Process Modeling and Capability Feedback for Integrated Injection Molded Product Development

by

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B.S.E. Mechanical Engineering (1994)

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Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of
Master Of Science In Mechanical Engineering

at the

Massachusetts Institute of Technology

June 1996

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ABSTRACT

In order to limit new product development time and ensure quality, the engineer needs to understand the capability of the manufacturing process that will be used. Specifically, the engineer must be able to assess the feasibility of producing the parameters (i.e. dimensions and physical properties) of a design within their specified tolerances and understand how variation will affect the ideal function of the product. Concurrent engineering has taken a holistic approach to the problem by developing management methods to promote greater communication between designers and manufacturing engineers. However, this method of assessing process capability relies only on the "experience" of manufacturing engineers. A more quantitative method is needed.

This thesis considers the needs of both design and manufacturing engineers with regards to understanding the capability of a manufacturing process. A methodology is presented that shows how an enterprise can improve its understanding of its manufacturing processes by effectively managing the information generated by these processes. It is proposed that feedback of production data to process modeling tools used in the design phase will satisfy this need. The application of this methodology will lead to continuous improvement of the capability of both the manufacturing process and the design process. These improvements will stem from a better understanding of how to apply manufacturing process models. Furthermore, engineers will be able to improve the management of tolerance allocation and process development efforts.

The details of the implementation of this methodology are demonstrated through a case study involving injection molding. A model was created to enable design and manufacturing engineers to anticipate and track the variation of critical parameters, thereby promoting feedback. A commercial software package for the simulation of injection molding was evaluated through the use of designed experiments. These experiments were run on a production line and in simulation. The verification included investigations of shrinkage and warpage predictions. Finally, methods of feedback into first-order models were developed. Based upon the results of this study, a model usage strategy was formulated.

Thesis Advisor: Kevin Otto
Title: Assistant Professor of Mechanical Engineering

Acknowledgments

Several people helped make this thesis and the research to support it possible. I would like to thanks the Leader's for Manufacturing Research Program and Eastman Kodak for supporting my research. Specifically, I extend my appreciation to Dave Bowllan, Bill Haessly, and Gary Glozer at Eastman Kodak, whose continual assistance over the past two years helped me get up to speed on injection molding and got me in touch with all the right people at Kodak. In addition, I thank AC Technology, the makers of CMOLD, who helped me negotiate the software's learning curve.

I am especially thankful to have an advisor at MIT who pushed me to develop my research skills without placing undue amounts of pressure upon me. Kevin Otto was also very good at helping me see the big picture when I sometimes got lost in the details. I wish him the best of luck in the coming years.

I am very grateful for the support of my friends and family. Mom, Dad, Lisa, I hope you all read this! Finally, a big thank you goes to my fiancee Sarah who, among the many things she has done for me, took on the brunt of the wedding planning so that I could concentrate on finishing this thesis. I look forward to spending the rest of our lives together.

Table of Contents

List of Figures

Chapter 1

Introduction

Within the past ten years, American companies have begun focusing their efforts on improving the quality and productivity of their manufacturing processes. Increased competition from their foreign counterparts has reduced the tolerance for inefficiency in today's business climate. One of the principal tools for improving the quality of a manufacturing process has been statistical process control. The use of this tool has led to an explosion of information about the capability of manufacturing processes. The challenge for the next generation of engineers and managers is to use this information effectively in order to continue to remain competitive. As Ed Miller, President of the National Center for manufacturing Sciences states, "The ability to transfer new information to [or from] the factory floor will separate leaders from laggards." [Gardner, 1992].

This thesis considers the needs of both design and manufacturing engineers with regards to understanding the capability of a manufacturing process. A methodology is presented that shows how an enterprise can improve its understanding of its manufacturing processes by effectively managing the information generated by these processes. It is proposed that feedback of production data to process modeling tools used in the design phase is effective. Furthermore, the application of this methodology will lead to continuous improvement of the capability of both the manufacturing process and the design process (the improvement of the latter resulting from a better understanding of how to apply the models of the manufacturing process). Finally, this thesis presents a case study involving injection molding, which helps describe some of the details and implications of this methodology.

The first chapter describes the motivation behind this research in production data management and modeling of process capability. Section 1 reviews the problems that this thesis addresses, and Section 2 develops the purpose and benefits of this methodology.

The rest of the thesis is outlined in Section 3, and the notation used in the thesis is listed in Section 4.

1.1 Research Motivation

The more prior knowledge that a designer has about a manufacturing process, the shorter the new product development time. In order to limit new product development time and ensure quality, the designer needs to understand the capability of the manufacturing process that will be used. Specifically, the designer must be able to assess the feasibility of producing the parameters (i.e. dimensions and physical properties) of a design to within their specified tolerances and understand how variations will affect the ideal function of the product.

Today, there is an increasing demand for parts with greater functionality as a result of pressures to cut assembly costs through the reduction of the number of parts. In fact, many of the common design for assembly rules [Boothroyd and Dewhurst, 1988] rely on the ability to manufacture complex parts that have greater functional capabilities. The complexity of these parts often forces designers to specify tighter tolerances, especially on critical-to-function dimensions. These tighter tolerance specifications put pressure on manufacturing engineers to improve the capability of the manufacturing processes. Although there are usually constraints on the capability of the manufacturing process, manufacturing engineers can often maximize the capability of the process by designing it properly. Still, much of the cost and the eventually optimal capability of the process is dictated by the design of the product. Thus, the focus of collaboration among design and manufacturing engineers must be the improvement of process capability.

Concurrent engineering has taken a holistic approach to the problem by developing management methods to promote greater communication between designers and manufacturers. The basic tenet of concurrent engineering consists of an organizational management of the product development process supported by a strong communication infrastructure [Carter and Baker, 1992] [King, 1980]. Now, manufacturing engineers are being consulted during the design process more frequently, but they often cannot assess the capability of achieving tolerances because they may not have experience with the shape or material in question. Bad experiences tend to make manufacturing engineers pessimistic about tolerances. However, as a designer on my industrial team has commented: "...if I listened to all of the *can't do's*, I wouldn't get half of my products out the door." [Harris, 1995] This comment illustrates much of the difficulties associated with the reliance upon concurrent engineering meetings to assess process capability. In some cases, design engineers are simply ignoring the manufacturing engineers because they no longer trust the manufacturing engineers' predictions.

Additionally, manufacturers and designers do not often speak the same language because they have different objectives. For example, the manufacturing engineers are concerned about optimizing the process to limit costs while ensuring quality. They are also concerned about controlling the process and meeting production targets. With the abundance of process parameters that can be monitored, manufacturing engineers need to uncover the critical process settings in order to control the process effectively. However, the design team is mostly concerned about the parameters that determine product quality, which are based on the product's functionality --hence the term *critical-to-function* parameters.

Thus, engineers need to continue to improve their understanding of the capability of their manufacturing processes in order to achieve tighter tolerances, improve quality, improve productivity, and reduce cost. Given the limited resources of most enterprises, the best course of action is to use process models to estimate the required information (as opposed to physical prototyping, which can be costly in terms of capital and time). Furthermore, the expertise that companies have in their understanding of the process is becoming one of their few remaining sources of competitive advantage (given the global nature of today's market and the labor costs of other countries). Consequently, there is a need for a methodology that addresses the following:

- Describes the proper management of manufacturing process and product control information
- Evaluates the effectiveness of the available models of the manufacturing process
- Provides for the development of a strategy to use the models (with the knowledge of their quality) and/or improve the models
- Promotes the effective management of tolerance allocation and process improvement

By addressing these issues, the methodology will provide a formal mechanism that design and manufacturing engineers can use to quantify the relationship between the production system capability and proposed design changes.

1.2 Background of Process Capability Modeling

There are several types of manufacturing process models, and each category usually serves a different purpose. A model can be defined as a representation (often mathematical) of the facts, factors, and implications of an object or situation, or in this case, a process [Webster, 1989]. Models are often used when the actual situation or process is too complicated and the engineer wants to focus on one specific aspect of the process, such as a controlling factor. Additionally, models are used as method of representing reality when it is not completely understood. These models yield predictions of outcomes of hypothetical situations. The predictions can then be used to drive the decisions that an engineer must make. When deliberating, however, the engineer must always remember the underlying assumptions that each model employs to approximate reality. The assumptions dictate the accuracy and the limits of the model itself. For example, many sensors rely on the linearization of a non-linear phenomenon. As shown in Figure 1.1, this linearization dictates the accuracy of the output of the sensor and the bounds of its operation.

The following sections contain descriptions of the different types of process models that are commonly employed, the reasons for using them, and the nature of the assumptions that are made in the models. In general, process models are employed for three basic reasons: 1) product design feasibility analysis, 2) process selection, design, and control, and 3) cost. Typically, a critical factor will have an effect on all three: the

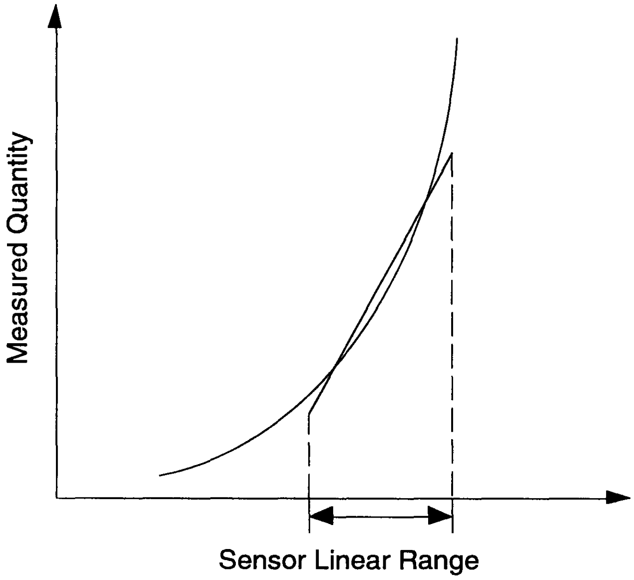

Figure 1.1: Linearization of Sensor Output

product, the process, and the cost. This thesis focuses on the discussion of models of product feasibility (or capability) and the effects of process design on this capability.

1.2.1 First Order Modeling

The term *first order modeling* is used to denote the preliminary modeling that a design team or manufacturing team uses to investigate one or more (usually limited to a few key parameters) effects of the process. There are several types of first order models, including theoretical equations and graphs, rules of thumb, tables, feature-based models, empirical equations and graphs, and experience. Depending on the accuracy of the models, they may be used in the conceptual design phase and/or the detail design phase. This level of modeling may be as much as is necessary, especially for non-critical areas.

There are several important areas that first-order process models must cover in order to be effective in the conceptual design phase. These effects represent the basics of what is normally considered process capability: *shape capability*, tolerance capability, cycle time, production volume, and *production feasibility*. The term, shape capability, refers to the capacity of a manufacturing process to produce a variety of part geometries. Usually, a design team needs to understand the constraints that the process physics place on the shape capability. For example, extruded parts must have a constant cross-section. The term, production feasibility, connotes in some manner, the general energy requirements and other process physics constraints not covered by shape capability. This term is also related to the cycle time and production rate of a process. For example, the material removal rate often dictates the type of machining process that a process engineer selects. Additionally, the type of material plays a role (in the case of machining, this property is called *machinability*). All five of these process effects will be discussed in greater detail in Section 3.2.3.

Generally, first-order models help design teams in several ways, including product feasibility, process selection, and project cost estimation. The models of product feasibility are usually empirical, and are often summarized as rules of thumb. For example, for sand casting, the parts must be designed to have a taper or draft in order to facilitate the removal of the part from the mold [Kalpakjian, 1992]. This level of detail is often sufficient for design teams in the conceptual design phase. Process selection, which depends on the material, cycle time, production volume, and cost (some would also add flexibility) often requires more analytical modeling and consultation with a manufacturing engineer. There can often be a few alternative processes that appear equally suitable for a product because of the lack of detail that these models provide. At the minimum, the models should provide direction for the design team so that the team members will be ready to discuss their options with the manufacturing engineers.

1.2.2 Computer-aided Process Simulation

With the advent of computers that have increasingly powerful microprocessors, the use of computer-aided process simulation has become more feasible within the time-frame of the product development cycle. These analyses generally rely on finite element methods to solve thousands of discretized equations in order to arrive at a representation of the continuum phenomena of the manufacturing process. Today, there are many commercial software packages available for the simulation of a variety of manufacturing processes (Polyflow, Moldflow, CMOLD) in addition to any simulation that an enterprise may develop internally. Generally, by *process simulation* it is meant to refer to finite element programs. However, the term can also include spreadsheet models and numerical models that solve and propagate the results of systems of equations, such as the homogeneous transformation matrices that are used in the error budgeting of machining processes [Slocum, 1992].

As mentioned previously, the product development team should use these models when the accuracy of the available first-order models is not sufficient. Ulrich and Eppinger [1995], in their description of a prototyping methodology, suggest that the decision to employ process simulation can be based on the teams' assessment of the risks associated with their lack of knowledge of the process and the gravity of those risks. There is much research that demonstrates that some process simulation, such as mold filling analysis, has progressed to the point that it can be employed in order to "troubleshoot" designs for shape capability and production feasibility [Medina, 1993]. In many cases, the increase in modeling accuracy comes at the expense of increased requirements of design detail. Once the design has progressed to a sufficient level of detail, changes are more costly and engineers are less willing to make them. For this reason, process simulation can often have more impact on the process design than on the product design.

Process simulation still has several limitations. Since a development team will inevitably make the trade-off between simulation and physical prototyping, the software creators must balance the accuracy of the model with the required computing time. Additionally, some of the physical phenomena involved in manufacturing processes may not be completely understood. Finally, the optimal finite element modeling techniques can be different for different physical effects. For example, fluid flow and heat transfer can be modeled by triangular elements rather well. Unfortunately, triangular elements are not as good as other element shapes, such as eight-node "bricks," for stress analysis. Currently, most software models need to use one finite element modeling strategy in order to keep track of all of the information developed during the simulation. This problem arises in warpage simulation for injection molding. Unfortunately, some engineers are not aware of the limitations of process simulation and have unrealistic expectations of these tools.

1.2.3 Statistical Process Modeling

Statistical process models are normally derived through experimentation and rely on data analysis tools such as regression and analysis of variance (ANOVA). They are used to help manufacturing engineers optimize the process and set control limits. In order to achieve these goals, the models must be created through experimentation on actual production. Typically, engineers employ the Taguchi method for the design-of-experiments, DOE [Taguchi, 1990]. By selecting the correct matrix of experiments, based on the number of variables and set points, the engineer can create models which are as accurate as the resources permit (unless the variable is random or seemingly random).

Unfortunately, this method of experimentation restricts the applicability of the model to a particular product line. Thus, the application of experimental data in new product development is dubious. Further, in many cases there are too many process parameters and product attributes that can be varied. As a result, the experimentation requirements can be too costly or time-consuming when one considers the entire platform of products. On the other hand, empirical relations can sometimes be identified that describe the effect of a particular material or machine across several products. These empirical relations may help to predict process capability for new products, but they are the only result from statistical process modeling that a product design team might be able to use. Experience has proven this approach to be difficult, as the lack of such models would indicate, given the large number of experiments done in practice.

1.3 Thesis Overview

Following this chapter, Chapter 2 discusses the modeling methods that are currently used in industry. These models provide varying levels of detail and accuracy. Each has its place in the feedback approach.

In Chapter 3, the feedback methodology is presented. The product development process is reviewed, and the method for integrating feedback into the process is discussed. Although the detailed feedback will be different for each manufacturing process, certain common factors that affect the implementation of this approach were identified.

A case study is presented in Chapter 4, involving the injection molding process. The concepts described in Chapter 3 are specifically applied and examples of feedback are shown. The data and figures shown are intended to enrich the understanding of the methodology and demonstrate its potential.

Finally, the feedback approach for injection molding is summarized in Chapter 5. Conclusions and potential future work in this field are then given.

1.4 Notation and Conventions

This thesis uses the following formatting conventions:

- *Italics* are use to identify important terms when they are first defined.
- Mathematical or logical expressions are shown separately from the body text.
- Diagrams and pictures are labeled as "Figure #.#"; equations are labeled as "(#.#)"

Chapter 2

Current Practices and Research in Design for Manufacturing

The focus of research in design-for-manufacturing (DFM) today includes the management techniques of concurrent engineering and modeling efforts for production processes and new products. These efforts have led to several design tools and methodologies that have been shown to improve quality and increase speed-to-market. Essentially, these tools and methods help guide companies in their attempt to optimize their products as well as their product realization process (PRP). Several of these tools and methods have been applied in the development of the methodology presented in this thesis.

2.1 Related Work

The scope of this thesis work covers the areas of design-for-manufacturing, process modeling, computer-aided-engineering, and statistical process control. The unifying force behind the research in these areas is the attempt to use production data to guide the design of future products. Similar work has been completed in this area in [Otto and Ho, 1995], in which a model of the variation in the quality of low-temperature co-fired ceramic circuits was developed and a methodology for the continuous improvement of that model was promoted. With proper data collection (such as bar-coding of parts and material as they run through production) and several iterations, the knowledge gained about the process and product can be retained in the form of an optimized model. This method presents an alternative to the reliance on engineers who have developed a "feel" for the process based on years of experience.

The approach of many design-for-manufacturing efforts consists of the identification of best-practices in design that will limit the cost associated with the production of parts. This technique has been successfully applied to the assembly of parts in [Boothroyd and Dewhurst, 1988], and has become known as *design-for-assembly* (DFA). Additional design guidelines for specific manufacturing processes have been promoted by industry and academia in the form of tables, diagrams, and rules of thumb (see, for example, [Kalpakjian, 1992]). However, both the DFA and "guideline" approaches remain too general in their description of the capability of the process. Additionally, there have been many counter-examples to some of the "rules" suggested by DFA, including the reduction of the overall part count. As [Ulrich, et al., 1993] have noted, the application of the reduction in parts strategy may result in the development of very complex parts. If these parts become too complex, the actual design or development of the custom tooling for the parts may become the time and cost drivers for the product development process. Thus, the cost savings from the reduction in part count must be traded off with potential cost and time increases that result from more complex parts. However, the philosophy of DFA, when not applied to its extreme (as in the above example), has become generally accepted *design-for-manufacturing* (DFM) practice.

The two main goals of research in manufacturing process modeling are process improvement (optimization) and output prediction (process capability). Ulrich and Subramanian [1994] discuss the usage of process models to evaluate producibility for a variety of manufacturing processes. Dixon and Fathailall [1994] discuss a method for determining the effect of the shape of a design upon the ability of various manufacturing processes to hold tolerances on that shape. These methods aid process selection and are part of the first order modeling of process capability described in Section 1.2.1.

2.2 Process Capability Modeling Methods

Many different methods for modeling process capability have been examined in this research, and several have been found especially useful. Some modeling methods are specific to injection molding, and these will be discussed later, in Section 4. The tools discussed in the following sections can be applied to many different product or process modeling situations. The methods reviewed are:

- Cause-And-Effect Diagrams
- Axiomatic Design
- Process Window Creation
- Taguchi's Method and Design of Experiments
- Regression and Analysis of Variance

2.2.1 Cause-and-Effect Diagrams

Cause-and-effect diagrams (*CE diagrams*), also known as *Ishikawa* or *fishbone diagrams*, are networks which classify end results as related to the contributing factors to those results. CE diagrams have been noted to be extremely useful for the identification of the key characteristics of a product or process, as discussed in [Ishikawa, 1992], [Clausing, 1994], and [Kiemele, 1990].

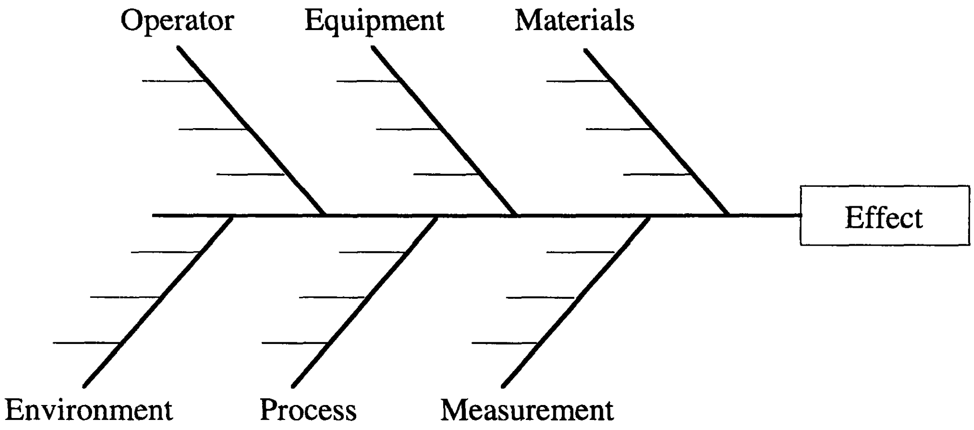

Figure 2.1: A Fishbone Diagram, showing the major classifications of causes

Fishbone diagrams were first formalized by Dr. Ishikawa of the University of Tokyo in the 1940's. These diagrams illustrate the key characteristic, function or failure mode (known as effects) and its corresponding causes. A sample CE diagram is shown in Figure 2.1. The general structure consists of the effect on the right and the corresponding causes extending from the effect to the left in a branch-like fashion. The main causes can also have underlying causes (also known as sources). In the context of statistical quality control, the effect is usually the undesirable variation of a key characteristic and the sources of variation usually consist of the raw material, the machine, tooling or other processing equipment, the process (i.e. the machine settings), and the measurement [Ishikawa, 1992]. One can also add the environment and the operator as additional sources of variation [Ho, 1995].

The CE diagram allows design and manufacturing engineers to improve their understanding of the variation and focus their reduction of variation efforts by providing a graphical guide to their approach. Typically, these diagrams can be generated through brain-storming. Additionally, these diagrams help ensure that the sources are rigorously defined as long as the aforementioned six categories are each considered in some detail. For example, for effective statistical process control, the first step in setting up the measurement system must be to decide upon the critical process parameters. Since this tool is not quantitative, it can only be used for identification purposes. Thus, the CE diagram is an effective method for beginning this step, and final confirmation of key measurement variables will then be based on the statistical analysis of the data.

2.2.2 Axiomatic Design

The framework for the *axiomatic approach to design* was developed by Nam Suh [2]. This approach can be applied in order to determine the key characteristics of a part or process. There are a few key concepts that are described in this approach: the concept of domains, the hierarchies of those domains, and the mapping between those domains. The two design axioms comprise the rules of behavior within the design world that encompasses these domains.

There are four basic domains in the axiomatic approach: the customer domain, the functional domain, the physical domain, and the process domain (see Figure 2.2).

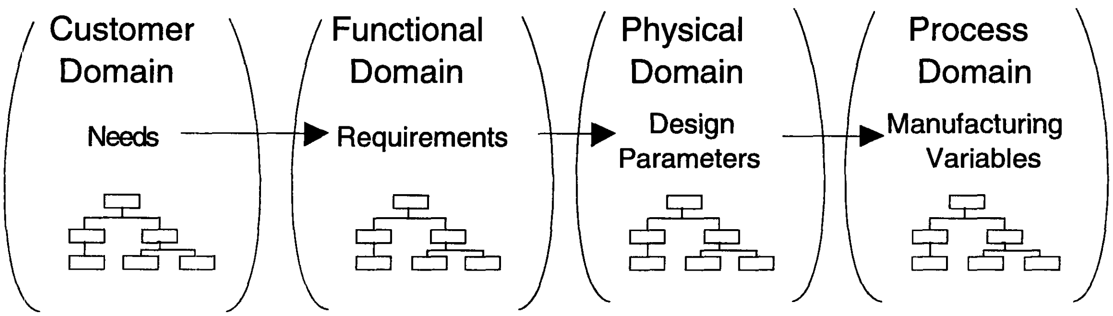

Figure 2.2: The four domains

Customer needs (CN's) are assessed in the Customer Domain; Functional Requirements (FR's) are determined in the Functional Domain; Design Parameters (DP's) are created in the Physical Domain; and Process Variables (PV's) are set in the Process Domain.

Normally, a person works within two domains at a time. The domain on the left corresponds to "what you want to achieve" and the domain on the right corresponds to "how you propose to do it". The transition between the "what" and the "how" determines the mapping. Furthermore, the requirements, or the "what", will change as you describe the "how". Typically, additional requirements will be added as the nature of the "how", or the parameters (of the design or the process), is determined with increasing detail. For example, if the requirement is "to provide shelter", additional requirements will be different depending on whether the person decides to use a tent or a house. Essentially, hierarchies of the "what" and the "how" are created and the person zigzags between these domains in order to add more detailed requirements and parameters (see Figure 2.3). By completing the design in this fashion, the engineer can keep track of the critical dimensions and the factors that affect those dimensions.

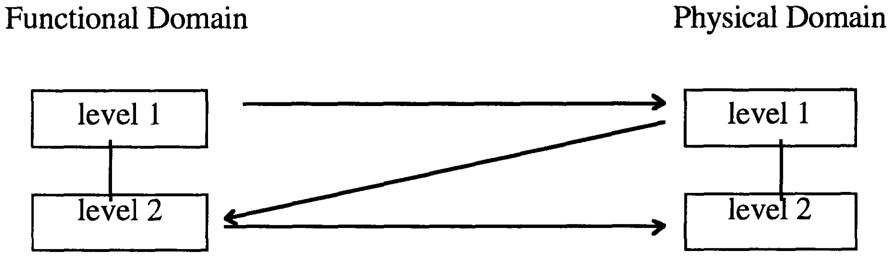

Figure 2.3: Mapping between Domain Hierarchies

Suh advocates that two design axioms comprise the rules of behavior within the design world that encompasses these domains. The rules, or axioms, set the criteria for the creation of good designs. The first axiom, the Independence Axiom, states: "Maintain the independence of the functional requirements." By definition, the functional requirements are independent with respect to themselves. If that were not the case, some of the requirements would be redundant. If the designer does not maintain this independence when creating the design parameters, the resulting design will be coupled, and it will be difficult to satisfy the functional requirements (i.e. the design will not be "robust"). Typically, the critical parameters of a design are those which are difficult to satisfy. In most cases, they refer to dimensions that have coupling.

The degree of coupling depends on the tolerances that one places on the design. In Suh's design matrix [A] (which relates each of the FR's to each of the DP's), the relationship between an FR and a DP is given by the partial derivative of that FR with respect to that DP.

$$[\mathrm{FR_i}] = [\mathrm{A_{ij}}][\mathrm{DP_j}] \tag{2.1}$$

$$\mathrm{A_{ij}} \equiv \frac{\partial(\mathrm{FR_i})}{\partial(\mathrm{DP_j})} \tag{2.2}$$

As stated in Theorem 8, if the tolerance on the function requirement is greater than the summation of the variations of the DP's times their interaction coefficients (refer to Equation 2.3).

$$\delta\mathrm{FR_i} \geq \sum_{\substack{j\neq i\\ j=1}}^{n} \frac{\partial\mathrm{FR_i}}{\partial\mathrm{DP_j}} \Delta\mathrm{DP_j} \tag{2.3}$$

That is, the effects of some sources are only noticeable when tight tolerances are required. Essentially, the fullness of Suh's design matrix is dependent upon the tolerances required.

The second axiom, the Information Axiom, states: "Minimize the information content" or alternatively, "Maximize the probability of success." Obviously, the best design is the one that is most likely to succeed. The relationship between these two axioms is clear; the more coupled the design (the less independent the embodiment of the functional requirements), the more information required to satisfy those requirements and therefore the lower the probability of success (Corollary 7). Consequently, the more interactions that arise during the creation of the design, the more difficult it will be for the design to succeed because there will be more chances for variation to have an effect.

The axiomatic approach to hierarchical decomposition leads to an often complex picture of the cause and effect relationships that are captured so well by fishbone diagrams. However, through Suh's design matrices, these relationships can be quantified more easily, and the interactions among the different sources (the "how") can be seen more readily. Axiomatic design is especially useful for understanding the assignment of critical dimensions and critical process variables, based on the assessment of the interactions among the process, the tool, the material, and the part.

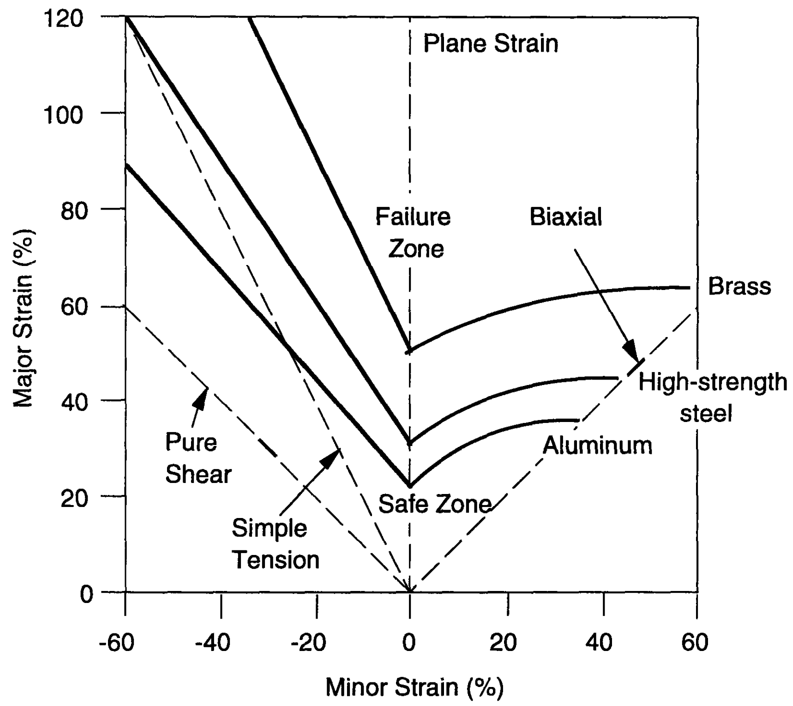

Figure 2.4: Forming-Limit Diagram for different sheet metals [Kalpakjian, 1992]

2.2.3 Process Windows

Manufacturing engineers normally use *process windows* to define the absolute physical limits of a manufacturing process. These limits are usually defined for some critical processing parameters, such as temperature, pressure, and/or time. A typical process window for sheet metal forming is shown in Figure 2.4. The limits are usually based on constraints from the machine, the material, or the control system, but they are also heavily influenced by the design of the part. If the operator tries to make parts by using set points which are outside the process window, the parts will usually have gross defects; or it will be physically impossible to produce any parts at all. Consequently, the process windows have been used as a guide for determining the set points on the machine that will produce quality parts [Rosato and Rosato, 1995].

These windows can also serve as a graphical representation of the capability of the manufacturing process. In the best case scenario, as long as the tolerances on the critical design characteristics are broad enough, the machine can be operated at any point within the window and still produce quality parts.

These windows are called "robust." In fact, the parameter limits that define the process window may not be the same parameters that limit the tolerance capability. The process window has also been used as part of the certification process for the production of new products [Wenskus, 1993]. If the processing parameters have enough latitude, or range of possible operation, and the resulting parts produced within the process latitude are still quality parts, then the manufacturing tool (and correspondingly, the part design) can be certified.

Following the certification of a new manufacturing tool, the target points for the processing parameters must be determined. The major function of the process window is to act as a guide for setting up the process. One common approach in injection molding is to choose set points that are in the center of the process window as starting points. These points will then change as the manufacturing engineers learn more about the process for that particular tool, which will enable them to optimize the set points. Even after the optimal set points have been found, the process window may still be used when the process has to be redefined after the machine has been shut down for maintenance, especially if parts have been replaced.

