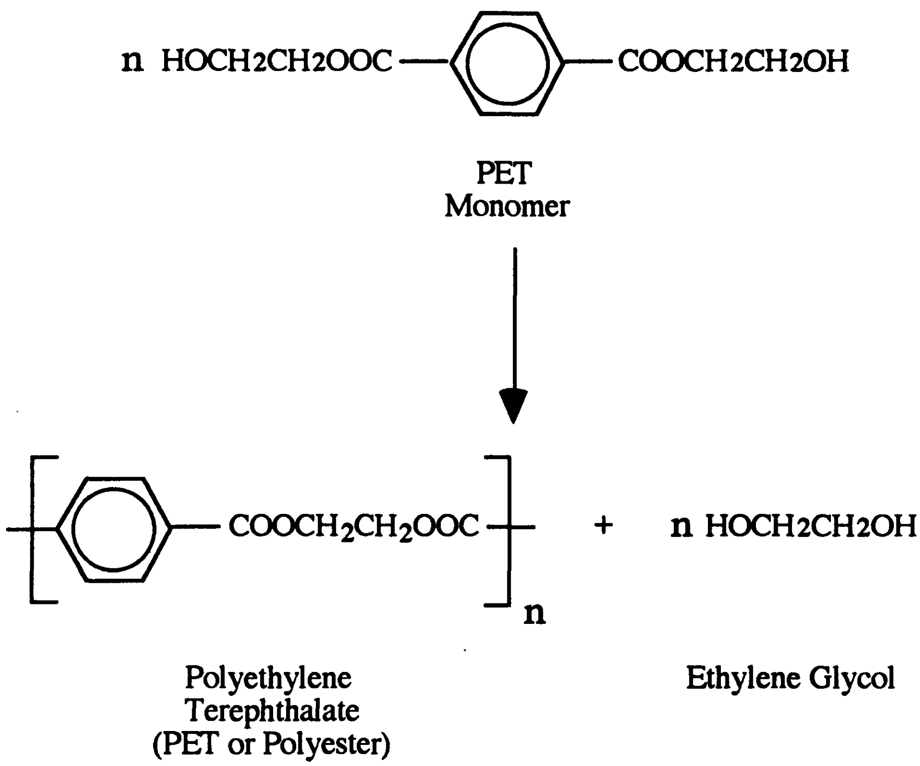


Figure 1.4: Condensation (Polymerization) Reaction

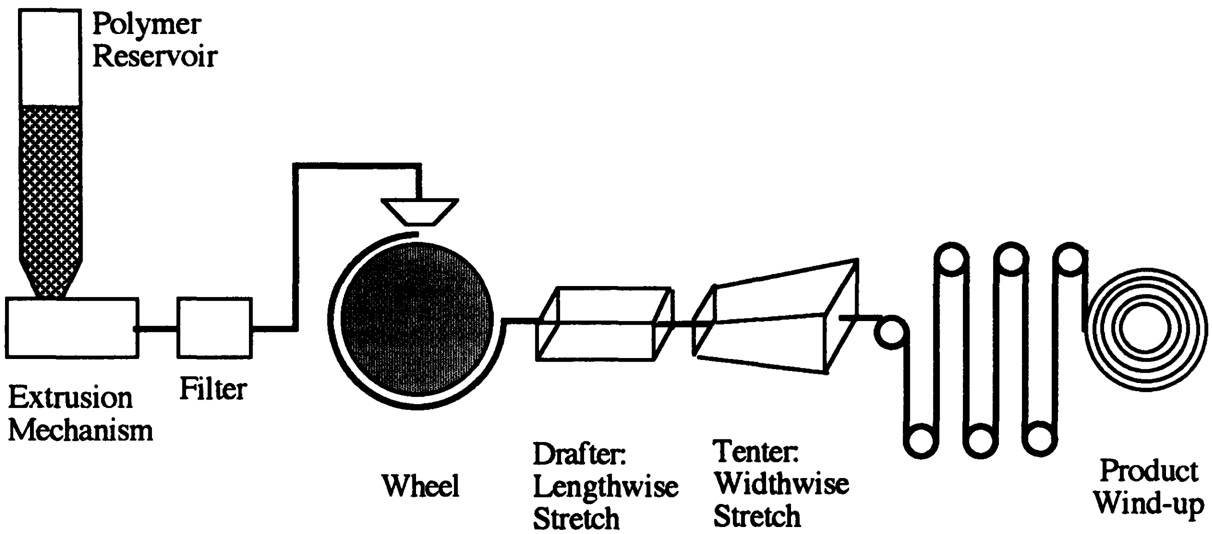


After the polymer achieves a certain chain length, the material is fed into a mixing chamber, into which a stabilizer is added. The actual function of the stabilizer is to block the progression of the ester exchange reaction. From the mixing chamber, the material proceeds into a silo, in which it is blended with the polymer from other batch lines. Anecdotal information suggests that the stabilizer also helps quench the condensation reaction.

Web Manufacture

The polymer produced feeds into a hopper, from which several web-making machines draw material to make the product. Figure 1.5 gives a conceptual diagram of the web manufacturing process flow.

Figure 1.5: Web Manufacturing Conceptual Process Diagram



An extrusion mechanism softens the material, which then feeds onto a wheel. The resulting film is several times thicker than the final product. As the web comes off the wheel, a mechanism called the drafter stretches the film out in the direction of the process flow. At the next major step, the tenter stretches the web normal to the direction of the process flow. Finally, the web is wound onto a roller. At different points throughout the web manufacturing process, primer coatings can also be applied to the web.

Degradation

The chemistry of the process as explained above simplified the actual situation by detailing only the desirable reactions that happen. At various stages in the recycling, polymerization, and web-making processes, the material is at appropriate conditions to undergo degradation reactions. The polyester chains do undergo undesirable side reactions that fall into two basic categories: polymer cross-linking and polymer degradation. Degradation can occur by a natural thermal means or also by side reactions with other substances such as water (hydrolysis of the ester bond). Mechanisms for cross-linking are more complicated. Examples of thermal degradation (Figure 1.6), hydrolytic degradation (Figure 1.7), and cross linking (Figure 1.8), are provided.

Figure 1.6: Thermal Degradation Reaction[1]

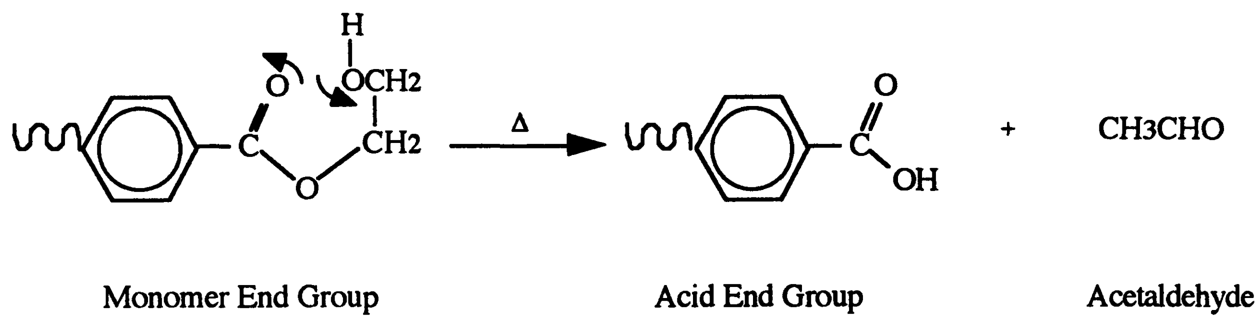
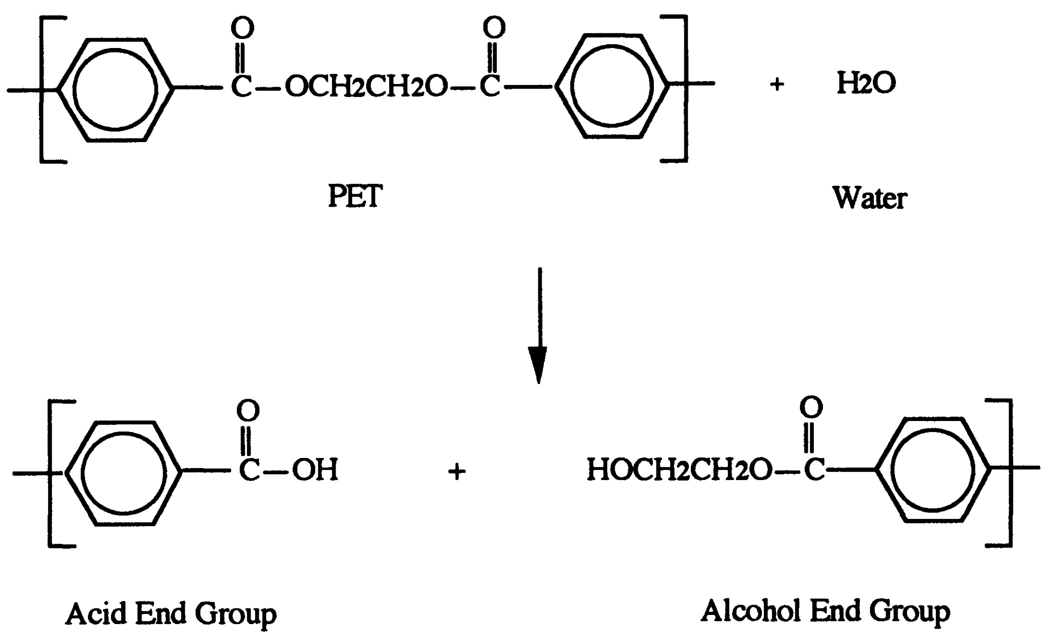
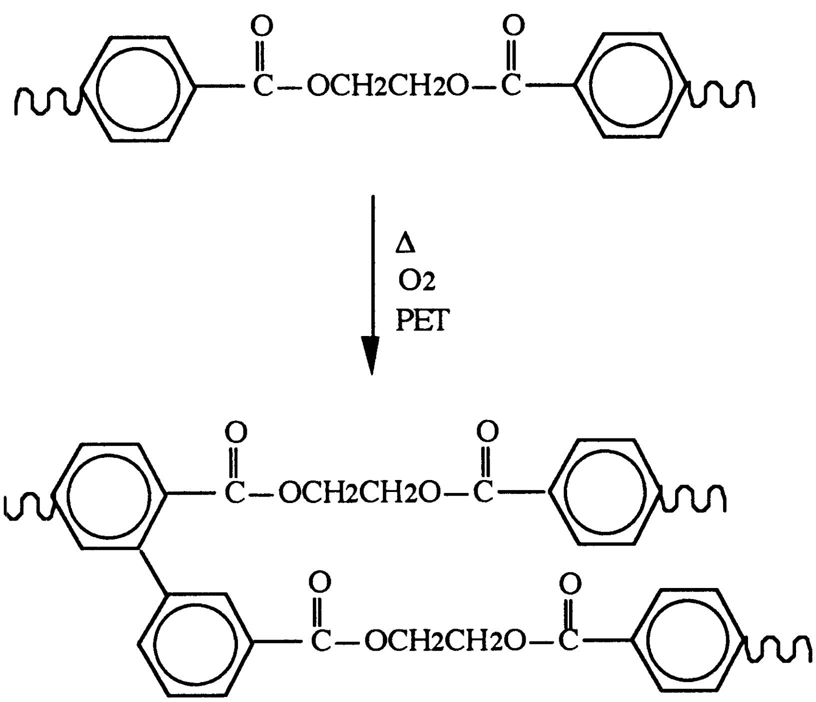


Figure 1.7: Hydrolytic Degradation Reaction



[1]Ravindranath and Mashelkar, "Polyethylene Terephthalate—I. Chemistry, Thermodynamics, and Transport Properties," *Chemical Engineering Science*, Vol. 41, No. 9, 1986, pp. 2197-2214.

Figure 1.8: Thermal-Oxidative Crosslinking of PET[2]



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[2]Nealy and Adams, *Journal of Polymer Science:* Part A-1, Vol. 9, 1971, pp. 2063-2070.
This mechanism is drawn conceptually rather than stoichiometrically. This is also not the sole product of PET crosslinking; rather, it is provided as an example.

Chapter 2: Description of the Problem

With the previous chapter's information on the process and the process chemistry as background, this chapter will describe the problem that this study addressed.

Background of Problem

The company has become increasingly concerned in the past few years over inclusions in the web. The presence of the inclusions, however, is not new. They have been there since the process was started up in the 1960s but were not problematic. Nevertheless, they are a problem now for two general reasons:

- Some new customer applications are very sensitive to inclusions.
- The inclusions might accelerate the plugging of the filter media that remove particulates from the molten plastic.

Defect Description and Measurement Technique

Inclusions have been classified into two varieties according to size. The two types are listed as follows:

Description	Size
Large	> 40μm
Small	10 - 40μm

As a further detail, the large inclusions are visible with the naked eye, whereas the small ones usually require magnification. Both types of inclusions are inspected by human eyes through a cross-polarizing screen with a background light source. In the normal procedure for counting the large inclusions, a 12" by 12" square of sheet is cut from a roll. As it is viewed under the light, each inclusion identified is circled with a film negative marking pencil. The total is noted. For the small inclusions, a 1-cm-diameter circle is drawn onto the sheet and is then inspected under a microscope in cross-polarized light. For comparison purposes the number of inclusions is normalized to account for the fact that demand calls for several different thicknesses of web. Since different thicknesses of web are made, the same area of material does not represent the same mass.

Because human eyes are involved in the inspection process, non-repeatability should be a concern. Although checking for inclusions beyond a certain size is an actual production task, keeping track of the inclusion count and logging the number is not. Typically only the process technician views the web for the purposes of collecting data. To verify the method, the technician and the author both inspected the same blind samples and came up with the following data, which have been normalized:

	Large Inclusions		**Small Inclusions**	
Serial Number	Technician	Author	Technician	Author
1	x	0	3y	y
2	7x	9x	5y	3y
3	7x	5x	4y	3y
4	2x	4x	12y	6y
5	27x	43x	113y	111y
6	29x	40x	300y	209y
7	67x	60x	250y	227y
8	38x	64x	125y	73y

While the data do not indicate complete repeatability and in some cases show large differences in count, they do indicate that the technician and author were identifying the same types of features as inclusions. For the purpose of data generation in this study, both the technician and the author looked at each sample used as a data point. Alternatively, either could look at the samples on two different occasions to ensure consistency. If the two views produced vastly different results, the sample was studied until the differences could be reconciled.

Analytical Information

It is critical to understand the chemical composition of the inclusions in order to determine the process parameters that influence them. Many samples of inclusions have been analyzed over the past few years. Although the company has developed useful techniques for freeing the inclusions for analysis, still only the large ones can be analyzed. It should be mentioned that several "outbreaks" of inclusion have happened and were attributable to specific, identifiable causes. The persistent, baseline ones are the focus here. The list below gives the chemical description of inclusions identified along with the possible source:[3]

Family	Possible origin
Organic acid	Terephthalic acid
Organic salt	Terephthalate salts of catalyst metals
Agglomerated PET	Cross-linked material
Chloride	Primer
High melter	Trimerized monomer

Why the Defect Is an Issue

The defect is an issue for two principal reasons. A description of why each is significant is discussed below.