Due to the nonlinear nature of many manufacturing processes, it can sometimes be difficult to determine the actual boundaries of a process window. For example, if the processing parameters interact in a linear fashion and are independent, then the process window can be determined by simply changing the set points in a one-at-a-time fashion. As Nam Suh [1990] states, however, in the case of the nonlinear process, the processing parameters will be generally coupled. If the tolerances are broad enough or if the process window is shrunk to a small enough region, the parameters will behave as if they were independent. The limits of this small region may be determined through one-at-a-time experimentation, but there will also be a larger region surrounding this region in which the processing parameters are coupled. For this larger region, it is difficult to define the process window because one cannot simply use the aforementioned one-at-a-time approach. As shown in Figure 2.5, changing one process parameter while holding the other constant in a nonlinear manufacturing process will not define the window properly. In this case, the actual maximum limit for ram pressure will not be reached since the upper limit itself is a function of temperature. Clearly, in a multidimensional case, understanding the window boundaries becomes much more complex. However, this approach is still useful as a starting point for understanding the process, and the manufacturing engineers will have to rely on experience to define the limits more thoroughly.

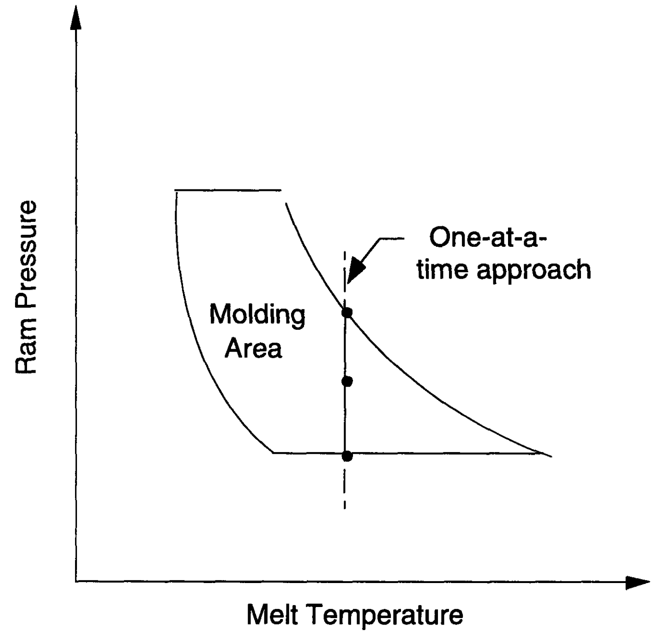

Figure 2.5: Molding Area Diagram for Injection Molding

2.2.4 Design of Experiments and Taguchi's Method

During the past few years, the technique known as *design of experiments* (DOE) has been applied as an efficient method for improving quality. First given widespread attention in the implementation of *Taguchi's Method*, and often called *parameter* or *factorial design*, DOE is a statistical tool that maximizes the amount of information about alternative parameter settings that can be obtained subject to a constraint on the number of experiments that can be performed.

Good discussions of how to apply parameter design can be found in [Clausing, 1994] and [Phadke, 1989]. Essentially, one uses a set of designed experiments in order to optimize the performance of a product. The process consists of selecting performance metrics, choosing the parameters that affect performance, and performing the experiment to determine which parameters have an effect on performance. In fact, by using different values, or *levels*, for each parameter, the team can determine the optimal settings for each parameter. The effect of each parameter on the quality of the product is given by a *sensitivity analysis* of the experimental results. Based on an understanding of the magnitudes of the effects of each parameter, the team can then assign "criticality" to the appropriate parameters and have the data to support these claims.

The mathematics involved in determining the minimum set of required experiments are beyond the scope of this thesis and have been well documented in the literature. Montgomery [1991] provides a good introduction to the theory of designed experiments. Before the conduction of the experiments, the team cannot assume that each of the parameters will have the same effect on the performance of the product independent of the levels of the other parameters. If this situation were true, then the optimization of the parameter levels could be easily performed through one-at-a-time experiments, which vary each parameter setting individually from the current settings. In most cases, experimenters apply DOE in order to determine the *main effects* of the parameters and the nature of the *interactions* among the parameters. Many people only look for two-way interactions, which involve only two parameters. In that case, the number of experiments can be limited to a fractional factorial (as opposed to a full factorial design, which would include every possible combination of effects and levels). Many statistical software packages, such as SAS and JMP, will automatically generate the set of experiments once the number of effects and levels have been decided.

The technique employed in parameter design is especially useful for situations where the theoretical underpinnings of the nature of the product's performance are not well understood or do not lend themselves to physical modeling. It is especially useful for gaining an understanding of the effect that variation of the levels of individual parameters will have on the performance of the product. However, the technique will only optimize the given set of parameters. If the team has not fully defined the design space, it will not determine the true optimization for the problem. Furthermore, the optimization will only be true for a particular product or problem. Any understanding that the team gains from the experiments will be empirical. As a result, the team may not be able to apply the "lessons learned" to new products or problems.

2.2.5 Regression and Analysis of Variance

Once a set of experiments relating to a process or product have been completed, *regression* and *analysis of variance* (ANOVA) techniques can be applied to determine the effect of individual parameters on the output of the experiments. This process is known as a *sensitivity analysis*. The level of a parameter's criticality will be based upon the output's sensitivity to changes of that parameter. Regression is a technique for describing the relationship between the parameters, or *independent variables*, and the outputs, or *dependent variables.* Analysis of variance is then used to decompose the total variation in the experiment into the sources of variation.

Linear and nonlinear regression must be used to determine the main effects of the parameters and the interactions among the parameters. In the simplest case, linear regression involves the fitting of the output, *y*, to the input, *x*, as shown in Equation 2.4:

$$y = \alpha_0 + \alpha_1 x + \varepsilon \tag{2.4}$$

where α_1 is the slope of the line, α_0 is the intercept, and ε is the random error about the line. There are two quick tests that show if the assumptions in the model chosen to fit the output are good. First, one can look at the ***squared correlational coefficient***, r^2, which measures the tightness of the fit of the data. An r^2 of 0 indicates purely random data, and an r^2 of 1 indicates a perfect fit. The second method of checking the assumptions of the model is to plot the ***residuals***, or e_i, versus the predicted values of y. Note that e_i is simply the difference between the actual y value and the predicted y value because the error terms are assumed to be independent of x. If the residual plot has any shape to it other than a random scatterplot, then the model is probably not correct.

In addition to the qualitative tests mentioned above, there are tests which describe the "goodness of fit" more quantitatively. These tests fall under the general description of analysis of variance. ANOVA can determine how significant the outputs' changes are with respect to changes in the input parameters. The main purpose of ANOVA is to determine the main sources of variation in the sample. This analysis usually involves a comparison of the variation of an individual parameter with the total variation of the sample. In general, an estimate of the standard deviation of the error, $\sigma(\varepsilon)$, known as *s*, can be found using Equation 2.5:

$$s = \sqrt{\frac{\sum_{i=1}^{n} e_i}{n-2}} = \sqrt{\frac{SS_{yy} - \alpha_0 SS_{xy}}{n-2}} \tag{2.5}$$

where n is the number of data points, SS_{yy} is the sum of squares around the mean of y, and SS_{xy} is the product of the deviations from the mean of x and y, also known as the cross product. Using this information, the *t-test* can be performed in order to check the hypothesis that the actual slope of the line is zero. This test will confirm the existence of the effect of a parameter through Equation 2.6:

$$t = \frac{\alpha_1}{\sqrt{s^2 / SS_{xx}}} \tag{2.6}$$

where SS_{xx} is the sum of squares around the mean of x. A common rule of thumb is that the slope of the line is non-zero if the absolute value of the t statistic is greater than 2 [John, 1990]. Finally, the *F-ratio* can be used to determine how much of the variation has been predicted. Essentially, it compares the predicted variation in y due to changes in x with the actual variation of y. The larger the F-ratio, the better the fit of the data. More complete discussions of regression and ANOVA can be found in [Hogg, 1992] and [John, 1990].

Regression and ANOVA are used in the interpretation of the results of the experiment performed in the case study in Chapter 4. More detailed descriptions of the application of these techniques accompany the description of the case study.

Chapter 3

A Process Capability Feedback Methodology for Integrated Product Development

An approach to the integration of design and manufacturing operations through the feedback of process information is presented in this chapter. The main concepts are first outlined in Section 1, which develops a vision of the product development process and how this methodology will fit into this process. Section 2 explains the methods of model creation and usage as a product is developed that ease the implementation of feedback. Section 3 closes the feedback loop with a discussion of the appropriate modes and locations for feedback. The final sections discuss the issues that arise during the implementation of this strategy.

3.1 Methodology Procedure Outline

In order to create an information feedback loop, one must first consider the nature of the information that is required and developed at the various stages of the product development process. Design and manufacturing engineers use different models to describe the capability of a manufacturing process because they have different information requirements. As a result, the nature of the information feedback will have to be tailored to each of the models that the engineers use. Different feedback loops will be created for the different stages in the product development process, allowing for system-wide improvement of process capability understanding.

3.1.1 Overview of the Product Development Process

Many books have been written on the nature of the product development process: what it is and how it should be performed, [Eppinger and Ulrich, 1995], [Suh, 1990], [Wheelright and Clark, 1992], [Andreasen and Hein, 1987], [Clausing, 1994], [Urban and Hauser, 1993]. In recent years, a major improvement in the quality of the development process has been achieved through the introduction of concurrent engineering. This practice has replaced the former "throw it over the wall" process of design and manufacturing that was the previous standard. In the old standard, product design was completely separated from the manufacturing side of the business. This separation invariably led to the development of products that were difficult to manufacture. Some companies even had separate departments within the manufacturing divisions that would redesign the parts "sent over" from the designers in order to make them manufacturable [Lieberman, 1994]. With the advent of concurrent engineering, the use of cross-functional teams has become more prevalent; and consequently, the communication among design and manufacturing engineers has improved. In addition, in an effort to speed up the development process (in order to become more responsive to the needs of the marketplace), many tasks that had been completed in a serial fashion are now being done in parallel. For example, manufacturing engineers will now begin to design the process and tooling for a product before the part design is complete. As a result, it is difficult to abstract the product development process to a simple diagram.

In fact, this "shuffling" of the elements of the design process has spawned a new research field devoted specifically to the organization of design tasks. [Smith, 1992] and [Whitney, 1990] have added to earlier work by [Stewart, 1981] on this subject. Essentially, the design tasks are listed in a matrix, and based on previous experience, the design engineers describe the amount of communication necessary to complete a pair of tasks. These matrices will then be used to set up the overall design teams. For example, if the completion of two tasks requires that the engineers in charge of those tasks communicate every day, those two engineers will be placed on the same team. For the purposes of this discussion, the operations of the design and manufacturing engineers are separated for clarity, as shown in Figure 3.1.

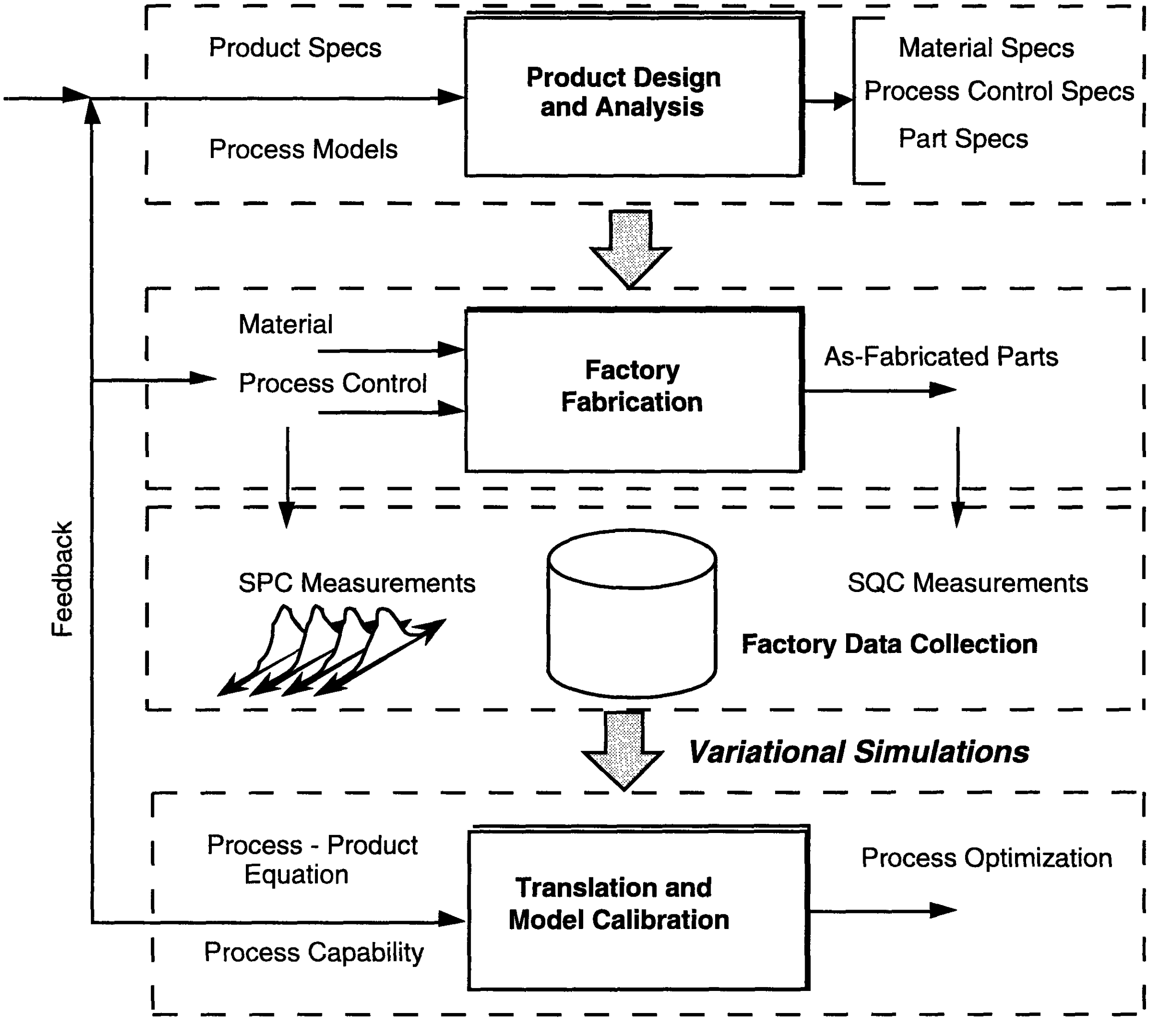

Figure 3.1: The Product Development Process with Feedback

There are two major inputs to the design process: customer needs (or engineering specifications) and constraints. The constraints can be based on many things, including: geometry, physics (the laws of nature), economics, or the manufacturing process. As soon as the manufacturing process is selected, a wide range of constraints are placed on the product, most of which involve the shape of the part. These constraints often include: filleting or draft requirements, surface finish limits, tolerance capability limits, and minimum wall thicknesses. Because there are so many constraints, design engineers employ process models to understand the effects of the constraints on the product. Essentially, these models are used to determine the production feasibility of a new design, which will consist of part, material, and process specifications.

When in production, the manufacturing system takes in material, applies process control to a process, and produces a set of actual parts. At this stage, the manufacturing engineers also need models of the process in order to determine how to set up the process control, including the set points for the various process parameters and the control limits. Again, these models reflect the effects of the various constraints from the manufacturing process, including: components of the machine, the tool, and the material. Statistical Process Control (SPC) is used to measure the process during production, and Statistical Quality Control (SQC) is used to measure the incoming material and outgoing produced parts. With proper data collection (such as the bar coding of parts and material as they run through production) these various measurements can be correlated to a model to understand sources of variation [Otto and Ho, 1995].

One can consider a piece part design-for-manufacturing analysis tool as analogous to a production system as described above. This class of analysis tools includes common finite element simulation tools such as C-Mold or Moldflow, but also includes simple tabular tools such as the Society of Plastics Industries guidelines [SPI, 1993]. Any model of a manufacturing process used during a design process is a candidate. Rather than manipulating actual material as the real process does, however, an analysis tool requires a specification of material. Similarly, the process itself is presumed or parameterized. With these two specifications, a prediction of the resulting part shape is provided by the tool. By understanding the process capability from SPC and incoming material measurements, these can be used in the design phase DFM analysis to predict production capability of the new parts being designed.

3.1.2 The Quantification of Experience

The key to this feedback methodology lies in the fourth box in Figure 3.1, "Translation and Model Calibration." Once the production equipment has been properly instrumented and the product measurement process has been set up, the amount of product and process information will accumulate rapidly. Many manufacturing enterprises generate very large data sets but use only a small fraction of the information contained in those data sets. The success of this methodology will depend on the ability of the enterprise to distill the appropriate information from these data sets and transform it so that the information can be fed back into the models of the process. Since manufacturing and design engineers often use different models of the process because they have different priorities, it is logical to expect that the data will have to be transformed before the models can be calibrated. Although it is difficult to generalize about the nature of these transformations and

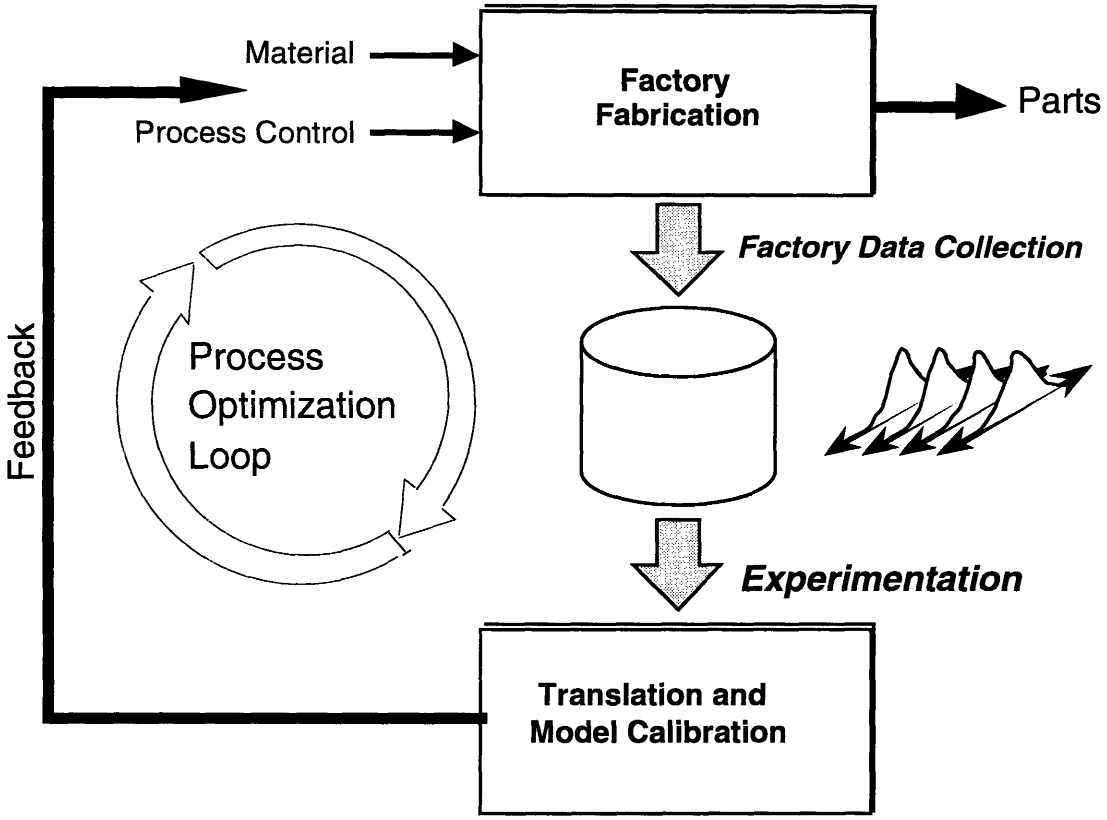

Figure 3.2: Process Optimization Feedback Loop

interpretations irrespective of the type of manufacturing process, this methodology will provide guidelines for those tasks and suggest techniques when appropriate.

When the production process is set up and certified for quality, manufacturing engineers will often employ certain tests or experiments to help them optimize the process settings. These tests may be enterprise-specific or industry-standard. An example of the latter would be the use of designed experiments, as described in Section 2.2.4. The results of these experiments are interpreted and "fed back" into the set up of the process as part of the "Process Optimization Loop," which is shown in Figure 3.2. In addition to the knowledge that is gained for the manufacturing process of a particular part, the process models can be refined to reflect the new understanding of the process. In previous years, this second step has been completed only in the minds of the manufacturing engineers and has been known as the accumulation of experience. Later sections will describe more detailed ways to institutionalize and quantify this experience through the feedback approach.

As shown in Figure 3.3, however, additional benefit can be gained by feeding back the information garnered from the manufacturing process to the process models that design

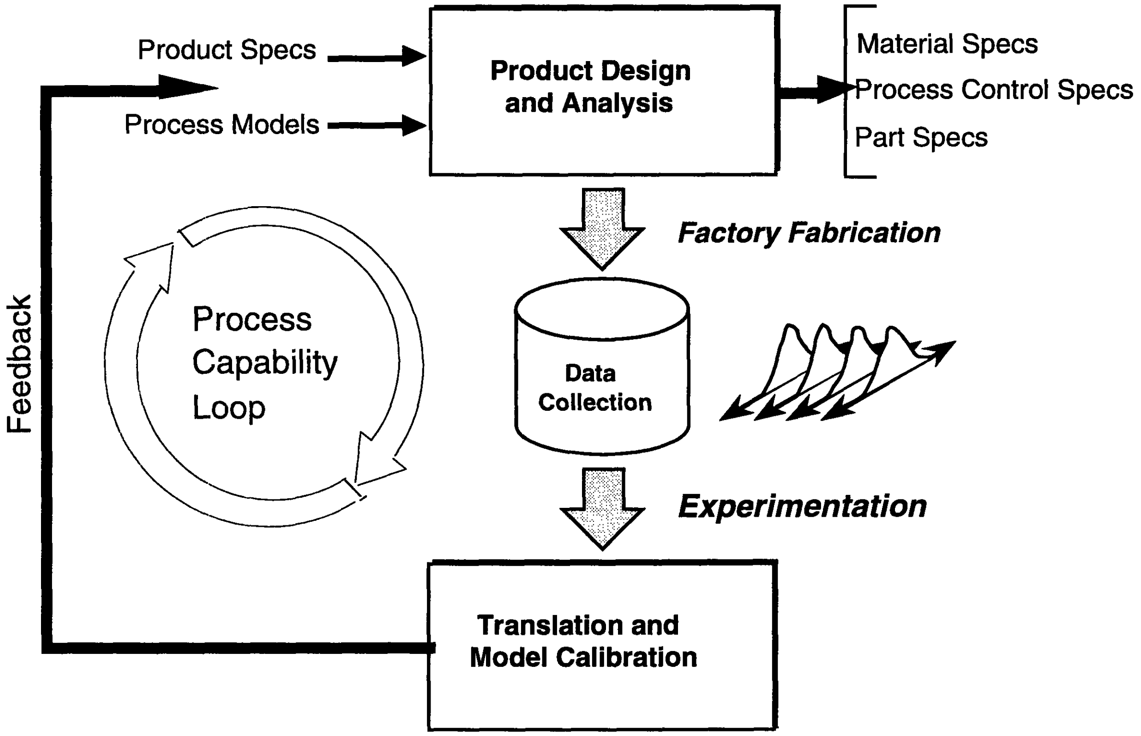

Figure 3.3: Process Capability Feedback Loop

engineers use. This feedback is called the "Process Capability Feedback Loop." As stated earlier, design engineers use process models to gain an understanding of the constraints that a particular process places on the design of a part. Many of the engineers on my industrial team commented that the only time they are contacted after the design leaves their hands (i.e. when it is sent to production) is when a problem arises. Many were curious to see if the assumptions that they were making about the capability of the process were accurate [for example, Vickers, 1994]. For this feedback loop, more data translation and interpretation will be necessary because the design engineers often use different models of the manufacturing process to meet their needs (as opposed to the models that manufacturing engineers use). In this approach, the experience that the manufacturing engineers gain from experimenting with the process will also be gained, to a degree, by the design engineers.

3.2 Making Feedback Possible

As stated in the previous section, the interpretation and transformation of production-generated data is critical to the success of this methodology. Consequently, it is important to prepare the manufacturing organization to facilitate this data translation and to handle the information flow through the feedback loop. One could describe part of concurrent engineering as a holistic method to accomplish this task in that it forces engineers to qualitatively share experiences. Similarly, this methodology describes how computers need to share data from these "experiences" and how models can incorporate that data.

The first steps in this preparation consist of modifying the structure of the product data management (PDM) system. Since it is difficult to keep track of all of the parameters that describe a design or production process, many enterprises have chosen to assign a designation of *criticality* on the parameters that the engineers believe are most important, or best describe the design or production process. Much of the terminology and philosophy behind this choice evolved from Taguchi's description of parameter design, as discussed in Section 2.2.4 and [Phadke, 1989], [Taguchi, 1990], and [Clausing, 1994]. The concept of assigning *critical parameters* is believed to be a useful one that through efforts described here can become more well defined as a practice. The next section considers both the voice of design and the voice of manufacturing in these definitions for product dimensions. This consideration makes an important distinction in the assignment of critical dimensions from solely accounting for product functional concerns. By including manufacturing engineers in the discussion, the management of *critical-to-function dimensions*, from assignment to production, will become more effective.

3.2.1 Choosing Critical Metrics of Quality

Different people have different definitions of what makes a dimension critical-to-function. One senior level design engineer described them as the dimensions that he thought would be difficult to manufacture. However, if one does not assign tolerances carefully, a non-critical dimension may turn out to be unnecessarily difficult to manufacture. Unless the design engineer has an intuitive understanding of the process, it will be difficult for him to anticipate every dimension that will be difficult to manufacture. There are other times when a dimension may be called critical-to-function in industrial practice. For example, there can be dimensions that are difficult to measure with the available measuring equipment. Calling these out as critical to the mold design engineer can help ensure that the tolerances on these dimensions are held by focusing more attention to them [Covington, 1995].

In this thesis, *critical-to-function dimensions* are defined as those dimensions that directly affect the performance of the part as opposed to those that merely describe the geometry of the part. There can also be *critically-constrained dimensions*, which are dimensions that have tight limits based on their interfaces with other parts and "negative" specifications (such as "the box shall not exceed 5 inches in length"). For simplicity, these dimensions will be lumped with critical-to-function dimensions, but one should be wary of designs that have artificially tight constraints.

Critical-to-function dimensions are based on a design engineer's conceptual embodiment of a solution that satisfies the customer's needs. For the purposes of the feedback approach, dimensions that are designated as critical-to-function are needed for streamlining the PDM system; reasons and methods for proposing this identification are beyond the scope of the thesis. Essentially, an engineer must describe a geometry that fulfills the engineering specifications for the performance of the part. Using axiomatic design, or other product decomposition approaches, one can map the functional requirements to the design parameters (dimensions) [Suh, 1990] and [Pahl and Beitz, 1996]. One can then assign the critical dimensions based on the importance of a particular function to the customer using the House of Quality [Clausing, 1994] or other techniques.

Finally, through the use of tolerance analysis, designed experiments, and/or functional prototyping, the design engineer can assign preliminary tolerances on the critical-to-function dimensions. Methods for determining the relationship between the critical parameters and part quality have been well-documented [Phadke and Taguchi, 1987] and [Clausing, 1994]. Given the set of critical-to-function dimensions, the next step is to evaluate the manufacturing capability with respect to these dimensions.

In order for this to be done, however, the factory floor must be properly instrumented. Each measurement of material, process and part must be correlated in time. Typically, this entails bar coding of parts, to stamp each measurement to a piece of work in progress. As a result, the variations upstream and downstream can be properly correlated, so that root cause analysis is meaningful. This level of data collecting becoming more prevalent, with the current focus upon manufacturing quality.

Coordinate Measuring Machines (CMMs) are becoming the standard measurement tool for quality control. Given the point contact method of measuring parts and the variations in the shape of parts, many points must be taken in order to define a dimension and capture the design intent of that dimension. Typically, the designer who assigns plus/minus tolerances uses a worst-case analysis and intends the tolerances to refer to *extremal fits*, the intended limit of a surface dimension [Hopp, 1993]. For example, when the designer assigns a tolerance to the distance between two surfaces, he is usually concerned (for functional reasons) with the minimum separation distance. Many CMMs, however, have algorithms to create *average fit* distances to a surface plane based on a least squares approach. However, such averaging algorithms can mask the effects of the manufacturing process on the shape of the part, especially for large surfaces that may be warped, thereby yielding erroneous results. It has been suggested that "averaging fits are less sensitive to [CMM] measurement errors than are extremal fits" [Hopp, 1993]. It is not clear how to treat this averaged data when the functional concerns include extremal notions such as warpage. Further, one may not have enough measurement capability to use extremal fits. Thus, there is a need to balance the trade-off between accurate part description (many points) and measurement time (few points).

In order to define the appropriate measurement strategy for quality control (SQC), one must determine which dimensions are most sensitive to variation in the process. These dimensions are defined as *critical-to-monitor* dimensions. Logically, these dimensions will be a subset of the critical-to-function dimensions. Due to the complexity involved in interpreting SQC data and the time required to complete dimensional measurements, it is desirable to minimize the amount of measurements required to ensure quality. This minimization can be accomplished through the proper application of sampling theory [Hogg and Ledolter, 1992] and the assignment of critical-to-monitor dimensions. Through a regression analysis technique that is described in Section 3.3.4, a minimal set of critical-to-monitor dimensions can be defined [Zemel and Otto, 1996]. Note that this is a decision that must be made not exclusively by the manufacturing process engineers, but through cooperation with the design engineer who initially specified the dimensional tolerances.

3.2.2 Choosing Critical Process Parameters

Much of the emphasis of statistical process control (SPC) is placed on keeping the process stable [John, 1990]. Traditionally, manufacturing engineers have used SPC to monitor the variability of process settings, and they have attempted to find the minimum set of variables that are necessary to determine the stability of the process. As a result, the set of monitored process variables commonly does not contain enough information to create or evaluate process models for design teams.

For the feedback approach, *critical process parameters* are defined as those process settings or variables that provide machine maintenance monitoring information and quality control information. Some process parameters will be directly controllable by a "knob" on the machine, such as timer. Others will be the result of the interaction of several process settings and the machine; these parameters are often a form of output from a stage in the process or describe the entire process history. For example, for sintering, the time and temperature processing profile will dictate the final material structure [Kalpakjian, 1992].

By distinguishing between the machine maintenance concerns and the quality concerns, the definition of the critical parameters allows for the possibility that a part of the machine will wear out without immediately causing the machine to produce bad parts. For example, if a heater begins to falter, it may exhibit a gradual loss in temperature over time, or it may fluctuate wildly. By understanding what the control limits are and how these control limits relate to the quality of the end product, the manufacturing engineer will be able to determine the machine shutdown criteria. In one case, the control limits for a parameter will be based on the predicted quality of the produced part. Different control limits may be used to detect problems on the machine.

There are several methods for determining the critical process parameters. *Fishbone diagrams*, *Fault Tree Analysis*, and *Failure Modes, Effects, and Criticality Analysis* are three common techniques for assigning criticality [Ishikawa, 1992], [Pahl and Beitz, 1992]. As described in [Ho, 1995], these techniques provide a good structure for brainstorming and qualitative analysis of the process, but extracting quantitative modeling information from them may prove difficult. Process simulation and experimentation (such as DOE), provide more quantitative methods for assigning criticality as described in Section 3.2.3. In general, it is useful to reduce the amount of simulation or experimentation time by qualitatively reducing the set of critical process parameters. Once the final set of critical parameters is confirmed, other parameters can still be useful as *secondary parameters*, which can provide additional maintenance information and guide the root cause analysis in failure investigations.