Product Concerns

The area in which there is the most impact is one in which the customer use of the product is so stringent that inspection with laser scanners is necessary for the incoming product to ensure that light will be able to pass through all parts of the sheet. To a lesser degree, inclusions are also a problem because they cause surface non-uniformity. Such non-uniformity can cause discontinuities in the coatings that are applied over the sheet and result in undesirable final sensitometric properties.[4] While the inclusion issue impacts only a small minority of the end-use customers, it is believed that this small minority may grow to a larger percentage of the customer base and perhaps limit gaining new customers. Internal benchmarking studies have generated the following summary of relative inclusion count magnitudes for several disguised alternative brands. The normalized numbers reveal that in some cases other companies produce cleaner web in this specialty market. In light of the availability of this cleaner web, the threat of not gaining new business has credibility, at least in the specialty market studied.[5]

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[3]Internal company analytical reports.

[4]If there is a thinner photographic layer over an inclusion, that area will appear different from the surrounding area.

[5]The source of this information is an internal benchmarking analysis subjecting competitors' web to the same test. The material tested was 0.007" thick and was intended for a printed circuit application. The large inclusions are those found in approximately 1 square foot of this material; whereas the small inclusion count it that from a circular field of view 20mm in diameter.

Company	Large Inclusions	Small Inclusions
Kodak (Rochester)	x	2y
W	0	0
X	2x	20y
Y	0	y
Z	0	y

Process Concerns

The presence of inclusions is believed to impact the manufacturing operation. Standard in polyester processing, the melt is filtered before extrusion. As the filter removes particulate from the melt, the media fill up with the particulate. Over the past several years, the manufacturing group has noticed the service life of the extrusion filters has been decreasing. Productivity loss results because production must stop long enough to change out the filter. The manufacturing organization assumed that an increase in inclusions must be involved because the small ones are on the order of the size of the pores in the filter medium. Although it is plausible to reason that inclusions might be responsible in part, it is difficult to conclude with certainty for the following reasons:

- Detailed inclusion count data do not exist for more than 2 years, whereas filter life data exists for at least 10 years.
- Even in the past two years, the filter data have not been continuously correlated with the inclusion data.
- Maintenance schedules have changed.
- Filter medium has changed.
- Production system has changed.[6]

Similarities with Other Industries

A great deal has been studied about defects of this size in the context of polyester manufacturing. In the latter, filaments are drawn through a small orifice known as a spinneret to form the fiber. Defects of the size given above cause problems in the fiber industry because they can plug spinnerets. In fact, most of the literature identified about

[6]As part on an ongoing effort to reduce cycle times and inventory levels, the web manufacturing operation conducts more product changes that in past years. These product changes might produce conditions that would allow inclusions to form.

the issue is written in the context of the fiber industry. The following excerpt, however, suggests that the issue is the same one. The defect is described as "grains with included core" which "in polarized light...can be observed particularly well."[7] The defect characterized in this description was analyzed to be a polyester gel.

Awareness

Although most people in the manufacturing organization and the supply chain are aware that the issue exists, there is little feeling that the problem actually has a product cost. For the most part, the current accounting system does not assign a significant cost to the issue because entire rolls of material often can be reclassified as rolls for less stringent—and more plentiful—applications. In addition, no specific internal goals for reducing inclusion counts have been set although this situation might well change once clearer understanding of the process variables that drive inclusions is at hand.

Information that the business units have provided through the product engineers suggests that customers do not cancel product orders because of the problem. Furthermore, they rarely return product because of inclusions. In the product line that consumes the most base, there is the report of a "stray" inclusion every two to three months.[8] It is difficult to quantify the number of customers that balked and did not buy the product because it contained inclusions. At least two of the six lines of business say that high price is the major reason why customers and prospective customers cease or never begin to buy the product. There is the feeling in the company that some prospective customers that are concerned about the price of the final good would also be even more strongly dissuaded against using the product because it contains inclusions or possible other blemishes. From the business unit feedback, however, no prospective customer has ever stated a concern over inclusions explicitly.

The problem at hand, therefore, becomes more of a strategic issue than an issue of reducing current accounting losses. The problem is difficult to sense because there seem to be so many contradictory factors. For example, the problem is perceived as an important one to solve, yet product does not get rejected because of the issue. Trying to overcome these apparent contradictions to determine what might be necessary to solve

[7]Hoffrichter, "Investigation of Grains in Polyester Filaments," *Faserforschung und Textiltechnik*, No. 19, 1968, pp. 304-312. and
Broughton, "The Detection and Analysis of Particulate Contamination in Poly(Ethylene Terephthalate) Filament Yarn," *Textile Research Journal*, March 1976, pp. 155-158.
[8]Internal company information.

the problem became the subject of a KJ.[9] The problem statement of the KJ read: "What stands in the way of inclusions being solved?" The final grouping or answer said: "The perceived non-financial nature of the inclusion issue de-emphasizes the analytical and organizational attributes necessary to solve it." This answer is striking because it suggests that non-financial impact—or at least the non-financial perception—is a major problem here. This will become the topic of later discussion.

Who Works on the Problem

A group of employees in the web manufacturing operation and its supply operations comprise an improvement team chartered with reducing the defect. The functional description of the people involved in the team is listed below:

List of the employees on the defect reduction team
Web Manufacture Product Engineer (Team Leader)
Web Manufacture Product Engineer (Consultant)
Web Manufacture Process Engineer
Web Manufacture Maintenance Representative
Web Manufacture Technician
Polymer Process Engineer
Internal Technical Consultant (Recent addition)

The team is comprised of people, most of whom have demanding responsibilities in day-to-day manufacturing or maintenance needs. An internal technical consultant also takes part in team activities but works on extrusion-related issues on a development basis rather than on a sustaining routine. Still, this consultant is no less busy than the others since he has many projects to work on within the web manufacturing operation. Management intends that he focus more on the inclusion issue once there is a greater understanding of what the major causes of the problem are.

The team holds meetings twice per month. Usually the agenda for the meeting is issued shortly before the meeting. The team leader, who prepares the agenda, often solicits input from the other team members to see if they are interested in having any of the meeting time. If an item does not make it onto the agenda, the meetings are not so

[9]KJ is a abbreviation for Kawakita Jiro, a Japanese professor and founder of this method, which uses groupings of concrete, observable facts to make broader generalizations about the sources of problems. The description of the method can be found in *A New American TQM* by Shoji Shiba, *et al.*

rigidly run that additional items cannot be discussed. Usually, however, there are more items to be discussed than time permits. Members of the team usually are not explicitly required to come to the meeting; accordingly, approximately one-fourth of the team members might be missing from any one meeting.

There are several observations that could be made from observing the meetings. During the meetings, the members discuss the projects they are working on to reduce the magnitude of the defect. The members of different organizational groups usually discuss issues as they relate to their organization. In effect, the team is not working to find a global optimal for reducing the defect. Rather members seek out factors within their individual organizations that they believe can impact the problem and work on those issues. In many ways the two different organizational units (Photochemical and Polymer Manufacturing Division and Roll Coating) blame the other for the problem. Because of the polite culture of the organization, however, team members usually do not voice their concerns explicitly.

Another strong undercurrent is the rewards for individual performers. Like many other companies in the 1990s, this one is headed more toward work in teams instead of the more traditional agglomeration of individual efforts. The old culture is slow to change, however. Employees still feel as though individual performance is ultimately what is rewarded.[10] Accordingly, employees working on the issue feel that they must latch onto the part to which they can contribute the most and execute that part, rather than having the group outline the work as part of an overall plan and then dividing up the work on a priority basis.

Previous Work

As a result of previous meetings and work in general, the groups involved determined in May 1992—slightly over a year before the current study began—the following list of items that might be impacting the inclusions issue.[11]

- Air Leaks
  - Can cause gels to form.
- Water Contamination
  - Can degrade polyester into acids.
- Dead Spots in Line
  - Long residence time can cause polyester to degrade thermally.
- High Molecular Weight PET
  - Can become insoluble in bulk material.

[10]Personal discussions with company personnel.
[11]Taken from an internal company memo.

- High Stabilizer Level
  - Can form insoluble salts.
- Low Stabilizer Level
  - Can allow reactants to form degradation products.
- Insulation Problems with Resin Lines
  - Can cause cold spots in line and increase residence time.
- Improper Resin Line Cleaning
  - Can leave residue to break off into product.
- Resin Contamination
  - Can provide raw materials to form side reactions.
- Raw Material Filtration Problems
  - Can allow for passage of material that has not been filtered properly.
- Shutdown/Start-up Frequency
  - Can cause flow disturbances that could cause material to flake off or could increase residence time, allowing for degradation to occur.
- Catalyst Quality/Level
  - Insolubles may be formed.
- Miscellaneous Contamination
  - There are several other sources of contamination in the process that could exacerbate the problem.
- "Plugged" Resin Filter
  - As the filter pores fill, the likelihood increases that a trapped particle will become "untrapped" and pass through the other side.
- Raw Material Quality
  - Other contaminants might be coming in with the raw materials.

The list is lengthy and somewhat unmitigating when the amount of time and effort that might be required to examine all the items on the list in close detail are considered. It will be discussed later, however, that some of the items are ramifications of the same process attributes.

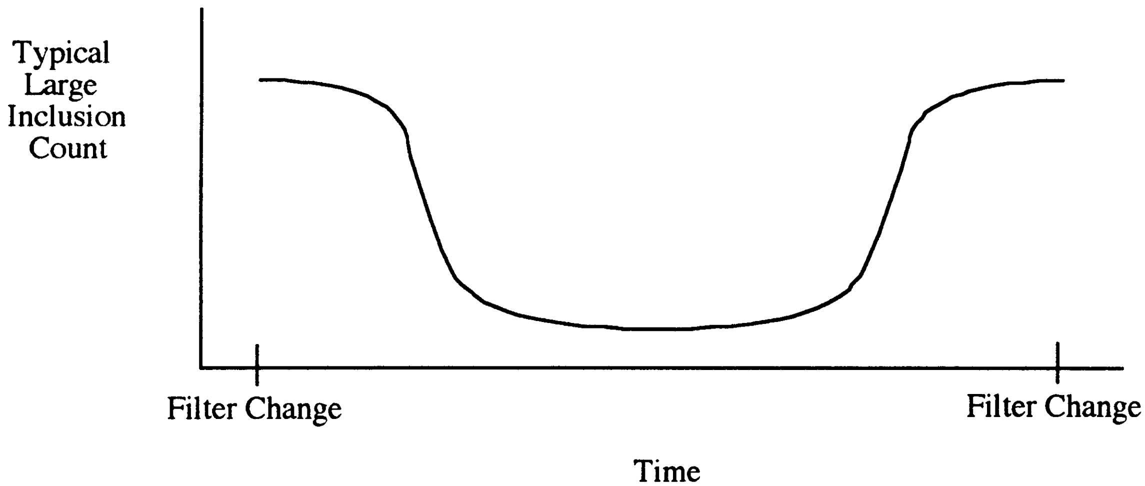
Part of the current work tried to examine how many of the previous items had been addressed. The most conclusive work done prior to the current study suggested the following correlations:

- Inclusions increase as more material is passed through the same filter elements.
- Small inclusions track with primer contamination.
- Small inclusions increase when recycled material is being used.

Filter Service

The more of the media that get filled with particulates, the more particulates come out in the final product. The conceptual graph in Figure 2.1 illustrates the usual observation of inclusion counts as a function of the life cycle of a resin melt filter.

Figure 2.1: Inclusion Count with Filter Life Schematic



It is believed that the inclusions start out high because of the process upset involved in changing the filter. They then subside for a while before increasing as the filter service time increases.

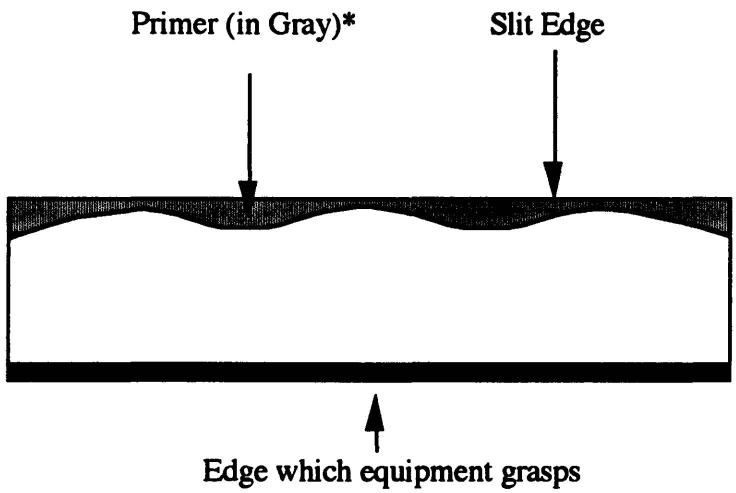
Recycling

A certain amount of the web edging is slit off and recycled. Since this material has already been extruded, returning it to the process increases the average residence time of the bulk. This increased time allows additional time and conditions for the thermal, hydrolytic and cross-linking degradation reactions to happen. The recycled polymer also contains primer coatings, which may be part of the problem.

Primer

The primer margin, which is a narrow band of the coating material originally placed onto the sheet, inevitably remains on the recycled edging and is returned to the process. The group had previously worked with a statistician, who determined that the number of small inclusions tracked with the width of primer margin parameter. It is thought that the material comprising the primer can supply raw materials for degradation products to form.[12] Figure 2.2 illustrates a piece of edging showing the primer margin.

Figure 2.2: Primer Margin on Slit Edge



*Primer margin is considered the area in gray.

No Common Database

Although the company had conducted experiments and correlations, no common database of information was produced. With different groups working on different aspects of the same problem at the same time, lack of a common database meant that there was little certainty that a change in the number of inclusions could be related to a specific action that had been taken since activities were sometimes confounded.

The Result

Although the problem spanned several organizational units in possible origin, the highly divisionalized or compartmentalized nature of the company enforced a natural inclination for an organizational unit to work on issues that were completely within its realm. For example, the Maintenance Group, which keeps the filter parameter data, lies in an entirely different functional organization from the group that manufactures the web. Although the two groups work closely together on many issues, the organizational structure causes a natural division of labor that may not be the best one for solving the

[12]Some large inclusions have been determined to contain chlorine, which is related to the composition of the primer.

problem of inclusions. A specific example of this is the non-integrated filter life and inclusion database. Although inclusions seem intuitively tied to filter life, data could not be identified to prove the point.

The company recognized that perhaps its own structure has interfered with solving the problem, and this reason helped it to make the decision to support a study conducted with the help of someone that the company's structure and past biases have not encumbered.

Chapter 3: Deciding What to Do

The previous two chapters have provided background information on the process and product, as well as the problem of inclusions. This chapter and the subsequent ones address the issues of determining the causes of inclusions and suggesting solutions.

Brief Overview of Work

This task began with interviewing a variety of people who had been involved with the issue—even if only peripherally—in the past. The subsequent tasks began with actually working many of the different line jobs in the process to gain familiarity with the whole process. To clarify the work done, categories of activities and the approximate amounts of time spent at each are summarized below.

Number Weeks	Activity
2	Getting acquainted with the people and the organizations
4	Working in Polymer Manufacturing to gain understanding of the processes
2	Working in Roll Coating to gain understanding of the processes
4	Presenting the plan for the actual work and gaining collective ideas through meetings
4	Preparing for data gathering and understanding the implementation requirements better
6	Gathering data on the previously determined process variables (and other tasks)
4	Performing data analysis, confirmation, solution planning, and final results

Perhaps the most difficult conceptual part of the work involved trying to realize the difficulties that the company faced in the past in trying to solve the problem. Since the problem was really a strategic one that had possible origin in a few distinct organizations, definite challenges involving trying to cut across the organizational boundaries and increasing awareness lay ahead. The focus became trying to determine the primary causes of inclusions in light of the environment described. Of course, the only reason for wanting to know what the causes are is to eliminate the problem. This purpose could be divided into three parts, which are then discussed in detail:

- Making the problem manageable.
- Framing the task as a solution plan that could work in a busy manufacturing environment while simultaneously unifying the effort.
- Providing some tools to raise awareness about the problems from the standpoint of there possibly being greater costs associated with the problem today than had previously been thought.

Making the Problem Manageable

Meeting

The first step in the solution process became gathering together all parties involved. It was necessary to gain input from these people to determine the current state of knowledge of the items from the list of possible inclusion causes generated several months before. To do this, two meetings were convened to bring forth the old issues together with new developments. The two meetings discussed the same type of information. The reason for having two meetings instead of a single one arose more as a result of manageability issues than of any other consideration. Having two meetings instead of one also served the purpose of encouraging uninhibited dialogue since groups that might affect the comments of each other were not scheduled for the same meeting. Each meeting lasted about three hours. The organizations represented in each meeting and the contribution each organization made are summarized in the following table.

Organization	Meeting	Principal Contributions
Polymer Manufacturing	First	Details of the polymer manufacturing process and past inclusion improvement efforts
Analytical	First	Summaries of past analysis done on inclusions
Research and Development	First	The possible mechanism behind inclusion formation
Web Process Engineering	Second	Details of the web making process and past inclusions improvement efforts
Maintenance	Second	Information dealing with filter service life
Process Development	Second	Information on how the process might lead to inclusion mechanisms

The request before each meeting was that the invitees come prepared to discuss any facts they can add concerning the items on the list as well as anecdotal or "gut feel" types of information. The stated deliverables from the meetings were as follows:[13]

- A list of process parameters to monitor simultaneously
- A list of noise variables affecting the process
- A series of experiments to test the effects of the parameters discussed in the meeting
- A quantified goal for the improvement effort (both in terms of time and number)
- A forum for communicating about the inclusions issue
- A list of improvements for reducing the factors that have stood in the way of solving inclusions in the past

During the actual meetings, the plan of annotating each new item with large amounts of new, systematic information did not happen as planned. Essentially the meetings revealed that there was not a great deal more systematic information known beyond the original three points discussed previously. In essence, the knowledge that we did not have enough data was some of the most valuable information gained. The meetings were very helpful in assessing which of the factors could be examined further and how this would be done. Therefore, from the group input, the following list of factors on which to keep concurrent data emerged. The specific factors are as follows:[14]

List of process parameters to monitor simultaneously

- **High molecular weight PET**
  Analytical results have suggested that some inclusions are made of high molecular weight PET. Monitor:
  - Oxygen level of polymer coming into the web-making machine
  - Residence time of the material

- **Catalyst level/quality and interaction with stabilizer**
  The literature has suggested degradation processes that the catalyst system could cause. Monitor:
  - Catalyst and stabilizer levels in polymer coming into the web-making machine

- **Recycling contamination/primer contamination**
  Past work at Kodak has indicated that primer contamination could lead to inclusions; moreover, the recycled polymer generally has more acid end groups resulting from its different thermal history. Since the analytical results have indicated that some inclusions are terephthalate salts—a byproduct of acid end groups—then it is

[13]Taken from meeting notice issued by Michael Raftery to all invitees on August 20, 1993.
[14]Meeting minutes issued by Michael Raftery on 9/1/93. Some items were added later.

reasonable to suspect that some inclusions might come from the recycle. Monitor:
- Amount of recycled material
- Average primer margin

- **Water contamination in the process**
The literature has stated that hydrolytic breakdown of the polymer can lead to acid end groups, which could be linked to inclusions by the reasoning just given. Monitor:
    - Intrinsic viscosity of the polymer entering the process and leaving the process
    - Water vapor trapped interstitially in the bulk polymer[15]
    - Acid end group concentration in the web and in the polymer[16]

- **Oxygen contamination in the process**
The literature states examples (cited previously) of oxygen leading to PET cross-linking, which leads to higher molecular weight PET, a compound found in some inclusions. Monitor:
    - Interstitial oxygen content entering the web-making machine

- **Degree of filter plugging**
Kodak has observed that, after start-up of a clean filter, inclusions rise as the filter starts to plug. Monitor:
    - Pressure difference between upstream and downstream sides of the filter
    - Filter head number (not all filter heads have the same area)
    - Cumulative resin throughtput through a filter

Occasional tracking of data from these factors in the past revealed that there exist natural perturbations in both the process parameters and the output responses (number of inclusions). Trend tracking for later multivariate analysis emerged as a reasonable first step. In addition, it was surprising that a short list of process monitoring variables determined in the meetings could elucidate so many of the individual issues that the company determined previously as important. The accompanying list is the same one from Chapter 2. In review, the list contains possible contributing factors to inclusions as Kodak determined months before this current study began. Written under each item on the list is the process monitoring activity —mentioned above— that would address the possible inclusion source.

- Air Leaks
    - High molecular weight PET
    - Oxygen contamination in the process
- Water Contamination
    - Water contamination in the process

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[15]Doing this would allow a test for possible air/water leaks in the web making equipment only. As the polymer degrades, its chain length shortens and it becomes less viscous. Intrinsic viscosity is a parameter that is relevant because the hydrolysis reaction is a faster degradation reaction than thermal decomposition and is therefore more likely to cause degradation and, thus, viscosity loss.
[16]Doing this should allow for testing of thermal degradation of the polymer in the web-making equipment at least to some degree.

- Dead Spots in Line
  - High molecular weight PET
- High Molecular Weight PET
  - High molecular weight PET
- High Stabilizer Level
  - Catalyst level/quality and interaction with stabilizer
- Low Stabilizer Level
  - Catalyst level/quality and interaction with stabilizer
- Insulation Problems with Resin Lines
  - **Not covered here**
- Improper Resin Line Cleaning
  - Timing: collect data around cleaning
- Recycling Contamination[17]
  - Primer margin parameter/use of recycle
- Raw Material Filtration Problems
  - **Not covered here**
- Shutdown/Start-up Frequency
  - High molecular weight PET
- Catalyst Quality/Level
  - Catalyst level/quality and interaction with stabilizer
- Miscellaneous Contamination
  - There are several other sources of contamination in the process that could exacerbate the problem.
- "Plugged" Resin Filter
  - Degree of filter plugging
- Raw Material Quality
  - **Not covered here**

A list of noise variables affecting the process

The meeting also generated a list of noise variables to be aware of when collecting the process data:[18]

- Air and water leaks
  - These leaks are typically non-predictable.
- Filter type changes
  - There is a project underway to change some of the filter element types in the polymer manufacturing and recycling operations. The results after the change could be different from the ones before the change.
- Catalyst Composition Change
  - There was a program in effect to change the level of some catalyst components. The inclusion counts before and after the change could be different.
- Change in Filter Room Procedure
  - Some of the maintenance procedures in the filter room were to be changed. This change could make results before and after the change different.

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[17]As it turned out later, recycle itself did not become part of the study because the data were gathered around the existing process rather than creating perturbations (experimentation). All of the data gathered were produced with recycling being on.

[18]This list was taken from the Meeting Minutes written by Michael A. Raftery and issued on 9/1/93.

- Special Causes
  - There are inevitably incidents in which the inclusion level changes because a certain atypical action is taken.

A series of experiments to test the effects of the parameters discussed in the meeting

The first experiment would not be an experiment at all, but rather a process monitoring of the different parameters determined to be important. This differs from experimentation *per se* because the process inputs are not deliberately disturbed in this instance. Since both the dependent and independent variables undergo natural perturbations, it became attractive to take advantage of these natural perturbations as a first pass at getting the information without upsetting production schedules.

A quantified goal for the improvement effort (both in terms of time and a number)

As part of the meeting, the participants received a feedback sheet that asked several questions including each participant's input on the magnitude of improvement and the date by which it could be achieved. The averages were as follows:[19]

Average reduction of inclusions as % of original number:	52%
Time required to accomplish this:	10 months

It was clear that the student would be around to help only for six months. Therefore, the student's work would be finished when the time allotted for the improvement elapsed. The student did not consider it reasonable to force these numbers on the group and therefore just let the number be known informally.

A forum for communicating about the inclusions issue

The group agreed that the best forum for communication would be the mainframe-based electronic mail available on site. The attendees also indicated the willingness to participate in a short meeting every month.[20]

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[19]The average of the values from the surveys collected.

[20]As it turned out, no other meetings were held with so large a group of participants. Instead, some smaller meetings were held on a less regimented basis than once per month.

A list of improvements for reducing the factors that have stood in the way of solving inclusions in the past

A question was posed in the meeting to get the participants thinking about why the inclusion problem has been difficult to solve. The spirit of the question is attributable to a quotation from *The Fifth Discipline* by Peter Senge: "True proactiveness comes from seeing how we contribute to our own problems."[21] The context was appropriate because the Production Manager for the web manufacturing operation considered the inclusion reduction undertaking to be a proactive solution. In the spirit of Senge's statement and the Production Manager's intention, the question posed to the meeting participants was: "How do we contribute to our own problems in solving inclusions?"

The responses to the question fell into three categories, the specifics of which were relayed to management:[22]

- Technical Issues
  - Many people had already formed a conclusion about what was responsible for inclusions, and they wanted their idea implemented.
  - Many people were frustrated by the fact that we did not know which "knobs" to turn to impact the number of inclusions.
- Low Awareness
  - There was a lack of understanding about what inclusions were.
  - There was no quantified goal for improvement.
  - There was insufficient data gathering or reporting.
- Organizational issues
  - There was no ownership of the issue.
  - There was a need for better communication between the polymer manufacturing operation and the web manufacturing operation.

Many of the statements made in the feedback indicated a large amount of friction between the two organizations involved in making the web. The reason for asking for feedback in this area was to provide management information to enhance the likelihood of solving the problem. During the course of the work, management received the feedback. Since changing the relationship between the two groups would require much more time than that available for the work, no further work was done on this issue.

The Seven Step Method

At the meeting, the Seven Step Method for quality improvement was introduced.[23]

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[21] Senge, *The Fifth Discipline*, 1990, p. 21.
[22] Presented by Michael Raftery in the Project Update on October 15, 1993 in which the Division Managers for both the web manufacturing operation and the polymer manufacturing operation were in attendance.
[23] Shiba, Graham, and Walden, *The New American TQM*, 1993, pp. 73-140.

The method represents a refinement in the continuous improvement concepts that the American international quality guru Deming brought to Japan in the 1950s. In fact, the company's own internal process improvement methodology is probably based on Deming's ideas. Several Japanese academics and industry representatives (e.g., Kume, Shiba) further refined Deming's ideas into more implementable steps. A greater, more practical credential of the process is that its application in the United States has been facilitated with success by the Center for Quality Management at actual companies such as Analog Devices[24] and Teradyne.[25] Although these companies did not set out to solve technical problems specifically, the methodology is general enough that it can apply to a variety of problems, including technical ones. An explanation of the steps is discussed below:

1. **Theme selection**
   - This step defines the problem and describes its importance.

1a. **Initial hypotheses***
   - This step provides a list of possible causes to guide the data gathering effort

   *This is not an "official" part of the process as depicted by others. It is added because it is difficult to know what data to gather if there is not some initial hypothesis that is to be tested.

2. **Data collection and analysis**
   - This step collects data to determine which areas need to be looked into further.

3. **Causal analysis**
   - This step analyzes the data to determine which three primary areas the improvement areas should address.

4. **Solution planning and implementation**
   - This step formulates a way to solve the problem and puts the proposed solution into effect.

5. **Evaluation of effects**
   - This step makes sure that the solution determined actually works. If it does not, the process iterates back to step 4 to reformulate the solution.

6. **Standardization**
   - This step ensures the solution becomes built into the process so that it happens as automatically as possible.

[24]Fraser and King, "Seven Steps To Reducing Paperwork For Field Sales Engineers," *The Center for Quality Management Journal*, Vol. 2, No. 2, Spring 1993. and
Buss, "7-Steps to Reducing New Product Time-to-Market," *The Center for Quality Management Journal*, Vol. 1, No. 1, Autumn 1992.

[25]Bradley and Petrolini, "How a 7-Step Process Reduced Road Blocks Impeding Quality Improvement Teams at Teradyne," *The Center for Quality Management Journal*, Vol. 2, No. 1, Winter 1993.

7. **Reflection on process**
   - This often-overlooked step looks back over the process to evaluate what might be done differently if the problem were to be solved over again. This information is useful in approaching different problems later on.

How the Inclusion Issue Fits into the Methodology

At the time of the meeting, some of the steps were already complete or were far along. This section describes how the work was to proceed along the steps of the methodology:

Theme selection

The theme had already been formulated in large part at the project inception:[26]

Reduce inclusion level in product to increase outgoing quality and increase filter life.

Ideally some refinements needed to be made:

- There needed to be a quantified goal as an improvement. This issue had been discussed earlier.
- A cost of inclusions was necessary. Making an estimate of the future cost associated with the issue might focus more attention onto it:

"We'll lose x% of our sales by 1995 if we don't reduce inclusions by y%"

- A deadline for the project was needed. The methodology guidelines suggest that it usually takes only three to four months to complete all seven steps.[27] From the start it was expected that the process would require more time than that.

Initial hypotheses

The initial hypotheses consisted of the factors that the group considered important from prior consideration and from the meetings. These items have been listed earlier.

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[26]Michael A. Raftery. Thesis Proposal, August 2, 1993.
[27]Shiba, MIT Sloan School "Total Quality Management (15.766) course notes, 1992.