There is an additional criterion for the selection of critical process parameters, but it remains specific to the manufacturing process. For an example of critical process parameter selection, refer to Section 4.2.2. In general, the critical process parameters may need to capture additional information which will allow design and manufacturing engineers to evaluate their process models. It may be possible to obtain this information on a one-time basis during certification or experimentation, or it may be necessary to continuously monitor the parameter. The cooperation of both design and manufacturing engineers will be necessary to ensure that monitoring process for this information is properly installed.

3.2.3 Application of Process Models

Once the critical parameters for the product and the process have been defined initially, design and manufacturing engineers can use process models to understand the effects of the process on these parameters. In the case of both critical design parameter and critical process parameter determination, the application of the process models will dictate the definition of the final sets of critical parameters based upon a better understanding of the effects of their variation. The first decision that an engineer must make is to determine the level of detailed modeling that is required. This level of detail will depend upon the type of effect, the criticality of the effect, the accuracy of the available models, and the time and resources available for modeling. Unfortunately, engineers do not always have confidence in the models available to them, or more generally, they do not understand the risk associated with using the results from the models. As described in Section 3.4, by incorporating feedback into the following model usage methodology, the engineer will be better prepared to make this decision.

3.2.3.1 First Order Models

The first type of models that all engineers should use are first-order models, as described in Section 1.2.1. Too often, when engineers have a high level of modeling capability available to them in the form of simulation tools and statistical methods, their tendency is to skip over the first-order modeling methods. These methods are a quick way for the engineer to establish "ballpark figures," which also help them to determine the plausibility of the results from more detailed modeling methods. At this point, design and manufacturing engineers will be concerned with four things: shape feasibility, production feasibility, cost, and tolerance capability.

Design engineers often have rules of thumb that they use to estimate the shape feasibility of a manufacturing process. For example, in metal casting, certain limits must be placed on the variation in wall thickness and the sharpness of corners in order to produce a part without gross defects [Heine, et al., 1967]. Again, design engineers will only be concerned with these effects as they pertain to the design of a part. These defects are also known as *attribute defects* in some industries.

Manufacturing engineers will often be concerned with shape feasibility; in their case, they will want to determine the appropriate operating region in the process space. Additionally, they will want to assess the production feasibility of a particular shape in order to select the appropriate machine for the job. Manufacturing engineers model these constraints with a process window. In some industries, there are software packages available that claim to be able to predict the size of the process window before a design has been produced [CMOLD, 1995a].

3.2.3.2 Process Windows

If the software or other models are not available, the manufacturing engineer can create a process window by considering the material state equation that defines the change that a part undergoes during processing. For example, in sheet metal forming, the state equations are the stress-strain relationships. In addition, the manufacturing engineer must consider the method of process control. For sheet metal forming, the metal is bent into the desired shape through the application of a set displacement. By applying Hooke's Law (where the force is equal to the spring constant times the displacement), the manufacturing engineer can solve for the stress applied to the metal. This stress can then be used in the material state equation to define the strain-to-failure window, as shown in the forming limit diagram from Figure 2.4. The use of these equations can also aid in critical process parameter determination. By forming the process window in this fashion, the manufacturing engineer will be able to determine the shape feasibility of the part based on the displacement required to achieve that shape. Finally, the manufacturing engineer will be able to model the production feasibility of the design via this method in that the force required to form the part will have been calculated. The force requirement will dictate the type of press that can be used.

Manufacturing engineers will also rely upon rules of thumb and experience to make machine purchasing decisions. In injection molding, for example, the manufacturing engineer must determine the amount of force required to keep the mold closed (called the *clamp force*) before selecting the appropriate machine. For most parts, manufacturing engineers often multiply the projected area of the part times three to five pounds per square inch to estimate the clamp force [Augonis, 1995]. In the case of thin-walled parts, this assumption can break down because of the higher pressure required to inject the plastic into the cavity. Given the costs associated with purchasing a new machine, the accuracy of any models used to determine production feasibility and the skill of the manufacturing engineers are very important.

3.2.3.3 Cost and Cycle Time Modeling

In fact, the process selection decision is usually dictated by cost. Much research has been devoted to cost modeling for each manufacturing process [Kaganov, 1984], [Busch and Field, 1989], and cost modeling is beyond the scope of this thesis. Much of the variable cost of a product is dictated by the production cycle time. Cycle time can also dictate the fixed cost, to a degree, because it can determine how many machines are necessary to meet the anticipated volume demand. Again, the engineer will often use a first-order model to quickly estimate this quantity for a proposed design. Unfortunately, for many net-shape manufacturing processes, cycle time is often dictated by heat transfer, which does not always lend itself to simple first-order modeling. As a result, more detailed modeling may be necessary. The decision to move to more detailed modeling should be dictated by the engineer's understanding of the validity of a model's assumptions.

The price of more detailed modeling is that the design engineer needs to provide more information about the design. In many cases, more decisions about the design will have been "frozen-in" by the time an analyst is able to use process simulation to model the product. Even if the design engineer is open to changing the design, more work will be lost if changes are made due to the level of detail. However, process simulation can be used as a quick "design check" to troubleshoot designs and consider possible problems for which there is no good first-order model. In addition, if the design team has not selected the final design, process simulation can compare the manufacturability of the alternatives. Finally, process simulation can serve as an aid for tool design and process design. Even if the final tolerances have not been assigned to the design, the manufacture of the nominal shape design can be simulated to help manufacturing engineers choose the critical process parameters and help tool designers lay out the cooling system.

3.2.3.4 Tolerance Modeling

The final area of process capability modeling, tolerance capability is usually the major source of discussion among design and manufacturing engineers. One can consider a piece part design-for-manufacturing analysis tool as analogous to a production system as described in Section 3.1. This class of analysis tools includes common finite element simulation tools such as C-Mold or Moldflow, but also includes simple tabular tools such as the one shown in Figure 3.4. Any model of a manufacturing process used during a design process is a candidate. Rather than manipulating actual material as the real process does, however, an analysis tool requires a specification of material. Similarly, the process itself is presumed or parameterized. With these two specifications, a prediction of the resulting part shape is provided by the tool. By understanding the process capability from SPC and incoming material measurements, these can be used in the design phase DFM analysis to predict production capability of the new parts being designed.

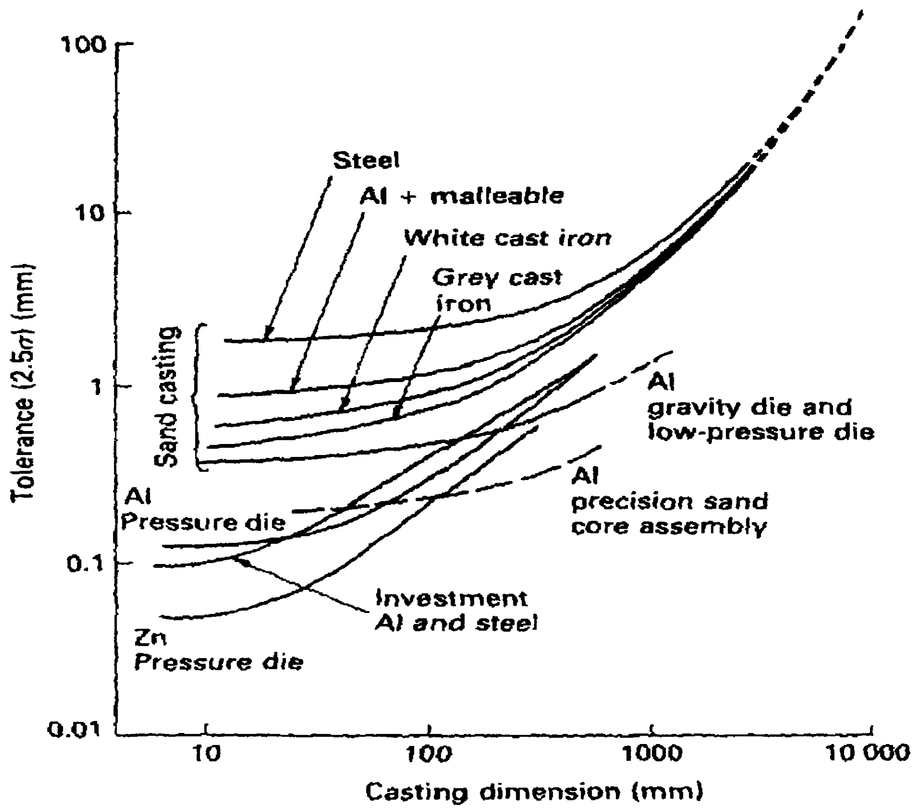

Figure 3.4: A Tolerancing Chart for Casting [Brown, 1994]

Most of these tolerance diagrams plot tolerance versus length and differentiate among the various materials that can be processed. They allow design engineers to obtain rough estimates of the tolerance capability but do not provide any information about the reasons for the variation. In addition, the diagrams do not provide any guidance for design engineers who are looking to exceed the suggested tolerance capability. In order to improve the precision of the manufacturing process, the major sources of variation must be modeled.

By gaining an understanding of the variation, the design and manufacturing team will be able to do four things: assess the tolerance capability, determine if the part will function properly through tolerance analysis, assign the aforementioned *critical-to-monitor* dimensions, and set up a measurement scheme for quality control. Furthermore, reduction of variation investigations and other development efforts will be focused on the areas that have the potential to add the most value. For example, [Fussell, et al., 1994] have created a model of aluminum extrusions which enables them to set up the coordinate measuring machine (CMM) measurement program to properly capture the shape of the parts. They are now looking to apply this model to the monitoring and control of the extrusion process. As they have found, one must take great care in setting up a measurement program for quality control.

3.3 Critical Tolerance Evaluation and Assignment for Net-Shape Manufacturing Processes

The following section describes a methodology for applying the different process models in order to define critical-to-monitor dimensions and assign tolerances to dimensions for a net-shape manufacturing process, injection molding. By linking the evaluation and assignment of tolerances on critical dimensions to the setup of the quality monitoring system, the methodology helps make the completion of both tasks easier and more logical. This methodology can also be generalized enabling engineers to apply it to critical process parameters and the modeling of the effect of the process on attribute defects. The modifications/generalization method will be discussed where appropriate.

3.3.1 An Injection Molded Part Integrated Development Method

In "The Language of Tolerances," Theodore Hopp makes the following observation:

> *"Use of statistical tolerancing requires the designer to use information about the capability of the manufacturing process--the expected distribution of the shape variation. Unfortunately, there is no formal way for the designer to record, as part of the tolerance, the process-capability information that makes the tolerance a faithful representation of the design intent. Leaving out this information can have as much impact as not placing tolerances on the drawing in the first place..."* [1993b].

He then gives an example: when the manufacturing process is improved, the (process capability) distributions used (assumed) for setting the tolerances are no longer valid and the drawing is no longer appropriate! Through the following methodology, design and manufacturing engineers will be able to drive the tolerance specifications of new products and processes through the use of existing production data. As mentioned in Section 3.2, this methodology places new requirements on the product data management system to incorporate the proper feedback of data.

There are four basic steps to injection molded part tolerancing, based upon critical-to-function and process capability identification, as shown in Figure 3.5. First, one must determine the critical-to-function dimensions based on the product specifications, function analysis, and functional prototypes. At this point, the design engineer only specifies tolerances on these dimensions for functional reasons. In contrast to the paradigm of tolerance assignment described by Hopp, the assignment of tolerances for functionality is decoupled from tolerance allocation based on process capability. Next, create a finite-element model of the part and simulate the injection molding process at several points within the process window. These simulations will yield shrinkage and warpage data, which can then be used to determine the relationships among the dimensions that describe the part. This step includes regression fitting and assessment of confidence limits. The results from this analysis can then be used to define a set of critical-to-monitor dimensions

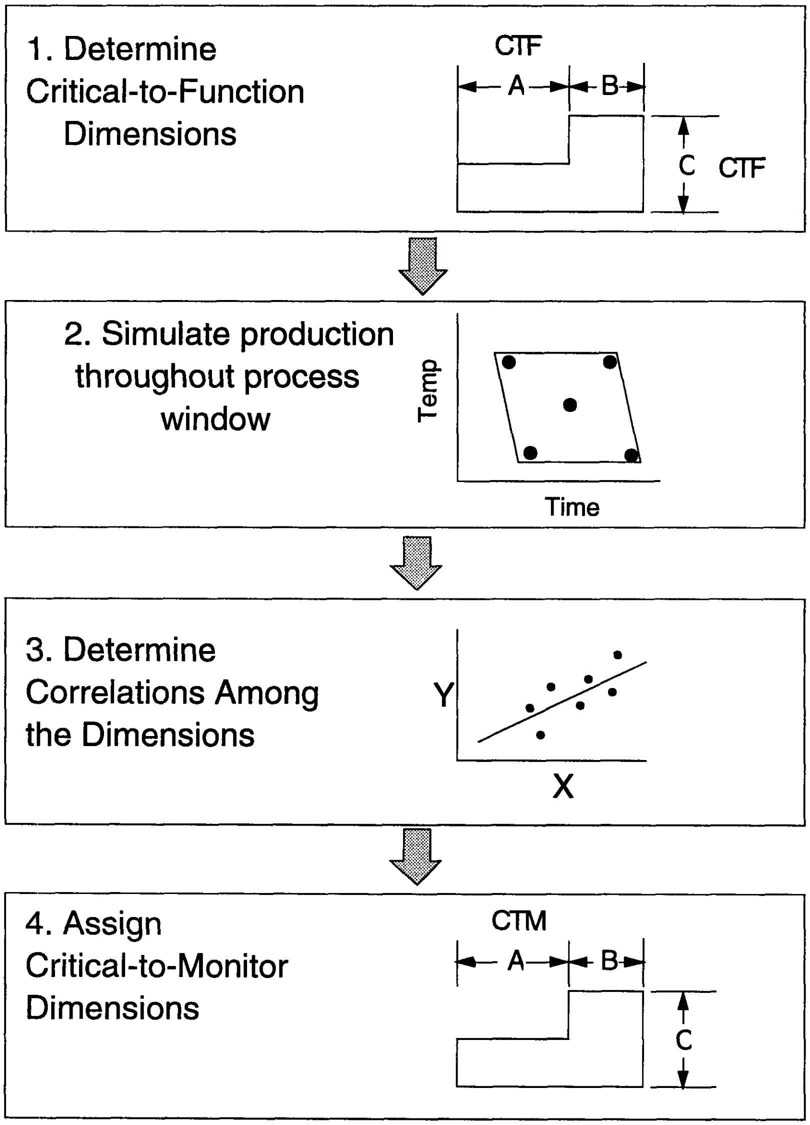

Figure 3.5: Overview of Critical Dimension Tolerancing.

which are a subset of the critical-to-function dimensions. Using these dimensions, the engineer can evaluate any tolerance analysis studies that were completed in the first step and assign reasonable tolerances on non-critical dimensions. Finally, the engineer will be able to define a measurement program for quality control. Once the simulation predictions have been verified with production data, the engineer can then tighten or loosen tolerances in order to limit the amount of measurement time while maintaining a high standard of quality.

3.3.2 Step 1: Determine Critical-to-function Dimensions

As described in Section 3.2.1, critical-to-function dimensions are defined based on a design engineer's conceptual embodiment of a solution that satisfies the customer's needs. Essentially, an engineer must describe a geometry that fulfills the engineering specifications for the performance of the part. Using axiomatic design, or other product decomposition approaches, one can easily map the functional requirements to the design parameters (dimensions) [Suh, 1990] and [Pahl and Beitz, 1996]. One can then assign the critical dimensions based on the importance of a particular function to the customer using the House of Quality [Clausing, 1994] or other techniques.

Through the use of tolerance analysis, designed experiments, assembly modeling, and/or functional prototyping, the design engineer can assign preliminary tolerances on the critical-to-function dimensions. Methods for determining the relationship between the critical parameters and part quality have been well-documented in [Phadke and Taguchi, 1987] and [Clausing, 1994]. It is important to note that the design engineer should only specify tolerances based upon the functionality of the part. When creating the design, the design engineer will have an idea about the order of magnitude of tolerances that will be required, and this estimate will be used to select the manufacturing process. However, at this point, the design engineer should be concerned with the performance of the design and how that performance drives the assignment of critical-to-function dimensions. As discussed in Step 4, the final tolerance specification task, during which the actual process capability is considered, will be undertaken by the manufacturing and design engineers. Given the set of critical-to-function dimensions, the next step is to evaluate the manufacturing capability with respect to these dimensions.

3.3.3 Step 2: Simulate the Part at Points within the Process Window

At this stage, a finite element model of the part must be prepared for process simulation. Additionally, one must estimate the process window for the part before simulation. In the case of injection molding, the process window is the region of process variable space in which a part can be made without gross attribute defects such as flash or short shots. This region can also be defined by material limitations, such as heat-induced plastic degradation. The estimation of the process window can be based on experience with similar parts or first-order modeling such as using one-dimensional strips, for example. A derivation of the process window and the key process parameters from a theoretical standpoint is given in Section 4.3.3. Some simulation software packages include process window estimation capability, but these are first-order estimates only and may not take into account all of the limiting factors. In general, for these simulations, it is important to first understand the key process variables which can affect the part dimensions, and to be sure and vary these process variables within the process window. It is true that simulation can help identify these key variables, but in order to limit the simulation time, a reasonable understanding of the process is necessary. Some variables to consider include melt temperature, mold temperature, pack pressure, fill time, and pack time, cool time [Glozer, 1995]. Sections 3.2.2 and 3.2.3 describe the method for determining the key variables for other manufacturing processes.

To select points to run the simulation, there are several trade-offs to consider. As stated earlier, the process set points must be sufficiently varied such that the part dimensions are reasonably affected. An easy way to guarantee that the dimensions are affected is to simulate the process at the extremes of the process window. However, the predictions of the extremes of the process window may not be realistic, so one should not deviate too far from reasonable set points (based on experience). Finally, in order to determine realistic relationships among the dimensions, several sample points are needed. One can satisfy this need by varying several process variables or by simulating at several levels of a few variables. This sampling need must be balanced with the time allotted for simulation. Similarly, the effect of the process on the generation of attribute defects can be modeled by simulating the process at various points within the process window. Unfortunately, the ability of a particular machine to limit the variation of the critical process parameters cannot be determined through simulation. This effect must be determined on the factory floor and fed back into the model.

3.3.4 Step 3: Determine Relationships Among Predicted Dimensions from Simulation

Having obtained the simulation data from the various points within the process window, one can now determine the linear correlations among the various critical-to-function dimensions. When using linear correlations in this approach, the engineer must not assume any causality based on the fact that two dimensions may vary in the same manner. These linear correlations may arise for more complicated reasons, as discussed in Section 4.3.2, or they may simply arise by chance. Since individual dimensions cannot be independently controlled in net-shape manufacturing processes, it is reasonable to expect linear correlations among dimensions. In this approach, the use of the linear correlations does not depend on the analysis of their underlying causes.

For any two dimensions, one can perform a regression analysis that produces a squared correlation coefficient, commonly known as r^2. Alternatively, one can also determine the correlational matrix across all the dimensions (consisting of r for every possible pair of dimensions) and then perform regressions on only the dimensions that are clearly correlated. Given r^2, we then know how much of the variation of dimension Y can be explained by the variation of dimension X.

In addition to yielding the correlational coefficient, a regression analysis produces a least squares fitted line for dimension Y as a function of dimension X:

$$\mathrm{f(x)} = \mathrm{Y} = m\mathrm{X} + b + \varepsilon \tag{3.1}$$

where: m is the fitted slope of the line, b is the fitted intercept, and ε is the error about the line. This error is usually assumed to follow a normal distribution with $\mu = 0$ and $\sigma = \sigma(\varepsilon)$. In order to estimate $\sigma(\varepsilon)$, one can calculate s:

$$s = \sqrt{\frac{\sum_{i=1}^{n} e_i}{n-2}} = \sqrt{\frac{SS_{yy} - bSS_{xy}}{n-2}} \tag{3.2}$$

where e_i are the sample values of ε, SS_{yy} is the sum of squares around the mean of y, and SS_{xy} is the product of the deviations from the mean of x and y, also known as the cross product. Please refer to Section 2.2.5 for more information about regression.

From this information, the engineer can approximate what we call the *model tolerance* of dimension Y. The model tolerance of dimension Y, Δ_y, is the distribution of

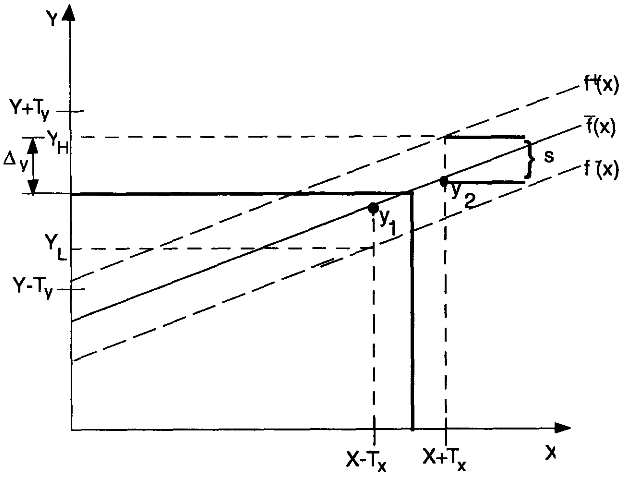

Figure 3.6: Y as a function of X.

dimension Y that is predicted when the specified tolerance on dimension X, T_x, is applied to the regression model fit. The model tolerance is not the same as T_y, the specified tolerance on dimension Y. As shown in Figure 3.6, the s statistic can be used to find Δ_y. Accordingly, the model tolerance can also be expressed by the following:

$$\Delta_y = \frac{1}{2}(y_2 - y_1) + s \tag{3.3}$$

where y_2 and y_1 are the predicted Y dimensions based on X+T_x and X-T_x. Note also that the line, $f^+(x)$ represents the upper bound (based on the three sigma limits) for the dimensional data and $f^-(x)$ represents the lower bound. Thus, the linear correlations among the dimensions can be extended to linear correlations among the tolerances on those dimensions using the definition of model tolerance.

For the case of attribute defect generation, the engineer can define a contour map throughout the process window for each attribute. Alternatively, the effect of each process setting may be plotted individually. Since many attribute defects are subjective in nature, this level of analysis is as detailed as required.

3.3.5 Step 4: Define Critical-To-Monitor Dimensions

In order to define the appropriate measurement strategy for quality control, one must determine which dimensions are most sensitive to variation in the process. These dimensions are defined as *critical-to-monitor* dimensions. Logically, these dimensions are a subset of the critical-to-function dimensions. If the model tolerance of a dimension is less than the design engineer's specified tolerance, the dimension does not have to be monitored directly because its variation will be "captured" by another dimension.

$$T_y \leq \frac{1}{2}(y_2 - y_1) + s \tag{3.4}$$

By comparing all possible pairs of dimensions, a minimal set of critical-to-monitor dimensions can be defined. Note that this is a decision that must be made not exclusively by the manufacturing process engineers, but through cooperation with the designer who specifies the dimensional tolerances.

Often, the mapping of tolerances on X to tolerances on Y is not as easily applied. For example, there are many instances where the specified nominal value of X does not map directly to the specified nominal value of Y. This situation can arise when the mean production dimension is not equal to the target dimension (i.e. it is "off aim"). In other cases, the tolerances on Y, T_y, may not be completely bilateral. These two situations lead to a result that is shown in Figure 3.7, where the mapping of tolerances on X overlaps regions in and out of the specification of the tolerances on Y. The development team has two options in these situations. First, it can ignore the relationship and measure both dimensions. Second, it can possibly reduce the number of measurements by applying a sequential plan to the measurement process. That is, measure dimension X first. If the measured dimension maps to regions within the specified tolerances of the other dimension (i.e. the region between $f(Y_L)$ and $X+T_x$ for the X dimension measurements will still map to a region within the tolerance band around Y), then Y does not need to be measured. If the measurement of X does not map to within the appropriate tolerance zone, then the additional dimension must be measured.

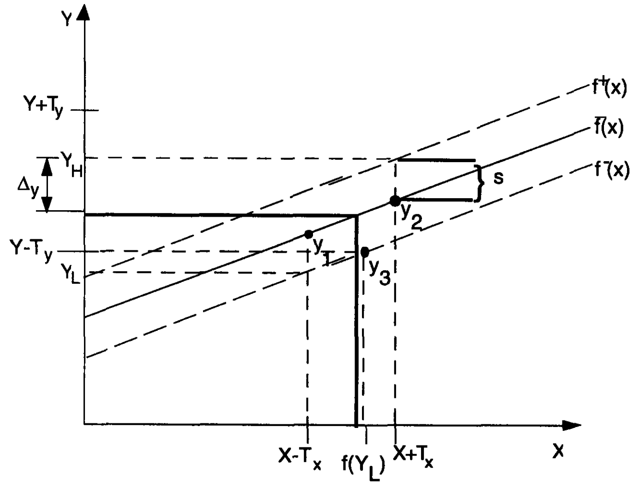

Figure 3.7: Mapping of X to Y with Overlapping Tolerance Bands.

In fact, if the process has the capability to hold some tolerances tighter than the specifications, then the manufacturing engineer can arbitrarily tighten critical tolerance specifications in order to further reduce the number of critical-to-monitor dimensions. As shown in Figure 3.7, if one can easily tighten T_x, one might be able to reduce Δ_y so that it will be within T_y.

Finally, tolerances on non-critical dimensions can now be defined based on the appropriate model tolerances so that they will never become critical-to-monitor dimensions by "accident." Normally, design engineers attempt to be conservative when applying a first-order tolerancing chart (such as the one shown in Section 4.3.2) to non-critical dimensions by assuming that the dimensions can be held to within the worst-case line on the chart. The method proposed in this section provides the engineer with greater confidence that the non-critical dimensions' tolerances will not be arbitrarily tight, as opposed to this conservative application of the first-order tolerancing chart. Although the method relies on the accuracy of the simulation software, once the part is produced, the critical-to-monitor dimensions can be reevaluated, and tolerances can be adjusted as necessary.

3.4 Process Capability Feedback

Once the part has been produced and data from the process and from the product is being generated, it is time for the final step in the product development process: Data Translation and Model Calibration, as described in Section 3.1.1. Through this step, the information about the process can be fed back through the process capability and process optimization feedback loops, as discussed in Section 3.1.2. As a rule, the feedback should start with the process optimization loop and then continue with the process capability loop because the process capability data will become obsolete if the process is improved in any way through optimization efforts.

3.4.1 Data Feedback

One of the first methods of feedback should be to determine the capability of the process for these critical process parameters. Much research has been devoted to the study of machine capabilities and manufacturing engineers can easily use this information to justify machine replacement or rebuild decisions [Naitove, 1993]. In addition, these process parameter capability distributions can then become the inputs to the process simulation tools in the next product development cycle. However, it will still be important to simulate throughout the process window because the capability of a machine to maintain its set points will vary depending upon the location of the process within the window. For example, if the machine is operating near its pressure limit, the process parameters may fluctuate more than if the machine is set up near the center of the window. Based on a few product cycles, however, the manufacturing engineer will be able to benchmark the capabilities of each machine in the factory to see which machines perform consistently better or worse than the others. These machines can then be reserved for the more important jobs or shut down for maintenance as warranted.

The second method of feedback can be the feedback of tolerance capability. The easiest method for this feedback is to plot the variation of the critical-to-monitor dimensions on the first-order tolerancing chart that the design engineers use to estimate the capability of the process. In time, the tolerancing chart will then move from an industry standard capability chart to an enterprise capability chart. This method of plotting will also enable manufacturing engineers to benchmark themselves with respect to the industry. An example of this feedback will be shown in Section 4.5.2. The tolerance capability can also be decomposed into separate types of capability. For example, the capability for one machine will be different than the capability for ten machines. Similarly, the capability for one mold cavity will be different than the capability for 16 mold cavities. By using the information from this decomposition, design engineers will be able to estimate the effect of production volume on tolerance capability. In effect, by creating a pareto chart of the major sources of variation, the manufacturing engineers will be able to focus their variation reduction investigations and help guide design engineers' material and process selection decisions. Finally, the tolerance capability for a particular product can be fed back to design engineers by electronically linking the measurement system for quality control into the overall product data management system. This task may not be as simple as it sounds because the PDM software may not be prepared to accept production data.

3.4.2 Model Evaluation

Once the data feedback has been completed, additional benefit can be gained through process model evaluation. The suggested methodology in this thesis relies upon the usage of first-order models, process windows, process simulation, and statistical techniques.

The accuracy of each modeling method can be evaluated. As mentioned in the previous section, the tolerancing charts can be evaluated on a rather subjective basis through the plotting of the actual variation on the chart. It is likely that there will be a lot of spread in the data, but the actual tolerance capability can then be shown through the use of tolerance bands. In time, design engineers will become confident that dimensions with tolerances that are greater than band's upper limit will never be critical-to-monitor dimensions. Additional tolerance investigation will be warranted in the tolerance specification is within the tolerance band.

The second level of model evaluation and feedback is for process windows. There are several benefits that can be gained from process window feedback. First, the nature of the process window is such that the critical parameters for attribute defects may be different than the critical parameters for tolerance capability. In effect, two windows may be defined, which can then be used to define the process control limits if they haven't been defined through experimentation. The actual process windows can also be compared to the predicted process windows from simulation software and/or the modeling technique described in Section 3.2.3. The size of the process window also indicates the room that a manufacturing engineer has for optimization. Finally, the process windows can be used by simulation experts and mold design engineers when they are trying to analyze similar products in the future.

The evaluation of process simulation can be more difficult. Because of the detailed nature of the modeling, it will be difficult to quantify the accuracy of the model. However, the predicted dimensions can be compared to the actual dimensions, and a statistical confidence in the simulation can be developed. Furthermore, the predicted variation can be compared to the actual variation through the F-test in order to develop another confidence statistic. If the simulation predictions are not "on aim," it still may be possible to scale the predictions based on the analyst's understanding of the assumptions in the model. These issues can then be discussed with the software vendor. It is important to separate the appropriate source of actual variation to the predicted variation because it is unlikely that one model will be able to capture the many possible sources of variation. It will become easier to understand the potential for feedback to a process simulation tool by looking at the case study in Chapter 4.

Statistical models can also receive limited feedback in terms of new data. Since the models themselves will be linear fits of actual data from limited runs, however, the advantage of data feedback appears rather small. If some of the information from the statistical models can be extracted and generalized to apply to more than the original part that the model is based upon, the feedback of data to the statistical model will add more value. Unfortunately, these empirical models have been difficult to create for manufacturing processes (as evidenced by the lack of published information in the literature) because of the many different materials and machines that can be used for the same process.

3.5 Key Benefits and Limitations

There are several benefits to the feedback approach. By coordinating the communication among design and manufacturing engineers through the use of actual data, the methodology pushes the "tolerance argument" to the discussion of facts, not opinions. In addition, it provides a structure for the involvement of manufacturing engineers in the design process, and gives them the chance to justify tolerance changes. Thus, the critical parameter allocation method is better defined and more realistic. Design and manufacturing teams will be able to drive the tolerance specifications of new products and processes based upon existing manufacturing process and product data.

The strategy of feedback to the process models allows design and manufacturing engineers to evaluate the accuracy of the models and consequently, the risk associated with using the predictions from the models. As shown by [Ho, 1995], the feedback approach also promotes the continuous improvement of the models. By promoting a better understanding of the underlying assumptions in each process model, the feedback method will help engineers to make the trade off between the level of detail involved in a model and the level of its accuracy. In the case of tolerance capability feedback, design engineers will be able to gage the tolerance capability for similar designs. In the case of the feedback of process windows, the chief advantage of the feedback is how it will help analysts make their simulated process parameter settings more realistic. Finally, through the continued feedback and model evaluation, a model usage methodology can be developed within the enterprise. As a result, the enterprise will institutionalize its understanding of the capability of its manufacturing processes. Through continual evaluation of its models and its process capability, the enterprise will be able to benchmark its manufacturing and development capability and focus future efforts for improvement.