Cost of Inclusions

In trying to estimate the actual cost of inclusions, a few different approaches are possible for evaluating the impact:

Possible Costs of Inclusions
Added recycling costs
Added operating costs (filter changes)
Product changes
Customer dissatisfaction (actual or anticipated)

Of these possibilities, customer dissatisfaction provides the primary reason for undertaking the reduction effort and arguably should be the metric to assess what the issue costs. To address the other two issues briefly, the only one that is directly measurable is the added recycling costs. Since rolls are very infrequently scrapped for inclusions, it could be argued that pursuing the inclusion issue to reduce scrap would save relatively little money. The issue of decreased filter life has likely had contributors from several other areas such as change in media and procedures. It would, therefore, be difficult to marginalize any effect inclusions might have on the number of filter changes that have to be performed. Another reason for concentrating on the product cost rather than the possible cost in filter changes is that concentrating on filter changes defocuses the improvement effort away from what ultimately matters: customer satisfaction with the product.

There certainly exist difficulties in trying to attach a cost to customer dissatisfaction. In this case the problem lies in trying to quantify the amount of business lost or not gained because of the issue. For this reason, an approach that assumed lost market share was taken.[28]

The calculation was made that a certain small percentage of Kodak's business in the product line most sensitive to inclusions would have a net present value of ($4.4 M).[29] The main point is that the entire profit margin on the end product is lost, rather than just the cash flow conversion cost of transforming the polymer material into web. This number could be used to increase awareness when solution plans are in place or to make capital decisions.

[28]Representatives from Kodak Financial Services Division have said that lost market share arguments have been used as the basis for assessing the worth of solving problems in the past (specifically involving capital expenditures). The "certain small percentage" is not given for confidentiality reasons.
[29]Various company cash flow discounting and margin criteria were used to calculate this number.

Remaining Steps

The other steps in the Seven Step Method involve carrying out the plans set forth in the meeting described above. These steps are the subject of the next three chapters.

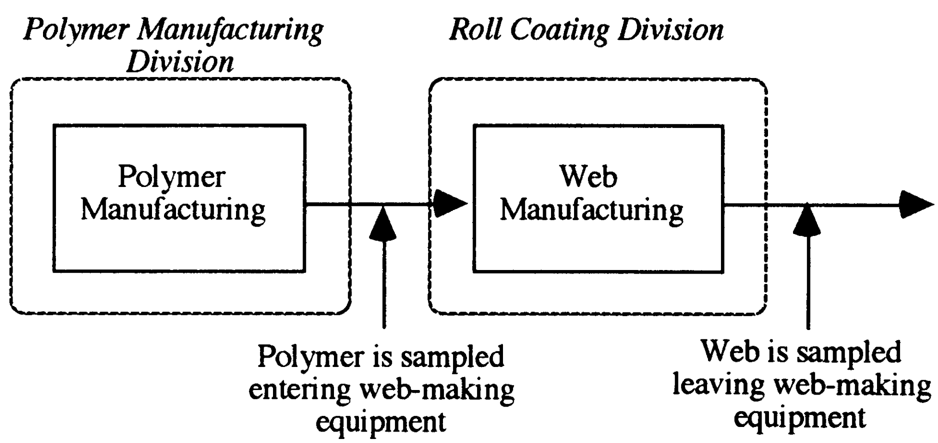
Chapter 4: Collecting the Data

As the previous chapter described, the major focus of the work came from gathering and analyzing process data that had not been gathered simultaneously before. This chapter describes the data gathering process.

Sampling Point Overview

In short, the goal was to see how some of the attributes of the polymer change as it is processed. There were a variety of points in the process to gather polymer samples (either in resin form, final web form, or intermediate forms). The choice for gathering pre-extrusion resin samples at the polymer entry into the web making machines (or exit from the polymer hopper) arose in large part to circumvent the averaging that results from polymer lines feeding into the same hopper. Coincidentally, the data gathering was split along organizational boundaries. The actual reason for the split was the technical one given above. Figure 4.1 depicts the sample gathering points on a backdrop of the organizational structure.

Figure 4.1: Sampling Points along the Process Flow



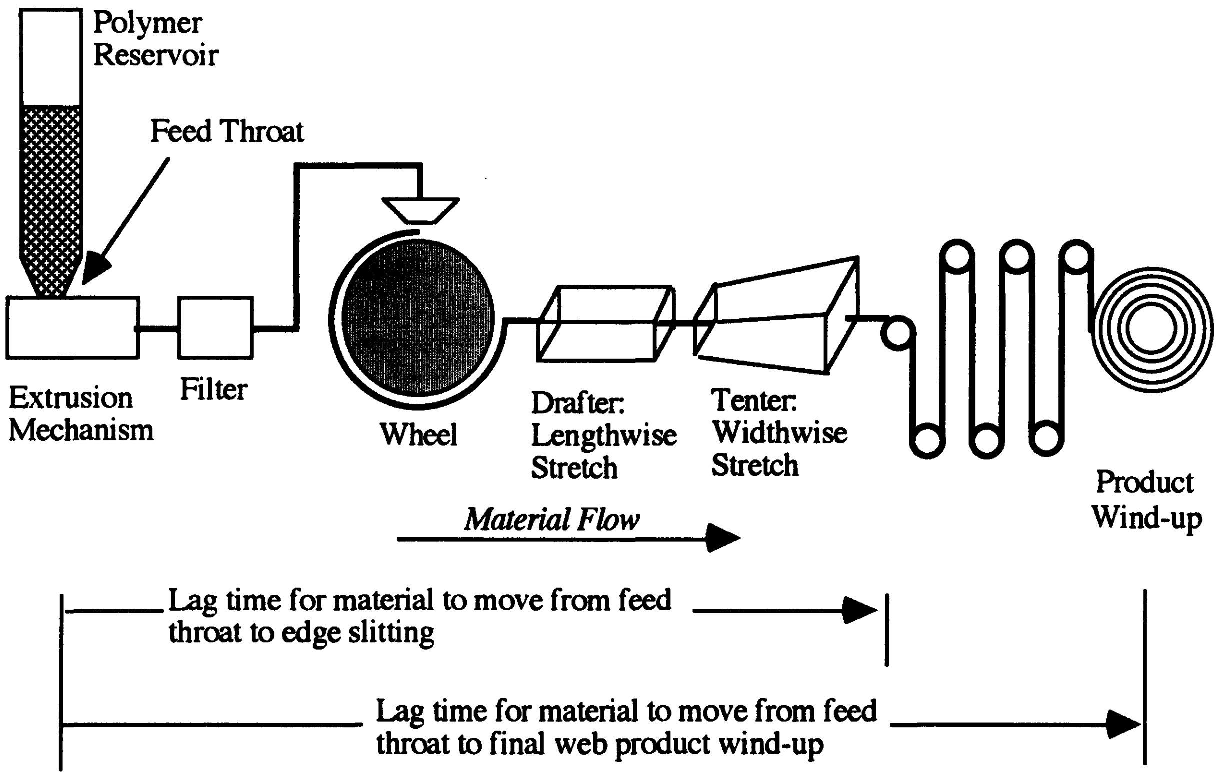
Sampling Details

In the spirit of simplification, two machines were studied. The machines that were chosen could make the highest value products and also had the most comprehensive set of historical inclusion data available for them. These machines were also scheduled to be cleaned during the time in which the samples would be taken. Therefore, gathering samples before and after the cleaning would permit measuring the impact of cleaning intervals on inclusion levels. The goal for the sample gathering consisted of obtaining 30 complete sets of data (polymer-web samples together with all the process parameters determined in the meeting to be important to gather). Historic and anecdotal information alike suggested that the process can be stable for periods of time on the order of several hours. This stability allowed for sampling increments of twelve hours. Production work was already done on this time increment; therefore, the sample gathering could tie in with other periodic work being done on the same interval.

The largest factor to overcome was not an equipment-related one. The only necessary equipment-related task consisted of installing an oxygen meter on each of the two machines under study. Instead, the largest factor was a human-related one. The instructions had to be as easy as possible to remember, otherwise it was unlikely that samples and data would be gathered. Several routine tasks were performed on a daily or shift-wise basis. Integrating the data gathering steps with those routine tasks was deemed necessary to help ensure the success. The penalty for missing even one sample or data point was that an incomplete data set for that time slot would result.[30] A case in point of the simplification is the staggering of the sample taking. If it is imagined that there is a certain control volume of resin about to pass through the feed throat and into the extrusion mechanism, then the desirable result is that the resin, edging, and web samples all come from that control volume. Since there would be a delay from the time the resin entered the feed throat to the time it reached the other two sampling points in the process, this delay had to be built into the sampling plan. Still, since the machines can run at different flow rates and thus have different lag times, each flow rate would require a different lag time between polymer sampling and edge gathering or web gathering. In the interest of simplifying the data collection process for the operators, a constant, nominal time was chosen instead of one that changed with machine flow rate. Figure 4.2 provides a diagram to help visualize the data gathering points and the time lag from the polymer feed throat to the product wind-up.

[30]The computerized process control equipment kept track of many of the parameters. Wherever possible, this was used to simplify the data collection process. In addition, missing data points could sometimes be found in this system.

Figure 4.2: Diagram Indicating Sampling Lags in the Data Collection



The types of samples to be gathered and the data to be recorded are given below.

Samples to be Gathered	**Gatherer**
Solid polymer before entry into extrusion system	Polymer Operator
A length of slit edges from the extruded web	Roll Coating Operator
Final web	Roll Coating Operator

The following data points were to be logged	**Recorder**
Interstitial oxygen concentration of polymer	Polymer Operator
Filter parameters	Maintenance Rep.
Process upsets	Roll Coating Operator
Recycling in use	Roll Coating Operator

The samples of polymer (pre- and post-extrusion) were sent to the lab for analysis of concentrations of the catalyst components and other chemical properties such as acid end group concentration. The process technician and the student performed the counts for the number of inclusions and for the width of the primer margin.

The Actual Instructions

Below is the text of the actual instructions. The entire set of instructions resided in both organizations (Roll Coating and Polymer):[31]

> We're trying to improve the inclusions situation and need to collect some data. We need your help.
>
> 1. Each trick between 6:20 and 6:40 or 18:20 and 18:40, the Polymer Department operator making the rounds will go to Machine A and Machine B and do the following in order:
>   - Log the oxygen concentration (%) into the log sheet.
>   - Open in-line valve to allow air to flow to meter
>   - Switch on oxygen sensor, and turn to "Horn Off" position
>   - Wait at least 2 minutes for % oxygen to stabilize
>   - Write % oxygen onto log sheet
>   - Turn off valve and meter when done
>   - Open stopcock and allow polymer to run into bin for 5 seconds
>   - Place an 8-oz. jar under spout and fill
>   - Close valve (stopcock)
>   - Place cap on jar
>   - Fill out label and place onto jar
>   - Place jar into box on floor for someone else to pick up
>
> 2) Each trick between 7:00 and 7:10 or 19:00 and 19:10*, the MEMO Improvement Coordinator will go and fill out the usual information of the log sheet (such as cumulative throughtput, P2, P3, etc.)
> *The night trick logging can be done the next day from accurate historical data.
>
> 3) Production (Roll Coating) will take the samples as follows
>   - When 2,500 ft. are left before the end of the inclusion sample roll, the wind-up operator will notify a coater to cut an edging sample.
>   - The coater should cut the sample within 5 minutes of being notified. There should be 1 N sample and 1 S sample. Both samples should be about 3 feet.
>
>   Deliver edging sample to wind-up operator.
>   - The wind-up operator should cut off 2 inclusions samples and label as usual except write the time and date, too.
>   - The wind-up operator should label the edging samples the same as the inclusion samples.
>   - Deliver all samples to Quality Bench and place it in box that says "Test Code #140—Inclusion Count Attention: Technician."
>
> 4) The coater should make notations in the MAR for the following situations (if this is not done already):
>   - No edging going into chopper

---

[31]Operations Memorandum written by Michael A. Raftery and effective from 10/5/93 to 11/15/93.

- Log the time whenever edging stops going into chopper.
- Log the time that edging starts going into chopper again.

- Product change and reason
  - Log the time that a product is changed.
  - Log the reason why a product was changed (choose either "end of scheduled run," "high inclusions" or "other.")
- Shutdowns/Restarts
  - Log the time that the machine is shutdown.
  - Log the time that the machine is restarted after a shutdown.

5) If problems arise or you don't understand the directions, please call Mike Raftery at x 82432 (days) or 723-9697 (evenings).

The different groups involved in the data gathering process reviewed the instructions. As the final step in approval, the team leader in Roll Coating reviewed the instructions and approved them.

Presenting the Plan to Production

Presenting a written Operations Memorandum—especially of the length in this case— does not guarantee that the samples will be taken. Therefore, to facilitate the sample gathering, some informal and some formal training was provided.

In the case of the group that was to gather the polymer, the OM was reviewed with the person who would be collecting the samples from one particular shift as well as the team leader. The document requested that those people put the procedure through their internal knowledge dissemination mechanism so that the employees who would be doing the work on all four shifts would understand what to do. The group made a strong start in collecting the resin samples and even took the initiative to make minor modifications to the equipment to help them gather their samples and make the oxygen concentration readings. The strong start is particularly impressive since the polymer sample gathering process is not something that is normally done in the course of a day's work. Toward the end of the process—and there had been some interruptions in sample gathering for other reasons—more reminders needed to be put forth to get the samples.

A difference between the web/edging sample gathering and the polymer sample gathering was that the production crew assigned to a web-making machine would gather the samples from its own machine, whereas the same crew from the Polymer Department was gathering polymer samples and taking oxygen measurements from both machines. The presence of two crews meant that training had to be done for two groups here. Principally, the only major difference from what was asked to be done compared to normal procedure was coordinating the edging sample with cutting the archive sample.[32]

[32]The web sample was physically the same as the archive sample; therefore, the procedure asked for an additional archive sample to be cut as the web sample.

While the whole issue was about to go to the floor, members of one of the web-manufacturing teams was having a break from their normal duties because their machine was down for retrofits. During that period, this team received a briefing collectively on what was about to happen. The primary purpose was to introduce what the procedure was, why it was necessary, and how it impacted their work. During and after the presentation, the team seemed enthusiastic about solving the problem at hand. The other team on whose machine the new procedure started up did not have this training. Although both teams required intervention to get the needed samples—particularly the edging samples—the team that did not receive the training was able to obtain the samples more consistently. The difference between the two web-making teams might result from their ability to transfer knowledge within the team. The same hypothesis could be made about the reason that the polymer team—at least initially—was able to obtain the polymer samples more consistently than the web-making teams were able to obtain the edging samples.

After several weeks had passed—with some gaps in data collection from scheduled machine maintenance and other reasons—enough points had been gathered to make at least a first pass at analysis.

Chapter 5: Analyzing the Data

The previous chapter detailed the data gathering process. Although the details of the data analysis were not the principal focus of the work, a summary of the analytical procedures used is found below for additional information. The discussion then interprets the analytical results and ties them to possible sources within the process.

Description of Analytical Methodology Used

At first, the data were analyzed by trying to build a principal component analysis model. The model that resulted required ten parameters to explain 90% of the variation in the data. Since only 26 sets of data generated the model, the resulting high order was deemed to be too inconclusive.[33]

The results were more encouraging when a technique called partial least squares fitting was used. Many people are familiar with ordinary least squares fitting. The major difference between ordinary least squares and partial least squares is that ordinary least squares requires that some of the independent variables be deleted explicitly (i.e. manually) before a reduced-order, relational model between dependent variables and the remaining independent variables can be made. With partial least squares, however, no potentially important independent variables need be deleted explicitly. The mathematical routine determines what combinations of independent variables are most important. The crux of partial least squares is that the independent variables have some degree of correlation with one another. The method tries to determine which combinations of the variables are the most significant. From this result, the significant individual contributor variables can be determined.

Mathematics of Partial Least Squares[34]

The goal was to cast the independent variable data, in this case, the factors believed to influence inclusions in a different form as follows:

[33]Twist, Internal technical report draft.
[34]Jackson, *A User's Guide to Principal Components*, 1991, pp. 282-290.

$$\mathbf{X} = \mathbf{TP} + \mathbf{E}$$

where:

X is the original independent variable matrix (n sets of p potential factors).
T is a matrix ($n \times k$) of latent variables that summarize **X**.
P is a matrix ($k \times p$) representing the loadings of the vectors of **T**.
E is the matrix of residuals ($n \times p$).

The k dimension refers to the number of linear combinations of independent variables that will be allowed in the model. How k is determined will be discussed later.

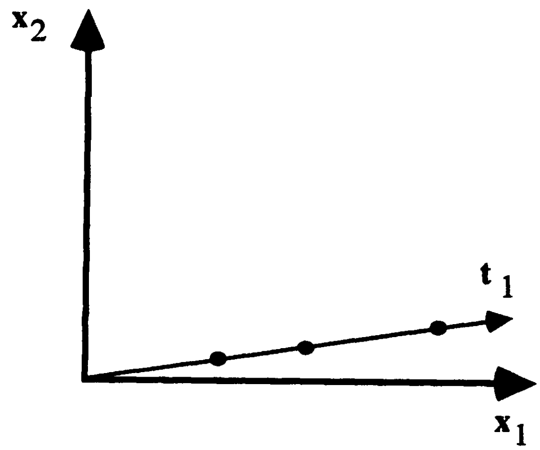
In other words, the original matrix is put into a form in which a number of vectors k, less than the original number p, is used to characterize the whole independent variable set, with residual terms contained in the **E** matrix. The specific contribution of each latent variable in **T** to the independent variables in **X** is contained in the **P** matrix, or the matrix of loadings. A two-dimensional example can be used to illustrate the idea of a latent variable more clearly. Figure 5.1 shows data in the $\mathbf{x}_1$ by $\mathbf{x}_2$ space. For simplification, $\mathbf{x}_1$ and $\mathbf{x}_2$ are orthogonal. The data can be characterized by the vector $\mathbf{t}_1$, which is formed from linear combinations of $\mathbf{x}_1$ and $\mathbf{x}_2$. In essence, in the case of no residual values, all that is required to represent a data point is its coordinate along $\mathbf{t}_1$, the latent variable, rather than its two coordinates along $\mathbf{x}_1$ and $\mathbf{x}_2$, the original variables. Therefore, the dimensionality of the data has been reduced by one degree. The mathematical expression would read:

$$\begin{bmatrix} x_{11} & x_{12} \\ x_{21} & x_{22} \\ x_{31} & x_{32} \end{bmatrix} = \begin{bmatrix} t_{11} \\ t_{21} \\ t_{31} \end{bmatrix} \begin{bmatrix} p_{11} & p_{12} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$\mathbf{X} \quad = \quad \mathbf{T} \quad \mathbf{P} \quad + \quad \mathbf{E}$$

The partial least squares technique performs this type of data reduction on the entire set of $\mathbf{x}_k$ vectors which comprise the **X** matrix discussed previously. Similarly, the resulting latent variables $\mathbf{t}_k$ form the **T** matrix.

Figure 5.1: Latent Variables Decrease Data Order



$$t_1 = \alpha x_1 + \beta x_2$$

The dependent variable data are reduced to the same number, *k*, of latent variables, which are the vectors of the **U** matrix below. Furthermore, the loadings of the vectors of the **U** matrix used to predict the **Y** variables are given in the **Q** matrix.

$$\mathbf{Y} = \mathbf{UQ} + \mathbf{F}$$

where:

Y is the original dependent variable matrix (n sets of q dependent variables).
U is a matrix ($n \times k$) of latent variables that summarize **Y** .
Q is a matrix ($k \times p$)representing the loadings of the vectors of **U**.
F is the matrix of residuals ($n \times q$).

The resulting model itself is in the form of:

$$\mathbf{Y} = \mathbf{TBQ} + \mathbf{F}$$

where:

B is a diagonal matrix consisting of the coefficients of the **X** latent variables (or the **T** matrix) used to predict the **Y** latent variables (or the **U** matrix).

The other notation was described above .

Essentially, the model is constructed by conducting a regression of the latent variables of **X** against the latent variables of **Y**. There will be a regression coefficient for each dimension, *k*, of the model. The number *k* is chosen as greater than or equal to 1 but as small as possible. Models are constructed iteratively with increasing numbers of latent variables (i.e. *k* is increased) until a desired amount of variance is accounted for by the model. If there is not a great deal of correlation between independent variables, then *k* approaches the number of independent variables, *p*, and no practical solution to the question of which independent variables account for the changes in the dependent variables exists.

Latent Variables to Assess Important Process Variables

As a final point about the mathematics, there are two separate classes of outputs from the model. The model may say that a particular independent latent variable (a vector from the **T** matrix above) tracks with a dependent latent variable (a vector from the **U** matrix above). The desired output, however, is what variables of **X** (from which **T** is derived) track with which variables of **Y** (from which **U** is derived). Two attributes called the communality and the regressions coefficient provide an answer. The communality assesses the importance of one vector of **X** in accounting for the overall variation in the dependent variables (the vectors of **Y**) as determined by the predictive model. On the other hand, the regression coefficient tells what the multiplier of a certain independent variable should be to fit in with the model, regardless of whether or not the independent variable itself is important.

In the simplified example given previously in Figure 5.1, partial least squares would determine a predictive model for the data using the latent variable $\mathbf{t}_1$. There would be a regression coefficient for each independent variable—in this case α for $\mathbf{x}_1$ and β for $\mathbf{x}_2$—that would result from the least squares fitting. The communality indicates the importance of the contributions of each independent variable. In the example, the data are almost collinear with $\mathbf{x}_1$; therefore that variable itself could almost be used to predict the data. It is said that $\mathbf{x}_1$ has a high communality. Conversely, $\mathbf{x}_2$ has a low communality. Since communality and regression coefficient are both important, then using the product of the two numbers to assess the predictive value of each independent variable is appropriate.

Discussions of the Derived Parameters Analyzed

Although the immediate objective had been to collect process parameters as well as samples, those two types of information had not been targeted as being useful in themselves. Instead the data analysis considered certain process parameter transformations which could test the hypotheses formed about the data. The following list describes the various transformations used as independent variables in the model.

Machine

Different machines might have different inclusion levels.

Cumulative Throughput

The number of inclusions might be related to the total amount of material passed through the filter set.

Specific Cumulative Throughput

This number represents the throughput through a filter divided by the surface area of the filter elements. The transformation factors in the reality that some filter sets (usually corresponding to different machines) have different surface areas and therefore abilities to handle different amounts of resin before plugging.

Oxygen Concentration

This value is not a transformation, rather the actual oxygen concentration in the interstitial to the polymer.

P2

This number represents the actual pressure on the upstream side of the melt filter.

P3

This number represents the actual pressure on the downstream side of the melt filter.

ΔP

This value is the difference between P2 and P3.

P2/P3

This value is the ratio between P2 and P3.

Product Thickness

This value became part of the analysis in case the actual thickness of the product affects the number of inclusions in a specific volume of material.

Number of Residence Times from the Last Process Interruption

This parameter captures the effect of process flow disturbances on the number of inclusions. Since the production of the web requires viscous flow though the ductwork of the machinery, there is a stagnant boundary layer of material against the inner walls of the machine. The hypothesis asserts that it could be possible to liberate inclusions that might be contained in the stagnant boundary layer by disrupting the flow rate of material through the machine. The actual calculation is as follows:

$$\text{Number Residence Times} = \frac{\text{Amount of material passing through since last interruption}}{\text{Average material hold up in extrusion system}}$$

Primer

This parameter consists of the sum of the average maximum and average minimum primer margin left on the edging. This provides a relative measurement of how much of the primer gets returned into the process.

Catalyst and Metal Impurity Concentrations

Analysis of the web and the polymer determined the concentrations of the various catalyst components and metal impurities from Inductively Coupled Plasma (ICP). The subscript "P" is for polymer, whereas "F" is for film. The different components tested were as follows:

Atoms Tested For	Symbol
Zinc	Zn
Phosphorus	P
Antimony	Sb
Chromium	Cr
Magnesium	Mg

Acid End Groups

This means the concentration of acid in the polymer. [Recall that several of the polyester degradation reactions evolve carboxylic acid end groups]. The analysis considered both the polymer ("P") and the film ("F").

ΔAcid Ends

This calculation represents the change in acid end group concentration upon extruding the polymer.

%ΔAcid Ends

This is the same calculation as ΔAcid Ends except it is expressed as a percentage of the acid end groups in the polymer.

Inherent Viscosity (IV)

This value is determined from analysis of the polymer ("P") and the film ("F"). It provides an indication of both the length of the polymer and can hold information about non-acidic degradation of the polymer.

ΔIV

This number represents the change in inherent viscosity resulting from extrusion of the polymer.

%ΔIV

This number represents the change in inherent viscosity resulting from extrusion of the polymer but expresses as a percentage of the original inherent viscosity.

[Zn]/[P] Average

Since the phosphorus-based stabilizer is added to the process to inhibit the zinc catalyst, there is hypothesized to be and actually are stoichiometric relationships.[35] This ratio captures that theory.

Moisture

Since water is necessary in the most rapid degradation reaction (hydrolytic), the vapor trapped interstitially between the polymer clusters could be important. To estimate the amount of water from the environment, psychrometric numbers gathered

[35] Internal company documents.

at the factory location were used. Specifically, the number put into the analysis represented the mass of water per volume of interstitial air. This gives a relative measure for how much air-originating water can be expected to remain with the polymer during the extrusion process.

Product Temperature

Since thermal degradation is a source of compounds believed to lead to inclusions, the temperature used in extrusion was factored into the analysis.

Machine Clean?

Certain cleaning aspects of the routine maintenance were historically believed to lower the inclusion levels. This binary variable noted on which side of the routine maintenance the data point fell.

The Number of Large and Small Inclusions (Dependent Variables)

The number of large inclusions and the number of small ones comprised the dependent variables in the analysis. Both types were counted according to the method described earlier. Each sample had the inclusions counted at least twice to ensure as accurate a count as possible under the current method. The number fed into the analysis was the number of inclusions counted standardized to the material volume to take into account the differences in material thickness, which lead to different masses when a constant area is examined as in the normal test.

The Results of the Analysis

The mathematical analysis with partial least squares[36] led to a model with six latent variables. The reduction in the number of latent variables represented an improvement over the original principal component analysis, which required ten variables to account for a similar amount of variation. The product of communality and regression coefficient is plotted for each of the different independent variables analyzed in Figure 5.2 (for large inclusions) and 5.3 (for small inclusions). From the previous discussion, the larger the product is for a certain independent variable, the greater that factor's contribution to inclusions is determined to be.

[36]Exponential smoothing was used in the analysis.