The most difficult part of the implementation of this methodology is the organization of production data and translation of the production information into the language of the process models. In many cases, complex and detailed feedback will be difficult to standardize for every product. First order model feedback will be much easier to complete. Finally, it will be important for management to emphasize the coordination of both design and manufacturing engineers in this effort. Manufacturing engineers may initially believe that they are merely providing a service to the design engineers. Design engineers will have to involve the manufacturing engineers in the tolerance allocation process and other design decisions at the front end of the feedback loop in order to provide motivation for both groups.

Chapter 4

Application of Feedback Methodology for Injection Molded Product Development

The following case study was conducted at the same time as the development of the methodology presented in the previous chapter. Many of the generalizations that are present in the methodology will become much easier to understand through application. In addition, some new material will be presented that is specific to injection molding.

In Section 1, an overview of the injection molding process and plastic materials is given. The definition of critical parameters for the case study is then made in Section 2. The common models that are used, and how they can be prepared for integration into the feedback approach is discussed in Section 3. These models are then evaluated in Section 4 through the use of experiments on a production line. Finally, methods of feedback to design and manufacturing engineers are discussed in Section 4.

This portion of the thesis research was conducted in cooperation with Eastman Kodak Company. Due to the sensitive nature of the product studied, certain information has been omitted to maintain proprietary rights and confidentiality. The values given are actual results from analysis, but only the information that is necessary to illustrate the methodology is included.

4.1 Background

This case study involves the production of 35 millimeter film spools. Kodak manufactures millions of these spools every year through injection molding. The process and the current design strategies for the process is discussed in the following sections.

4.1.1 Injection Molding

Injection Molding is a net-shape process for the manufacturing of plastic products. It is a serial process that involves four stages: *plastication*, *injection*, *cooling*, and *ejection*. In *plastication*, plastic pellets are fed from a hopper into a heated barrel, where they are melted through the combination of heat supplied from a rotating screw (which causes viscous heating) within the barrel and heaters that lie around the outside of the barrel. Refer to Figure 4.1 for a schematic representation and Appendix A for actual pictures and more detailed information. As the screw rotates, material builds up in front of the screw until a specific volume is accumulated. This volume is the amount of plastic that will be injected in one shot, and is commonly known as the *shot size*. Since the barrel has a constant cross-sectional area, the shot size is usually measured in inches of *screw position*.

At this point, the injection cylinder causes the screw to move forward via hydraulic

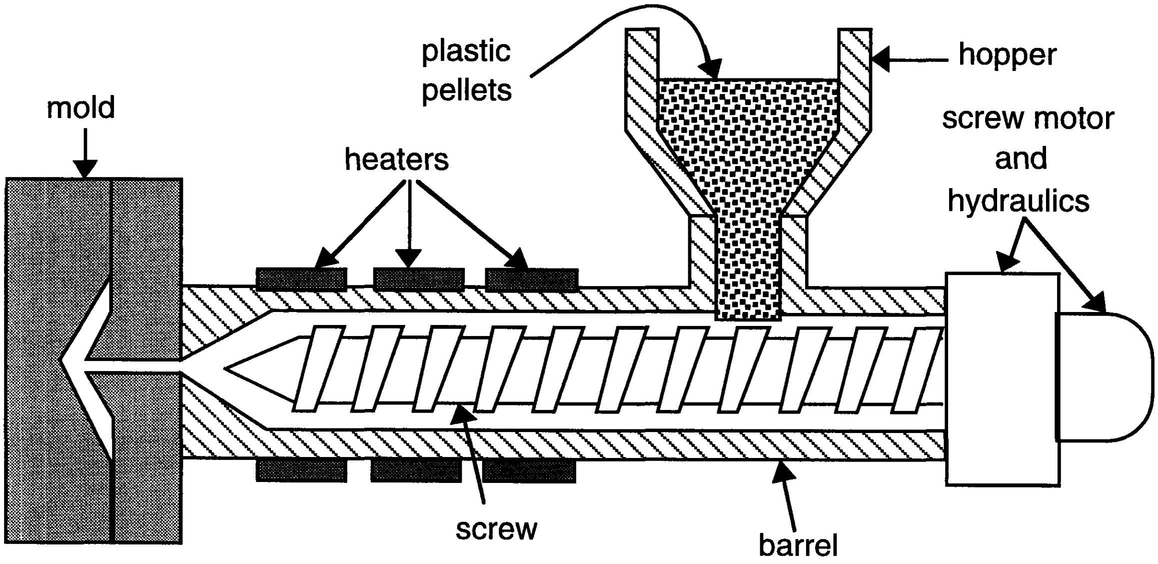

Figure 4.1: An Injection Molding Machine

pressure, *injecting* the plastic into the mold. The plastic flows from the barrel through a material delivery system to get to the gate, which is the entrance to the mold cavity. The material delivery system is comprised of runners that transfer the plastic from the nozzle to the gate. There are two types of runners: *cold runners*, which solidify upon filling and have to be ejected with the part; and *hot runners*, which are always full of molten plastic. Heaters are placed at various points along the path of the hot runner system in order to keep the plastic molten. The time it takes for the molten plastic to fill the mold cavity is known as the *fill time*. Manufacturing engineers commonly measure the screw position as a function of time and choose 98 or 99 percent of the full travel of the screw as the fill time.

As soon as the plastic enters the mold, *cooling* begins. As the plastic cools, it changes from a liquid to a solid and consequently shrinks. Shrinkage will be discussed in more detail in the following section. For that reason, molders attempt to *pack* the plastic into the mold after it is initially filled. In general, the more plastic that is packed into the mold, the less the part will shrink. This process occurs at the end of the injection stage. The fill-to-pack switch-over occurs at the same 98 or 99 percent of the screw travel point. There are several other methods of fill-to-pack stage transfer, including time, in-cavity pressure, and parting line control; for more information, refer to [Rosato and Rosato, 1995].

When the gate freezes, the machine can no longer pack additional plastic into the mold, but additional cooling is usually necessary. Once the plastic has cooled to the point where it will not deform upon *ejection*, the mold opens and the parts are ejected from the mold into a bin. There are several techniques for ejecting parts, and the choice of ejectors usually depends on the part shape, among other factors. After ejection, the mold closes and the process repeats. The *cycle time* for injection molding, therefore, is comprised of the fill time, the pack (or hold) time, the cooling time, and the mold-open time (this time refers to the time it takes for the mold to open, eject the part and close). Most cycle times range from a few seconds to a few minutes.

4.1.2 Plastic Materials

There are a few key characteristics of plastic materials that drive the injection molding process. The rate at which molten plastic can be injected into the mold is dictated by the viscosity, η, of the plastic, which causes it to resist flow. In a Newtonian fluid, the viscosity is independent of the shear rate applied to the fluid. That is, the fluid's resistance

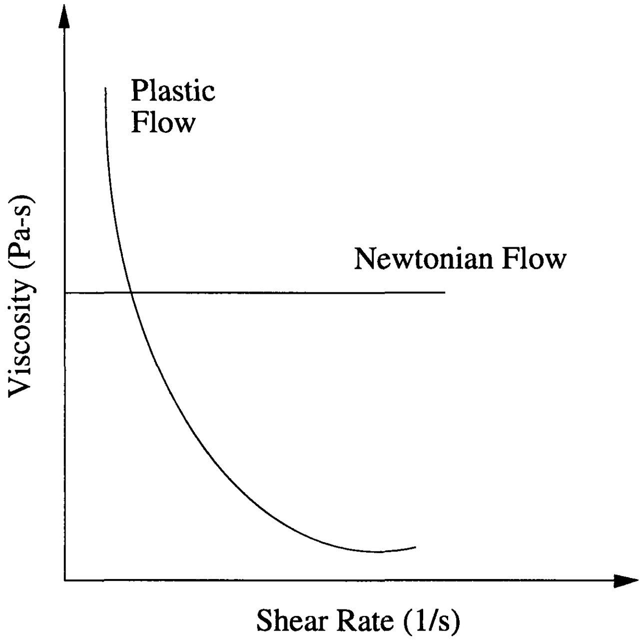

Figure 4.2: Viscosity versus Shear Rate for Plastic [Rosato and Rosato, 1995]

to flow is independent of how fast the fluid is pushed. Plastic exhibits non-Newtonian behavior, as shown in Figure 4.2, in that its viscosity decreases with increasing shear rate. This phenomenon is known as *shear-thinning*. The definition of viscosity is the ratio of the shear stress (required to push the plastic) and the shear rate, as shown in Equation 4.1.

$$\eta = \frac{\tau}{\dot{\gamma}} \tag{4.1}$$

In addition, the viscosity of the plastic will vary with the temperature of the fluid. In order to properly model the filling and packing stages of the injection molding process, the effects of temperature and shear rate must be considered [CMOLD, 1995b], [Aslam, et al., 1994].

The rate at which a plastic material can be cooled in the mold is dictated by the *thermal diffusivity*, α, of the plastic. This quantity, which is the ratio of the thermal conductivity, k, to the product of the specific heat, c_p, and the density, ρ, is on the order of 1000 times smaller for plastic than for metal. For this reason, plastic makes a good insulator. This property has several implications. First, it makes the measurement of the temperature of the plastic at any point during the cycle difficult because the steel surrounding the plastic will transfer heat to the sensor much faster than the plastic itself. Second, it allows temperature gradients to exist within the plastic. This phenomenon can

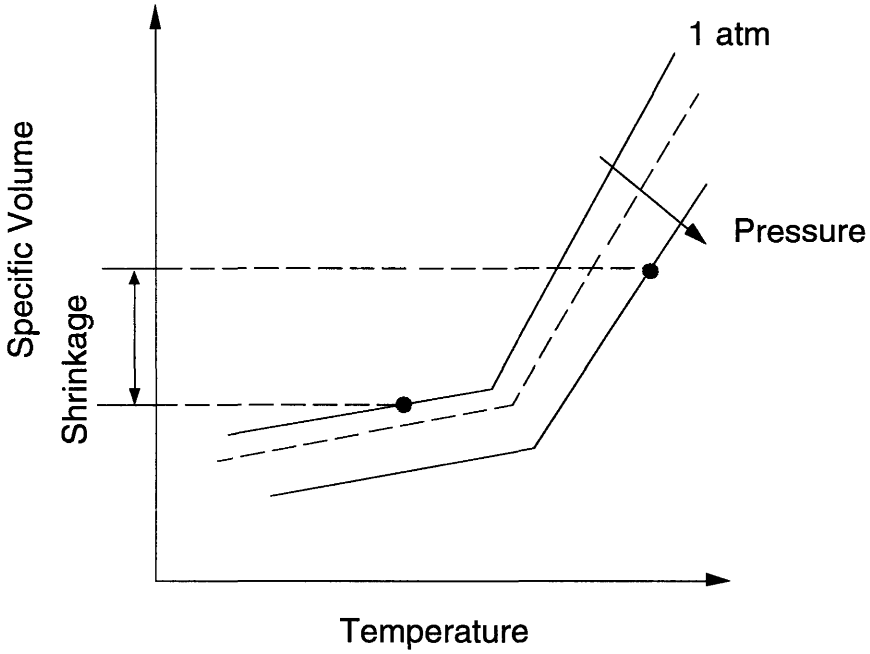

Figure 4.3: PvT Diagram for an Amorphous Plastic

cause core or insert materials to retain more heat than the surrounding mold and it can lead to differential shrinkage.

As the plastic cools within the mold, it shrinks in size, as most materials do. This effect is normally described by the linear thermal expansion coefficient. However, in the case of plastics, there are additional factors that affect the amount of shrinkage. As shown in Figure 4.3, for the range of temperatures and pressures undergone by the plastic during injection molding, the density of the plastic does not remain constant. This phenomenon is known as *compressibility*. When the density is divided by the mass of plastic, the resulting quantity is known as the *specific volume*, which is used in the standard way of describing the relationship among the pressure, density, and temperature of the plastic. Notice that this diagram is valid for an *amorphous* plastic. In amorphous plastics, as in glass, the individual polymer chains have no specified order (like a bowl of cooked spaghetti). As a result, there is no real *melt temperature* that can be defined because the change from liquid to solid does not involve any microscopic ordering of the polymer chains. Some plastics do exhibit a structure on the molecular level, and these materials are known as *semi-crystalline* plastics (unlike metals, they do not form a complete crystal structure). Semi-crystalline materials generally exhibit greater amounts of shrinkage because they undergo a definitive phase change.

Shrinkage is defined as the change in the plastic's specific volume from the initial state when it enters the mold (at a raised temperature and pressure) to the final state when it leaves the mold (at atmospheric pressure and a lower temperature). Finite element simulations predict this shrinkage by calculating the initial and final state of pressure and temperature for each element in the part. Since the shrinkage may be different for different regions of the same part, residual stresses can build up within the material. In addition, if the cooling of the plastic is not evenly balanced throughout the part, the shrinkage will vary due to changes in the location of the final state on the PvT diagram. This variation in shrinkage can also lead to residual stress buildup. These two effects lead to *warpage*, which is a bending of the material in response to residual moments that build up within the material. For a more complete discussion of the properties of plastic refer to [Ferry, 1980] or [Rosato and Rosato, 1995].

4.2 Choosing Critical Parameters

As described in Section 3.2, there are many methods and tools available to aid in the selection of critical product and process parameters. An example showing the use of axiomatic design is employed for the case of critical-to-function parameter definition. This technique is especially helpful for cases where the design already exists. An example showing the use of a fishbone diagram is demonstrated in the definition of critical process parameters.

4.2.1 Critical-to-function Parameter Definition

For the 35 millimeter film spool, Eastman Kodak had previously defined its set of critical-to-function dimensions. The methodology of this thesis requires that this selection set be verified in order to ensure that proper and efficient feedback can occur. The following discussion of the spool design from an axiomatic design perspective shows the overall development of the critical-to-function definitions.

Film Storage System

Since the spool is only one part of a system that is designed to satisfy the functional requirement of 35 millimeter film storage, it is important to discuss the overall system. The basic functional requirements and design parameters are shown in the following diagram:

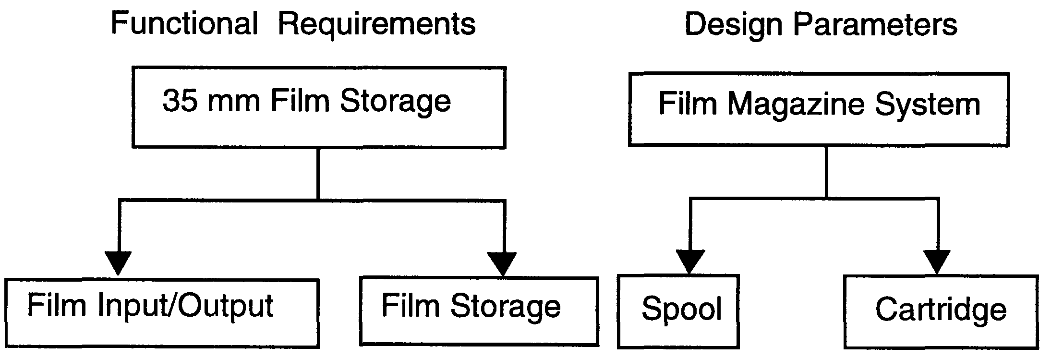

Figure 4.4: Basic Requirements and Parameters

As shown in Figure 4.4, the main functional requirements for the spool are film input/output (or access) and film storage (including protection). The two main design parameters in the film storage system are the spool and the cartridge that encloses the film and the spool. The functional requirements and design parameters can be related in the following equation:

$$\begin{Bmatrix}\text{Film I/O}\\ \text{Storage}\end{Bmatrix} = \begin{bmatrix} \text{X} & \text{O} \\ \text{X} & \text{X}\end{bmatrix}\begin{Bmatrix}\text{Spool}\\ \text{Cartridge}\end{Bmatrix} \tag{4.2}$$

The equation suggests that the spool should be the first part of the design to be created. However, because the cost of manufacturing the cartridges is so much greater than that of the spools, the spool is usually redesigned before the cartridge.

Constraints

There are additional objectives that the design engineer must consider during the initial stages of design. The considerations on the spool design come from each of the four domains and are often called constraints. As mentioned earlier, the cost of changing the spool design is less than that of the cartridge, so it is designed in order to interface with an existing cartridge geometry. This is a customer-driven constraint, where the customer is the enterprise. Although cost is treated as a functional requirement for the manufacturing process, it is difficult to treat cost as an FR for a design. Typically, the designer will have an overall cost limit or range, and the design will be evaluated for cost when the manufacturing process is selected.

There are also constraints on the function of the spool. These come from ANSI and are related to the film input/output functional requirement. ANSI has also set up constraints for certain dimensions of the spool, mostly so that the spool will interface with every existing camera that uses 35 millimeter film (the details of the ANSI standards can be found in Appendix A). Finally, there are constraints that arise from the process domain. The selection of the injection molding process places certain shape limits on the design and gives rise to certain potential attribute defects.

There are also constraints that are imposed as design decisions are frozen. For example, the choice of DP's on the third level of the 35 millimeter storage system are constrained by the choice of the spool shape and material on the second level. A designer can only add features to a spool shape once the decision has been made to use the spool shape. Similarly, the choice of the gate location constrains the location and orientation of the parting line and the vents in the mold. The higher level FR's, DP's and PV's always constrain the lower level elements within the domains and outside of the domain (in a domain to which the higher level element maps). These domain-to-domain constraints result from the zigzagging between domains.

Lower Level Spool Design

The functional requirements for film storage can be further decomposed in the following manner:

FR_1 = Film Input/Output
    FR_{11} = Accept Torque
    FR_{12} = Transmit Torque
FR_2 = Film Storage
    FR_{21} = Accommodate Film Width
    FR_{22} = Accommodate Film Wound Thickness

These second level requirements are related to the second level spool design parameters. The design uses a tape attachment; hence, FR_{12} is met through a specification of the tape-spool adhesion. The minimum strength of this bond is also constrained by ANSI (Appendix A). Each one of these requirements eventually becomes a constraint that cannot be violated during the detail design of the shape or the process design.

The following DP's are part of the spool shape:

DP_{11} = Ribs along the inside of the barrel (which are engaged by the camera's winding mechanism)
DP_{12} = Flange separation
DP_{13} = Flange outer diameter minus the shoulder outer diameter

The corresponding FR-DP equation is:

$$\begin{Bmatrix} FR_{11} \\ FR_{21} \\ FR_{22} \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ O & O & X \end{bmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \end{Bmatrix} \qquad (4.3)$$

This equation shows that the shape design is uncoupled at the second level.

Not all of the requirements are actively met by the spool shape. Some of the functional requirements become the customer needs for the material (in this case, the customer is the designer), which then map to physical properties specifications for the material. This mapping will be described when the functional requirements are decomposed to sufficient detail.

There are also features that are added to the spool in order to satisfy customer and functional constraints. These "functional" constraints are decomposed into the following hierarchy:

FC_1 = Preserve Film Integrity
    FC_{11} = Prevent Photoactivity--Block all light from openings in the cartridge
    FC_{12} = Protect against Impact (i.e. dropping)
    FC_{13} = Prevent Contamination of Film from Dirt
    FC_{14} = Preserve Physical Integrity of Film
        FC_{141} = Film Curl Limit
        FC_{142} = Prevent Scratches--Surface Finish
        FC_{143} = Prevent Pressure Marking
    FC_{15} = Preserve Thermal Integrity of Film

The satisfaction of constraints does not have to follow the Independence Axiom because the constraints themselves are not always independent. The following features or limits are added to the spool design in order to satisfy the constraints:

1) A thickness requirement to preserve the structural integrity of the spool (and consequently the film).

2) A minimum shoulder diameter based on the film curl limit.

3) A minimum "smoothness" of the surface.

4) A shoulder "step height" that would separate the tape from the film and prevent pressure marking.

Finally, there are some constraints on the design parameters of the spool as dictated by ANSI standards. Many of these standards reflect the need for the spool to interface with all types of camera designs. These dimensions are shown in Appendix A. Based on the design parameters and constraints, the spool has the following form:

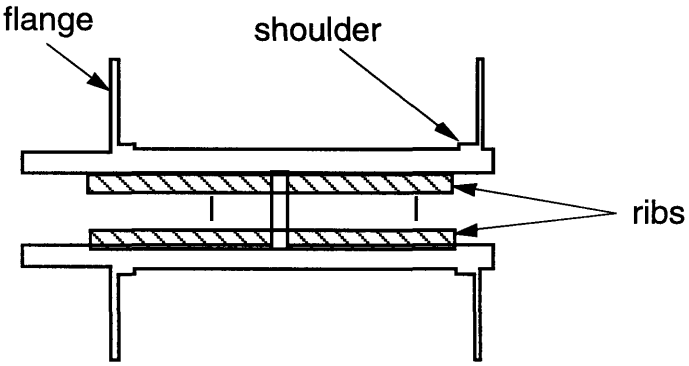

Figure 4.5: Spool Cross-Section Drawing

The dashed lines between the ribs on this drawing indicate the general minimum depth that the hubs (extensions from the flanges) must have. The designer would probably choose the thinner middle section as indicated because it would require less material. At this time, some portions of the design will have acquired limits or actual dimensions, but not all. The rest of the dimension definition can come after the assignment of critical-to-function dimensions.

Based upon the functional requirements, constraints, and the design parameter decomposition, an estimation of the critical-to-function dimensions can be made. Essentially, the criticality of the design can be driven by the design team's understanding of the importance of the customer needs that map to these customer requirements (which can be modeled by assigning weights to individual FR's) and the structure of the matrix that relates the FR's to the DP's. The design parameters that promote coupling on both sides of the diagonal matrix, or the design parameters that have the most off-diagonal terms in the decoupled case will have increased effect upon the performance of the design and therefore increased criticality. At this point, an estimate of the required tolerances on these dimensions is also necessary in order to determine stackups in assembly and the potential for constraint violation. From this information, eight dimensions on the spool were designated as critical-to-function dimensions. These dimensions will be referenced by the letters A-H.

4.2.2 Critical Process Parameter Definition

Critical process parameters are defined in order to allow manufacturing engineers to track the stability of the process through statistical process control. By understanding the relationship between the variation of the process parameters and the variation in part quality, manufacturing engineers can conceivably eliminate the necessity for part quality monitoring, or at least reduce the amount of measurements required. In addition, the manufacturing engineers will use the critical process parameters to monitor individual components of the machine and mold in order to catch parts that are wearing out and determine a preventative maintenance strategy. The selection of critical process parameters depends on the process control method, the machine used, the mold, and part design. Due to the proprietary nature of the information, the actual critical process parameters will be revealed. However, the basics of the design of the injection molding process are discussed using the axiomatic approach, similar to the previous section. This description will allow manufacturing engineers to track the interactions among the various control settings, thereby facilitating the selection of the critical process parameters. In addition, an example showing how to apply a fishbone diagram is discussed for the case of an attribute defect.

4.2.2.1 Axiomatic Approach to Process Design

This section covers the choice and design of the machine control system, the settings on the control system, and the control limits of the settings, which comprise PV_3 from the equation relating the design parameters to the process domain (4.4). As shown in Equation (4.5), the selection of PV_3 affects the part shape, the polymer structure, and the machine:

$$[\mathbf{DP}] = [\mathbf{B}][\mathbf{PV}] \tag{4.4}$$

$$\begin{Bmatrix} \text{Shape} \\ \text{Polymer Structure} \\ \text{Machine} \end{Bmatrix} = \begin{bmatrix} B_{11} & O & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & O & B_{33} \end{bmatrix} \begin{Bmatrix} \text{Mold} \\ \text{Polymer Blend} \\ \text{Process Design} \end{Bmatrix} \tag{4.5}$$

Before discussing the process design, the production requirements must be considered and decomposed. The higher level decomposition of the production requirements is usually sufficient for machine selection, but now that the manufacturing engineer is going to choose the process settings, the requirements must be decomposed in order to relate all of the settings to the machine:

FR_3 = Production Requirements (Note: FR_2 = material properties)

- FR_{31} = Create the spool shape
  - FR_{311} = Inject molten plastic into the mold cavity
    - FR_{3111} = Injection Volume
    - FR_{3112} = Injection Pressure
      - FR_{31121} = Fill Pressure
      - FR_{31122} = Pack Pressure

      (some might add an additional hold pressure here after the gate has frozen and before the part is completely cool)
  - FR_{312} = Cool part
    - FR_{3121} = Remove an amount of heat from part
      - FR_{31211} = Coolant Flow Rate
    - FR_{3122} = Keep mold halves together until the part is sufficiently solidified
  - FR_{313} = Remove part from mold
    - FR_{3131} = Ejector Force
- FR_{32} = Create the material structure
  - FR_{321} = Mix the polymer pellets
  - FR_{322} = Melt the polymer (to a specific temperature)

Some manufacturing engineers might select the machine based on its plastication ability, but most machines can meet the recommended melt temperature ranges for injection molding (as specified by the material supplier).

- FR_{33} = Production volume
  - FR_{331} = Available molding area
- FR_{34} = Production Rate
  - FR_{341} = Plastication Rate (blending is usually done off-line)
  - FR_{342} = Injection Rate (which can be decomposed into filling and packing rates)
  - FR_{343} = Cooling "Rate" (in this case, the cooling rate is a constraint and the required cooling time can be specified based on the overall cycle time)
  - FR_{344} = Mold Opening Rate (in general, this stage would include the Ejection time)
    - FR_{3441} = Clamp Opening Stroke
    - FR_{3442} = Clamp Opening Speed
  - FR_{345} = Mold Closing Rate

FR_{3451} = Clamp Closing Stroke (same as opening)
FR_{3452} = Clamp Closing Speed

The functional requirements for production rate are shown for completeness. In reality, the enterprise needs dictate one overall production rate but not the breakdown of the overall cycle time. The enterprise does not care how the cycle time is minimized, only that it is.

The machine design parameters that fulfill these requirements are as follows (please refer to the Van Dorn catalog page of Appendix B):

DP_3 = Injection Molding Machine
DP_{31} = Molding System
DP_{311} = Injector System capacity
DP_{3111} = Injection Volume Capacity (Shot size + Cushion)
DP_{3112} = Injection Pressure (Maximum)

Note: This maximum determines the capacity for both fill and pack pressure, but in the process domain, decomposition of these requirements is necessary for the different stages of the process.

DP_{312} = Cooling System capacity
DP_{3121} = Mold Temperature Control System (heat exchanger)
DP_{31211} = Coolant material and coolant channels are designed by the mold designers. The coolant flow rate is usually accomplished by a pump.
DP_{3122} = Clamp Tonnage
DP_{313} = Ejector System capacity
DP_{32} = Material Melting and Mixing System capacity
DP_{321} = Mixer, Hopper capacity (for material input into the machine)
DP_{322} = Screw Speed + Barrel heaters
DP_{323} = Back Pressure capacity
DP_{33} = Part Capacity
DP_{331} = Distance Between Tie Rods (the mold is supported by four tie rods, which are placed at the four corners of each mold platen)
DP_{34} = Cycle Rate
DP_{341} = Machine Plastication Rate (mixing is usually done off-line)
DP_{342} = Injector System Rate (usually the machine has a limit on this rate based on its hydraulic system)
DP_{343} = Mold Cooling System "Rate" (limited by the amount and size of coolant channels that can be fit into the mold and placed close to the cavities)

DP_{344} = Mold Opening Rate (note: the ejection rate is only limited by the mechanical or hydraulic response time--usually 0.2 seconds)

The mold opening and closing rates map directly to the production requirements that are specified above.

DP_{345} = Mold Closing Rate

The relationship between the FR's and the DP's on a general level can be shown in the following equation:

$$\begin{Bmatrix} FR_{32} \\ FR_{31} \\ FR_{33} \\ FR_{34} \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ X & X & O & \mathbf{X} \\ O & O & X & O \\ O & X & X & X \end{bmatrix} \begin{Bmatrix} DP_{32} \\ DP_{31} \\ DP_{33} \\ DP_{34} \end{Bmatrix} \tag{4.6}$$

Note: The shape creation and material mixing and melting requirements, FR_{31} and FR_{32}, and their corresponding DP's are reversed because the material must be melted before the shape can be created. As a result of this ordering of the process, the mixing and melting system has a slight effect upon the shape creation requirement in that the quality of the melted plastic "blend" will affect the filling and packing pressure requirements.

In the case of the spool, the method of creating the spool shape (DP_{31}) and the part capacity (DP_{33}) influence the production rate (FR_{34}). The injection volume capacity influences the injection rate (FR) and the part capacity influences the production rate by determining the number of parts that can be made each cycle. Both are measured in volume/time. The material melting system (DP_{32}) has the potential to influence the production rate, but in this case, enough material is melted during the cooling stage that it is not a factor. If the machine were designed to inject its entire capacity for each cycle, the melting system would then cause the production rate to be lower. The critical interaction is the one between the cycle rate and the shape creation (shown in bold). This interaction causes a coupling of the system at its highest level. Only one portion of the cycle rate (the injection rate) affects the shape creation, but the control of the shape creation is more difficult because of this coupling.

The relationships between the lower level decompositions are uncoupled or decoupled (depending on the coupling of Equation 4.6) except for the melting system and the injection rate. The functional requirement for melting is a specific melt temperature, but the main component that melts the plastic is the screw rotation, which causes the polymer pellets to melt via viscous heating. The effect of the back pressure, screw recovery time (effectively the melt time), and screw speed can be modeled analytically (with great difficulty), but it would be better to investigate this relationship through a design of experiments. For example, viscous heating depends on the friction that is created between the mixed-phase plastic and the screw. Because of this friction, the screw wears over time, and it is difficult to model this wear without looking at the screw itself. Furthermore, it is difficult to model the viscosity of the mixed-phase plastic at any one point in time because it decreases as the plastic melts.

Although the injection rate comprises only a small portion of the overall cycle rate, it dictates the ability of the machine to control the creation of the part shape. The injection rate (velocity) dictates the required pressure to push the plastic into the mold (because it is the derivative of the acceleration of the plastic). Unfortunately, the resistance of the plastic to injection, which is the polymer viscosity in the filling stage and the polymer compressibility in the packing stage, varies as the plastic flows through the runner system and into the mold. In addition, the properties of the material which dictate this resistance can vary, depending upon the mixing and melting system and the consistency of the raw material itself. As a result, it is difficult to control both the injection rate and the injection pressure to within narrow limits. Since a consistent volume flow rate of material into the mold cavities is desired (FR_{3111}), it is better to control the injection rate and let the injection force vary according to the resistance of the material. This control method is known as *velocity control.*

Now that the production requirements and machine parameters have been fully decomposed, the relationship between the process control system and the machine can be evaluated. For the most part, the control systems are designed so that the operator can set up the machine to achieve the production requirements directly:

PV_3 = Process Control System
    PV_{31} = Shape Creation Control
        PV_{311} = Injection Control
            PV_{3111} = Shot size + Cushion
            PV_{3112} = Boost Pressure
            PV_{3113} = Pack Pressure

Note: The boost and pack pressure are parts of the same injection pressure system. They are specified separately only for the convenience of describing the injection pressure profile

        PV_{312} = Cooling System Design
            PV_{3121} = Mold Temperature Control System Design (done by the mold designers)
                PV_{31211} = Coolant Flow Rate (depends on the pumping system)
            PV_{3122} = Clamp Force Control

PV_{313} = Ejection Force (depends on the design of the ejector system--it's a function of the clamping force)

PV_{32} = Material Mixing and Melting Control

PV_{321} = The design of the material handling system controls the mixing and the supply of pellets to the machine.