Figure 5.2: Large Inclusion Factor Responses

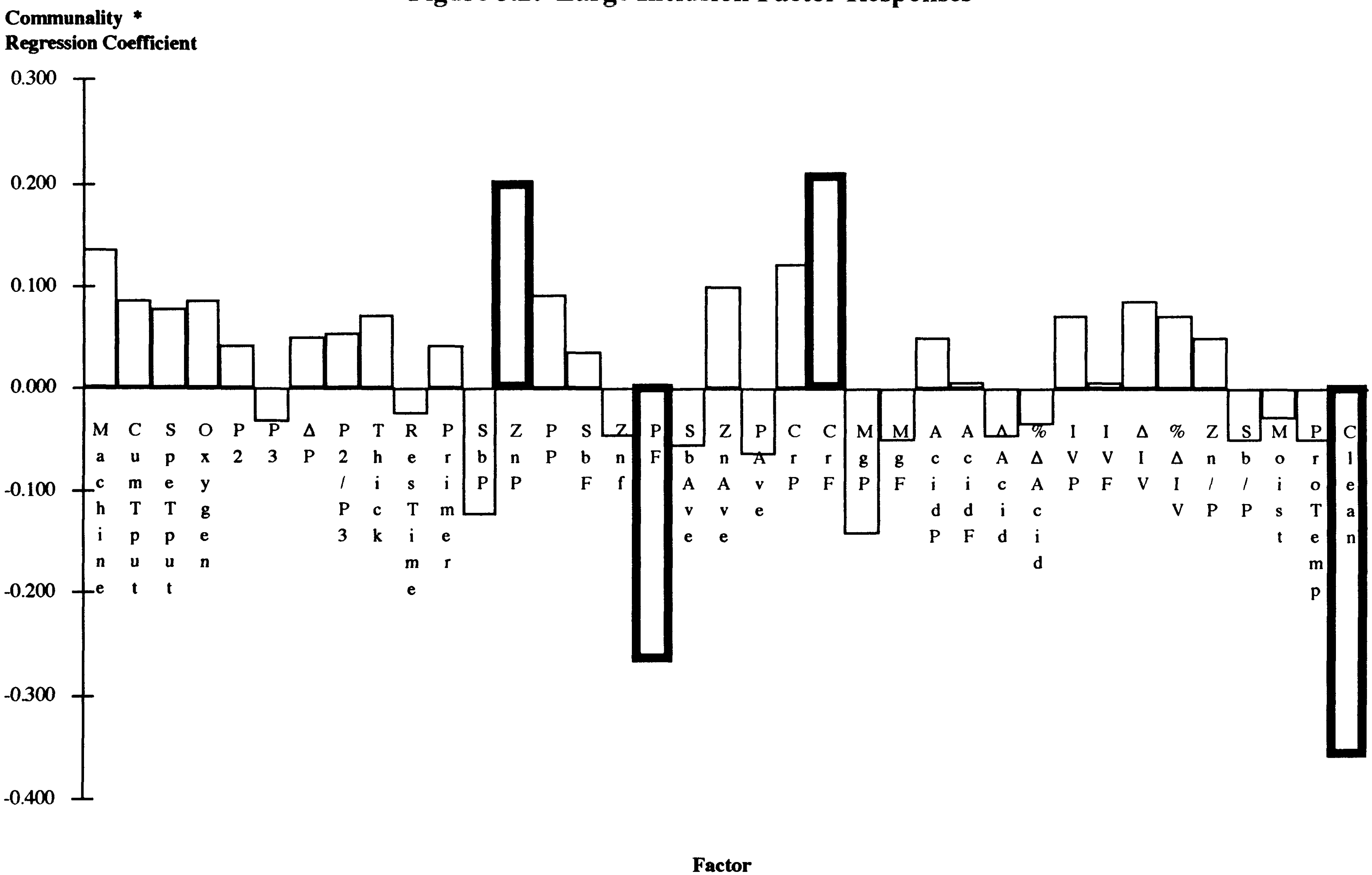
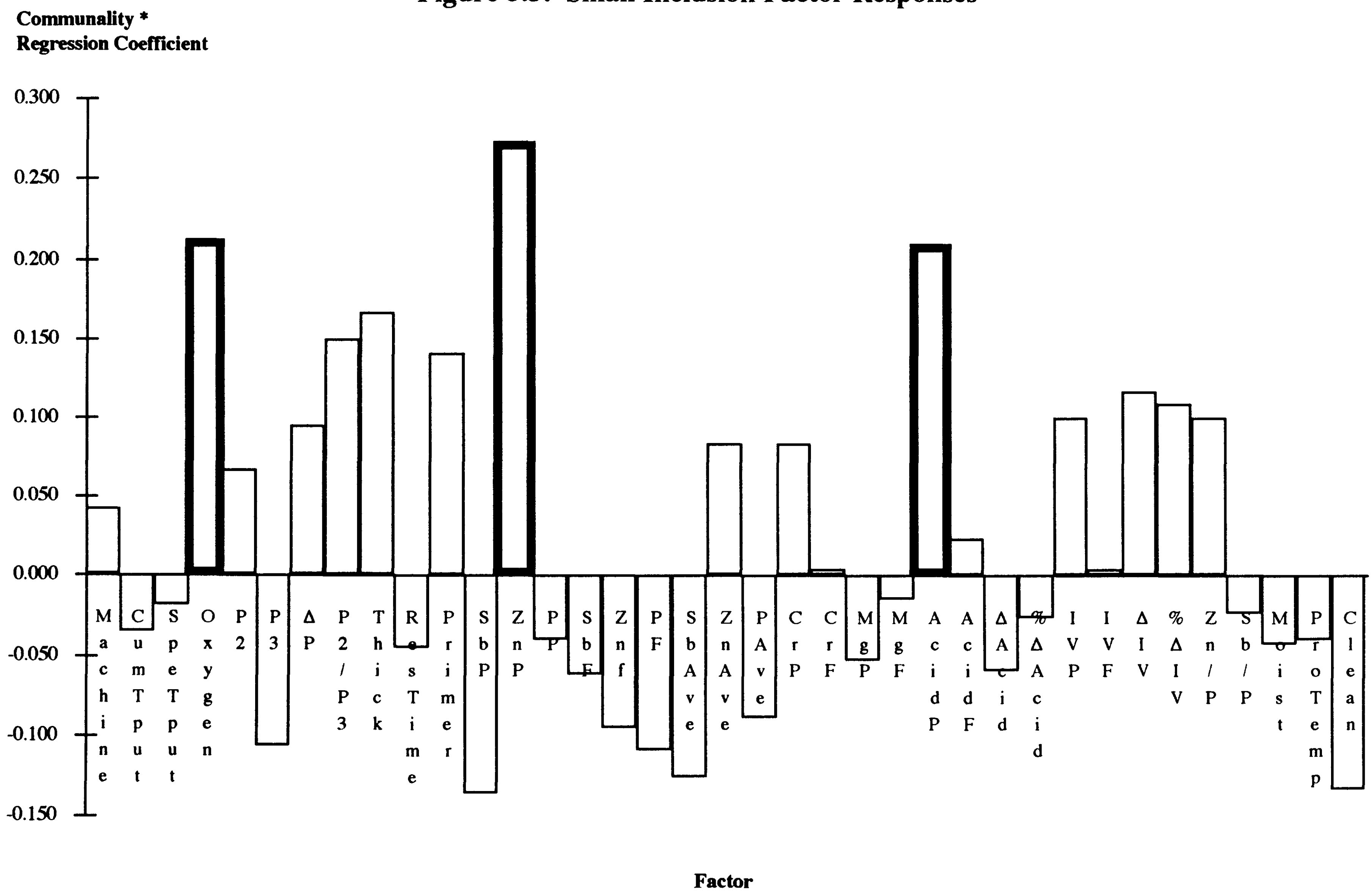


Figure 5.3: Small Inclusion Factor Responses



Although factors exist that are stronger than others, the numerical analysis does not lead to a specific criterion, above which the factor is considered important. The analysis also does not attempt to stratify reliably the number of inclusions resulting from each factor. The Seven Step Method suggests trying to identify and implement solutions for only the top three causes of an observed defect.[37] This simplification addresses a manageability issue for the most part. The discussion that follows addresses the most important factors, which are defined as having the largest products of regression coefficient and communality. These factors appear in bold-faced rectangles in Figures 5.2 and 5.3.

Large Inclusions

Machine Cleaning

For large inclusions, the machine cleaning produced the largest effect. In other words, after the machine had been cleaned, the product had significantly lower levels of large inclusions. Since the machine cleaning in this case addressed, in particular, resin lines between the downstream side of the filter and the extrusion die, the observation that the cleaning had the effect can be rationalized. That is, degraded resin adheres to the walls of the machine or in the stagnant boundary layer, and pieces occasionally break off and end up in the film. The cause seems evident, but the company has not been able to assess its magnitude compared to other factors believed to be important.[38] In fact, upon disassembling parts of the machine, black residue was apparent and was dispersed within the plastic.

Phosphorus Content of the Film

The effect is negative for the phosphorus. This means that as the phosphorus levels in the film increase, fewer large inclusions can be observed in the film. This is a rational expectation if the purpose of the phosphorus is considered. It acts as a stabilizer for the transesterification reaction in the process. If it is not present in sufficient amounts, it is possible for the polymerization, transesterification, and degradation reactions to happen because of the unstabilized catalyst availability. There seems to be a certain amount of conflicting research to support this point. A summary article written on polyester chemistry points out that the stabilizers are added during polycondensation to improve the thermal stability of the polyester as well as the quality.[39] On the other hand, it also

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[37]Shiba, MIT-Sloan School "Total Quality Management (15.766) course notes, 1992.
[38]Conversations with company employees.
[39]Ravindranath and Mashelkar, pp. 2197-2214.

mentions research suggesting that the stabilizers do not prevent the catalytic cycle from happening.[40] The article stops short of trying to reconcile conflicting research reports dating back to 1960, and this discussion will certainly not try to perform that function.[41] Instead, this discussion will rely on the previous suggestions that there is an actual role of the stabilizer and that decreasing the stabilizer concentration allows reactions to happen further. Some of these reactions can be degradation reactions leading to inclusions.

One issue that arises is that phosphorus in the film matters, yet the inclusion levels do not seem to be a function of the phosphorus levels in the polymer. Since the phosphorus in the film comes from the phosphorus in the polymer, a discrepancy appears to arise. An explanation for this lies in the observation that the incoming polymer has a significantly higher variance in phosphorus concentration than that in the outgoing film. Perhaps the averaging that occurs from backmixing in the extrusion equipment leads the phosphorus concentration in the film to be a better indication of the average bulk concentration than a single polymer sample.

Zinc in Polymer

The concentration of zinc present in the polymer seemed to be significant in the correlation of both large and small inclusions. The reason this would happen is uncertain. One hypothesis is that the zinc actually becomes part of the inclusion. The analytical results support this conclusion in as much as terephthalate complexes have been identified, and the background positive ions such as zinc present in the analysis are assumed to be the counterions. Another suggestion is the possible interaction with the phosphorus. Since the phosphorus is added to stabilize the zinc catalyst, perhaps the catalyst is free to catalyze degradation reactions. Although the mismatch in analysis point (polymer or film) exists when comparing the significance of zinc in polymer and phosphorus in film, this observation—as it will be suggested in greater detail later on—could be a manifestation of the fact that the zinc is mixed better in the polymer than in the phosphorus.[42]

Chromium in Film

The introduction to this chapter stated that the three largest contributors to each type of inclusion would receive a detailed discussion. The analysis highlighted chromium as being one of the more significant factors in the formation of large inclusions; in fact, it

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[40]Chang *et al*, 1982.
[41]The Ravindranath and Mashelkar article first cites the research of Terechowa and Petuchow from 1960.
[42]The reason concerns the different steps at which the two different components are added and the different methods used to add them.

was the third highest. Specifically the correlation suggested that the more chromium there was in the film, the more large inclusions existed in the film. Despite the relatively high ranking, it is difficult to link chromium to a process variable. Still, it is necessary to say a few words about this factor. When the issue of chromium was discussed with Research employees, they could not come up with a specific chemical reason why the presence of chromium would lead to increased activity of undesirable PET reactions. Perhaps a physical reason exists. Chrome plating is used in some of the process equipment, and chrome could be sloughing off into the polymer. It is unlikely that stainless steel is causing the observation because the large inclusions did not seem to track with iron. If some of the inclusions are chrome itself, then the observation would be explained.

Small Inclusions

Zinc in Polymer

The significance of the zinc in the polymer appeared to hold true for driving small inclusions as well. The same reasoning and the same caveats apply as described above under large inclusions.

Oxygen

Interstitial oxygen concentration at the point of polymer entry into the web-making equipment seemed to be an important factor in forming small inclusions. The most likely explanation for this is that many small inclusions are thermo-oxidative degradation products (crosslinked material or possibly oxidized material). If these represent an entirely different phase, then a possible explanation could be that the transport of the degradation product through the bulk PET melt is very slow, and the new phase is unable to agglomerate. The hypothesis that oxygen causes undesirable other phases (inclusions) is consistent with information in the literature. Although no information could be identified that would match the exact conditions of this process, the literature stated that air being passed over molten PET can cause anywhere from 0 to 80.1% of the original polymer to turn into gel.[43] The temperature discussed in that research was 300°C, which is hotter than the temperature that the polymer in the Kodak process endures. The value for gel conversions approaching 0%—the same order of magnitude as the Kodak small inclusion issue—occurred after 0.5 hour of exposure. Such a small resulting gel conversion was probably non-detectable with the instruments available at the time of the

[43] Yoda, Tsuboi, Wada, Yamadera. *Journal of Applied Polymer Science*, Vol. 14, 1970, p. 2360.

article and was likely irrelevant to the earlier research, which was concerned with more macroscopic conversions into gel.

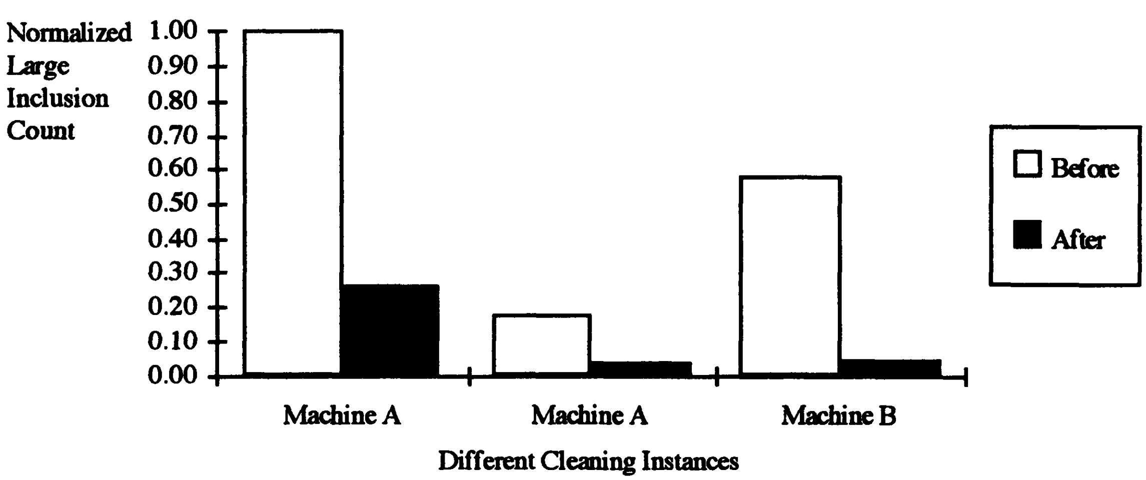
Acid End Groups

Acid end groups appeared to track with the number of small inclusions. The hypothesis is that the resulting terephthalates complex with metal ions present in the catalyst and form the inclusions. In fact, the acid end group argument is the complement to the assertion that zinc might be important. The analytical results have indicated a terephthalate component of the large inclusions, yet the small ones are too minute to analyze with current techniques. By extension from the large ones, many of the small ones might be terephthalate complexes as well.

Verification

It was not possible to go to archives to try to confirm all of the factors determined to be important since only archived web samples are kept on a consistent basis. It was possible, however, to check to see the effect of maintenance on the inclusion levels. The limited data available supported the analytical result that the cleaning is important. Figure 5.4 provides the data in graphic form below.

Figure 5.4: Effect of Cleaning on Large Inclusions



Chapter 6: Conclusions and Recommendations

The numerical analysis from the previous chapter ties inclusions to specific process attributes without actually recommending what should be done differently with the process. Recommendations of proposed solutions are discussed below. The recommendations have been divided into ones related specifically to process parameters discovered above (technical recommendations) and ones related to work process issues that might help reduce the problem (work process recommendations).

Technical Recommendations

Cleaning

The issue of cleaning the machine seems to have a significant impact on the level of inclusions in the process. The part that is unclear is what aspect of the cleaning is actually the most important one. There are several parts of the machine that are cleaned on a periodic basis. According to the company maintenance reports, over the years there might have been some productivity enhancements in the cleaning operations to the extent that some of the cleaning activities are performed on a less periodic basis.[44] The issues that need to be resolved about the cleaning are as follows:

- What is the actual cleaning step that is most important?
- Is it practical to do this step with the frequency necessary to maintain the effect?

Resolve Zinc Issue

The issue about why the zinc catalyst seems to track with inclusions is one that probably needs some input by the Research arm of Kodak. One of two suggested mechanisms might be happening. Depending on which explanation actually holds true, there might be a different solution. For example, if the zinc is the counterion in a terephthalate complex, then a solution might consist of reducing the number of terephthalate groups available. Since acid end groups are a source of these terephthalates, then a solution to problems arising from the zinc might be an issue of reducing the acid end groups, suggestions for which are listed below.

If the zinc is catalyzing another reaction, then the Research group would have to be consulted to determine if other mechanisms for undesirable products exist.

[44] Internal company maintenance reports.

Mix Stabilizer Better

It was suggested earlier that the stabilizer might show itself to be important because there is variation in the incoming polymer mixture. Since the stabilizer is intended to be stoichiometric with the zinc catalyst, it probably would not benefit final product repeatability to have significantly different variances in stabilizer concentration as compared to zinc concentration. The summary statistics from the data in the appendix are given below. The means and standard deviations themselves are not given for confidentiality reasons:

Statistic	**Zinc**	**Stabilizer**
Standard Dev. (% of mean)	0.065	0.179
Number Points	26	26
F-statistic (calculated)	2.75	
F-statistic (chart value) (v_1=25, v_2=25, α=0.05)	1.95	

Since the test statistic is greater than the chart statistic, the reasonable conclusion is that there is statistically significant variance between the concentration of the incoming zinc and the stabilizer added to stop its activity.