PV_{322} = Screw speed is normally fixed for every cycle, while the barrel heaters can be set

PV_{323} = Back Pressure

PV_{33} = Number of Machines

PV_{331} = Number of Cavities (constrained by the tie rod separation distance)

PV_{34} = Cycle Rate (time)

PV_{341} = Screw Recovery Time

PV_{342} = Injection Rate (through velocity control of the screw position)

PV_{343} = Cool Time (set on the machine and constrained by the amount of solidification required so that the part will not deform upon ejection)

PV_{344} = Mold Open Time (note, ejection is triggered by the position of the mold upon opening)

PV_{345} = Mold Close Time

The relationship between the design parameters and the process variables is shown below:

$$\begin{Bmatrix} DP_{31} \\ DP_{32} \\ DP_{33} \\ DP_{34} \end{Bmatrix} = \begin{bmatrix} X & O & O & X \\ O & X & O & O \\ O & O & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} PV_{31} \\ PV_{32} \\ PV_{33} \\ PV_{34} \end{Bmatrix} \tag{4.7}$$

This matrix is almost completely uncoupled. The only off-diagonal interaction is between the cycle rate (PV) and the molding system (DP). As stated earlier, since the variation of the molding system is affected by the cycle rate control method, it is better to focus the control of the process on the cycle first through velocity control and then the molding system (even though the FR-DP equation is coupled). The rest of the relationships between the lower level decompositions of the design parameters and the process variables are uncoupled (and have a one-to-one relationship) except for the cycle rate. This relationship is shown in Equation 4.8:

$$\begin{Bmatrix} DP_{341} \\ DP_{342} \\ DP_{343} \\ DP_{344} \\ DP_{345} \end{Bmatrix} = \begin{bmatrix} X & O & X & O & O \\ X & X & O & O & O \\ X & X & X & O & O \\ X & X & X & X & O \\ X & X & X & X & X \end{bmatrix} \begin{Bmatrix} PV_{341} \\ PV_{342} \\ PV_{343} \\ PV_{344} \\ PV_{345} \end{Bmatrix} \quad (4.8)$$

In this case, the matrix is coupled, but in this case, the coupling of the cool time with the screw recovery time allows the new plastic to melt sufficiently without adding any time to the process. The first column and row of the equation can then be eliminated from the monitoring system (although the movement of the screw must still be controlled, the melting stage will not directly affect the cycle time). The remaining 4 x 4 matrix is decoupled, a logical result of a sequential process.

Having a complete mapping of FR's to DP's and of DP's to PV's, one can understand the interactions across the domains and assign criticality. However, sometimes one wishes to understand the nature of defect generation from a process. In order to get a simple understanding of the this phenomenon, *Cause-and-Effect Analysis*, as described in the next section, proves useful.

4.2.2.2 Fishbone Diagrams for Attribute Defect Analysis

Cause and effect diagrams are useful tools for getting a basic understanding of the effects of different process parameter instabilities. They are easily formed and understood. An operator or technician could easily use them during a root-cause analysis of attribute defects. For example, in the diagram shown in Figure 4.6, some of the causes of *flash* are shown. *Flash* is a defect the results from the premature separation of the mold halves. When the mold halves separate, if the plastic has not solidified, it will flow through the crack. This effect is undesirable for most parts. The above diagram represents the parameters that can be measured and monitored off-line in order to detect the causes of flash. In fact, the flash itself can be detected with an LVDT that is connected to the two mold halves (Part Line Separation). As shown, the two major causes of flash are: excessive force pushing the mold open (High Cavity Pressure) and inadequate resistance to the opening force (Low Clamp Tonnage). The parameters that cause high cavity pressure comprise some of the settings that can be changed on the machine. Problems with these parameters can be caused by: operator "tweaking", machine component wear, particles in

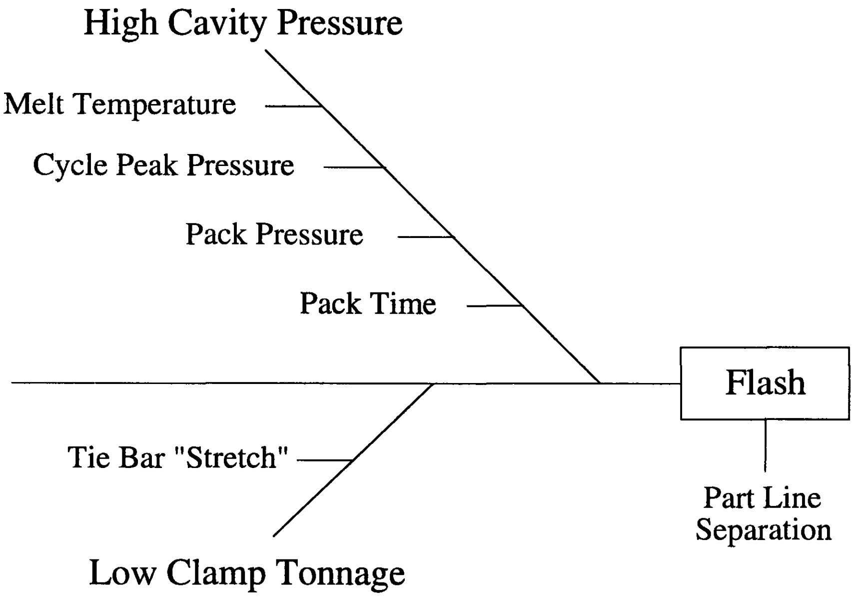

Figure 4.6: Fishbone Diagram for Flash

the machine oil (which causes valves to stick), and control system failure. Low clamp tonnage is a machine-related problem that can be monitored off-line through the use of a strain gage connected to the tie bars (these are the bars along which the mold moves to open and close). There are additional causes of flash, such as damage to the mold or plugged vents that can not be monitored directly unless a sensor measures the pressure of the plastic inside the cavity. These other effects are discussed in [Rosato and Rosato, 1995].

Fishbone diagrams can be created for each type of attribute defect, such as short shots, burns, and gate vestiges. For a more detailed diagram of variation sources and how they relate to critical process parameter selection, refer to Appendix C, which shows a diagram created by a process monitoring company.

4.3 Modeling of Injection Molding

Designers have many tools that help them to assess the capability of the injection molding process. Robert Malloy's Plastic Part Design for Injection Molding is rapidly becoming the standard reference for these tools [1995]. Typically, material suppliers provide "cookbook" guidelines for designing parts that use their specific materials. In addition, the Society of Plastics Industry (SPI) publishes guidelines for process capability based on several common materials. There have been several research initiatives in academia that have attempted to organize and improve these tools, such as the Net Shape Manufacturing Program at Ohio State, and Cornell's Injection Molding Program [Beiter, et al., 1995]. Finally, a designer can consult an analyst, who uses commercial simulation software, such as C-MOLD, Moldflow, and IDEAS. The following sections review the models for the appropriate effects that were considered for this study, including first-order models and process simulation.

4.3.1 Cycle Time Modeling

If one wants to estimate the cycle time for a part, a simple one dimensional heat transfer equation is usually adequate for thin-walled parts because the cooling time dominates the cycle. The following equation can be used:

$$t_{cool} = \frac{h^2}{\alpha\pi^2}\ln\left[\frac{4}{\pi}\left(\frac{T_{melt} - T_{mold}}{T_{eject} - T_{mold}}\right)\right] \tag{4.9}$$

h = wall thickness

$\propto$ = thermal diffusivity

T_{mold} = Mold-wall temperature

T_{eject} = Centerline temperature upon ejection

This equation is one solution to the Fourier heat conduction equation. Note that for parts with varying wall thicknesses, the thickest section should be used.

Unfortunately, this equation requires the engineer to estimate the ejection temperature and the mold temperature because both quantities are not known before molding. Material suppliers typically provide suggested ranges for these quantities, but both are sensitive to the mold and process design. For example, as stated in Section 4.1.1, ejection can only occur when enough of the part has solidified enough to withstand the ejection forces. The amount of desired shrinkage may place an additional constraint upon the cooling time necessary before ejection. Both of these effects are difficult to estimate. As a result, the ejection temperature may be difficult to determine. Similarly, the mold temperature can be difficult to estimate because cooling lines will often be employed order to transfer heat away from the mold. Finally, this equation can only apply to situations where the mold-wall temperature is the same for both sides of the mold. If any insert materials are used or if a hot-runner system is employed, this assumption can be easily violated.

Process Simulation can account for many of these factors. It can also model the effect of different part geometries more accurately because it considers the entire part shape and not just the thickest section. The price of this added accuracy is the fact that the part and the mold must be designed to greater detail. The part must be modeled with a CAD program in order to be meshed and analyzed. In practice, this step of modeling the part can dictate many of the design decisions (despite the quality of CAD software, it is easier to change the design before it has been drawn). The mold material and cooling lines (if any) must be selected in order to gain much of the benefit of process simulation. There are a few limiting factors, such as the heat transfer across the parting line and the heat transfer between different blocks of material in the mold (such as the gate assembly in a hot runner mold) that process simulation (in this case, CMOLD) does not take into account. These factors tend to cause the simulation to under-predict the actual cycle time.

As stated in Section 3.2.3.3, the purpose of calculating the cycle time during the design stage is usually related to the task of cost estimation and machine allocation for the part. Often, the first-order model will be enough to gauge the cost and number of machines for a particular product. Additional information from process simulation can then be used to refine the business model and show manufacturing engineers what the "optimal" cycle time might be. This information can then be used as a guide for designing the process.

4.3.2 Shrinkage and Tolerance Modeling

There are several possible causes of variation among dimensions. Since shrinkage is governed by the initial and final Pressure-Volume-Temperature states of the plastic (refer to Figure 4.3), factors that cause variations in the initial and/or final conditions of the plastic will cause shrinkage variation. These variations may only be consistent for certain regions of the part. For example, the core and the cavity for a mold may be comprised of different materials that have different strengths. These materials may deflect differently or wear at different rates, which, over time, will lead to different modes of variation. Additionally, the core of a cavity is usually inserted and removed through a mechanical linkage. This linkage may not produce the same effective clamp force on the part that the cavity wall will. These two examples show the effect on the initial and final pressures of the plastic. Additionally, tighter tolerances can be held on areas of the part that "shrink-on" to a mold wall (i.e. an insert). Tight tolerances on dimensions where the part loses contact or "shrinks-away" from the mold wall are not as easily achieved because they are sensitive to variations in the packing stage [Vacek, 1995]. As the amount of material packed into the

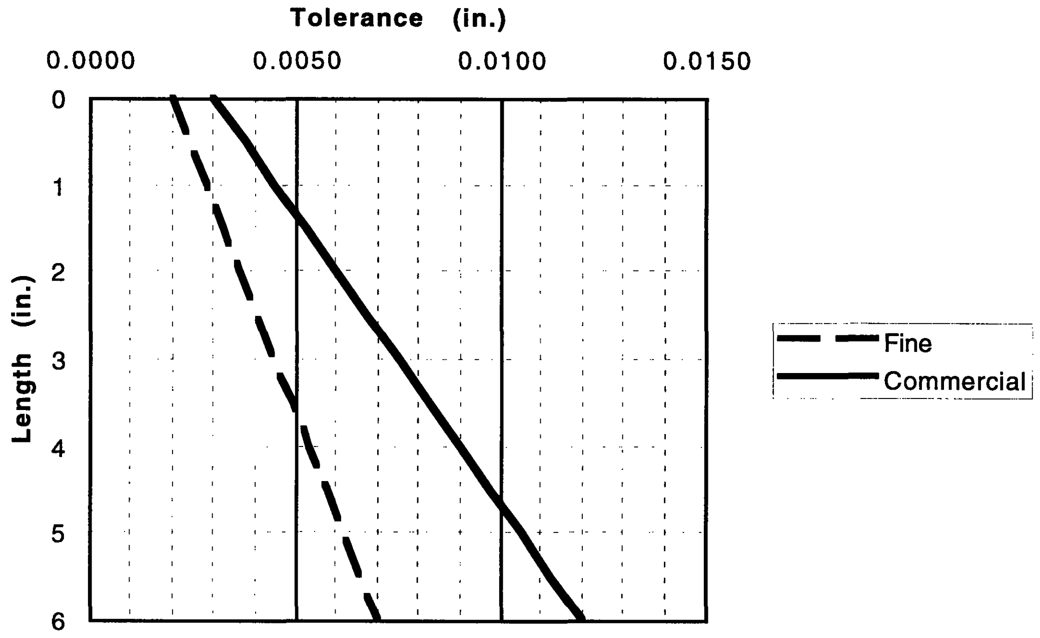

Figure 4.7: Format for a Plastic Part Tolerance Guide. [SPI, 1993]

mold varies, it leads to a change in the distance that the part shrinks away from the mold wall. Finally, the dimensions may vary as a function the filling pattern or the cooling design. Unbalanced filling or cooling can cause bending moments to be frozen into the material. Since bending, or warpage, is generally a nonlinear phenomenon, it can also be very sensitive to process variation.

The Society for Plastics Industries (SPI) publishes a list of guidelines for tolerance capability for a standard part geometry and several common materials [1993]. This guideline includes a graph of tolerance versus part length as shown in Figure 4.7. Notice that two lines are plotted. One line, called *commercial*, is treated as an industry standard that can be held at an economical cost. The other line, called *fine*, can be held by an "expert" molder at a greater cost. The guidelines also suggest the differentiation between "shrink-on" dimensions and "shrink-away" dimensions with respect to how the material shrinks with respect to the mold [Vacek, 1995]. Tighter tolerances can be held for "shrink-on" dimensions, such as holes or inner diameters, because the material can be frozen at that location.

There are several limiting assumptions in this set of guidelines. The tolerances are based on a constant 0.125 inch wall section. Depending on the type of design, tolerances for thinner or thicker wall sections may vary because of non-uniform (or differential)

GRADE	Standard Tolerance (in./in.)
Unreinforced	0.003
10% Glass Reinforced	0.002
20% Glass Reinforced	0.0015
30% Glass Reinforced	0.0010

Figure 4.8: Lexan® Part Tolerance Guide. [G.E. Plastics, 1994]

volumetric shrinkage in the part. Differential shrinkage can lead to an excessive amount of residual stresses to build up within the material. These stresses sometimes result in a bending moment that causes the material to distort or warp upon ejection from the mold. Since warpage is a bending phenomenon, it is sensitive to variations in process conditions because any slight change in the angle of bending will produce a corresponding change in the distortion equal to the change in the angle times the length of the moment arm.

In addition, there are several factors that influence tolerance capability and are not covered by the SPI guidelines, as discussed by [Ishii, et al., 1995]. The amount and location of packing can also influence the tolerance capability because it is used to combat the effects of differential shrinkage. Different amounts of fillers can affect the tolerance capability, as shown in Figure 4.8 for Lexan®. Finally, mold design has a significant effect on tolerance capability. Since packing is usually greatest at or near the gate, one must consider the effects of the gate location. Any variation in the balance of the runner system or the temperature of the mold, driven by the design of the cooling lines, can also affect the state and amount of plastic entering the cavity, resulting in dimensional variation. Thus, the above factors are known to influence tolerance capability, but it is difficult to incorporate them into a first-order chart because many of them are part, mold, material or process specific.

It has been suggested by [Ishii, et al., 1995a], that process simulation can also be used to determine the tolerance capability of injection molding for an individual part design. As part of this thesis research, a software tool sold commercially under the name CMOLD was used to test this hypothesis. CMOLD was created by AC Technology, Inc. in cooperation with the Cornell Injection Molding Program for the purpose of simulating the injection molding process. It is a finite-element -analysis program that calculates the relevant physical equations for the different stages of the injection molding process. The user creates a model of the part geometry and specifies the material, the process conditions, the machine, the mold material, and the coolant. The analysis is based on these inputs. During the injection stages, the program solves a set of fluid mechanics and heat transfer equations for each element of the part geometry in order to determine the nature of the flow of the molten plastic into the mold. For example, if the part has thin walls, the program will warn the user if the plastic will freeze before the part has completely filled (depending on the process conditions), a phenomenon which is commonly known as a short shot. During the packing and cooling stages, the program will determine the progression of the freezing of the plastic within the mold and calculate the time necessary to achieve a specified ejection temperature. After cooling, the program will solve for the residual stresses in the part geometry and combine this with a shrinkage calculation to model warpage in the part [CMOLD, 1995b].

Because of the numerous modeling assumptions and approximations with respect to the material properties and the part shape, the predictions of shrinkage and warpage are not completely accurate. However, some studies have verified these predictions for specific geometries and materials to within 10 to 25 percent [Ni and Wang, 1993], [Gennari, 1993]. In addition, verification studies have suggested that CMOLD's predictions are more accurate than predictions which are based solely on the material supplier's recommendations, which usually suggest a uniform allowance for volumetric shrinkage that is independent of part geometry [Gennari, 1993]. Unfortunately, the predictions for the shrinkage of specific dimensions do not all have the same accuracy; sometimes shrinkage is over-predicted and other times it is under-predicted. Furthermore, there have not been enough verification studies to truly characterize the variation of the shrinkage predictions across the spectrum of materials and part geometries. Individual companies, however, typically use a certain set of standard materials because of their relationships with specific material suppliers. Also, there are certain shapes and features, such as ribs and bosses, that part designers use repeatedly in different applications. By verifying the predictions for a reduced set of materials and features within the feedback approach, the engineers would become confident that CMOLD would be reasonably able to predict the shrinkage for new products with similar geometries and materials. A verification study for the spool is discussed in Section 4.5.3.3.

As part of the methodology for injection molded product development, process simulation is employed in order to allow engineers to evaluate the assignment of critical dimensions and assign tolerances. The quality of the information generated during the simulation step in this methodology strongly depends upon the assessment of the process window for the product. Thus, a method for the creation of these process windows for injection molding is needed.

4.3.3 Process Window Creation

As discussed at the end of Section 4.2.2.1, injection molding is a serial process. As a result, it is convenient to define a process window for each stage in the process. In this section, the process windows for the filling and post-filling stages are derived. Since the packing and cooling of the plastic occurs at the same time, these two processes cannot be separated and are therefore considered jointly in the post-filling stage. A process window could also be derived for the ejection stage based upon the state of the of the plastic at the end of the filling stage by balancing the pressure required to eject the plastic with the friction of the polymer-cavity interface as well as the strength of the plastic (it may not be completely solidified). Unfortunately, it is very difficult to model the friction of the polymer-cavity interface, and a simple balance equation does not exist for this situation. Consequently, the requirements for ejection will be considered as constraints that can be applied to the process window for the post-filling stage.

In the injection stage, the material balance equation that must be considered for the derivation of the process window relates the force required to inject the plastic into the mold to the resistance of the plastic to flow, a quantity known as the viscosity of the material. As shown by Equation 4.1, the viscosity is defined as the ratio of the shear stress to the shear rate.

$$\eta = \frac{\tau}{\dot{\gamma}} \tag{4.1}$$

One can consider the simple flow of the plastic through a tube as in the case of the flow through the runner system (and in extrusion). Based upon this assumption, the shear rate and shear stress can be described by the following two equations:

$$\dot{\gamma} = \frac{4Q}{\pi R^3} \tag{4.10}$$

$$\tau = \frac{\Delta P}{2(L/R)} \tag{4.11}$$

where Q is the volumetric flow rate, R is the radius of the tube (or the characteristic thickness, in general), ΔP is the injection pressure minus the plastic pressure, and L is the flow length of the plastic. Currently, there are two accepted models for the viscosity of the plastic in the filling stage: the Cross model and the Williams-Landel-Ferry (WLF) model [CMOLD, 1995b], [Aslam, et al., 1994]. Both account for the fact that the plastic viscosity is a function of the plastic's temperature and pressure as well as the applied shear rate (in the non-Newtonian case). The Cross model is shown in Equation 4.12:

$$\eta = \left(\frac{\eta_o(T,P)}{1+\left(\frac{\eta_o\dot{\gamma}}{\tau^*}\right)^{1-n}} \right) \tag{4.12}$$

where η_o denotes the zero-shear viscosity and τ^* is a material constant [CMOLD, 1995b]. The zero-shear viscosity is a material property that is also a function of the temperature and pressure of the plastic.

The goal of the filling stage is to inject the same amount of plastic into the cavity each time with the plastic having same temperature and pressure at the end of each filling stage. Since the flow length, L, and the radius, R, are constrained by the mold and part designs, the remaining controllable parameters are the temperature, T, the pressure, P, and the flow rate, Q. By combining Equations 4.10-4.12, one sees that the temperature can be controlled independently from the flow rate because it appears on only one side of the equation.

$$\frac{4Q}{\pi R^3}\left(\frac{\eta_o(T,P)}{1+\left(\frac{\eta_o\dot{\gamma}}{\tau^*}\right)^{1-n}} \right) = \frac{\Delta P}{2(L/R)} \tag{4.13}$$

Unfortunately, the pressure and the flow rate will always appear on opposite sides of the equation (unless they are placed in a ratio). As a result, the flow rate and the pressure cannot be set independently. In the framework of axiomatic design, these parameters are said to be coupled. Barring the use of a sophisticated control algorithm or a neural network, the only way to control the process is to set one of the parameters and let the other one vary. The two choices are velocity control, in which the flow rate is set, and pressure control. In pressure control, the temperature of the plastic will not be independent of the pressure because a given volume of plastic has a viscosity that varies with both. Consequently, the process window will be nonlinear.

In velocity control, the flow rate and temperature can be controlled independently. Thus, the velocity control method will be used in this process window definition. For a constant velocity, the key parameter becomes the fill time, as shown in Figure 4.9. Since the pressure is not set (the machine uses whatever pressure is required to inject the plastic),

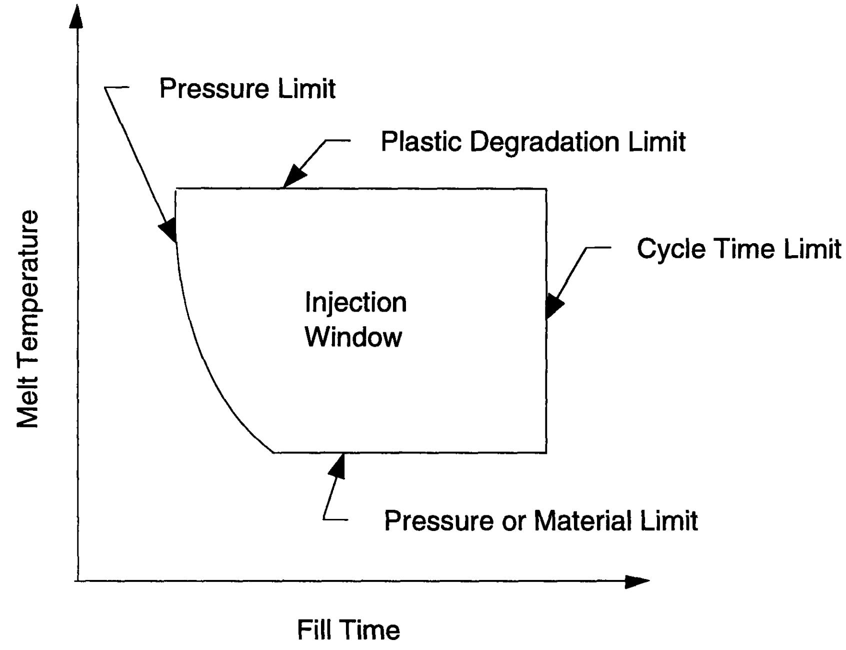

Figure 4.9: Process Window for the Filling Stage

it becomes a constraint in the window. For example, there will be a constraint that dictates the lowest fill time possible based on the available pressure from the machine. Similarly, if the plastic is too cold, the pressure required to inject the plastic into the mold may be too great. The other limits on the melt temperature (*melt temperature* is the term used to convey the temperature of the molten plastic, not the actual temperature of the transition from solid to liquid) are often based on the material. Finally, the upper limit for the fill time is based on the needs of the enterprise to maintain a low cycle time. As discussed in the next section, there can also be quality reasons for the upper limit on the fill time.

As stated in previous sections, attribute defects will appear on parts for which the process window limits have been crossed. When the plastic is too cold, it will freeze before it has a chance to fill the mold completely. The resulting parts are called *short shots*. In the case of the upper limit on the melt temperature, burns will appear on the part where the plastic has degraded. It is also possible for the injection pressure to cause the part to *flash* if the pressure exceeds the available clamping force.

One can also create a post-filling window with the same method that was used to define the filling window. During the filling stage, the temperature of the plastic stays relatively constant. Thus, only the fluid mechanics of the injection process need be considered. During the packing and cooling stage, the temperature changes, and thus the effect of the temperature change on the density (or specific volume) of the plastic must be

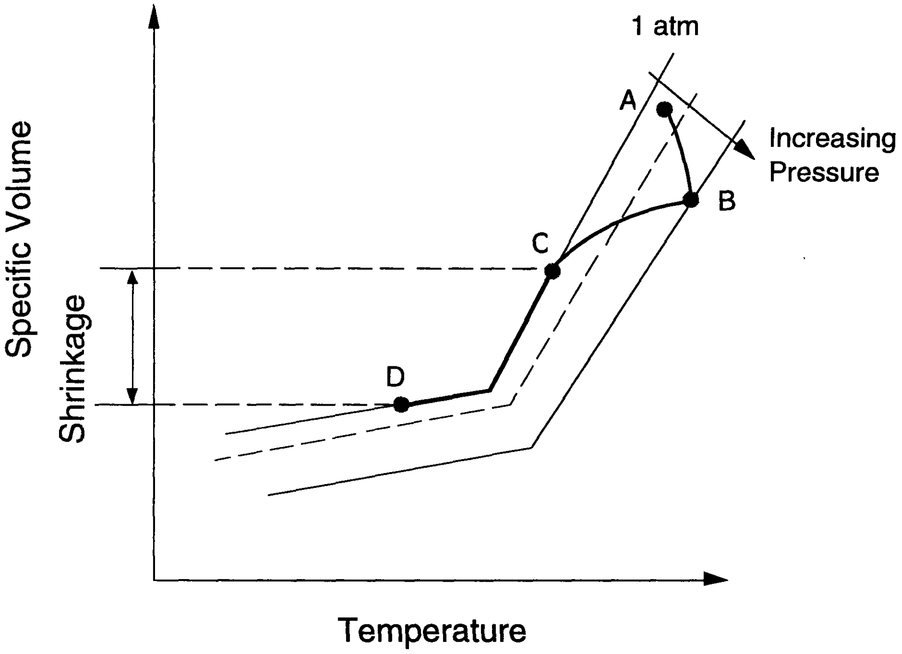

Figure 4.10: The Injection Molding Cycle on the PvT Diagram

considered. This effect is modeled by the Tait equation, which describes the curves of the PvT diagram, as shown in Figure 4.10. Essentially, the specific volume, v, is a function of both the temperature and the pressure of the plastic. In this case, the pressure of the plastic can be controlled to a degree with the pack pressure. The temperature of the plastic is mostly dictated by the design of the mold cooling system. Thus, the temperature can be controlled by the rate of coolant flow, the temperature of the coolant, and the time spent in the cooling stage.

The main goals of the post-filling stage are to cool the part until it is ready to be ejected and to combat the effects of shrinkage. If one does not attempt to combat the effects of shrinkage, residual stresses will build up inside the plastic in areas where it is prevented from shrinking by the mold. For example, the plastic could easily shrink on to an insert and stick to the mold. The time spent in the cooling stage is usually broken down into the *pack time*, during which additional plastic is "packed" into the mold, and the *cool time*. In this case, the *cool time* is the time required for the plastic to solidify in addition to the *pack time*. After the packing pressure has been released, the pressure in the plastic remains constant as it cools. The packing stage of the cycle is labeled in Figure 4.10 as the path from point B to point C. The cool time is then the portion of the cycle when the plastic moves from point C to point D. As shown in the figure, once the packing pressure is released, the plastic remains on the same PvT curve for the rest of the cycle. The additional cooling time is necessary to get the plastic under its transition temperature, which is the temperature that defines the transition from a liquid to a solid as shown by the change in the slope of the two lines on the PvT curve. For ejection reasons, the part must be cooled to below its transition temperature. Since the slope of the solid line in the PvT diagram is relatively flat, changes in the cooling time will not have as great an effect on the overall shrinkage as the combination of the packing pressure and time because the cooling time affects the position of point D, whereas the packing pressure and time dictate the position of point C (which is on a curve that has a much greater slope). Therefore, the two parameters that dictate the process window for the post-filling stage are the *pack pressure* and *pack time*.

As demonstrated in Figure 4.11, the boundaries on the pack pressure and pack time can be defined by the attribute defects that arise when those boundaries are crossed. In this case, the limits on the pack pressure and pack time cannot be defined independent from one another because the Tait equation is nonlinear. The upper limit of the post-filling window is reached when the part either flashes or *sticks* to the mold. The lower limit is also dictated

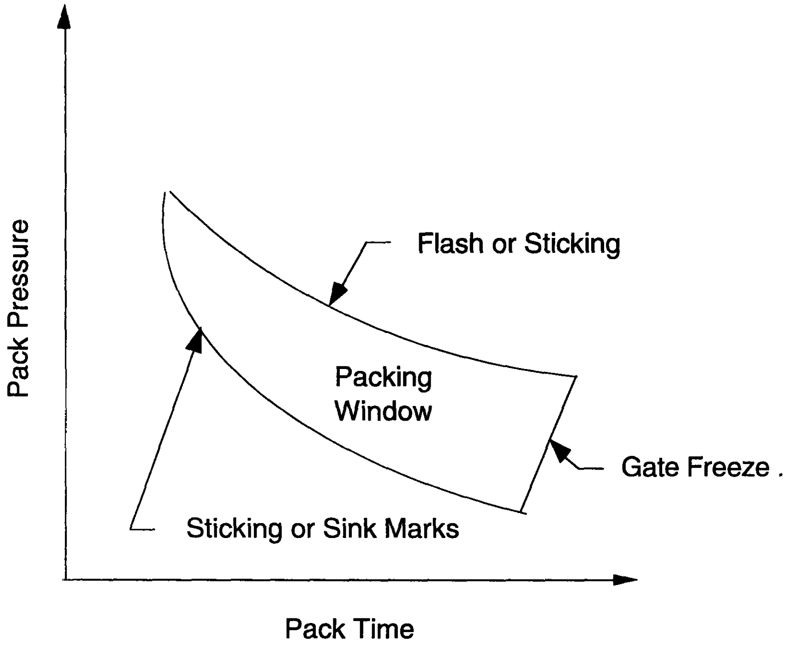

Figure 4.11: Process Window for the Packing Stage

by sticking or other part defects, such as sink marks. The part will stick to the mold if it has not cooled sufficiently before ejection (this effect is also dictated by the cool time) or if the plastic shrinks too much. Excessive shrinkage is a function of not enough packing pressure or not enough packing time. If there is no pack pressure, the plastic will attempt to expand isothermally (or vertically on the PvT diagram), leading to a much larger overall shrinkage. In other cases, the mold can be *over-packed*, in which case, the plastic will expand upon the opening of the mold, causing it to stick inside the cavity. Over-packing can also lead to flash if the cavity pressure exceeds the available clamping pressure. Finally, there is a maximum limit on the packing time that is dictated by the state of the plastic at the gate. The area of the gate is usually very small. In a cold runner system, when this small area freezes, no additional plastic can be packed into the mold. In a hot runner system, the gate never actually freezes. However, a similar limit on the pack time can be defined based upon the characteristics of the gate separation. For example, if the gate does not decrease in temperature enough before the mold opens, the gate may not fully separate from the runner. This phenomenon is sometimes called a "stringy gate" because the effect is similar to that of pulling on the melted cheese in a pizza. The process for determining these windows in production will be discussed in the next section.