When the employees in the operation that makes the polymer heard this result, they immediately thought of the method that is used to introduce the stabilizer. Essentially a relatively small amount is introduced into a mixer holding several thousand pounds. There is some reservation about how well the stabilizer ultimately gets mixed when introduced by this method. This concern is supported by the qualitatively poor way that the stabilizer wets the polymer.[45]

In addition, some productivity improvements once added to be able to make a batch of polymer quicker have become cause for concern. The change itself involved how the stabilizer is introduced. The group that makes the polymer agreed to revisit both the introduction techniques as well as the productivity improvements to see if the incoming polymer can become more uniform in stabilizer concentration.

[45]This conclusion was made by observing the situation when stabilizer is introduced with a pipette into a test tube containing the polymer rather than by a quantified experiment.

Acid End Group Reduction

There are so many locations in the process at which acid end groups may form that it becomes an issue of which of the areas probably represents the best improvement opportunity. Since the acid end group formation can occur either because of thermal degradation or because of the presence of water as described in the degradation reactions previously, it would first seem reasonable to follow an improvement plan centered around the more significant mechanism. Company reports indicate that the hydrolytic degradation is faster than thermal in most cases. It works out conveniently, however, that the apparent best opportunity for reduction of acid end groups formed by hydrolysis occurs simultaneously with the apparent best opportunity to reduce the degradation product by thermal degradation sources. According to past company reports giving data on polyester degradation, an expression giving the temperature at which the degradation rate exceeds the polymerization rate could be developed:

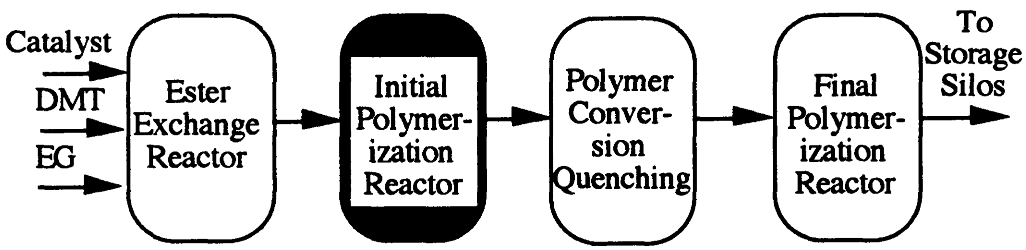
$$\frac{k \text{ degradation}}{k \text{ polymerization}} = \exp\left[18.166 - \frac{9931.5}{T(K)}\right]$$

where:

k degradation is the degradation rate
k polymerization is the polymerization rate
$T(K)$ is the temperature in Kelvin

According to this expression, the rates are equal at 546.7K or 273.7°C or 524.7°F. In the processing equipment from polymer manufacture through web manufacturing, the hottest vessel is the initial polymerization reactor. Although it is not hot so that degradation and polymerization rates are the same, it is close. This vessel also has a possible source of water vapor. The vessel is under vacuum to draw off the ethylene glycol produced in the condensation reaction to drive the equilibrium in the direction of producing the polyester. When the reaction is finished, the vacuum is broken. Sources close to the process said that to save costs, the operation started using undried atmospheric air to break the vacuum rather than the dry nitrogen that the system is plumbed to provide. Although it has not been explicitly proven that this vessel is responsible for inclusions, the presence of high temperature, oxygen and water vapor gives it an inclusion forming environment. Since the equipment is already plumbed with dry nitrogen, breaking the vacuum with this gas is already possible. Figure 6.1 is provided to review the position of the hottest vessel, the initial polymerization reactor.

Figure 6.1: Initial Polymerization Reactor is Hottest



Better Nitrogen Purge over Resin

One of the ways to decrease the interstitial oxygen in the resin is to provide a dry nitrogen purge gas over the polymer hoppers. The plumbing for such a mechanism already exists, but the achievable flow rate is insufficient to decrease the oxygen levels substantially.[46] Plans already existed to increase the purge rate on one of the machines that was not a subject of this study. If there is an improvement in the inclusion levels that this machine generates, then the modified mechanism should be carried over to other machines, including those that were the subjects of this study.

Eliminate Primer Being Sent Back into the Process

Other work done at Kodak on inclusion sources has pointed to the issue of the edging with some amount of primer reentering the extrusion mechanism without the polymer first being recycled and remanufactured. The data presented in this study show that there is a relationship here as well. Other Kodak locations have mechanisms in place that ensure that the primer material does not enter the extrusion system. One such location has much lower levels of large inclusions than the Rochester site although there exist process differences between the two plants. Perhaps this fix should be tried in Rochester at least on some machines.

[46]When the nitrogen purge gas was turned on for one of the machines studied, the decrease in the interstitial oxygen concentration was less than 10% of its original value.

Check Plating Integrity

It might be worthwhile to check the integrity of the chrome plating in the web production equipment wherever practical to make sure it is not delaminating from surfaces and ending up in the final product.

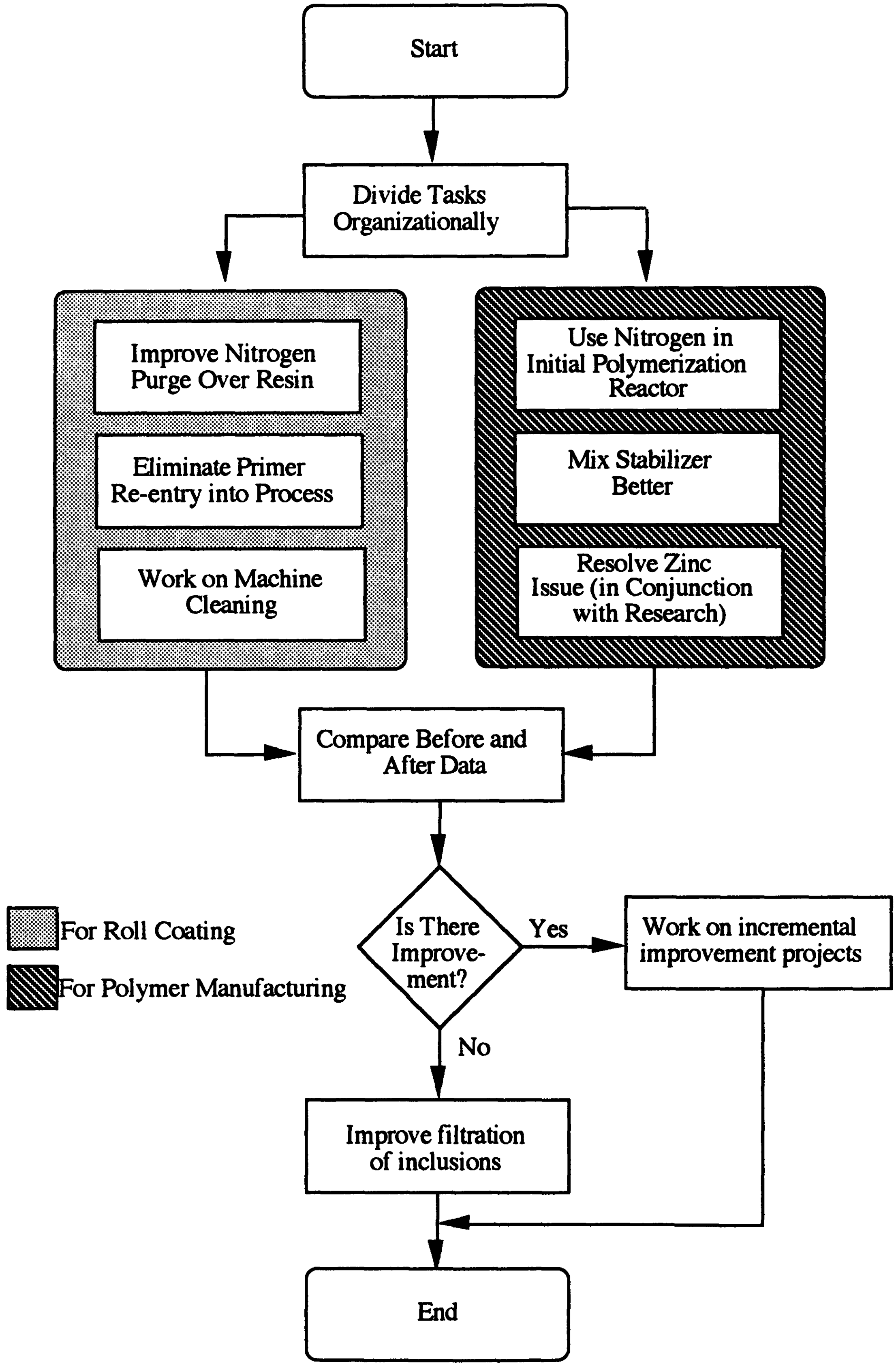
A Final Note on Analysis

There might be value in continuing to collect the kind of data discussed as part of this work. Although the results led to conclusions that can easily be rationalized—along with some that require additional thought or work—the analysis was nevertheless done on twenty-six data points. Certainly this number is insufficient to form a rigorous mathematical model of the entire inclusion formation process. A balance should be struck between having enough data to direct improvement efforts toward a few factors from a list of ones that people were already thinking might be important and being able to model mathematically every possible cause of inclusions. The former goal is the focus of the conclusions presented here since the latter would be difficult to achieve in practice.

Implementation

A flow diagram shown in Figure 6.2 provides a plan for acting on the findings of the study as they relate to the process variables. In addition, the plating integrity should be checked. This study did not gather enough information to assess the cost of each action, which would involve differing amounts of capital and operating expenses. Instead of a ranking by cost, the actions have been arranged in order of decreasing ease with which each likely could be implemented. The terminal action is increased filtration of the melt to get the inclusions out mechanically rather than trying to prevent them from forming in the first place, the issue this work addressed specifically.

Figure 6.2: Flow Diagram for Implementing Action Items



Work Process Recommendations

Review Process before Changes for Productivity Improvements Are Made

There seems to be a pattern of productivity improvements or cost reductions causing adverse effects on a downstream group. Specifically, the changes in the cleaning activity, the mixing of the phosphorus, and the venting of the initial polymerization reactor could have caused an increase in inclusions. Since the changes might have occurred before inclusion data was even kept, assessing the impact of a past decision would prove difficult. Nevertheless, there probably exists the need to have some universal buy-in to productivity or cost improvements that might have an adverse effect on factors determined to drive inclusions.

Following Through on the Methodology

The Seven Step Methodology suggests looking for other causes or solutions if the ones first identified do not work. Although political pressures usually favor keeping alive solutions that do not work, the latter is unfortunate in a manufacturing organization, where efforts to simplify tasks are usually going on and the tolerance for new activities is low. At some point, the solution that does not work should be scrapped in favor of something else.

Better and More Regular Detection

The inclusion information generated in this study was a special development task. If the organization fully believes that inclusions represent a threat to business, then more regular, repeatable data need to be gathered as a normal production routine, not as off-line development activity. One of the problems is that the current inspection procedure is difficult to teach with high repeatability from person to person and is very tedious. The company has been working on a mechanism to detect inclusions and stratify them by size as an off-line activity. Such a device would certainly prove useful in the data collection effort. The data should be collected together with other factors that appear to drive inclusions.

The inclusion levels could also be worked into a multivariate control charting scheme if a certain number of off-line tests could be automated. Multivariate control charting resembles customary Shewhart control charting except that it tracks the same linear combinations of process variables (the latent variables) determined to be significant in the principal components analysis. When one of the latent variables goes out of control, the algorithm decomposes that variable into the actual process variables that made the component fall outside of the control limits. Doing this, however, would require that any analytical test for the catalyst components be done on-line.

Create Crisis

It is difficult to implement solutions to problems in a manufacturing environment even when actual tangible costs or ramifications exist. Similarly, it is exceedingly difficult to implement measures to correct problems like inclusions, which are largely strategic rather than a proven money sink. Creating a certain amount of crisis might help with this effort.

Chapter 7: What Were the Lessons?

At first glance, this project appeared to be almost entirely one of solving a technical problem. Nevertheless, some important, more general lessons emerged. These lessons originated from observations of what it finally took to determine answers to the technical problems as well as some conjecture about what factors have stood in the way in the past. The reason for listing them is to allow them to be applied to other situations later on.

The Importance of Manageability

Kodak has vast technical prowess. The knowledge base of the people involved generated an extensive list of potential causes of the problem. Ironically, the extent of this list may well have become a problem in itself. Constantly thinking about how large a task is does not help to solve it. Paring down an extensive and possibly exhaustive list of items into a more manageable and measurable one became of primary importance. Several people involved in the project were seeking perfect data and perfect transformations of the data. Unfortunately, neither of them occur very often. After manageability was at hand, the issue became "Management by Fact," or gathering data to test hypotheses. Complete sets of extensive data are difficult to gather in practice. In fact, ensuring the data were gathered consistently became one of the most challenging parts of the work.

Strategic Problems Should Be Cast as Operational Problems

The problem of inclusions gets the factory's attention primarily from the operational inconvenience of filter life, yet conclusive data to establish a linkage between inclusions and filter life are lacking. The ultimate reason why inclusions are of concern is a strategic reason. Customers do not want inclusions in their product, and the present level of inclusions might well increase the likelihood of a future stabilization of or drop-off in business.[47] Yet the factory, by and large, does not understand this because none of the factory metrics capture the essence of a strategic problem. In short, the perception of this being a costless defect does nothing to help solve it. The focus of the work thus far has been in determining the most significant causes of the problem. Once the final solutions are tested and in place, there will likely still be the same difficulty in bringing about recognition of the problem. For this reason, it would benefit the ongoing maintenance of the problem to capture it as an operational problem, even if it is primarily strategic. This

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[47]Conversations with company managers.

can be accomplished by assigning a cost to inclusions and keeping track of that cost metric at the factory level. Kodak has carried out novel approaches of this in the past in one of its subsidiaries.[48] The approach could be taken as a motivation tool even if the actual costs are not know for certain.

Conducting Development in a Manufacturing Environment

An issue present at this company and in many others is conducting development-type work in a manufacturing environment. Most problem-solving methodologies stress the importance of having all aspects of the organization involved in solving the problem. An articulation of this point from a recent text reads as follows:

> Everyone in a company must be involved effectively in customer satisfaction and continuous improvement activities. TQM [Total Quality Management] is a mass movement. In today's world it is not sufficient to depend only on the few geniuses and highly effective people in a company. Today everyone in the company must be mobilized to improve the way they do their jobs and satisfy customers. To mobilize everyone to achieve these goals, companies must change the way they think about and organize work.[49]

This organization originally tried to solve the problem by assigning it to employees who have day-to-day production tasks as their primary responsibility. The drawback to this approach is that addressing day-to-day manufacturing issues requires a completely different time horizon and concentration span from solving problems of long duration.[50] Furthermore, these same people were expected to solve the problems by crossing organizational boundaries that probably had not been sufficiently crossed at a higher level. It is expected to be the case that the tasks of shorter or more imminent duration will be the natural focus of any person having the two types of tasks since neglect of the shorter duration project will be evident more immediately. Frustration results among both management and the employees trying to solve the problem because progress in solving the longer range problem might not be evident. The problem of inclusions seems to be going the way of being outsourced to internal and external people functioning as consultants. On the one hand, this approach brings new insight and fewer organizational encumbrances to the issue. On the other hand, however, the action also distances the organization from its own problems, some of which may even threaten its existence.

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[48]Texas Eastman Company case from the Harvard Business School. Although Eastman Chemical Company is now an entirely separate company from the Eastman Kodak Company, the former was part of Kodak during period of this work.

[49]Shiba, Graham, and Walden, p. 249.

[50]Schein, Edgar H. *Organizational Culture and Leadership*. (2nd ed.), 1992. By extension about the difficulties manufacturing and sales have in dealing with one another.

To benefit from the insight of an outsider best, perhaps also assigning the issue to an insider as primary his/her responsibility could be useful. A plan to free up time among people in the organization to work on their own problems would involve delegating other tasks. For example, the organization under study has its engineers with the most process experience in the role of product engineer. One of the tasks of the product engineer is to disposition rolls of material that production operators flag for one reason or another. Since the organization is moving more toward empowerment of workers at all levels, then allowing operators to flag and disposition product themselves would fall under the realm of empowerment and would free up the experienced product engineers' time to work on other issues such as inclusions. The primary goal of freeing up the time of a person within the organization is to retain ownership of the problem while addressing the need for the problem to be solved and for the employee(s) charged with the responsibility to avoid the frustration of having multiple tasks of differing time horizons.

The Tools are There to Solve Other Problems

During this work, an effort was made to provide tools that would be useful in solving other problems that arise. Certainly, quality improvement cycles are useful devices if they are followed correctly. If the study were to be reconducted, it might have been better to choose a quality improvement cycle that already existed at the company to avoid the issue of employees having to relearn a slightly different version of something they had been taught before.[51]

Another aspect of this work is that solutions presented here might reduce defects other than inclusions. The defects themselves are usually characterized by visual descriptions, rather than by suspected process origin. Inclusions, as they are described, could very well be depicted unconsciously as other types of defects just because other types of defects look different from inclusions. If other defects are simply inclusions that look different, then solutions to inclusions could improve other defects as well.

Organizational Learning

One of the most important lessons for the work suggests the need to answer the question of how does the organization step outside of itself to learn what areas it needs to improve to solve the problems facing it. This is the thinking behind the modern quest of

[51]Kodak uses a modified version of the Deming Cycle. While the steps of the Deming Cycle are Plan, Do, Check, Act; the steps of Kodak's cycle are Assess, Plan, Do, Verify. Essentially the two are the same as each other and as the Seven Step Method, which splits some of the Deming or Kodak Cycle steps out into other steps.

designing the learning organization. An excerpt from Peter Senge's the *Fifth Discipline* addresses the type of problem:

> Traditionally, organizations attempt to surmount the difficulty of coping with the breadth of impact from decisions by breaking themselves up into components. They institute functional hierarchies that are easier for people to "get their hands around." But, functional divisions grow into fiefdoms... The result: analysis of the most important problems in a company, the complex issues that cross functional lines, becomes a perilous or nonexistent exercise.[52]

This is a dramatic and virtually unrestrained statement. Nevertheless, it illustrates the point that the problems a company will face—even its most critical ones—usually will not fit conveniently into the organizational structure of the company. Therefore, the organization must work on itself to accommodate the problem better. Specifically in relation to the inclusion issue, the source could be several places along the process flow. Since this process flow crosses organizational boundaries, collecting information about the issue almost automatically runs into the obstacles the organization creates. In many ways, addressing these obstacles becomes the hardest, yet most necessary, work.

[52]Senge, p. 24.

Appendix

The following pages contain the data gathered for the study. Where appropriate, the data have need normalized, typically as a fraction of the largest value. Percentage change values have been left in tact.

Serial	Date	Machine	Spec. Cum. T'Put	[Oxygen]
1	10/1/93	A	0.40	0.64
2	10/2/93	A	0.47	0.69
3	10/3/93	A	0.54	0.69
4	10/4/93	A	0.61	0.75
5	10/5/93	A	0.68	0.72
6	10/5/93	A	0.72	0.83
7	10/6/93	A	0.74	0.72
8	10/6/93	A	0.78	0.73
9	10/7/93	A	0.81	0.67
10	10/7/93	A	0.85	0.68
11	10/8/93	A	0.88	0.67
12	10/8/93	A	0.91	0.72
13	10/9/93	A	0.97	0.72
14	10/10/93	A	1.00	0.72
15	11/12/93	A	0.47	0.83
16	11/12/93	A	0.50	1.00
17	11/13/93	A	0.56	0.89
18	11/14/93	A	0.60	0.94
19	11/15/93	A	0.67	0.89
20	10/8/93	B	0.44	0.81
21	10/11/93	B	0.60	0.83
22	10/12/93	B	0.65	0.53
23	10/12/93	B	0.68	0.72
24	10/13/93	B	0.72	0.61
25	10/18/93	B	0.21	0.92
26	10/26/93	B	0.52	0.72

Serial	P2	P3	ΔP	P2/P3
1	0.81	0.91	0.74	0.75
2	0.79	0.88	0.73	0.76
3	0.79	0.87	0.74	0.77
4	0.82	0.88	0.76	0.78
5	0.86	0.88	0.82	0.83
6	0.86	0.87	0.82	0.84
7	0.82	0.80	0.79	0.86
8	0.86	0.92	0.81	0.80
9	0.90	0.85	0.88	0.90
10	0.86	0.97	0.80	0.75
11	0.93	0.84	0.91	0.94
12	0.83	0.97	0.75	0.72
13	0.83	0.92	0.78	0.77
14	1.00	0.85	1.00	1.00
15	0.71	0.86	0.64	0.71
16	0.73	0.89	0.65	0.70
17	0.70	0.85	0.63	0.70
18	0.71	0.89	0.64	0.68
19	0.69	0.80	0.63	0.73
20	0.54	0.93	0.40	0.49
21	0.71	0.95	0.62	0.63
22	0.72	0.94	0.63	0.65
23	0.74	0.93	0.65	0.67
24	0.80	1.00	0.71	0.68
25	0.59	0.92	0.47	0.54
26	0.43	0.79	0.32	0.46

Serial	# Res. Time from Inter.	Primer	[Sb] P	[Zn] P
1	0.41	0.25	0.91	0.95
2	0.26	0.56	0.82	0.95
3	0.55	0.48	0.88	0.92
4	0.84	0.41	0.79	0.87
5	0.22	0.65	0.88	1.00
6	0.00	0.34	0.88	0.92
7	0.14	0.92	0.88	0.97
8	0.11	0.45	0.82	0.83
9	0.26	0.51	0.88	0.95
10	0.40	0.11	0.88	0.88
11	0.55	0.30	0.85	0.92
12	0.02	0.06	0.85	0.82
13	0.26	0.11	0.88	0.86
14	0.02	0.59	1.00	0.96
15	0.49	1.00	0.82	0.83
16	0.63	0.45	0.79	0.79
17	0.06	0.45	0.82	0.84
18	0.21	0.45	0.82	0.86
19	0.51	0.77	0.82	0.82
20	0.03	0.00	0.91	0.94
21	0.46	0.59	0.91	0.94
22	0.70	0.85	0.88	0.84
23	0.82	0.28	0.88	0.84
24	0.97	0.25	0.91	0.84
25	1.00	0.34	0.91	0.96
26	0.01	0.56	0.91	0.87

Serial	[Sb] F	[Zn] F	[P] F	[Sb] Average
1	0.97	0.97	0.77	0.97
2	0.91	0.95	0.77	0.89
3	0.88	0.91	0.68	0.91
4	0.85	0.96	0.72	0.85
5	0.91	0.99	0.68	0.92
6	0.88	0.89	0.74	0.91
7	0.94	1.00	0.83	0.94
8	0.88	0.89	0.87	0.88
9	0.97	0.95	0.81	0.95
10	0.94	0.97	0.91	0.94
11	0.91	0.93	0.87	0.91
12	0.91	0.88	0.79	0.91
13	0.94	0.93	0.74	0.94
14	0.94	0.97	0.77	1.00
15	0.91	0.93	0.89	0.89
16	0.88	0.88	0.98	0.86
17	0.91	0.92	0.98	0.89
18	0.85	0.91	0.98	0.86
19	0.85	0.88	0.91	0.86
20	0.88	0.95	0.89	0.92
21	1.00	0.92	0.70	0.98
22	0.94	0.88	0.74	0.94
23	0.94	0.89	0.74	0.94
24	0.94	0.88	0.53	0.95
25	0.97	0.96	0.83	0.97
26	1.00	0.96	1.00	0.98

Serial	[Zn] Average	[P] Average	[Cr] P	[Cr] F
1	0.97	0.76	0.33	0.08
2	0.95	0.65	0.28	0.25
3	0.92	0.62	0.38	0.25
4	0.92	0.79	0.28	0.22
5	1.00	0.65	0.72	0.22
6	0.91	0.71	0.54	0.32
7	0.99	0.76	0.54	0.22
8	0.87	0.87	0.36	0.25
9	0.95	0.81	0.28	0.15
10	0.93	0.91	0.46	0.30
11	0.93	0.86	0.33	0.18
12	0.86	0.74	0.41	1.00
13	0.90	0.77	0.49	1.00
14	0.97	0.77	0.39	0.10
15	0.89	0.86	0.50	0.20
16	0.84	0.81	0.67	0.27
17	0.89	1.00	0.44	0.20
18	0.89	0.92	0.38	0.28
19	0.86	0.95	0.33	0.23
20	0.95	0.90	0.33	0.10
21	0.93	0.70	0.28	0.15
22	0.87	0.77	0.42	0.17
23	0.88	0.76	0.48	0.15
24	0.87	0.54	0.39	0.14
25	0.97	0.92	0.89	0.25
26	0.92	0.93	1.00	0.48

Serial	[Mg] P	[Mg] F	[Acid ends] P	[Acid ends] F
1	0.63	0.36	0.62	0.60
2	0.75	0.43	0.57	0.85
3	0.69	0.34	0.69	0.69
4	0.38	0.36	0.64	0.58
5	0.56	0.40	0.54	0.54
6	0.63	0.43	0.87	0.77
7	0.50	0.47	0.59	0.58
8	0.41	0.38	0.71	0.91
9	0.38	0.57	0.62	0.72
10	0.50	0.60	0.78	0.98
11	0.38	1.00	0.56	0.65
12	0.49	0.83	0.78	0.45
13	1.00	0.79	0.67	0.56
14	0.62	0.64	0.64	0.70
15	0.81	0.64	0.76	0.70
16	0.88	0.70	0.78	0.68
17	0.63	0.57	0.63	0.81
18	0.75	0.55	0.77	0.86
19	0.63	0.51	0.69	0.65
20	0.50	0.16	0.57	0.62
21	0.41	0.40	0.64	0.62
22	0.48	0.38	0.92	0.42
23	0.43	0.38	0.80	0.74
24	0.81	0.40	1.00	0.79
25	0.53	0.28	0.80	0.75
26	0.41	0.83	0.92	1.00

Serial	Δ[Acid ends]	%Δ [Acid ends]	IV P	IV F
1	0.25	18.7	0.98	0.98
2	1.00	81.1	0.99	0.98
3	0.32	21.4	0.98	0.99
4	0.16	11.3	0.97	0.96
5	0.26	22.1	0.90	0.97
6	0.15	7.9	0.98	0.97
7	0.25	19.8	0.91	0.95
8	0.84	54.8	0.98	0.97
9	0.56	41.7	1.00	1.00
10	0.89	52.9	0.97	0.95
11	0.51	42.1	0.99	1.00
12	-0.51	-30.4	0.99	0.97
13	0.02	1.7	1.00	0.97
14	0.47	34.5	0.99	0.99
15	0.20	12.1	0.98	0.95
16	0.10	5.9	0.96	0.95
17	0.77	56.4	0.97	0.94
18	0.60	35.8	0.98	0.95
19	0.22	15.0	0.96	0.94
20	0.40	32.0	0.99	1.00
21	0.25	17.9	1.00	1.00
22	-0.89	-45.0	0.98	0.97
23	0.20	11.4	0.97	0.99
24	-0.07	-3.4	0.97	0.97
25	0.25	14.3	0.98	0.97
26	0.65	32.5	0.98	0.97

Serial	ΔIV	%ΔIV	[Zn]/[P] Avg.	[Sb]/[P] Avg.
1	0.58	4.49	0.79	0.72
2	0.69	5.25	0.91	0.78
3	0.44	3.39	0.93	0.83
4	0.60	4.72	0.72	0.60
5	-0.29	-2.44	0.96	0.80
6	0.77	5.94	0.79	0.72
7	0.02	0.17	0.81	0.70
8	0.81	6.24	0.62	0.57
9	0.65	4.88	0.73	0.66
10	0.77	6.03	0.64	0.58
11	0.56	4.28	0.68	0.60
12	0.79	6.07	0.72	0.70
13	1.00	7.56	0.73	0.69
14	0.62	4.76	0.78	0.73
15	0.94	7.21	0.64	0.59
16	0.69	5.39	0.64	0.60
17	0.88	6.84	0.55	0.50
18	0.92	7.09	0.60	0.53
19	0.81	6.43	0.56	0.51
20	0.44	3.35	0.65	0.58
21	0.52	3.96	0.82	0.79
22	0.69	5.32	0.70	0.69
23	0.44	3.39	0.72	0.70
24	0.67	5.18	1.00	1.00
25	0.75	5.78	0.65	0.59
26	0.69	5.31	0.61	0.60

Serial	Moisture	Machine Clean?	Large inclusions	Small inclusions
1	0.31	N	0.06	0.10
2	0.71	N	0.08	0.60
3	0.50	N	0.04	0.32
4	0.20	N	0.17	0.35
5	0.50	N	0.41	0.67
6	0.02	N	1.00	6.24
7	0.44	N	0.12	0.27
8	0.00	N	0.12	0.18
9	0.59	N	0.16	0.42
10	0.67	N	0.07	0.19
11	0.91	N	0.13	0.25
12	0.44	N	0.22	0.14
13	0.72	N	0.34	0.14
14	0.16	N	0.17	0.32
15	0.49	Y	0.02	0.34
16	0.10	Y	0.01	0.47
17	0.32	Y	0.02	0.26
18	1.00	Y	0.02	0.22
19	0.96	Y	0.02	0.35
20	0.90	N	0.04	0.09
21	0.35	N	0.64	0.68
22	0.40	N	0.49	1.00
23	0.26	N	0.28	0.25
24	0.13	N	0.09	0.29
25	0.15	N	0.68	0.82
26	0.38	N	0.49	0.35

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