4.4 Experimental Evaluation of Models

During the summer of 1995, a set of experiments were conducted on the production line for the 35 millimeter spools. There were several goals that were defined for these experiments. As part of the Process Optimization Feedback Loop (discussed in Section 3.1.2 and shown in Figure 3.2), the experiments were designed to help the team determine the appropriate settings on the machine in order to minimize the variation in the quality of the spools. Based on the understanding of the resulting variation, control limits for the process settings could then be defined. In order to further facilitate the tasks of SPC and SQC, the definition of critical process and monitor parameters (for design) would be confirmed, and a relationship between the two would be defined. Finally, the results from these experiments could be used to evaluate the models of process capability that design and manufacturing engineers use as part of the Process Capability Feedback Loop (shown in Figure 3.3).

Since there are many process settings that have an effect on the output of the machine, it was decided that the *design of experiments* approach, as described in Section 2.2.4, would be the best way to model the variation in the process and optimize the settings. Through several discussions with the manufacturing team, five process settings were selected to be evaluated for the experiment: melt temperature, fill time, pack pressure, pack time, and cool time. Once these settings had been selected, the next task was to determine the process space for the experimental design. In order to maximize the understanding of the process and truly optimize the settings, it is important to experiment over as large a process space as possible. This need put the team in somewhat of a dilemma: in order to determine the limits of the process space, it had to understand the complex interactions among the five process settings; but the purpose of the DOE was to gain this understanding. Thus, pre-experimentation was used in order to determine the process windows for the selected machine settings. These process windows provided a general idea of process space by modeling two-way interactions among the settings.

4.4.1 Filling Window Determination

The first process window that was defined was the filling window, which models the interaction between the melt temperature and the fill time. Most of the limits of this window were known ahead of time. The upper and lower limits on the melt temperature had been previously defined based upon the plastic degradation limit and certain characteristics of the hot runner system. Normally, a *short shot* test could be performed in order to determine the fastest fill time for the temperature range under consideration. Unfortunately, short shots were not a feasible option because of the increased potential of mold damage upon removal. In order to keep the rectangular array of the design of experiments, the fast fill time limit was therefore constrained by the machine hydraulic pressure limit based on the lower melt temperature limit running at the fastest fill possible and including packing.

The slow or upper limit on the fill time can be chosen arbitrarily in this case because there were no machine limits. Consequently, the two factors that dictated the upper limit were cycle time and quality. Obviously, the cycle time limit would translate into the fastest fill possible. In order to have a real process window, the quality of the parts was then considered. In order to minimize the effect of the variation in the material, specifically the viscosity, it is recommended that the process be operated in the region where the shear rate does not have a large effect on the viscosity. Based on the industry-accepted theory of velocity control, variations of up to ± 30% in the viscosity can then be tolerated [Aslam, et al., 1994]. This shear rate-region will be different for different melt temperatures. The

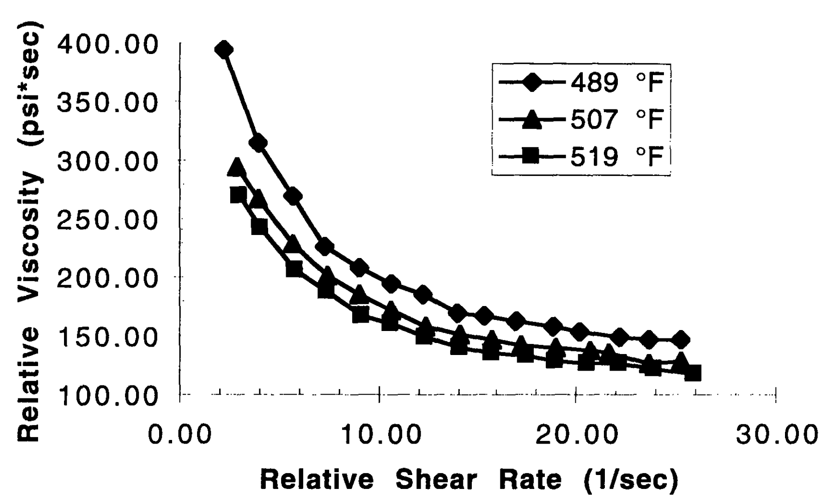

Figure 4.12: Relative Viscosity versus Shear rate

best way to model the effect of the melt temperature and shear rate on the viscosity of the material is to keep the mold open and run an *air shot* test. This test, as described in [Rosato and Rosato, 1995], determines the effect of the temperature and the runner system design on the pressure required to inject the plastic. Essentially, the runner system is used as a capillary rheometer, and Equations 4.10 and 4.11 as described in Section 4.3.3 can be used to determine the relative viscosity of the plastic as a function of the shear rate. That is, one can experimentally measure Q and P to determine the relative viscosity.

$$\eta = \frac{\tau}{\dot{\gamma}} \tag{4.1}$$

where

$$\dot{\gamma} = \frac{4Q}{\pi R^3} \tag{4.10}$$

$$\tau = \frac{\Delta P}{2(L/R)} \tag{4.11}$$

Thus, the relative viscosity, η, of the material is based upon the peak injection pressure, P, and the flow rate, Q, since all the other parameters are constant. As shown in Figure 4.12, the operating region for the process should remain on the flat portion of the curve. This flat portion can be defined as the region where the viscosity variation is less than thirty percent, which corresponds to a shear rate of approximately 11 on this graph. As a result, the upper limit for the fill time can be defined from this shear rate.

4.4.2 Packing Window Determination

As shown by Figure 4.11 in section 4.3.3, the packing window is highly nonlinear. As a result, the limits for the packing window cannot be simply defined from a one-at-a-time approach to experimentation. Without additional understanding of the process, the best way to determine the packing window is to vary the pack pressure to its lower and upper limits for several increments in pack time. This approach establishes a grid region for experimentation. The other process settings for the experiment can then be kept constant.

4.4.3 Experimental Design

Based upon the understanding of the two process windows and a test for the minimum cool time for ejection, the experimental region was determine. Since resources were limited, only two-way interactions were considered. In order to investigate the effect of these interactions beyond a linear model, a central composite design of experiments was selected. This design contains 16 factorial points, (which are necessary to model the two-way interactions of five variables), 10 axial points (which provide higher order information about the two-way interactions), one center point, and 5 replicates, for a total of 32 experiments. As shown in Figure 4.13, the high and low values for the set points were used to define the factorial points, and the middle values were used to define the center point. The axial points were defined by keeping four of the variables at their middle values and placing the remaining variable at its high or low setting.

Even though the experiment changed the location of the process in the process space by a considerable amount, there was some concern that the shot-to-shot variation would confound the results. Additionally, the variation of the dimensions across the multi-cavity mold was also a concern. Thus, the dimensional measurement strategy was defined in order to capture all three types of variation. Thirty consecutive shots containing every spool from the mold were collected for each process condition. By sampling from this collection of spools, the shot-to-shot, mold, and process variability could be estimated.

Process Variable	*High*	*Middle*	*Low*
Fill Time (sec)	1	0	-1
Melt Temperature (°F)	1	0	-1
Pack Pressure (psi)	1	0	-1
Pack Time (sec)	1	0	-1
Cool Time (sec)	1	0	-1

Figure 4.13: Normalized Experimental Design Levels

Due to the complex interaction of the sequential stages in the injection molding process, it was not possible to anticipate the effects of operating at each condition in the process space that had been defined. Although the process windows had been defined for some of the more important interactions, a problem arose as a result of the interaction of all five settings. The parts were sticking in the mold at the low cool time, high melt temperature, fast fill, high pack time, and high pack pressure levels. In order to keep the size of the process space as large as possible, the pack pressure, pack time, and cool time were all changed until parts could be made repeatedly (as opposed to changing just one variable, which would have curtailed the process space much more than this approach and would have reduced the possibility of gaining an understanding the interactions involving that variable). Thus, even though the process windows can be defined through the use of the tests described in the two previous sections, the actual limits of operation may be slightly less broad due to the interaction of all of the machine settings.

4.5 Feedback Applications of Results

After the experiments were completed, the final step in the product development process: Data Translation and Model Calibration, as described in Section 3.1.1 could begin. The following sections focus on two types of feedback. In order to facilitate the implementation of feedback into the product development process, the initial feedback must be simple, and in a form that is familiar or easy to understand. This information is *first-order feedback.* During the creative stages of design, design and manufacturing engineers rely on first-order modeling methods. This type of feedback can have an immediate impact on those models. In addition, the simplicity of this feedback will facilitate the introduction of feedback into the product data management system.

The second type of feedback involves detailed model evaluation. This type of feedback is directed primarily at process simulation, but can also include statistical modeling. The goal of this feedback is to enable engineers to understand the effect of the assumptions in these models and the best way to use these tools. These issues can then be discussed with the software vendor, when appropriate. The following sections discuss both types of feedback and the type of feedback necessary for the process effects that are considered.

4.5.1 Critical Process Parameter Capability

The simplest form of feedback can be accomplished by monitoring the variation of the process parameters. By accumulating enough data over time, the capability of specific injection molding machines can be determined. This information can then be used to rank the machines and compare the machines to industry standards. An example of these standards is shown in Appendix C. When a new product is sent to production, its tolerance capability requirements can then be used to select the most appropriate machine (in addition to the other requirements, such as clamp force and plastication capacity). Maintenance schedules and purchasing decisions for the machines can be justified through this process parameter capability feedback.

4.5.2 Cycle Time Model Evaluation

In order to realistically model the effect of a deviation in the actual cycle time from the predicted cycle time on the business model of a product, the cycle time modeling method must be evaluated. For the spool, the first-order model described in Section 4.3.1 was used.

$$t_{cool} = \frac{h^2}{\alpha \pi^2} \ln\left[\frac{4}{\pi}\left(\frac{T_{melt} - T_{mold}}{T_{eject} - T_{mold}}\right)\right] \tag{4.9}$$

Since the mold temperature was not known a priori in the design stage, an estimate was based upon the material supplier's recommended processing range of 100 to 140 °F. The ejection temperature was not known by the design engineer in the design stage either. However, based upon measurements of the ejection temperature, a reasonable estimate could be made for the variation in the ejection temperature. As a first guess, the transition temperature of the plastic (approximately 220 °F) could be used. The temperatures used in this study were sometimes higher than the transition temperature because they were measured at the gate as opposed to the thickest section of the spool. The following chart shows the difference between the actual and predicted cool times (4.14).

Two different mold temperatures are shown in Figure 4.14: 100 and 123 degrees. The first is the recommended limit on the process from the material supplier. The second mold temperature was selected to show the minimized deviation between the actual and predicted values. As a result, the six-sigma accuracy of the cycle time model (based upon the cool time) was determined to be roughly ± 20 percent. Note that since the ejection temperatures were measured at the gate, the pack time did not have to be considered as part

Actual Eject Temperature (deg F)	Mean Melt Temp	Predicted Cool Time Tmold = 100 deg F	Difference between Prediction and Actual Cool Time	Normalized Difference	Predicted Cool Time Tmold = 123 deg F	Difference between Prediction and Actual Cool Time	Normalized Difference
223.06	540	4.18	0.39	0.05	4.61	-0.03	0.00
230.16	539	4.02	0.55	0.07	4.41	0.16	0.02
226.71	538	4.09	0.49	0.06	4.50	0.09	0.01
232.48	519	3.84	0.15	0.02	4.22	-0.22	0.03
225.66	518	3.99	0.59	0.07	4.39	0.19	0.02
236.37	554	3.99	0.40	0.05	4.36	0.03	0.00
212.50	554	4.52	1.15	0.13	5.01	0.66	0.08
255.68	551	3.60	-0.21	0.03	3.90	-0.51	0.07
250.45	554	3.72	-0.34	0.05	4.03	-0.65	0.08
233.58	539	3.95	0.32	0.04	4.32	-0.05	0.01
228.40	539	4.06	0.51	0.06	4.46	0.11	0.01
226.11	535	4.09	0.47	0.06	4.49	0.06	0.01
227.40	536	4.07	0.51	0.06	4.47	0.11	0.01
241.03	548	3.86	0.15	0.02	4.21	-0.19	0.02
234.03	550	4.01	0.56	0.07	4.39	0.19	0.02
237.33	514	3.72	0.30	0.04	4.07	-0.05	0.01
247.61	513	3.51	-0.11	0.01	3.82	-0.42	0.06
252.70	517	3.44	-0.03	0.00	3.74	-0.32	0.05
211.88	515	4.29	0.78	0.09	4.76	0.30	0.04
225.25	534	4.10	0.49	0.06	4.51	0.08	0.01
231.80	536	3.97	0.61	0.07	4.35	0.23	0.03
219.77	537	4.24	1.14	0.13	4.68	0.70	0.08
227.77	537	4.07	0.53	0.06	4.47	0.13	0.02
246.27	536	3.68	0.03	0.00	4.01	-0.30	0.04
221.94	554	4.30	0.77	0.09	4.73	0.34	0.04
209.34	553	4.59	1.07	0.11	5.10	0.56	0.06
220.10	550	4.32	0.75	0.09	4.76	0.31	0.04
199.95	517	4.61	1.06	0.11	5.17	0.49	0.06
215.18	519	4.23	0.84	0.10	4.69	0.38	0.04
203.96	521	4.53	1.13	0.13	5.06	0.60	0.07
217.80	538	4.29	0.57	0.07	4.74	0.12	0.01
232.92	537	3.96	0.61	0.07	4.33	0.23	0.03
			average error	0.07		average error	0.03
			Euclidian	0.07		Euclidian	0.04
			max error	0.13		max error	0.08
			std deviation	0.03		std deviation	0.02
			6 sigma	0.21		6 sigma	0.15

Figure 4.14: Cycle Time Evaluation Chart

of the cooling phase because it can be assumed that the material in the gate area was at the melt temperature at the end of the packing stage. Since the thickest section of the spool was close to the gate, this approximation had a minor impact on the results. Finally, some of the deviation between the actual and predicted values can be explained by the fact that the mold temperature was not constant on both sides of the cavity. This constant mold-wall temperature is the major limiting requirement of this model. In this case, the difference did not severely affect the predictions.

The confidence that the first-order model of the cycle time will be accurate to within twenty percent of the actual cycle time allows design engineers to realistically model the effect of cycle time on the business case for a new product. However, this model can only be applied to situations where the mold-wall temperature is relatively constant. For other situations, such as in insert molding, it is recommended that the design engineer use process simulation.

4.5.3 Shrinkage and Tolerance Model Evaluation

Using the results from the designed experiments, three important goals can be accomplished: evaluation of the SPI Tolerancing Chart, confirmation of critical-to-monitor dimensions, and evaluation of CMOLD as a tool for predicting shrinkage and variation of shrinkage. The following sections discuss each goal separately.

4.5.3.1 SPI Guideline Evaluation

Normally, design engineers attempt to be conservative when applying the SPI guidelines to non-critical dimensions by assuming that the dimensions can be held to within the commercial line on the SPI chart. As shown in Figure 4.15, however, there can be a wide range of tolerance capability for dimensions of the same magnitude on the same part. This figure graphs the variation among the spool cavities from one shot, demonstrating the *mold dimensional variation*. Each data point represents the three-sigma deviation for each measured dimension. This information can be used by design engineers when they are designing parts that have a similar shape or are part of the same product platform. In addition, the plot shows the results for a specific number of cavities. Through the accumulation of information about molds with different numbers of cavities, engineers will

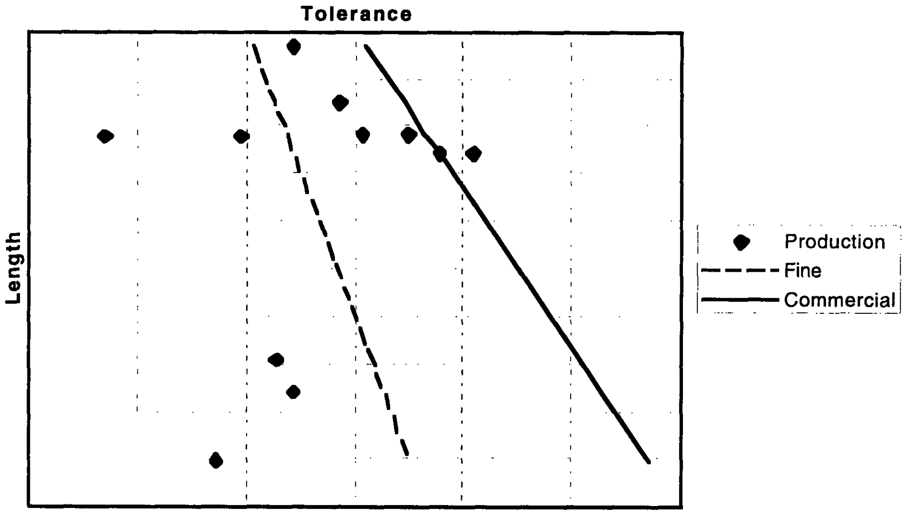

Figure 4.15: Three Sigma Mold Variation Plotted on an SPI Tolerancing Chart.

be able to trade-off the demands of production volume and quality. Additional benefit could also be gained from plotting the shot-to-shot variation on the SPI chart. Unfortunately, time and resources did not permit a complete decomposition of the shot-to-shot variation as a function of the length of the various spool dimensions.

The final type of information that would aid design engineers in their evaluation of this model of tolerance capability is a plot of the variation across the process space for the experiments. This plot, shown in Figure 4.16, shows that, no matter what point in the process space that the manufacturing operations selects, the three sigma variation of some dimensions will always be within the commercial or even fine lines, whereas others will not.

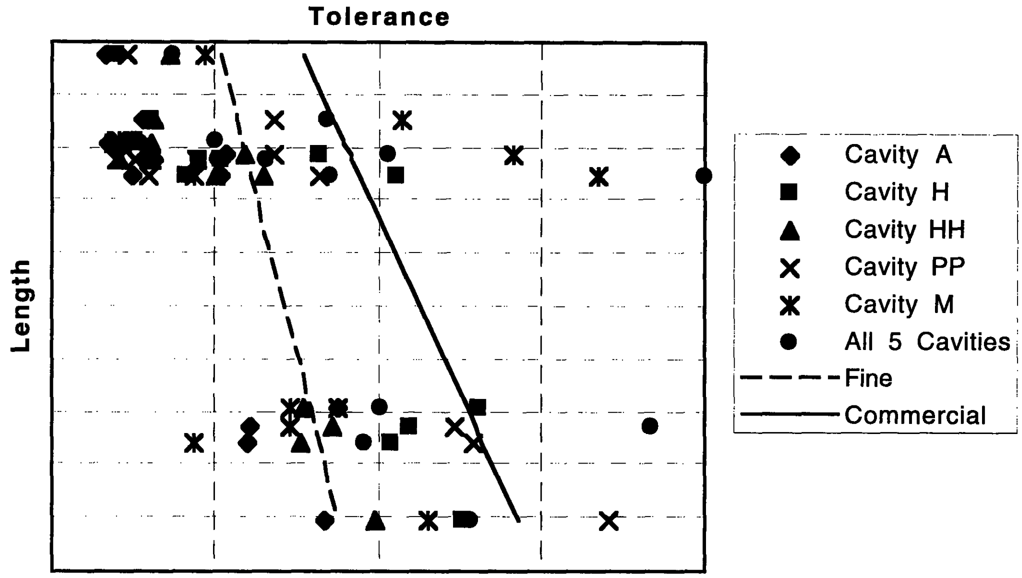

Figure 4.16: Individual Cavity Dimensional Variation Plotted on SPI Chart

4.5.3.2 Critical-to-Monitor Dimension Verification

The information shown in Figure 4.16 can be used to reduce the set of critical-to-monitor dimensions by virtue of the fact that no matter where the process settings are moved within the process window, certain dimensions will always be held to a tight tolerance. By using the process capability index, C_p, two of the original nine critical-to-function dimensions were eliminated from the set of critical-to-monitor dimensions.

$$C_p = \frac{\text{USL - LSL}}{6\sigma} \tag{4.14}$$

As shown in Equation 4.14, the process capability index is defined as the difference between the upper specification limit (USL) and the lower specification limit (LSL), divided by six times the standard deviation of the measured parts. The critical-to-function dimensions that were removed from the set of critical-to-monitor dimensions both had a C_p of 2.0 or more, which corresponds to a defect rate of approximately 3.4 parts per million [John, 1990].

Using the correlation technique described in Section 3.3.4, where the variations of two critical-to-function dimensions are fitted to a regression model, an additional two critical-to-function dimensions can be eliminated from the set of critical-to-monitor dimensions. As shown in Figure 4.17, the variation of both of these dimensions could be captured by Dimension A, as demonstrated by the high degree of linearity in both figures. Finally, an analysis was performed to match the model tolerances to the tolerance allocations for these dimensions (E and H). As a result, the final set of critical-to-monitor dimensions was reduced to four dimensions.

Up until this point, first-order models and some statistical modeling techniques that have been applied to the problem of understanding the tolerance capability of injection molding have been evaluated. The next section describes the usage of process simulation to model the capability of the process.

4.5.3.3 CMOLD Evaluation

There are three levels of information that CMOLD can reliably provide about the shrinkage and tolerance capability of the injection molding process: nominal shape prediction, critical dimension variation correlation, and the effect of the location of the process within the process space on the variation in the dimensions (through the DOE). Due to some of the limitations involved with modeling the runner system and the pressure drop across the runner system, accurate predictions of the shrinkage were not obtained.

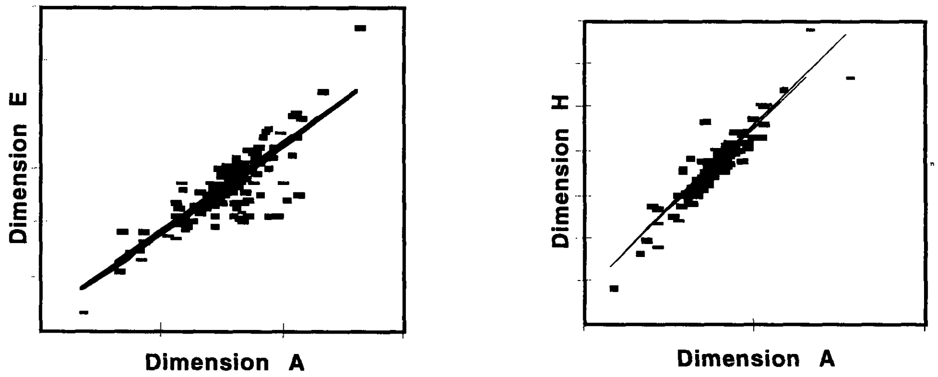

Figure 4.17: Linear Fit Plots for Three Critical-to-Function Dimensions

Through process simulation, the resulting shape of the part can be reliably predicted. As shown in Appendix D, the filling pattern can be predicted very well. Normally, experienced mold engineers are able to anticipate the filling pattern to some degree. With the advent of complex moldings, however, it has become increasingly difficult to visualize the filling pattern without the aid of simulation. This flow visualization can help mold and design engineers modify the part to prevent attribute defects, such as air traps. Melt or weld lines, where two flow fronts meet, can also be better managed through computer-aided flow visualization.

In addition to flow visualization, the deformation of the spool through shrinkage and warpage was predicted rather well. For example, the software predicted the location of the minimum distance between the spool flanges, which was a key consideration in the design of the mold. A magnified picture of the deformed finite-element mesh is shown in Figure 4.18. By understanding the pattern of the shrinkage, mold engineers can anticipate trouble areas and possibly reduce the number of iterations required to match the shrinkage allowance in the mold to the actual part shrinkage. Furthermore, the shrunken mesh can be used to help set up the measurement program for the Coordinate Measurement Machine by showing where the machine should collect its data points. For example, the minimum distance between the flanges is predicted to occur at a certain location around the barrel. This information can be used to limit the number of points that need to be sampled in order to capture the dimensional information. Fussell, et al. have taken a similar approach by creating a model of aluminum extrusions [1994]. Even though the shrinkage and flow-

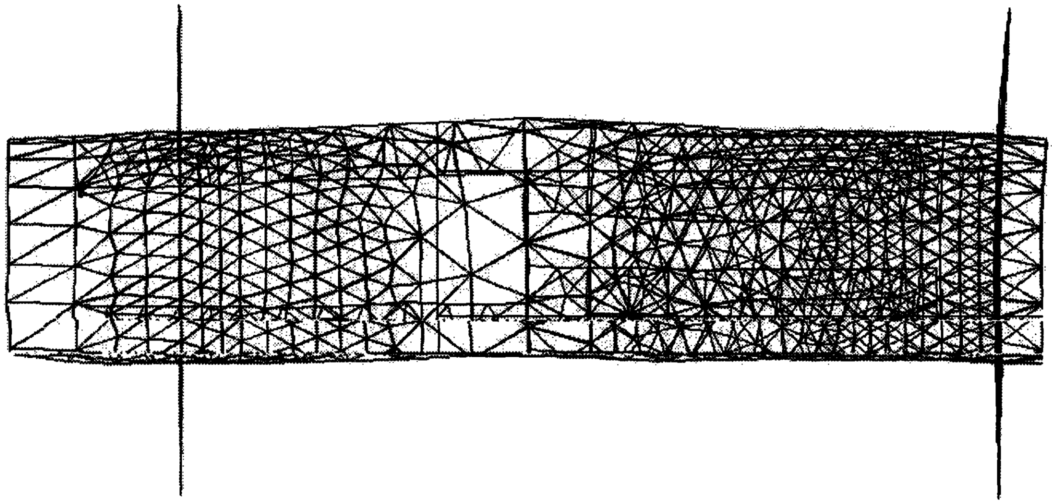

Figure 4.18: Predicted Spool Shape (scale increased)

visualization capability of CMOLD and other process simulation packages has been verified in the literature, it is important to present real-life examples to the engineers within the enterprise in order to fully gain their acceptance of the tool.

The critical-to-monitor dimension assignment method described in Section 3.3 can also be evaluated at this point. By simulating the process at the same points in the process space that were used for the set of designed experiments, the variation of the critical-to-function dimensions could be modeled and correlations were found. More correlations that resulted in possible critical-to-monitor dimension set reduction were found in simulation, but the strongest correlations were for the ones that were also found to exist in reality. For example, the correlation between dimensions A and H was particularly strong in simulation, as shown in Figure 4.19. Based upon the correlations predicted by simulation, it was predicted that five critical-to-function dimensions could be eliminated from the set of critical-to-monitor dimensions. In comparison to the actual dimensions that were removed from the set, four of the dimensions were the same. Two of those dimensions were removed from the actual set because their variation throughout the process space was well within the tolerances allocated to them. Thus, the simulation predictions for critical-to-monitor dimension set reduction agreed with the actual critical-to-monitor dimension assignments, although the simulation tended to suggest a greater amount of correlation across the board.

The final area in which CMOLD can be used in order to understand the nature of the shrinkage of the plastic at different points within the process space. Unfortunately, the

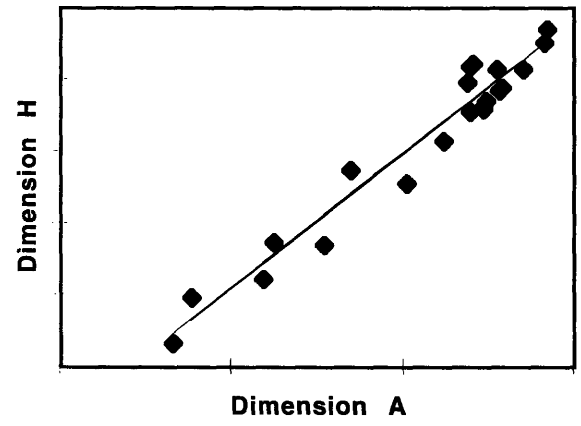

Figure 4.19: Predicted Correlation between Critical Dimensions A and H

dimension predictions did not nominally match well to the measured dimensions. There are several possible reasons for this discrepancy. Chief among these reasons is the current modeling limitations that CMOLD has for hot runner molds. Based upon the modeled mold-wall temperature difference (which is a result that CMOLD calculates in order to aid the mold engineer in the design of the cooling system) and the measured ejection temperatures, CMOLD's model does not adequately predict the variation in mold-wall temperature. In addition, CMOLD's predicted ejection temperatures are much cooler than the measured ejection temperatures. As stated in Section 4.1.2, one of the major sources of warpage is unbalanced cooling. Since CMOLD's predictions do not adequately capture this cooling imbalance, the predicted warpage (which has a large effect on some of the dimension predictions) is much less than in reality. The major reason that the software predicts lower ejection temperatures and more constant mold-wall temperatures is because it models hot-runner systems by applying an initial condition to the plastic in the runner system such that the runner is full of molten plastic at the specified melt temperature. Unfortunately, the model does not account for the output of the heater that is required to keep that plastic at the melt temperature. As a result, it does not adequately model the temperature of the mold steel surrounding the hot runner. This steel also comprises one half of the mold cavity. Thus, the effect of a hotter mold and unbalanced cooling is not properly modeled by CMOLD for a hot runner system.

Despite the fact that CMOLD could not predict the nominal shrinkages of the

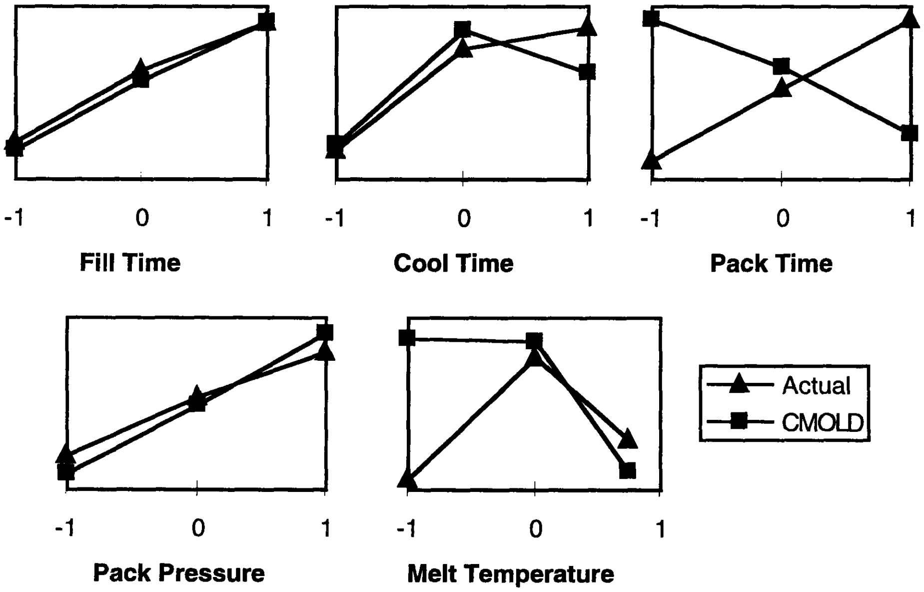

Figure 4.20: Main Effects for Dimension A

various sections of the spool accurately, it did predict the effect of setting up the process at various points within the process space. By plotting the results from the DOE across the process space, it is possible to isolate the effect of each process setting. These effects are known as *main effects*. As shown in Figure 4.20 and Figure 4.21, when the predicted dimensions were scaled to match the actual dimensions, many of the predicted effects of the changes in the process space were similar to the actual effects. In the case of Dimension A, the software predicted the general trends for the main effects in every case except the pack time effect. In the case of Dimension F, the software main effect trends matched the actual trends in every case except the melt temperature effect.

The discrepancy for the effect of the melt temperature can be discounted because the melt temperature cannot be considered as a discernible effect (as opposed to an effect that arose by chance) because its F-statistic was much greater than 0.05 (or 95 percent confidence). As discussed in Section 2.2.5, effects can only be considered significant if their F-statistics (which compares the regression-predicted variation of the output due to changes in the input with the actual variation of the output) are greater than 95 percent confidence. The discrepancy for the effect of the pack time on Dimension A cannot be explained as easily. Since the longer pack time puts the plastic at a point that is further down the PvT curve, less shrinkage would be expected in that case (as shown in Figure 4.10 and discussed in Section 4.3.3). In addition, Dimension A is one of the "mold-breathing" dimensions. These dimensions are not (as) fixed in length and will expand

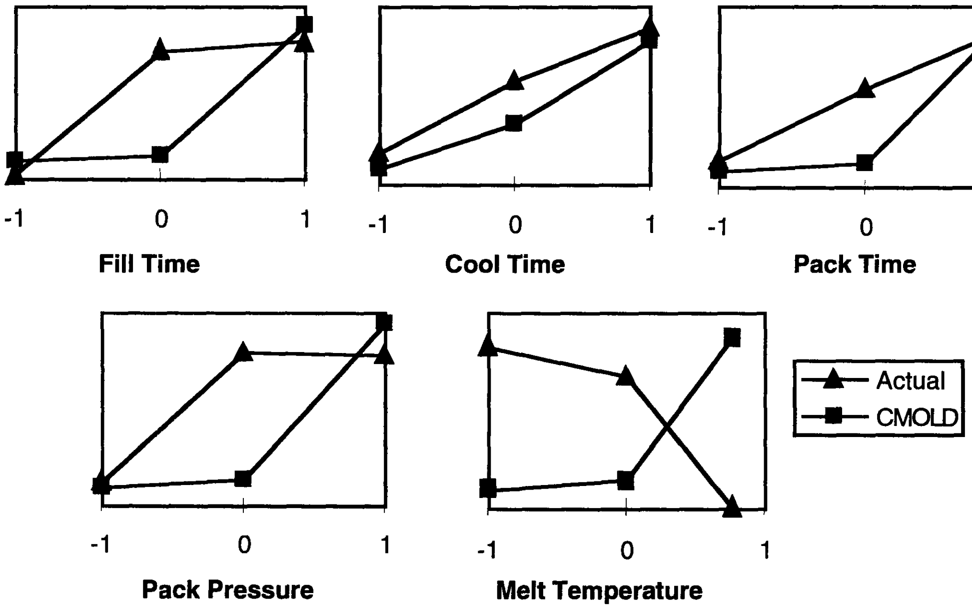

Figure 4.21: Main Effects for Dimension F

under pressure and temperature (as opposed to a single block of steel, which will only expand under temperature). CMOLD cannot model this effect because it assumes that the mold has fixed dimensions. Dimension F is a fixed dimension in the mold, so this effect did not have to be taken into consideration. For all other effects, the increases or decreases in length with respect to the placement in the process space that were measured matched the predicted effects.

This information can help the engineer decide upon a particular location to set up the process within the process space. Also, the main effect predictions allow the engineer to correlate the part measurements with the process variation. If the fill time is running high, for example, an increase in Dimensions A and F should be expected. After CMOLD has been evaluated for several products, an average scaling factor could be developed. With this scaling factor, CMOLD could be used as a guide for setting control limits on the process variables. However, it is recommended that experimentation be used to verify these control limits until the software has been expanded to model the hot runner system in a more detailed fashion.

4.5.4 Process Window Feedback

The previous discussion discussed the evaluation of the CMOLD software as part of the feedback methodology. This type of model requires a lot of information feedback in order to calibrate it. One of the critical pieces of information that can help calibrate the process simulation model is the process window. By feeding back process windows available to the simulation experts and/or mold engineers, the enterprise can enhance its analysis capability. As the simulation software improves, it may be able to predict the shapes of these process windows accurately. Until that time, the engineer needs to have a good understanding of the actual process window for the part before setting up a set of designed experiments in simulation.

In the case of new products, the actual process windows may not be the same. However, the air-shot test described in Section 4.4.1 could be used to help determine the filling process window as long as the same material is used for the new product (there will be an additional effect of the runner system that also must be considered). Since the ease of setting up and controlling the process is directly proportional to the size of the process window, the feedback of the process windows can also be used as a check of the "robustness" of the design.

There are some additional lessons that can be learned from the nature of the injection molding process windows themselves. First, although the process window diagrams show clearly defined boundaries, it is not feasible to operate the process at or near any of these boundaries because secondary effects will potentially impede production. For example, one of the factorial points in the DOE was not feasible even though the set points were within both the packing and filling windows. The combination of all five process settings made this factorial point unreachable. Second, it must be remembered that the DOE space is essentially an n-dimensional cube (this shape is used for statistical reasons) that will not capture the entire process space. When setting up the DOE, it is important to ensure that the experimental design space captures a large enough region of the process space and that the true optimal point is expected to lie within that region. Finally, experimentation showed that the packing window is highly nonlinear. Consequently, it is difficult to predict the shape of this window. Therefore, much of the benefit from process window feedback can be gained through the feedback of the packing window.

Chapter 5

Conclusions and Future Work

This final chapter summarizes the conclusions from the case study by suggesting a process capability model usage strategy. In addition, the achievements of the thesis research and future research is discussed.

5.1 Suggested Model Usage Strategy for Injection Molded Product Development

As the injection molding process moves from an art to a scientifically-understood activity, the companies involved in this industry need to improve their product development processes to take advantage of this new understanding and remain competitive. Through the application of the process capability feedback methodology, as expressed in Figure 5.1, these companies can limit new product development time and ensure quality.

In the first stage of the product development process, the engineering team considers the design and manufacturing requirements and develops the product concept. Initial definitions of critical-to-function dimensions and critical process parameters are made at this point. Through the application of DFM analysis and process simulation, the team can understand the effects of the process on the design and refine the concept through iteration. Based upon a better understanding of the process, the critical parameter assignments can also be evaluated at this point. Once the design is ready for production, certain experiments can be performed to certify the capability of the process and improve the understanding of the effects of the process on the design. Finally, the information from

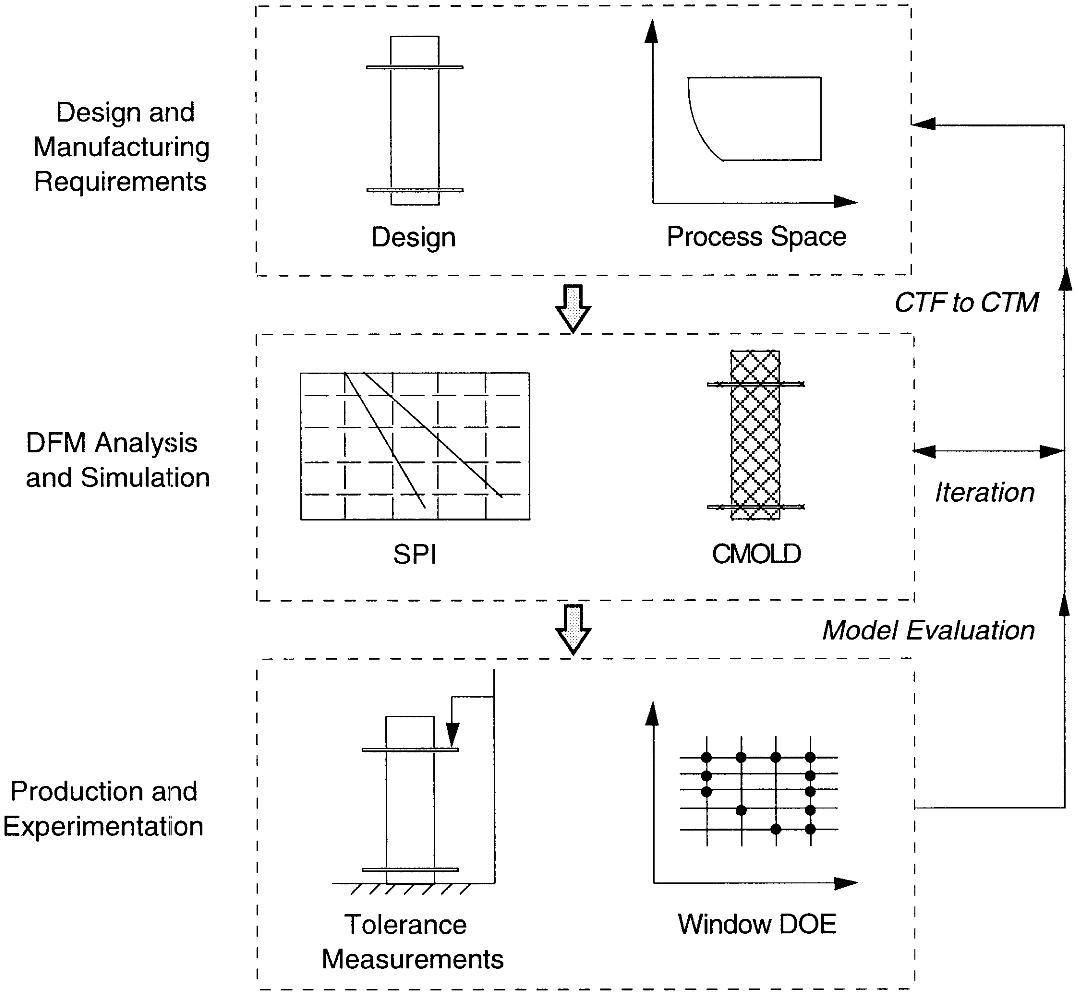

Figure 5.1: Process Capability Feedback Implementation

these experiments can be used to evaluate and improve the models of the process capability. This information will also be fed back into the product data management system to enable the team to solidify the critical parameter assignments and tolerances.

There are a few key details in this methodology that are important to successful implementation:

- During the design phase, assign tolerances on the part for functional reasons only. The separation of tolerancing based upon functionality from the tolerancing based upon the process capability will promote cooperation between design and manufacturing engineers and make a realistic assessment of part quality possible.
- When estimating tolerance capability, use, in order of increasing accuracy: the standard SPI guidelines, an internal enterprise capability chart (with a "scatter factor" to

account for the spread about the line), and/or process simulation. The level of modeling is dictated by the criticality of the part and the dimensions.

• Use process simulation to help define the critical-to-monitor dimensions, estimate shrinkage and variation (for cold-runner systems), and optimize the process design.

• The feedback of process window information is important to aiding the simulation process at this time. It is a quick, first-order diagram and experiment that will help design and manufacturing engineers gauge quality of both the process and the design.

• Feedback is an ongoing project that promotes the continuous improvement of the models of the process. Simulation software is improving every year, so it is important to maintain a current understanding of its true capability in order to take full advantage of it.

5.2 Achievements of Thesis Work

In order to remain competitive, today's manufacturing companies need to continue to improve their understanding of the capability of their manufacturing processes in order to achieve tighter tolerances, improve quality, improve productivity, and reduce cost. Concurrent engineering has taken a holistic approach to this problem by developing management methods to promote greater communication between design and manufacturing engineers. Unfortunately, manufacturing and design engineers do not often speak the same language because they have different objectives. For example, design engineers must be able to assess the feasibility of producing the parameters (i.e. dimensions and physical properties) of a design within their specified tolerances and understand how variation will affect the ideal function of the product. On the other hand, manufacturing engineers are concerned with the design of the process in order to make parts with tight tolerances as well as maintaining the machine that makes these parts. By addressing these issues, the methodology described in this thesis provides a formal mechanism that design and manufacturing engineers can use to quantify the relationship between the production system capability and proposed design changes. Specifically, the achievements of this thesis can be summarized as follows:

• A feedback methodology that will promote effective management of process capability information was developed.

• A critical tolerance evaluation and allocation strategy was developed.

• The injection molding process was optimized for the spool based upon the determination of the process-product relationship.

- The accuracy of several models used for injection molding was assessed including a simulation software tool.
- A model usage strategy was developed for injection molding. This model usage strategy can be developed for any manufacturing process through the application of feedback.

5.3 Future Work

The case study in this thesis provides only one example of the many manufacturing systems that can implement this methodology. Many net-shape manufacturing processes, such as metal casting, could also benefit. Through the application of the concepts developed in this thesis to other industries, this methodology can be refined and abstracted to a theory.

One of the major requirements for the successful implementation of this methodology is a well-organized product management system. With the increasing use of electronic networking more information can be shared throughout the enterprise. The task now becomes to manage the flow of that information. At the writing of this thesis, a follow-on project is being defined to address these needs. Specifically, it will have to address the needs of design and manufacturing engineers at the different levels of detail design. In addition, one of the requirements for the construction of a "process capability database" is that it must be easy to maintain. Since this thesis does not rely very much on the generation of new process capability information (that was not being generated as part of company-practice), the crucial issue that remains is the appropriate method for data translation and model calibration. It is hoped that this thesis will serve as an example in that regard.

Finally, by following the doctrine of continuous improvement, enterprises will be able to improve their own process capability models. Additional coordination with outside vendors will be necessary for the improvement of the commercially available simulation software packages. The enterprise should continually strive to improve its understanding of what information is needed at each step of the product development process in order to improve its development capability and ensure quality.

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Appendix A
ANSI Standards for the 35 mm Spool

American National Standard for Photography (Film) -

135-Size Film and Magazine - Specification

1. Scope

This standard specifies the following:

(1) Dimensions of four standard film lengths normally supplied. The film lengths provide, respectively, a nominal number of twelve, twenty, twenty-four, or thirty-six 24 mm x 36 mm full-frame exposures or twenty-four, forty, forty-eight, or seventy-two 18 mm x 24 mm half-frame exposures.

(2) Latent image frame numbering.

(3) Latent image digital bar code to identify the film product class and the individual film product, in the case of color negative films.

(4) Dimensions of daylight-loading film magazines for use in still 35 mm picture cameras.

(5) Magazine bar code to identify the film product and the nominal number of exposures in the roll.

(6) Camera auto-sensing areas, which provide an electrically readable encodement of ISO speed, number of exposures, and recommended exposure latitude setting for appropriately designed cameras.

(7) Information panel on which the film identification, ISO speed, and number of exposures are visible through a window in the back of the camera.

(8) Film pull-out force specification.

(9) Film-spool attachment strength specification.

This standard is not intended to apply to "bulk" 35 mm film for reloading into 135 magazines nor to the reloadable magazines themselves.

NOTE: It is not intended in this standard to specify the actual location of photographic images on film.

2. Referenced Standards

2.1 Referenced American National Standards. This standard is intended to be used with the following American National Standards:

ANSI MH10.8M-1983, Materials Handling - Bar Code Symbols on Unit Loads and Transport Packages

ANSI/IEEE 268-1982, Metric Practice

ANSI PH3.501-1991, Picture Sizes - Roll Film and Disc Film Still-Picture Cameras

10. Information Panel

This area displays key information about the film contained within the magazine. It is visible through a window in the back of any appropriately designed camera.

10.1 Location and Dimensions. The information panel area shall be located on the magazine surface and dimensioned as shown in Figure 7 and Table 14.

10.2 Contents of the Information Panel. The human-readable data located within the information panel should contain the following:

(1) Film identification
(2) ISO speed or manufacturer's recommended exposure index
(3) Number of exposures

If the ISO speed or exposure index is included in the film identification (1) , it need not be repeated to fulfill (2).

11. Film Pull-Out Force

The initial force to begin pulling the film out of the magazine lip shall be 5.0 N maximum. After 100 mm of film has been extracted from the magazine, this force shall not exceed 2.5 N throughout the balance of the roll. These specifications apply both at the time of manufacture and throughout the manufacturer's specified product life (when stored according to the manufacturer's recommendations for storage).

12. Film-Spool Attachment Strength

A pulling force of 40 N on the film shall not break the film-spool attachment. The 40 N specification applies both at the time of manufacture and throughout the manufacturer's specified product life (when stored according to the manufacturer's recommendations for storage).

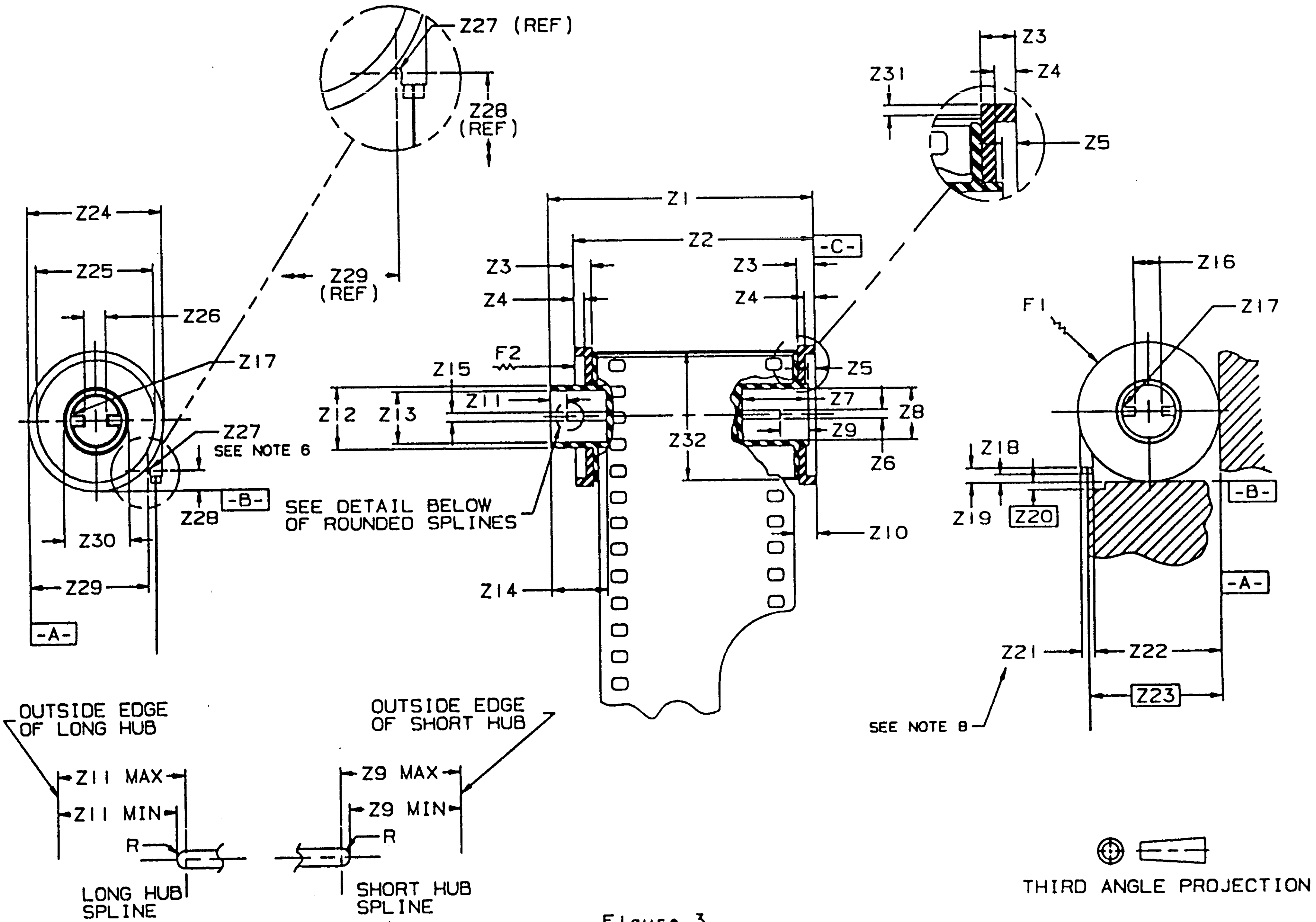

Figure 3

Dimensions of 135-size film magazine[1]

---

[1] See Table 5.

	SIZE mm					SIZE mm			
Dimension	Minimum	Basic	Maximum	Reference	Dimension	Minimum	Basic	Maximum	Reference
Z1	46.89		48.00	Note 1	Z23		23.40 Basic		Note 4
Z2	42.39		43.80		Z24	24.89		25.30	Note 5
Z3	---		3.30		Z25	18.19		---	
Z4	0.79		1.55		Z26	4.50		5.00	
Z5	0.28		---	Note 1	Z27		1.00 nominal		Note 6
Z6	1.00		2.06		Z28		1.50 nominal		Note 6
Z7	9.65		---		Z29		20.50 nominal		Note 6
Z8	9.19		---		Z30	11.51		---	
Z9	4.00		5.56	Note 2	Z31	0.00		0.90	
Z10	2.80		5.10	Note 1	Z32	23.40		---	
Z11	2.01		3.91	Note 2	F1		4 N		Note 7
Z12	---		11.40		F2		4 N		Note 7
Z13	9.19		---		Spool Float	0.03		1.00	Note 9
Z14	10.00		---		Z1+SF	47.15		48.05	Note 10
Z15	---		2.11		Z1-Z11	43.11		---	Note 10
Z16	0.00		1.50	Note 3	Z1-Z11+SF	---		45.78	Note 10
Z17	---		0.41		Z1-Z14	14.87		---	Note 10
Z18	-0.51		3.59	Note 8 1)	Z1-Z14+SF	---		36.50	Note 10
Z19	1.39		3.59	Note 8	Z5+Z7	11.30		---	Note 10
Z20		1.27 Basic			Z5+Z27+SF	11.62		---	Note 10
Z21	---		3.53	Note 8	Z5+Z9	5.18		---	Note 10
Z22	21.49		---		Z5+Z9+SF	---		7.16	Note 10

1) Min is "below" B datum plane

Table 5
Dimensions of 135-size film magazine[1]

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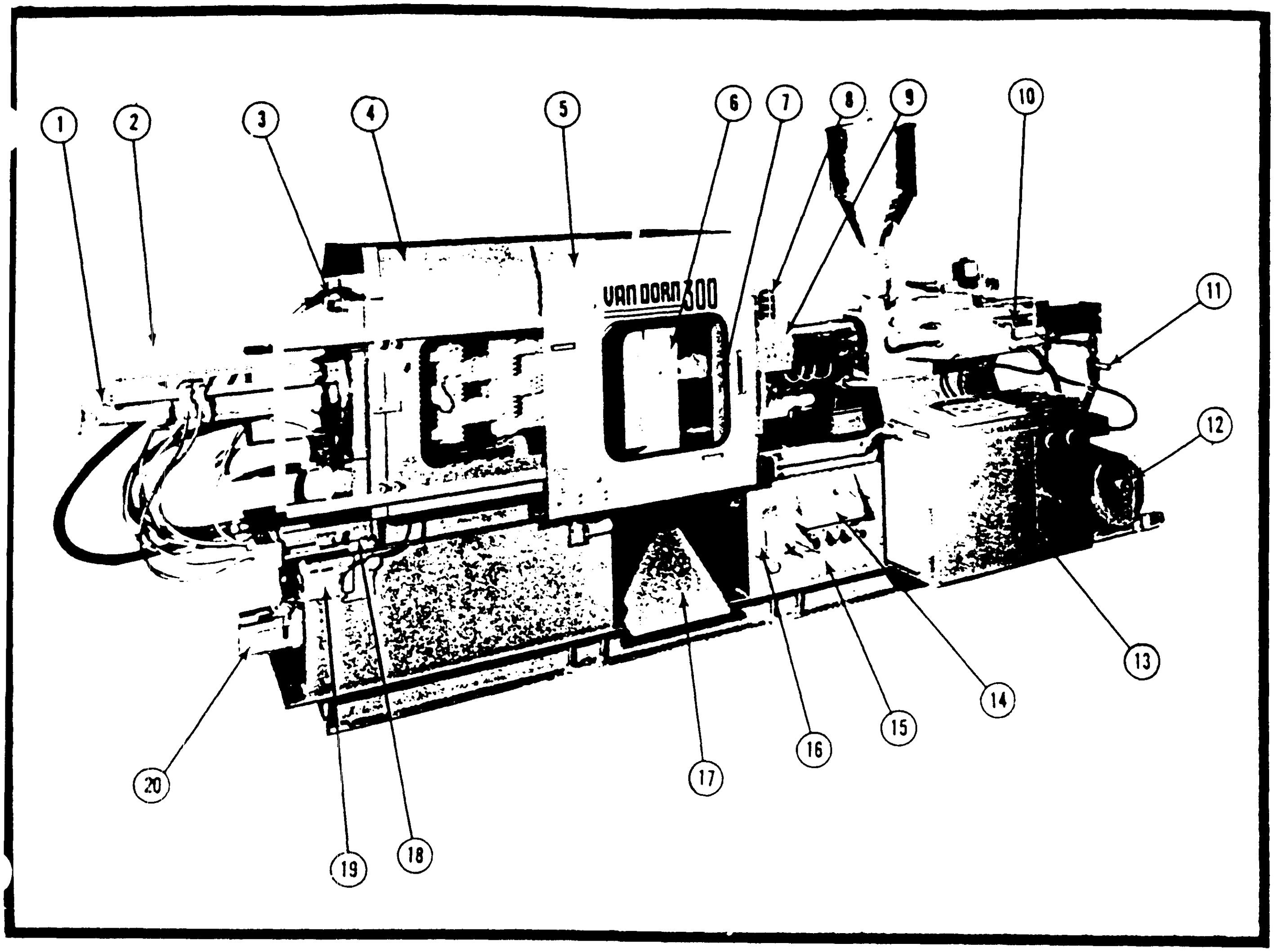
[1] See Figure 3.

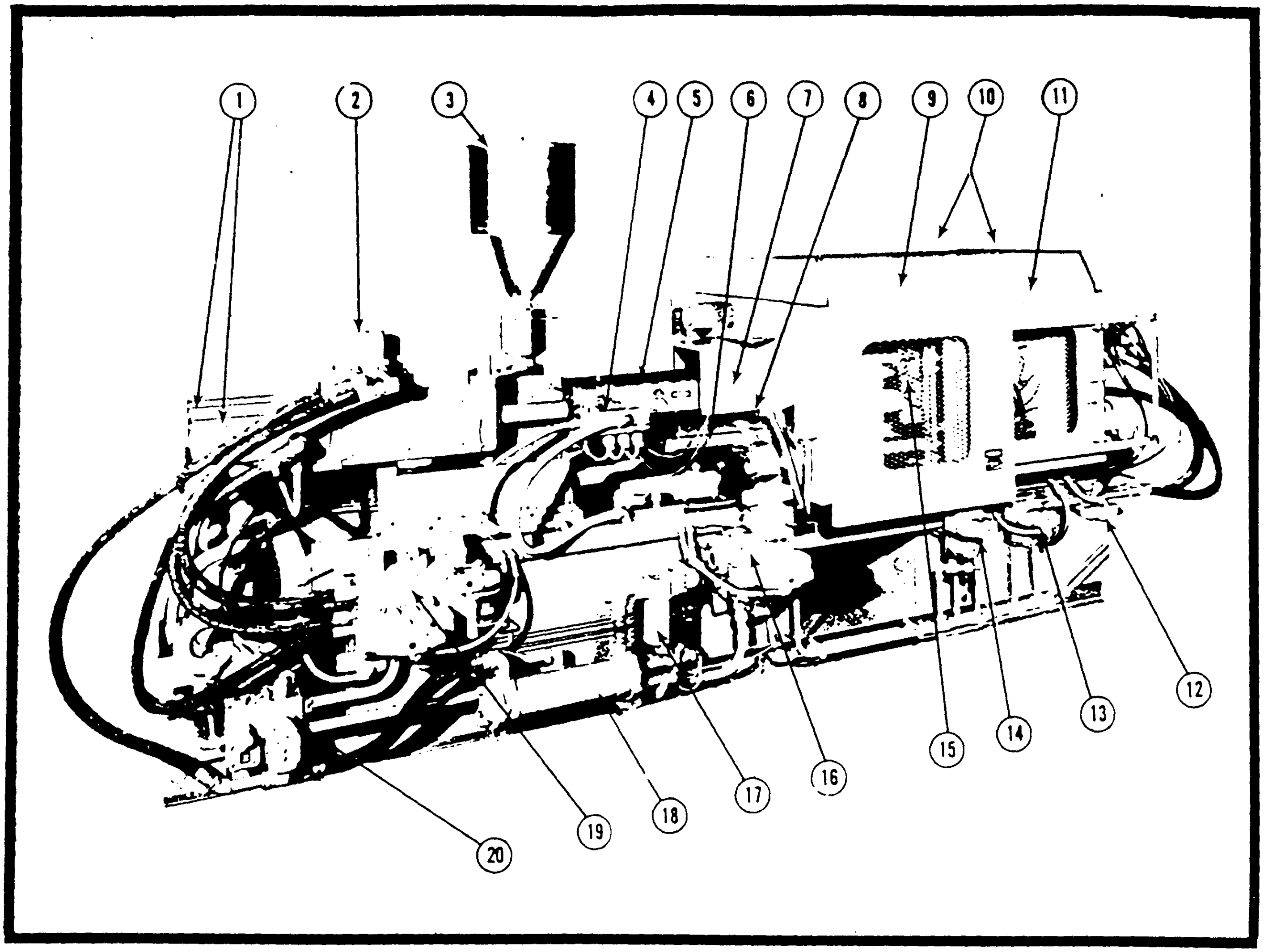
Appendix B
Injection Molding Machine Documentation



LEGEND

1. Clamp Cylinder
2. Clamp Limit Switch Assembly
3. Linkage Plate
4. Front Fixed Guard
5. Front Operator Gate
6. Movable Platen
7. Stationary Platen
8. Low Pressure Overtime Light
9. Operator's Electrical Control Station
10. Screw Fully Retracted (Shot Control) Limit Switch
11. Injection Speed Control Valve
12. Electric Motor (Pump Drive)
13. Electrical Control Panel (Solid State)
14. Operator's Injection Pressure Control Station
15. Hydraulic Oil Reservoir
16. Hydraulic Oil Level Gage
17. Parts Chute
18. Mold Height Adjustment Limit Switches
19. Machine Serial Number Nameplate
20. Automatic Lubricator Unit

FIGURE i-1 TOGGLE CLAMP INJECTION MOLDING MACHINE OPERATOR SIDE



LEGEND

1. Injection Cylinders
2. Screw Speed Control Valve
3. Hopper
4. Barrel Heat Power Plug-In and Thermocouple Box
5. Metal Shield (Heater Bands)
6. Carriage Positioning Cylinder
7. Purge Shield
8. Purge Shield Limit Switch
9. Rear Guard
10. Ejector Plate and Linkage Area
11. Rear Fixed Guard
12. Mold Height Adjustment Manifold
13. Hydraulic Ejection Manifold
14. Core Pull Manifold
15. Hydraulic Ejection Limit Switches
16. Clamp Manifold
17. Hydraulic Oil Filter
18. Heat Exchanger (Hyd. Oil Cooler)
19. Injection Manifold
20. Pump Manifold

FIGURE i-2 TOGGLE CLAMP INJECTION MOLDING
MACHINE NON-OPERATOR SIDE

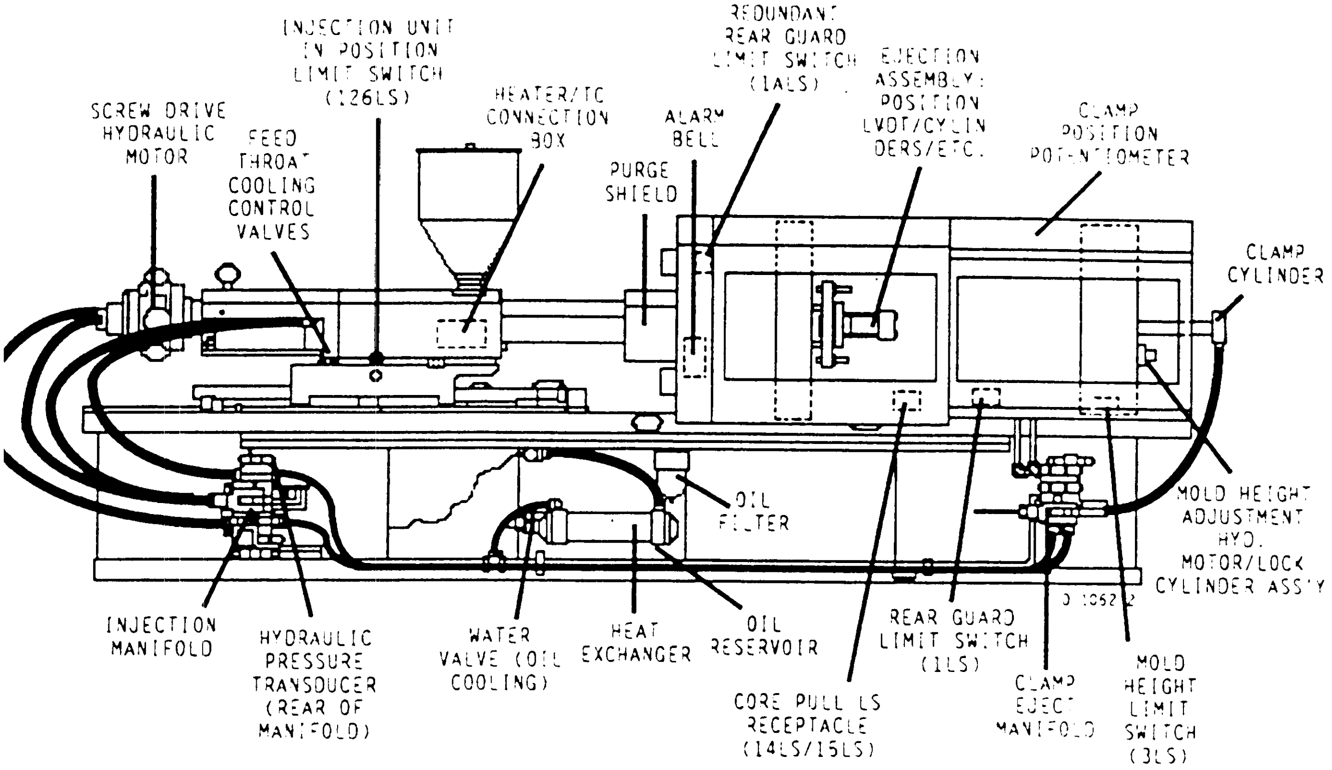


Figure 1-2. TOGGLE CLAMP INJECTION MOLDING MACHINE - REAR VIEW

e new Van Dorn Pathfinder® EL Microprocessor Control System provides the molder with the sophisti-
ed control capabilities to ensure cycle-to-cycle repeatability and machine efficiency. Some of the features the control system include closed loop process control, fast and accurate machine set-up, self-diagnostics, ocess monitoring, production status, and graphic displays. On screen prompts and menu displays step the erator through precise settings of all the machine functions and parameters.

e remainder of Paragraph 1.5 describes the operation and mechanical components associated with the amp Unit, the Injection Unit, the Hydraulic System, and the Pathfinder® EL Control System.

3. CLAMP UNIT

Consisting of clamp cylinder, link pins and linkage members, link (clamp cylinder) platen, moving laten, stationary platen, tie bars, mold height adjustment mechanism, and ejector mechanism, the double oggle clamp unit serves a major part in the injection molding process. Refer to Figure 1-3.

1. Description

Serving multiple purposes in the injection molding process, the clamp unit holds the mold in position between the platens, and applies a clamping force, rated in tons, on the mold which is sufficient to prevent the mold halves from separating under the opposing force of the fluid plastic injected into the mold. Later, when the molded part has cured, the clamp opens to allow ejection (knock-out) of the part, and then recloses to enable the mold to accept another shot of material, and the cycle repeats. The mold construction is such that the core half (moving side) possesses undercuts or other

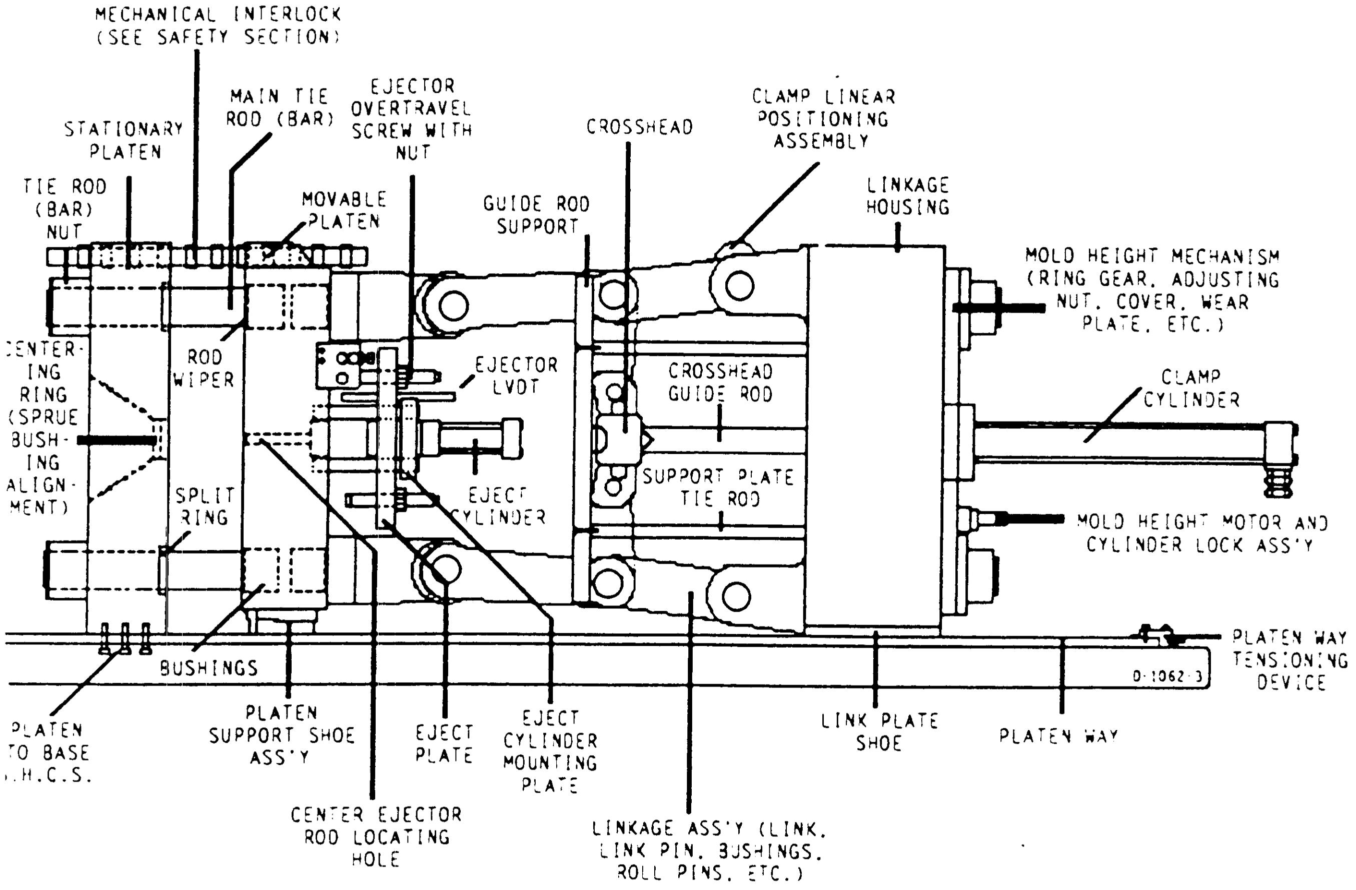


Figure 1-3. CLAMP UNIT—SIDE VIEW

During clamp opening, the unlocking of the clamp is performed at slower, controlled speed to prevent the kinetic energy stored in the stretched tie bars from causing the mold to snap open. The breakaway speed is only needed for unlocking, then the mold open fast position is reached and the clamp opens at speeds up to maximum capable. Once the clamp is opened sufficiently to allow part ejection, the ejector start position is set to start the ejector forward. The mold open slow position, reached just prior to the mold full open position, slows down the clamp in order to achieve smooth deceleration before reaching the mold full open position. If running in the Auto mode of operation, the Mold Open Timer, upon timing out , (if other cycle sequences have completed) permits the clamp to close for recycle.

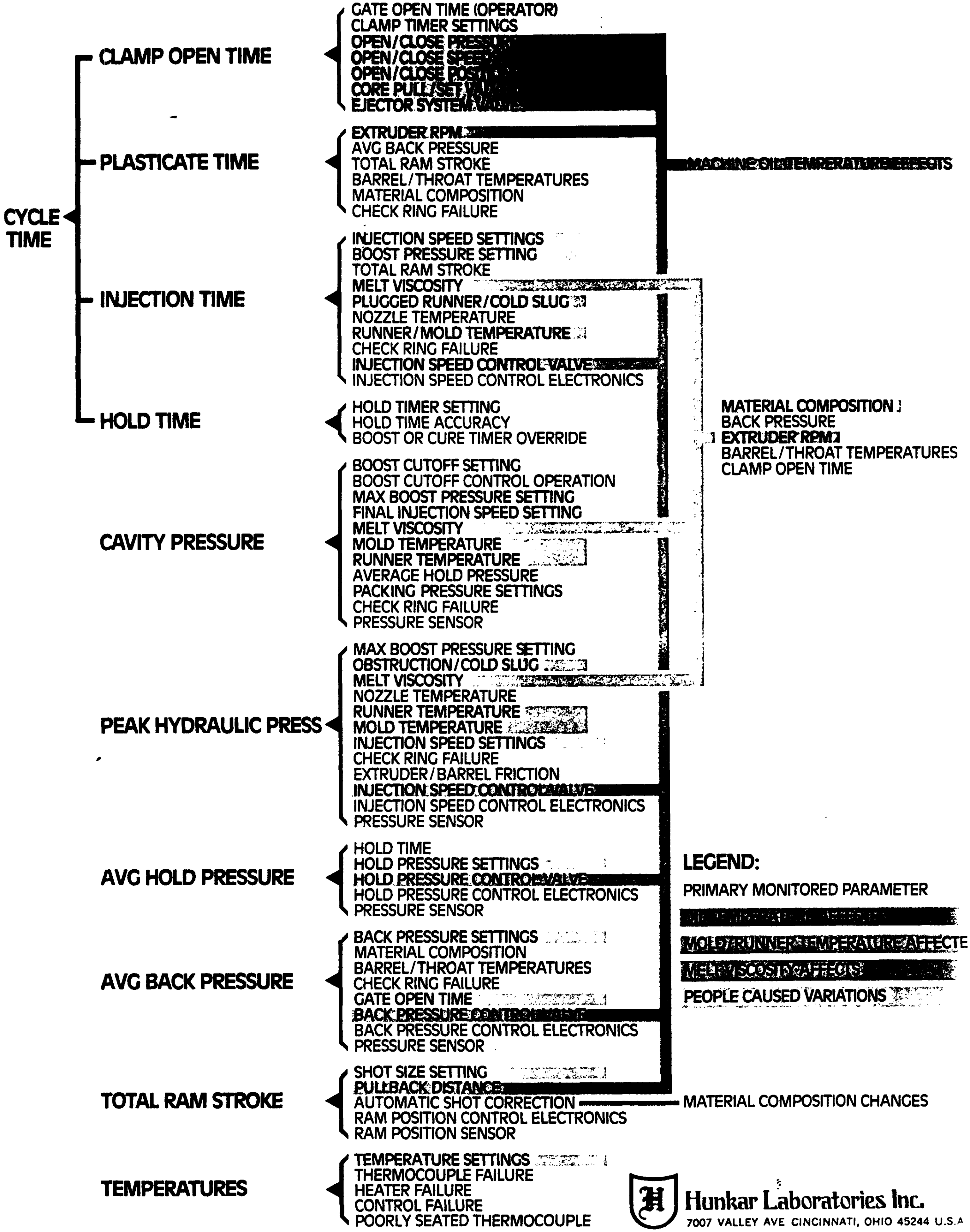
The exact sequence of the clamp will depend on which, if any, of the optional core sequences are selected. Basically the core can be set or pulled; at full open, during clamp open/close (on the 'fly'), at full open, or at a specific clamp open or close position(mid-die stop).

Mechanical Description

The clamp unit for the Van Dorn HT Series machine has been designed with all of the desirable features of past designs, but also with enhanced features and manufacturing quality to ensure long service life. These features include; motorized ring gear mold height adjust, automatic mold height mechanism lock, link platen and moving platen castings, crosshead casting, hardened steel/chrome plated toggle pins, front and rear tie bar supported crosshead guide rod supports, extended moving platen guide bushings, long stroke single eject cylinder, four ejector plate guide rods, brass contact spacers between moving and stationary links, brass contact plates between adjusting tie bar nuts and mold height reverse cover plates, self lubricated bushings in links, self lubricated bushings in ejector plate and moving platen, and adjustable self lubricated moving platen support shoes.

Appendix C
Process Modeling and Capability Information

Parametric Analysis Database for Statistical Process Control in Injection Molding



CYCLE TIME

- **CLAMP OPEN TIME**
  - GATE OPEN TIME (OPERATOR)
  - CLAMP TIMER SETTINGS
  - OPEN/CLOSE PRESSURE
  - OPEN/CLOSE SPEED
  - OPEN/CLOSE POSITION
  - CORE PULL/SET VALVE
  - EJECTOR SYSTEM VALVE
- **PLASTICATE TIME**
  - EXTRUDER RPM
  - AVG BACK PRESSURE
  - TOTAL RAM STROKE
  - BARREL/THROAT TEMPERATURES
  - MATERIAL COMPOSITION
  - CHECK RING FAILURE
- **INJECTION TIME**
  - INJECTION SPEED SETTINGS
  - BOOST PRESSURE SETTING
  - TOTAL RAM STROKE
  - MELT VISCOSITY
  - PLUGGED RUNNER/COLD SLUG
  - NOZZLE TEMPERATURE
  - RUNNER/MOLD TEMPERATURE
  - CHECK RING FAILURE
  - INJECTION SPEED CONTROL VALVE
  - INJECTION SPEED CONTROL ELECTRONICS
- **HOLD TIME**
  - HOLD TIMER SETTING
  - HOLD TIME ACCURACY
  - BOOST OR CURE TIMER OVERRIDE

CAVITY PRESSURE
- BOOST CUTOFF SETTING
- BOOST CUTOFF CONTROL OPERATION
- MAX BOOST PRESSURE SETTING
- FINAL INJECTION SPEED SETTING
- MELT VISCOSITY
- MOLD TEMPERATURE
- RUNNER TEMPERATURE
- AVERAGE HOLD PRESSURE
- PACKING PRESSURE SETTINGS
- CHECK RING FAILURE
- PRESSURE SENSOR

PEAK HYDRAULIC PRESS
- MAX BOOST PRESSURE SETTING
- OBSTRUCTION/COLD SLUG
- MELT VISCOSITY
- NOZZLE TEMPERATURE
- RUNNER TEMPERATURE
- MOLD TEMPERATURE
- INJECTION SPEED SETTINGS
- CHECK RING FAILURE
- EXTRUDER/BARREL FRICTION
- INJECTION SPEED CONTROL VALVE
- INJECTION SPEED CONTROL ELECTRONICS
- PRESSURE SENSOR

AVG HOLD PRESSURE
- HOLD TIME
- HOLD PRESSURE SETTINGS
- HOLD PRESSURE CONTROL VALVE
- HOLD PRESSURE CONTROL ELECTRONICS
- PRESSURE SENSOR

AVG BACK PRESSURE
- BACK PRESSURE SETTINGS
- MATERIAL COMPOSITION
- BARREL/THROAT TEMPERATURES
- CHECK RING FAILURE
- GATE OPEN TIME
- BACK PRESSURE CONTROL VALVE
- BACK PRESSURE CONTROL ELECTRONICS
- PRESSURE SENSOR

TOTAL RAM STROKE
- SHOT SIZE SETTING
- PULLBACK DISTANCE
- AUTOMATIC SHOT CORRECTION — MATERIAL COMPOSITION CHANGES
- RAM POSITION CONTROL ELECTRONICS
- RAM POSITION SENSOR

TEMPERATURES
- TEMPERATURE SETTINGS
- THERMOCOUPLE FAILURE
- HEATER FAILURE
- CONTROL FAILURE
- POORLY SEATED THERMOCOUPLE

MACHINE OIL TEMPERATURE EFFECTS

MATERIAL COMPOSITION
BACK PRESSURE
EXTRUDER RPM
BARREL/THROAT TEMPERATURES
CLAMP OPEN TIME

LEGEND:

PRIMARY MONITORED PARAMETER
[illegible]
MOLD/RUNNER TEMPERATURE AFFECTE
MELT VISCOSITY AFFECTS
PEOPLE CAUSED VARIATIONS

Hunkar Laboratories Inc.
7007 VALLEY AVE CINCINNATI, OHIO 45244 U.S.A

THE QUALITY STANDARD YARDSTICK

Earlier work (Ref. 1) determined the relationship between the variation of an individual process parameter and the effect on dimensional tolerance and stress of the molded part. These relationships are used to construct a set of process control windows where the importance of each process parameter is weighted to an optimum point so as to prevent over or under qualification, where the process control limits are used to sort acceptable and unacceptable parts.

TABLE 1

ACCEPTABLE TOLERANCES FOR QUALITY CLASS CLASSIFICATION

PARAMETER		CLASS1	CLASS2	CLASS3	CLASS4	CLASS5	CLASS6	CLASS7	CLASS8	CLASS9
CYCLE TIME	SEC	.20	.24	.29	.35	.41	.50	.60	.72	.86
HOLD TIME	SEC	.02	.02	.03	.03	.04	.05	.06	.07	.09
INJECT TIME	SEC	.04	.05	.06	.07	.08	.10	.12	.14	.17
CLAMP CLOSED	SEC	.10	.12	.14	.17	.21	.25	.30	.36	.43
CLAMP OPEN	SEC	.10	.12	.14	.17	.21	.25	.30	.36	.43
PLASTICATE	SEC	.15	.18	.22	.26	.31	.37	.45	.54	.64
CAVITY PRESS	PSI	15.00	18.00	21.60	25.92	31.10	37.32	44.79	53.75	64.50
PK INJ PRESS	PSI	20.00	24.00	28.80	34.56	41.47	49.77	59.72	71.66	86.00
HOLD PRESS	PSI	4.00	4.80	5.76	6.91	8.29	9.95	11.94	14.33	17.20
BACK PRESS	PSI	5.00	6.00	7.20	8.64	10.37	12.44	14.93	17.92	21.50
RAM STROKE	IN	.05	.06	.07	.09	.10	.12	.15	.18	.21
MOLD A TEMP	F	3.00	3.60	4.32	5.18	6.22	7.46	8.96	10.75	12.90
MOLD B TEMP	F	3.00	3.60	4.32	5.18	6.22	7.46	8.96	10.75	12.90
OIL TEMP	F	3.00	3.60	4.32	5.18	6.22	7.46	8.96	10.75	12.90
DEW POINT	V	.01	.01	.01	.02	.02	.02	.03	.04	.04
TEMP 1	F	2.00	2.40	2.88	3.46	4.15	4.98	5.97	7.17	8.60
TEMP 2	F	2.00	2.40	2.88	3.46	4.15	4.98	5.97	7.17	8.60
TEMP 3	F	2.00	2.40	2.88	3.46	4.15	4.98	5.97	7.17	8.60
TEMP 4	F	2.00	2.40	2.88	3.46	4.15	4.98	5.97	7.17	8.60

Table 1 indicates a set of Quality Class Factors ranging from Class 1, the tightest, to Class 9, the sloppiest.

We arrived at the class factors on the basis of a massive machine survey that included over 1800 machines currently in production. Accordingly, Class 1 represents the best machines in operation today and Class 9 represents the worst machines that can still produce acceptable quality on highly tolerant tooling and material combinations.

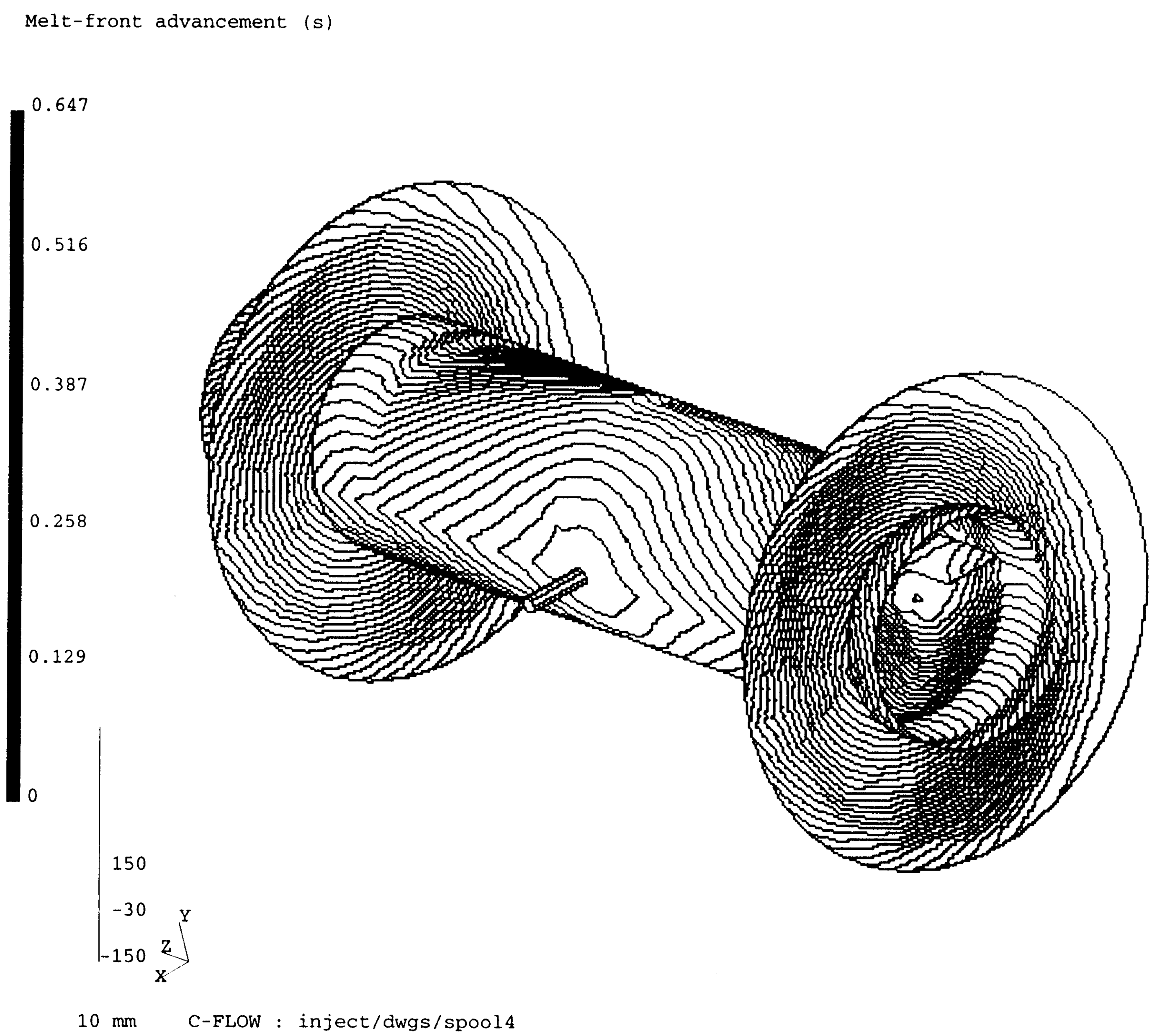
It is to be noted that the accuracy or validity of these classifications is of no importance. What is important is that a yardstick exists TO WHICH ALL MACHINES CAN BE COMPARED.

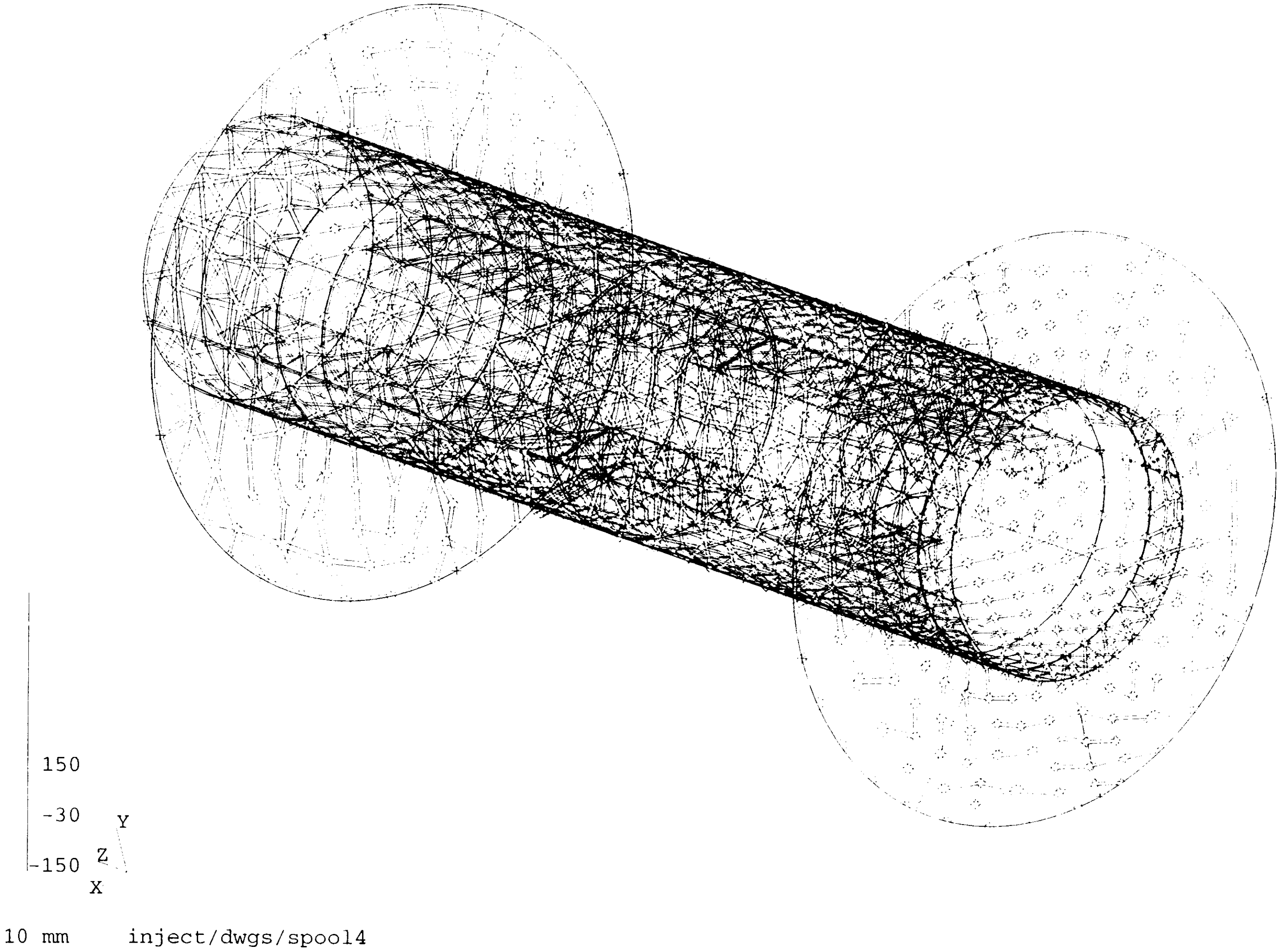
The data in Table 1 is now used by several processors to determine machine capability in the plant successfully. Accordingly, it is becoming a common standard among CIM users.

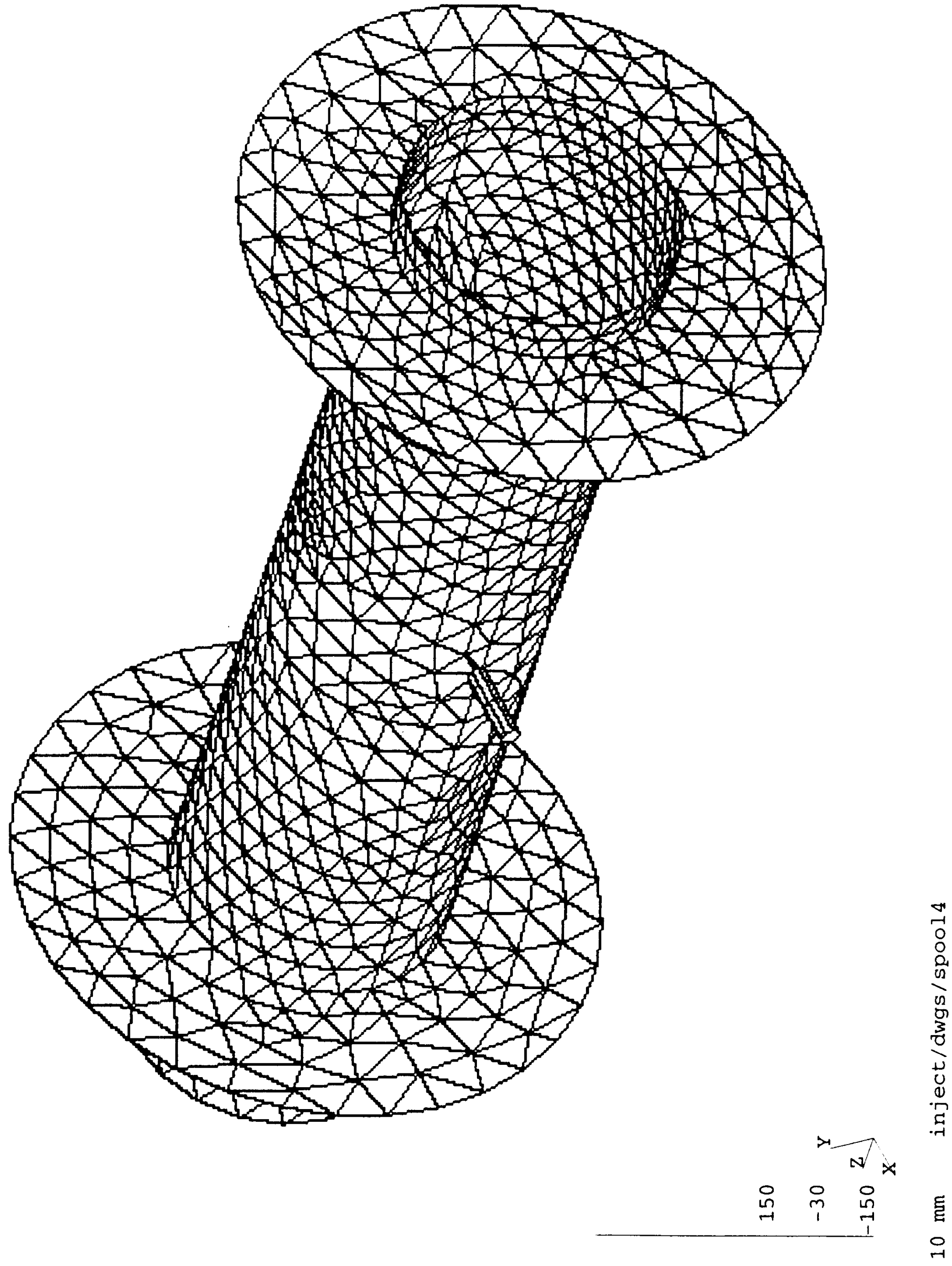
The ultimate objective is to determine the CURRENT MACHINE CAPABILITY and to improve each machine to a higher class level on a cost-effective "rifle-shooting" schedule.

[Hunkar]

Appendix D
CMOLD Analysis Documentation


Melt-front advancement (s)
0.647
0.516
0.387
0.258
0.129
0
150
-30
-150
Y
Z
X
10 mm
C-FLOW : inject/dwgs/spool4


150
-30
-150
Y
Z
X
10 mm
inject/dwgs/spool4


10 mm
inject/dwgs/spool4
150
-30
-150
Y
Z
X